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iMAGINE—Visions, Missions, and Steps for Successfully Delivering the Nuclear System of the 21st Century

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Abstract: Nuclear technologies have the potential to play a major role in the transition to a global net-zero society. Their primary advantage is the capability to deliver controllable 24/7 energy on demand. However, as a prerequisite for successful worldwide application, significant innovation will be required to create the nuclear systems of the 21st century, the need of the hour. The pros (low harmful emissions, high reliability, low operational expenses, and high energy density) and cons (environmental damage, fuel waste disposal concerns, limited uranium reserves, and long construction time-frame) of nuclear are discussed and analysed at different levels—the societal and public recognition and concerns (accidents, weapons, mining, and waste) as well as the scientific/engineering and economic level—to assure a demand-driven development. Based on the analysis of the different challenges, a vision for the nuclear system of the 21st century is synthesised consisting of three pillars—**unlimited nuclear energy**, **zero waste nuclear**, and **accident-free nuclear**. These three combined visions are then transformed into dedicated and verifiable missions that are discussed, in detail, regarding challenges and opportunities. In the following, a stepwise approach to the development of such a highly innovative nuclear system is described. Essential steps to assure active risk reduction and the delivery of quick progress are derived as answers to the critique on the currently observed extensive construction time and cost overruns on new nuclear plants. The 4-step process consisting of basic studies, experimental zero power reactor, small-scale demonstrator, and industrial demonstrator is described. The four steps, including sub-steps, deliver the pathway to a successful implementation of such a ground-breaking new nuclear system. The potential sub-steps are discussed with the view not only of the scientific development challenges but also as an approach to reduce the regulatory challenges of a novel nuclear technology.

Keywords: nuclear; nuclear energy; nuclear reactors; nuclear waste management; iMAGINE; strategic development; vision development; mission development

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1. Introduction and Background

In October 2021, the UK committed to the use of advanced nuclear technologies as a significant share of the decarbonisation of the economy and delivering on its future net-zero obligations, which is ably highlighted in the following statement: "A clean, reliable power system is the foundation of a productive net zero economy as we electrify other sectors—so we will fully decarbonise our power system by 2035, subject to security of supply. Our power system will consist of abundant, cheap British renewables, cutting edge new nuclear power stations, …" [1]. This is a strong, positive message since the change to net-zero, with the elimination of hydrocarbons, will have a tremendous influence on the whole energy system due to the reduction of freely storable energy resources (such as storage-based hydro and hydrocarbon-based systems), which can be turned into secondary energy on demand [2], and defines the challenge for a future energy system. Nuclear energy production will give us the opportunity to fill this gap in a sufficient and sustainable long-term way, but only if we are able to close the fuel cycle and use fertile materials, such as U-238, as additional fuel resources [3].

However, at least acceptance, and ideally a clear positive recognition of nuclear, is one of the key factors for the future success of nuclear energy technologies. It is a prerequisite in order to achieve the development goals—by delivering the required contribution to energy production and positively influencing worldwide development. Problems in public perception and recognition have, for example, in Germany, led to the phase-out of all nuclear power plants even if they could have played an essential role in the "Energiewende" [4].

Historical accidents at nuclear power plants, such as in Three Miles Island (TMI), USA, Chernobyl, erstwhile USSR, or Fukushima, Japan, have increased the public's risk perception and reduced the acceptance of nuclear plants significantly [5,6]. These accidents were associated with reduced trust in nuclear power and an increase in environmental damage recognition and attitudes towards risk avoidance. These accidents represent some vulnerabilities experienced by society due to the operation of nuclear power plants and related consequences of accidents, for example, radiation exposure and its inherent perceived horror, rumours about adverse impact on individual's health and environment, and lack of trustworthiness due conflicting risk communication [7]. Bromet [7] found that people affected by such accidents had lower self-reported health, known as a strong predictor of people's risk of morbidity, mortality and social outcome, and suffered unexplained medical issues, such as anxiety. These results might be explained by the well-known discrepancy of individually perceived risk and the actual measurable risk [8,9]. The risk perception of nuclear power was historically impacted by the lack of transparency in reporting about the accidents, which also led to distrust and hostile attitudes towards governments and the scientific community.

Other concerns are related to the unsolved nuclear waste disposal problem and its perceived health threat in society. Till now, people do not approve of any plans to dispose of nuclear waste neither near their homes or further away [10]. A study from Finland by Vilhunen et al. [11] talked about the "intragenerational and intergenerational injustices" (p. 1) from community experiences when becoming a host for the final disposal of nuclear waste. Furthermore, radioactive waste is perceived by society as dangerous for "health, safety and environment" [12] (p. 69); [13]. The ignorance of societal concerns regarding nuclear waste by nuclear scientists contributed to increased negative attitudes in society against any final disposal decisions [10].

Furthermore, the public's perception that uranium mining is dangerous for individuals' health and the environment is based on the early stages of uncontrolled mining for military and monetary purposes [14]. The danger of uranium mining concerns the "health and safety of miners and mine sites; health and safety of people in the immediate vicinity who might be affected by the spread of radioactivity from the tailings or tailing ponds; and global health and environmental effects of increasing background radiation and water contamination" [15] (p. 470). Increasingly, research is carried out exploring the impact of uranium mining on the environment [16]. The study by Dewar et al. [15] states that uranium mining has a detrimental effect on the environment due to contamination with dust, radon gas and water-borne toxins and impacts people's risk perception. This negative risk perception might be caused by the historical and current release of ionizing radiation and limited interest in caring for the safety and protection of humans and the environment whilst mining uranium. However, the safety of the people and environment during uranium mining should have the highest priority, and the concerns of society should be taken seriously.

