iMAGINE – A Disruptive Change to Nuclear or How Can We Make More Out of the Existing Spent Nuclear Fuel and What Has to be Done to Make it Possible in the UK?

Bruno Merk, Dzianis Litskevich, Aiden Peakman and Mark Bankhead

Background The energy trilemma (e. g. by the world energy council *[1]*, an UN-accredited global energy body or the scientific community *[2]*) and the United Nations sustainable development goals (UN Sustainable Development Goal 7: "Ensure access to affordable, reliable, sustainable and modern energy for all as one piece of sustainable development of the future world"*[3]*) form the key drivers for the future of all kinds of energy research. These goals lead to a strong, urgent demand for reliable as well as controllable low carbon electricity production technologies to address the low carbon strategies following the commitments of the COP 21 agreement in Paris *[4]*. For the United Kingdom, Nuclear technologies are recognized to have the potential to become the key technology to meet the CO_2 reduction targets, but only if the development targets for nuclear will be met. However, the Emissions Gap Report 2017 of United Nations Environment Programme (UNEP) *[5]* identified that the Contributions set in Paris 2015 will even not be sufficient to hold global warming to well below 2 °C. In 2007, the UK formally re-introduced nuclear power into its overall energy policy followed by a long-term Nuclear Energy Strategy in 2013 *[6]*, leading to subsequent plans to build new reactors. These plans are now starting to materialize at the Hinckley Point C site *[7]* with the construction of two pressurized water reactors and the Wylfa project *[8]*, which is foreseen to lead to two advanced boiling water reactors, even if currently on indefinite hold. However, these projects rely on commercially existing technologies, delivered by worldwide acting companies, and are essentially based on technology developments of the 50ies and 60ies. In addition, the decision for the new build programme, along with the closing down of reprocessing in 2018 *[11]*, creates a demand for developing novel, innovative technologies to deal with spent nuclear fuel (SNF) of existing and upcoming reactors. The case for recycling (reprocessing) is driven by factors such as closing the fuel cycle and the costs of disposal/burning of transuranic, with various scenarios proposed *[16, 17]*.

In general, two different approaches for research and development (R&D) of new technologies can be distinguished: the demand or user driven innovation vs the technology driven. Historically, nuclear industry has been mostly applying the technology driven approach to create novel solutions and technologies in an evolutionary manner. A typical example is the development of the closed nuclear fuel cycle based on applying reprocessing technologies (PUREX process) which have been developed to separate Plutonium from irradiated fuel. The cycle can be closed using fast reactor technology which has existed since 1951, when the first power-generating nuclear reactor, the liquid metal-cooled fast reactor EBR1, was put into operation *[9]*. Another example is the nuclear waste management using the technology of partitioning and transmutation (P&T), separating long-lived TRUs and burning them in reactors *[10]*. The partitioning is based on the existing PUREX process with additional downstream processes for minor actinide separation and the transmutation uses liquid metal cooled fast reactors.

We propose a much more strategic approach applying demand driven innovation and strategic development procedures to direct nuclear technologies into a brighter future *[18, 19]*. In our view, the technology driven approach has not been successful in re-creating the strongly required belief in nuclear technologies, which has been lost in the 1980ies. However, belief in a technology is the key to get the urgently needed public, private and political support. The key points for the strategic development process are combined in the questions:

- What technologies are currently existing and where does these come from?
- What is the demand we are currently facing and what is expected for the future?

This information will be used to develop a vision for the future to provide a direction for the researchers and a mission to come as close as possible to this vision or dream.

Demand Driven Strategic Development

Based on the demand of sustainable power production, see "energy trilemma" and UN SDG7, the next, disruptive development step should be driven by an ultimate, holistic vision for any kind of energy production. This vision needs to be by definition much more advanced than the development goals of the first nuclear reactors, and broader than the goals of the Generation IV international Forum – a co-operative international endeavour, set up to carry out the R&D needed to establish the next generation nuclear energy systems *[12]*. This vision (call it a dream or the end of the rainbow) can be given with one simple, old phrase – "perpetuum mobile" or by the old promise of nuclear, "too cheap to meter" (nowadays economically as well as environmentally), whilst recognising that this represents as a conclusion an unattainable goal. Fredmund Malik characterizes the function of vision and mission as follows: "A mission is definitely necessary… It 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" *[13]*, see **Figure 1.**

When translating the vision into the mission some realistic limitations have to come into play to create a solvable challenge. It is fairly obvious why the vision is unattainable, the first and second laws of thermodynamics prevent the "perpetuum mobile" from operation outside of the hypothetical. Harsh economic lessons we have learned over the last four decades have shown that "too cheap to meter" is equally unobtainable in a modern world. Thus we should call both a dream or "the end of the rainbow". However, this dream provides a far-reaching development goal which should give R&D the right direction. The key words for our vision and the goals of our mission are given below:

The end of the rainbow

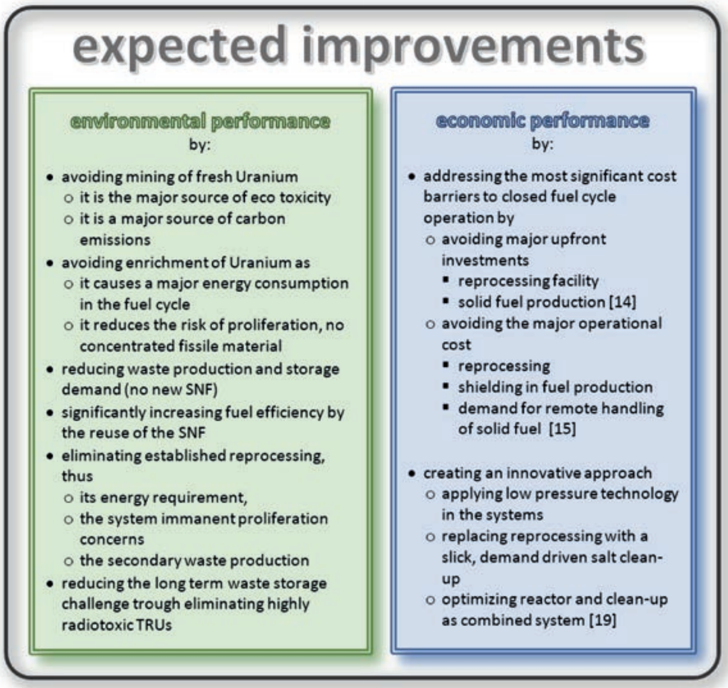
- No resources requested/used
- No waste produced
- Too cheap to meter, reliable, safe and secure

Real life objective

- Utilize existing material
- Produced as little additional waste as possible
- highly economic, reliable, safe and secure

Fig. 1.
The steps of the strategic development process for future nuclear reactor systems.

The very general vision has to be developed into a mission, which is demand specific. It reflects a weighting of the different attributes forming the vision. Our mission could be, to develop a reactor that can breed and burn its own fuel using existing SNF stockpiles. This mission for a disruptive nuclear energy system forms the basis for creating an economically as well as environmentally sustainable approach to deliver a solution for the future massive demand on low carbon energy production. Besides the discussed sustainability, the ideal disruptive nuclear system has to deliver a solution for historically created problems of nuclear reactor operation, the nuclear waste accumulation while avoiding the creation of additional proliferation issues. "Nuclear proliferation, [is] the spread of nuclear weapons, nuclear weapons technology, or fissile material to countries that do not already possess them" *[24]*. Our mission leads to a fast molten salt reactor and the related, significantly reduced fuel cycle with the potential for massively improved sustainability indices, see **Figure 2**. The approach is based on a system operating on existing SNF without prior reprocessing.



environmental performance
by:

- avoiding mining of fresh Uranium
  - it is the major source of eco toxicity
  - it is a major source of carbon emissions
- avoiding enrichment of Uranium as
  - it causes a major energy consumption in the fuel cycle
  - it reduces the risk of proliferation, no concentrated fissile material
- reducing waste production and storage demand (no new SNF)
- significantly increasing fuel efficiency by the reuse of the SNF
- eliminating established reprocessing, thus
  - its energy requirement,
  - the system immanent proliferation concerns
  - the secondary waste production
- reducing the long term waste storage challenge trough eliminating highly radiotoxic TRUs

economic performance
by:

- addressing the most significant cost barriers to closed fuel cycle operation by
  - avoiding major upfront investments
    - reprocessing facility
    - solid fuel production [14]
  - avoiding the major operational cost
    - reprocessing
    - shielding in fuel production
    - demand for remote handling of solid fuel [15]
- creating an innovative approach
  - applying low pressure technology in the systems
  - replacing reprocessing with a slick, demand driven salt clean-up
  - optimizing reactor and clean-up as combined system [19]

Fig. 2.
Expected improvements by the proposed disruptive demand driven, innovative development.

Assembling all given arguments, the aim is to harvest the fruits of the closed fuel cycle, while avoiding the massive upfront investment which has always been associated with liquid metal cooled fast reactors (like the French PHENIX/SUPERPHENIX reactors) and aqueous reprocessing (like THORP in Sellafield/UK).

Today, almost all nuclear reactors are operated in open fuel cycle mode, see **Figure 3**. This terminus describes, the process when fuel is produced, only once inserted into a reactor and then stored/disposed in the form of fuel assemblies without further treatment of the SNF. For a future nuclear system with improved sustainability indices, it