Finally, the experience of the use of nuclear weapons in Hiroshima and Nagasaki (1945) has proven that massive consequences occur when nuclear weapons are detonated. The risk of using nuclear weapons and, in consequence, the anxiety regarding nuclear warfare has risen again and is fostered by the war in Ukraine [17,18]. Research suggests that some people suffer from the anxiety of nuclear weapons—sometimes also called "Nucleomituphobia"—which is not unreal and represents a real danger for society [18,19]. People's concerns reach much beyond the use of nuclear weapons, with the mere existence and fallout of radiation during testing causing severe distress in society. It is known that exposure to large doses of radioactive substances has detrimental consequences on humans and the environment, such as death shortly after or cancer from longer term [20], and the widespread use of nuclear weapons would "lead to a cooling of the atmosphere, shorter growing seasons, food shortages, and a global famine" [21].

Thus, the societal challenges seen in public, given in Figure 1, can be summarised into the following points:

- Fear of accidents such as TMI, Fukushima and Chernobyl and their potential consequences
- Anxiety due to the nuclear waste problem—there is no final disposal. Thus we pass a problem on to the future generations
- Fear of environmental damage and CO_2 production due to the mining of uranium
- Fear of proliferation of nuclear weapons and the materials required for their manufacture through the use of civil nuclear technologies

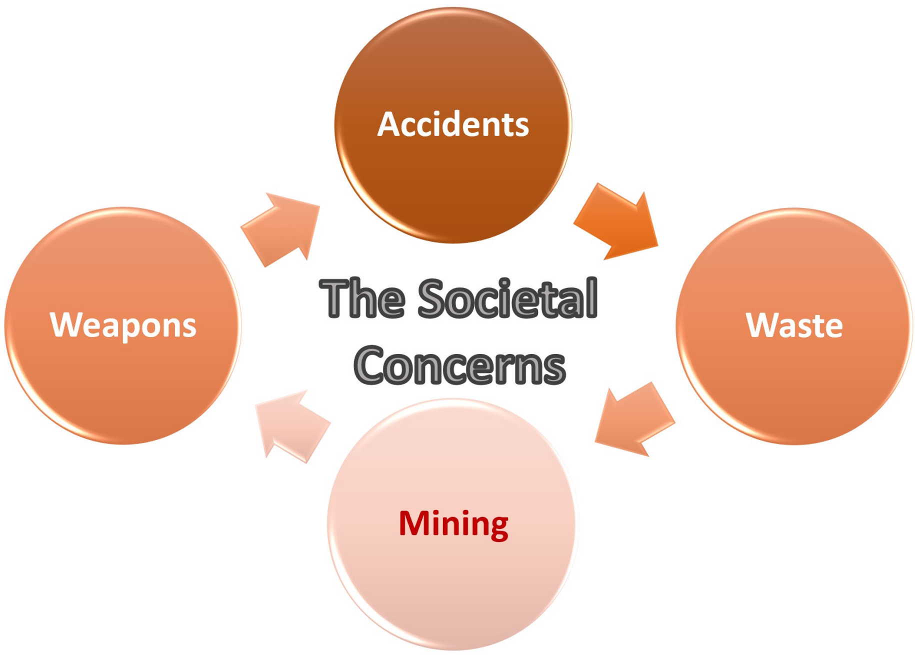

Figure 1. The societal concerns influencing the perception of nuclear energy at a glance.

Over the last decades, little has been done to address these societal challenges and fears and promote higher trust in nuclear power. However, a study by the Department for Business, Energy and Industrial Strategy [22] found that workshops and training sessions helped to increase people's positive views of nuclear power. Based on this experience, the vision of iMAGINE aims to consider these challenges and contribute towards lower risk perception and reduced risk for society and the environment.

Besides this public perception, there are independent, scientific/technical and business-oriented evaluations, for example, one recently published in NS Energy [23] highlighting the pros of nuclear (see Figure 2), proven through operational experience and physical/chemical boundary conditions. Key points are the low harmful emissions "Electricity produced from a nuclear power plant emits fewer greenhouse gas emissions compared to those released by coal power plants and other traditional power generation sources" [23], high reliability "When compared to renewable sources of energy such as solar and wind, power generation from nuclear power plants is more reliable. … Nuclear power units can produce power continuously for several months without any interruption" [23], low operational expenses "Although building nuclear power plants requires huge initial investment, the costs associated with operating them are low. The fuel costs of nuclear power plants are also low and the electricity produced from them is relatively inexpensive" [23], and high energy density "Nuclear energy sources have a higher density than fossil fuels and release massive amounts of energy" [23].

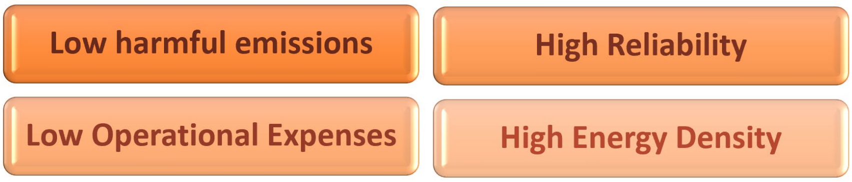

Figure 2. Pros of nuclear technologies as given in the NS Energy publication.

The already proven pros are contrasted with the cons (see Figure 3) based on scientific and economic analysis for a long-term and widespread sustainable operation of nuclear technologies. Interestingly, two points coincide with the public perception of nuclear, environmental damage and waste concern, while the two other points are long-term sustainability and economic attractiveness. The core points are on environmental damage "One of the major negatives of nuclear energy is the impact of uranium on the environment. While transportation of nuclear fuel to a power plant can cause pollution, the process involved in mining and refining uranium is also a concern" [23], on the fuel waste concerns "The vast amount of nuclear waste created by power plants can lead to high radiation and raise temperature levels. … The cost of managing nuclear waste is also high" [23], on the limitation of uranium reserves "Similar to fossil fuels, uranium reserves are limited and are found in few nations, while the processes carried out to mine and refine uranium involve huge costs…. As large quantities of waste are created during the refinement of uranium, any mishandling of the processes can affect the environment and pose health risks to human beings" [23], and on the long construction time-frame "The construction of nuclear power plants usually takes several years to complete as they require large infrastructure…. Massive investments are also required to build a nuclear power plant, as the associated costs of installing radiation containment systems are high" [23].

Figure 3. Cons of nuclear technologies as given in the NS Energy publication.

Limited uranium reserves are presently not seen as a problem for the current reactor operation. This is reflected in the investment in light water reactors without any discussion on fuel availability (using only 5% of the energy content of the fuel) and the decision for direct final disposal (discarding a potential massive energy source underground). Both approaches may be considered acceptable considering the current share of nuclear in the global energy mix [24], but they will not be a sustainable long-term solution if nuclear energy is envisioned to contribute substantially to the worldwide net-zero strategy. In order to avoid a massive increase in the fuel demand and waste generation, relying solely on existing technologies would require a massive increase in the energy content harnessed from nuclear fuel than the current maximum 10% delivered by new reactors.

The long construction time is another problem that is often discussed as one of the factors limiting the growth in the contribution of nuclear to electricity production, but it is, in addition, a problem of the financing of nuclear reactors due to the high share of upfront investment [25]. It has to be seen as one of the big problems in attracting investors since delays and related cost overruns do not allow a robust determination of the investment risk and the potential payback of the investment, which, in the end, makes the projects more and more costly [26]. The delays are often highlighted with respect to the current nuclear projects, such as Vogtle and VC Summer, USA, Olkiluoto, Finland, and Flamanville, Franc,e which face further schedule delays. However, a more detailed analysis using IAEA PRIS data [27], see Table 1, indicates that the problem had already appeared for other reactors with construction or project start/re-start after the Three Mile Island (TMI) accident, see Watts Bar, USA, Civaux, Golfech and Chooz-B, France, compared to the last nuclear power plants developed before the TMI accident, see Emsland, Germany (even if the physical construction started in 1982), or Chinon B 1 to 4, France. A conclusion could be that the increased complexity and the sharpened regulatory demands after the analysis of the TMI accident could be one reason. Another reason could be: "Did we lose the experience and the qualified people due to the massively reduced building activity after TMI?". Indeed, this seems to be the case as highlighted by the statement—"As the western nuclear industry flounders, Russia's Rosatom is building nuclear power plants (NPPs) on time and under budget around the world…" [28]—since other major players are still able to deliver on time and budget. This has to be seen as a challenge, especially when considering that the currently delivered VVER reactors are "claimed" to fulfil comparable safety standards as western products and clearly points to the lack of capabilities and capacities. Both had declined substantially in the decade after the TMI accident due to a lack of orders in the western world.

Table 1. Construction time of various nuclear power plant projects initiated before and after the TMI accident [27].

Country	Nuclear Power Plant Project	Construction/Completion Time (in Years)	Project Start
Germany	Emsland	6	Before TMI accident
France	Chinon B 1 to 4	5–6	
France	Civaux 1 and 2	9 and 8	After TMI accident
	Golfech 1 and 2	8 and 9	
	Chooz-B 1 and 2	12 and 11	
USA	Watts Bar 1 and 2	23 and 12 (+9)	

Based on the aforementioned discussion, we propose a vision for a nuclear system for the 21st century. The aim is to go well beyond the conceptual framework of the Generation IV international forum, not only working on reactor development but thinking about a comprehensive nuclear system incorporating the complete fuel cycle from cradle to grave. This vision will then be refined into a set of useful, tangible and achievable missions based on the approach of Fredmund Malik [29], followed by the approach proposed for the successful delivery of such a new challenge through a consequent stepwise paradigm, thus the implementation.

2. Vision for a 21st-Century Nuclear System

The demand analysis, as given above, indicates three partly interlaced areas:

- Fuel usage, the related environmental damage and the uranium reserves
- The system-inherent accumulation of nuclear waste and the related final disposal challenge
- Safe operation, fear of accidents and fear of nuclear weapon distribution

The first two themes are related to the efficiency of fuel utilisation since efficient usage of fuel will stretch the uranium reserves, reduce the environmental damage due to mining and also reduce the amount of waste that has to be disposed of. The third point coincides with "prevention of abnormal operation and failures" as level one of defence in depth strategy and the subsequent higher levels, see [30]. The last broader concern about nuclear technologies—long construction time-frame—falls under the topic of implementation and will be covered later in the section on delivery.

The core challenge for the development of the vision is now to get these demands reflected in an "as far reaching dream", as proposed by Malik as the point of origin for the mission development. "It [the mission] often follows from a very broad and far-reaching idea which could be called a vision or a dream. That dream, however, has to be transformed into a viable mission: this is the only way to distinguish useful from useless visions" [29]. In the beginning, only a singular vision—unlimited energy, or, more controversially, the Perpetuum Mobile—had been developed as the working basis for iMAGINE [31]. This has been expanded into a ternary vision now to reflect the full demand, see Figure 4.

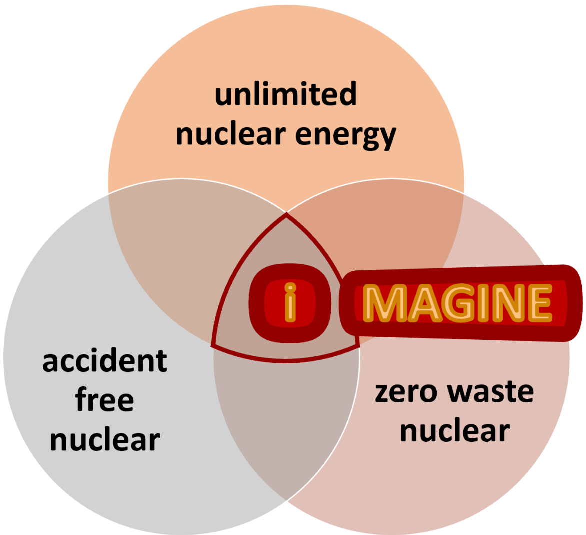

Figure 4. The ternary vision as the basis for the further development of the iMAGINE project.

In general, the vision for developing a new, comprehensive nuclear system, instead of just a reactor, is rather complex and should be very far-reaching. Thus, it seems appropriate to split it into three different core visions—**unlimited nuclear energy**, **zero waste nuclear** and **accident-free nuclear**. All three visions seem to be far-reaching enough to give guidance for the development on a very high level and all three visions are dreams, since it is clear that unlimited nuclear energy cannot be fully achieved due to the limited character of natural resources, whether it be uranium or uranium and thorium. The same can be said about zero waste nuclear since nuclear fission produces such a wide range of fission products—with some producing a high level of radiation and some producing a certain level of radiation for a very long time—that it seems unreasonable to claim that all materials can be re-used. Similar to the first two cases, accident-free nuclear cannot be absolute since engineered systems cannot be designed to be completely accident free, and the system's inherent probability for unexpected behaviour/failure increases with the number of systems being employed.

The next step in strategic development is now to translate these visions into viable missions.

3. Missions for iMAGINE

The following missions have been defined as a part of the strategic philosophy of iMAGINE, based on the visions highlighted above as guidance for the developers to find solutions to the given challenges.

The vision, **unlimited nuclear energy**, is obviously closely related to closed fuel cycle operation since the latter is already well recognized [32] as the gateway to improved uranium utilization. However, only limited progress has been made up to now in the successful implementation of closed fuel cycle operation in the nuclear industry. Even if it can potentially allow the release of a factor of 100 more energy out of the already mined nuclear material, such as spent fuel and tailings, compared to today's light water reactor technology. The mission aims to create a significant amount of energy without mining new resources, see Figure 5.

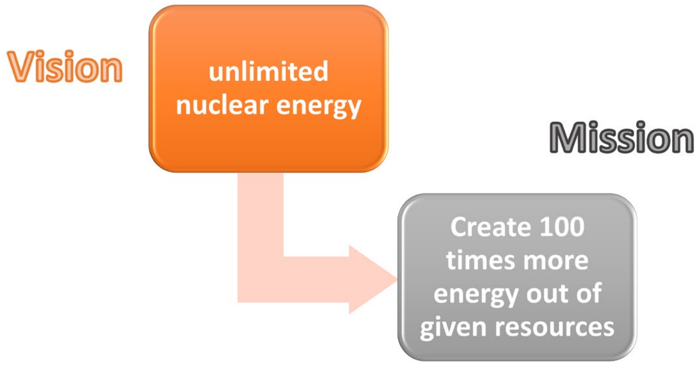

Figure 5. Translating the vision of unlimited nuclear energy into a viable mission.

The aim here is to make the already mined resources available through advanced technology development without creating proliferation issues while massively reducing the complexity of the fuel cycle compared to the one with external reprocessing proposed for solid-fuelled reactors, see Figure 6. The mission, in addition to the massively improved resource utilisation, delivers a significant improvement in resource security for all countries that have operated nuclear power plants in the past since stockpiles of spent fuel and tailings will be already available. At the same time, it also enables other nations the option to start the iMAGINE system with enriched uranium and subsequently feed it with the tailings accumulated during the enrichment process. The mission should be accomplished through the development of the closed fuel cycle in an integrated system. Rather, this disregards the complex split fuel cycle consisting of fuel production, reactor operation, fuel cooling and reprocessing in multiple cycles to ease future industrial implementation along with reduced investment into the whole nuclear system.

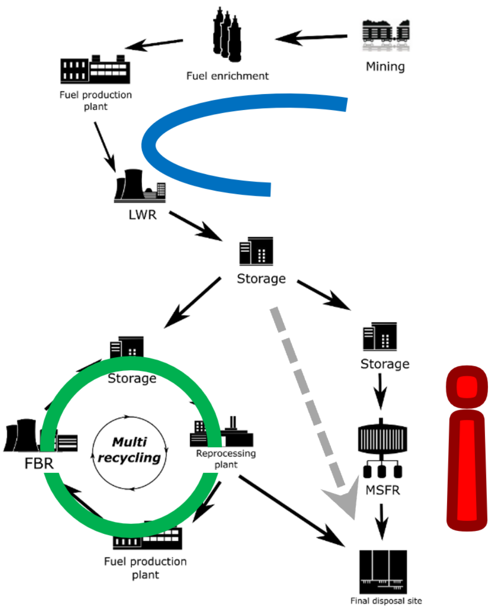

Figure 6. Fuel cycle options: open fuel cycle, closed fuel cycle and the envisaged implementation of iMAGINE.

The vision, **zero waste nuclear**, is closely related to improving fuel usage, but it should not be forgotten that nuclear waste—not having disposal solutions or a sustainable strategy implemented for the nuclear waste—in addition, is one of the major impediments of more widespread societal acceptance of nuclear energy. Improved fuel usage will ideally help to avoid the disposal of valuable material into the waste stream, as currently happens with U-238 in the spent fuel of LWRs, while the number of fission products created per unit of energy could be seen as a natural constant of nuclear energy conversion. Thus, integrated closed fuel cycle operation is one of the aims reflecting the demand of reducing the waste amount per unit of energy produced by releasing almost all energy from the material that has already been mined; this is the part that links to the mission of unlimited energy. The objective is to reduce the waste per unit of energy to 1% or lower, compared to LWR open fuel cycle operation, see Figure 7.

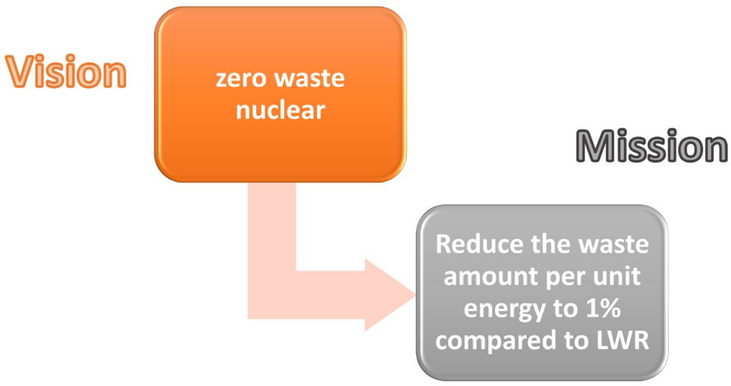

Figure 7. Translating the vision of zero waste nuclear into a viable mission.

This can be achieved partly through the subsequent use of almost all fissile and fertile material, as well as by developing reasonable strategies for the required fission product removal. However, this approach should ideally be accompanied by a recycling strategy—can we create sustainable use for some of the discarded material, as these are often required for the development of processes in other technologies [33]—thinking about a cascade of potential uses with reduced quality before final disposal of the material, as given in Figure 8. All these approaches will help reduce the amount of material to be disposed of. Even when the material has to be disposed of, it will allow the finding of better solutions due to the massively reduced amounts to be handled. This approach is currently not followed in nuclear energy production, especially not when applying the open fuel cycle accompanied by direct final disposal of spent fuel. The core idea of the cascading down approach will be identifying strategies for the use of fission products separated from the reactor instead of just declaring all fission products as waste.

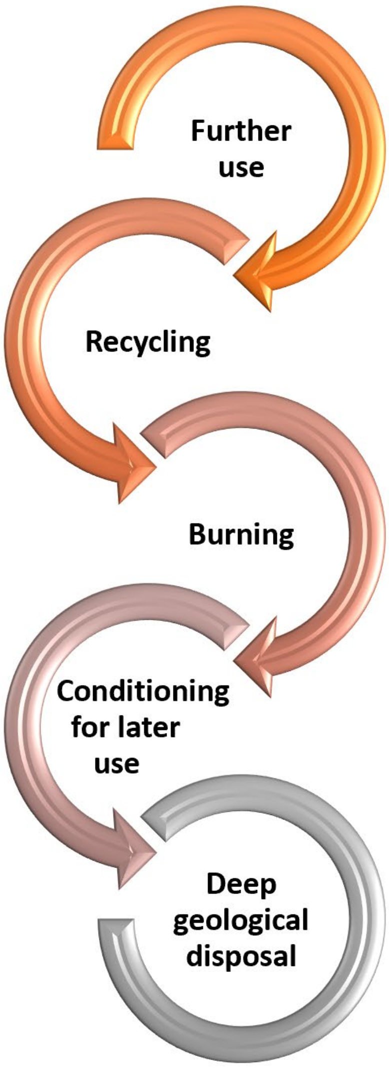

Figure 8. The cascade of potential re-use of materials before these materials should be considered waste needing disposal.

The vison, **accident-free nuclear**, surely has economic as well as societal components and, notably, applies to the completely integrated nuclear system in the case of iMAGINE. The economic components point to the availability/reliability of the facility, the cost of preventing accidents and their effect on the outside world. These points are even reflected in the GEN-IV objectives "Generation IV nuclear energy systems operations will excel in safety and reliability. … will eliminate the need for offsite emergency response" [34]. The societal component seems to be based on the fear of large-scale accidents with a massive release of radioactive materials and the loss of territory due to radioactive contamination, such as what happened in the case of the Chernobyl accident through the distribution of radioactive materials due to graphite fire. Thus, this vision is transformed into strategically reducing the driving forces for potential accidents (reducing the potential for release and spread of contamination) as well as limiting the consequences of accidents in the facility. The key points are relying on a low-pressure primary system and ideally developing a low-pressure energy conversion system that could deliver a higher efficiency as the potential link to energy. Other important factors are eliminating accident initiators, such as avoiding excess reactivity, and reducing the potential radiological source term of the system, see Figure 9.

Another objective is limiting the potential of proliferation and other high-risk incidents in the integrated nuclear system. The most prominent ones besides the risk of proliferation are the risk of misuse and theft of fissile material and the risk of unintended release of radioactive materials.

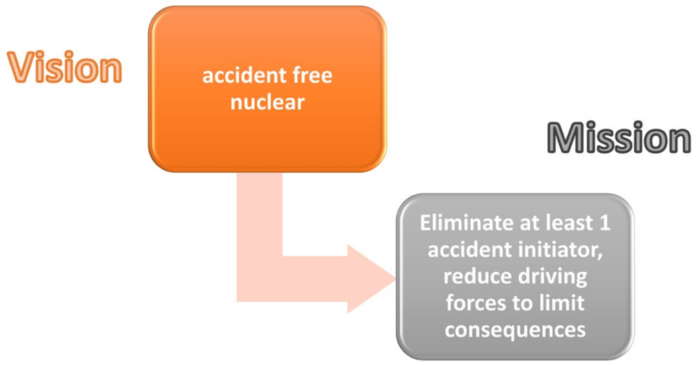

Figure 9. Translating the vision of accident-free nuclear into a viable mission.

4. The Technology

The described vision aims much higher than the approaches of GEN-IV [34] since it requires an integrated fuel cycle system to deliver a closed fuel cycle approach within the energy production system instead of just a reactor technology. The proposal is already supported by a significant body of research. The development is based on integrative thinking of the complete nuclear system for energy production [31] as well as for waste management [35] instead of focussing on reactor development while locating it, in the best case, in a complex, partly already existing, fuel cycle to allow the recycling of fissile material.

iMAGINE is based on molten salt fast reactor technology with a highly integrated fuel cycle operating with a continuous salt clean-up system based on the approach of reverse reprocessing based on a demand list, systematic optimization of the chemical approaches [36], inter-disciplinary studies [37] and operational analysis [38]. The system operates on a tertiary chlorine salt system $NaCl$-UCl_3-UCl_4 to allow a high heavy metal content in the core to support self-sustained breeding in a eutectic with reasonably low operational temperatures [39]. It is designed for operating on SNF or deleted uranium, making waste and tailings an energy resource to avoid the demand for the mining of new fuel materials [3]. The reactor is mainly controlled through very strong inherent feedback effects [40] and does not require excess reactivity due to the opportunity for online feeding. It is supported by online reverse reprocessing to improve recycling and conditioning options for fission products and to eliminate the demand for the separation of fissile material [33]. The design basis delivering homogeneous breeding and reverse reprocessing helps to avoid the separation of fissile material and thus will reduce proliferation issues. The stepwise approach for the development has already been studied to deliver the understanding of dimensions [41], control [42] and optimization [43] of a zero power experiment, as well as a general discussion of the role of such an experimental facility for the development of new technology [44]. The potential opportunities of this new approach to waste management and the final disposal situation of nuclear have already been discussed in [33].

The technology that comes closest could be BREST, developed in the Proryv project [45], demonstrating partly comparable approaches such as a fully integrated fuel cycle [46] and advanced reactor design with strong limitations on excess reactivity [47], but due to the use of solid fuel, the demand for the separation of fissile material and thus upcoming proliferation issues, cannot be avoided in the current development.

5. Implementation

Providing the vision and developing the missions provide a strong foundation for the development of iMAGINE as a nuclear solution for the 21st century, see Figure 10. However, the whole approach could still be seen as a dream without concrete plans for its implementation and delivery. This will also encompass the point of extensive construction times, the only point not tackled as a part of the vision and mission development.

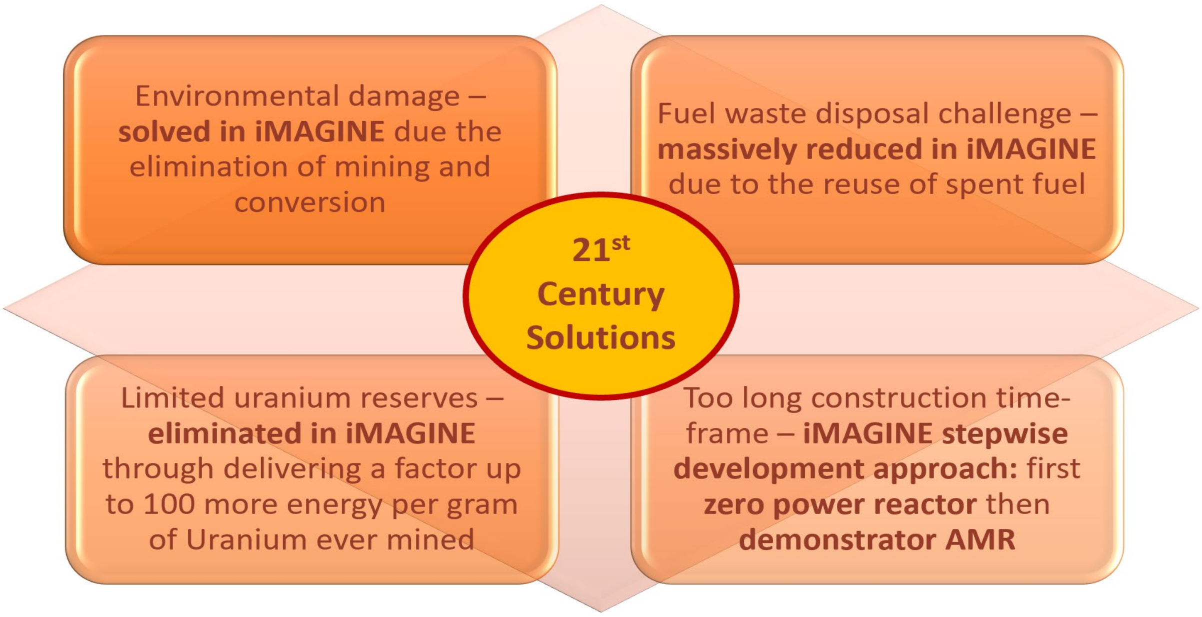

Figure 10. Overview of the solutions offered by iMAGINE to resolve the challenges of the 21st century in the view of the public as well as in the scientific and business community.

First of all, we need a good reason for the investment in the implementation of new technology. To make this argument, it is important to see the opportunities of the new technology as described in the vision and missions. It is also necessary to understand the risks of new development along with risk mitigation measures for potential investment at different levels. The long construction time is only one of these aspects, and the focus should be on identifying and reducing the broader technological risks. However, it is important to note that potential reasons for long construction times might be totally non-technical in nature and, instead, be rooted in a lack of political and/or societal support, which results in the withdrawal of required political will and/or in demonstrations leading, in the worst case, to civil disobedience. Nonetheless, from a technical point of view, some steps have to be delivered, and the aim has to be to develop a system that is simpler and quicker to build. Typical points are the use of a low-power system, a reduced number of highly complex safety and mitigation systems as well as the consequent use of inherent safety and stabilization processes already in the early stages of the design.

The general multi-dimensional risk reduction strategy in iMAGINE is as follows:

- Financial
  - A stepwise plan to mitigate the development risk by creating an approach to deliver quick feedback, early recovery from problems during the development phase and, in addition, the capabilities and capacities required for the successful implementation of a new reactor system [44].
  - Operational safety risk reduction due to a low-pressure system with significantly reduced accident risks and initiators and early safety demonstrations through experiments to enable lowering of insurance and off-site response requirements.
  - Consequent use of inherent safety approaches to reduce the reliance on complex, redundant technical solutions.
- Political/Societal
  - Mitigation of energy and resource security risk through the utilisation of materials that are already stored within the country's borders and transforming the waste disposal problem into reservoirs of huge energy resources and wealth.
  - Reduction of the nuclear waste storage challenge by achieving a new level of waste recycling and, ideally, harnessing additional accessible material resources as well as improving the chances of finding a final disposal site.
  - Decreasing the instability risks in national electrical grids by delivering reliable and controllable, 24/7 net-zero energy production based on existing resources.
  - Limiting the risk of proliferation, misuse and theft of nuclear materials by eliminating the enrichment process and the separation of fissile material in the fuel cycle.
  - Eliminating, by far, the largest environmental damage by avoiding mining and conversion and even reducing the very long-term release risk from final disposal.
- Building trust in society whilst considering health and safety concerns.

It is not only important to talk about risk reduction itself but also about effective risk communication, a point that was raised in public recognition. In most cases, the problem lies in not being able to effectively and transparently communicate with the general public about nuclear facilities, including their advantages, the existing or non-existing risks and mitigation measures. A future approach should be based on working with communities and listening to the concern of the people affected; we could call this a participatory approach.

6. Delivery

Acting on the long construction time is an essential part of success, and the fundamental philosophy of iMAGINE is returning to the development pathway used back in the 1950s, when nuclear really was a new technology, by applying a gradual stepwise approach to develop this highly innovative nuclear system. Such a paradigm shift is essential to enable the fast creation of operational experience, drive active risk mitigation and deliver quick progress [3,48]. An up-to-date four-step process has been developed on a historic basis, consisting of basic studies followed by zero power and other demonstration experiments, a small-scale demonstrator and an industrial demonstrator, see Figure 11. A comparable process is followed by Rosatom for the development of their molten salt reactor programme: national programme, research reference facility, research reactor and large-scale reactor, as published in 2019 [49]. This is in contrast to many of the recently proposed solutions for innovative reactors delivered by the private industry.

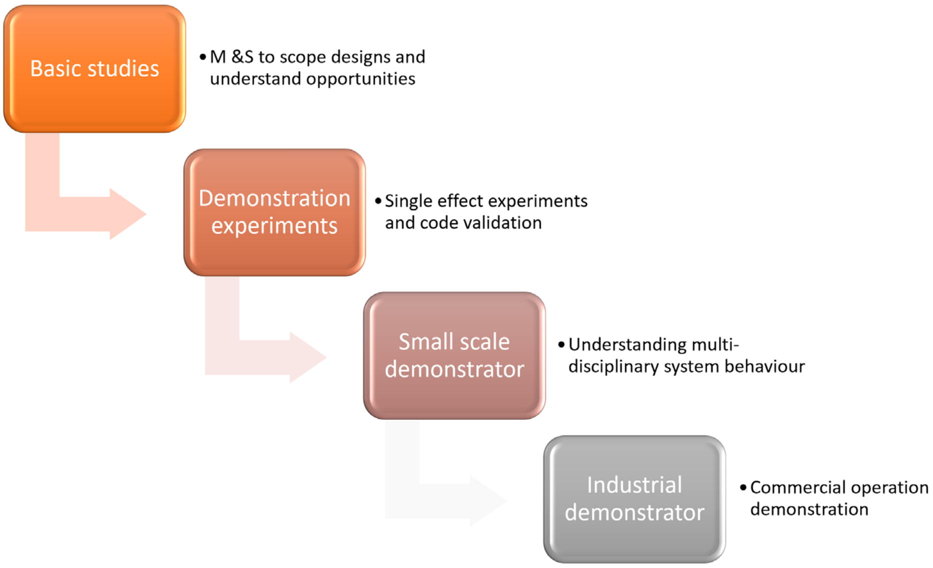

Figure 11. The four-step process proposed for the development of a breakthrough reactor system.

However, these four steps are only the beginning and will have to be filled with an additional set of small, intermediate steps within each main step, keeping in mind that the current regulations have been developed for light water reactors and completely new demands will arise for a system such as iMAGINE, see Figure 12. This challenge will have to be treated collaboratively between the developers and the regulators, similar to the situation when nuclear technologies were nascent and completely new. The key challenge for success will be for the developer to start a journey together with the regulator by defining the detailed steps in a mutually convenient shape for both partners as well as larger society. The process should be based on assuring timely feedback and stepwise learning in successive, partly overlapping projects. The aim must be to deliver an innovative key-step approach to assure rapid and sustainable progress, which is essential to make nuclear ready for a significant contribution to the net-zero goals in 2050. For this, a concrete fundament for discovering a highly innovative breakthrough technology has to be delivered by following a step-by-step process to open a game-changing opportunity. However, the key to success will not only be to get the regulator engaged early but also other future stakeholders and the broader public. The stepwise approach has to be delivered here, too, geographically from the wider to the narrower engagement while taking care of the sensibilities of the local host communities as soon as a site selection process has been started to receive positive and broad support from the host community while demonstrating the sensibility for the local concerns.

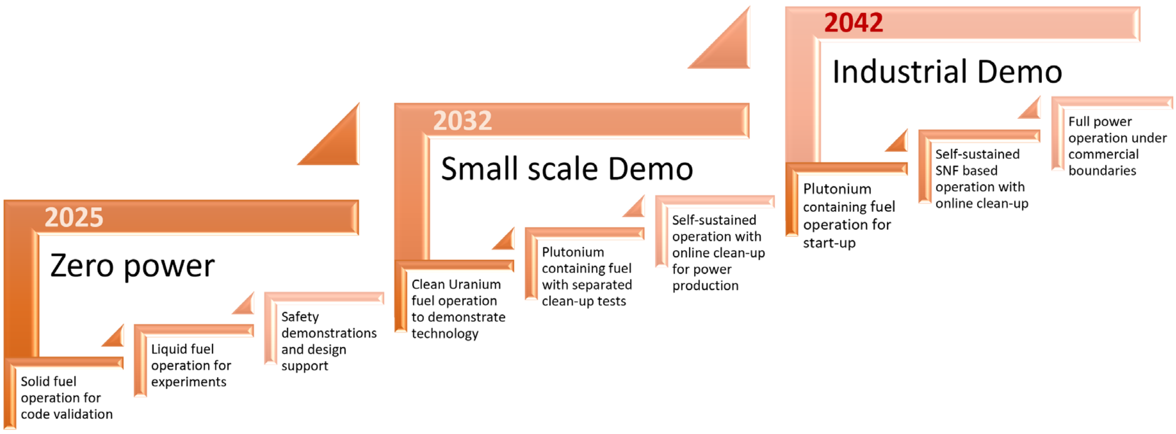

Figure 12. Proposed approach for a step-by-step approach for the development of iMAGINE with indicative dates.

The first steps that most probably have to be delivered in the framework of a national program are:

- A zero-power experimental facility for fast and inexpensive learning and delivery, as the first step into a new reactor technology, the related fuel production and regulation, as proven in the past [48]
- A small demonstrator AMR, operating ideally within 10 years for an estimated budget of £1Bn.

Interestingly this approach for the development and delivery of really new, innovative reactor systems through the initiation of national programs coincides again with the historic experience described by the Electric Power Research Institute (EPRI) in [49]. In addition, the new Russian programme on developing a molten salt reactor as a tier two burner for waste management follows a comparable stepwise approach [49] with the research programme recently investigated in an international project [50].

7. Conclusions

In order to ensure that nuclear technologies can attain their massive potential in enabling a global net-zero future, a highly strategic approach for the development of a set of demand-driven visions has been applied. The research for the demand is not limited to only a techno-economic analysis of the pros and cons of nuclear but is also based on the analysis of public perception and the fears articulated by the affected people. The proposed strategic, demand-driven approach should support the successful worldwide application of nuclear technologies by delivering significant progress compared to existing solutions with the aim of creating and delivering an innovative nuclear system of the 21st century, the need of the hour.

To create the basis for a truly demand-driven development, the pros and cons of nuclear are discussed and analysed on different levels—the societal and public recognition as well as a techno-economic level. Based on these analyses, a three-fold vision is delivered containing the three pillars **unlimited nuclear energy**, **zero waste nuclear**, and **accident-free nuclear**. After defining the visions, they are translated into explicit and verifiable missions, given as follows. A detailed discussion of these missions with respect to the evaluation of different approaches and support for future development is presented.

- **Releasing a factor of 100 more energy** out of the already mined nuclear material.
- **Reducing the waste per energy to 1% or lower**, compared to LWR open fuel cycle operation.

- **Reducing the driving forces for potential accidents** as well as **limiting the consequences of accidents.**

This is followed by the description of a stepwise approach for the development of such a highly innovative nuclear system to assure active risk reduction and the delivery of quick progress in response to the critique on the currently observed extensively long construction time associated with new nuclear plants. The four-step process—basic studies, experimental zero power reactor, small-scale demonstrator and industrial demonstrator—as the pathway to a successful implementation of a ground-breaking new nuclear system is presented.

The four-step process has been further refined with multiple intermediate sub-steps and risk mitigation at each stage. The process is rounded up with the proposal to work in close collaboration with the regulator to assure fast development and delivery of a highly innovative and holistic nuclear energy technology. However, the key to success will not only be to get the regulator engaged early but also other future stakeholders and the broader public.

The stepwise approach has to be delivered here, too, geographically from the wider to the narrower engagement while taking care of the concerns of the local host communities as soon as a site selection process has been started to receive positive and broad support from the host community whilst caring for the societal needs and public value.

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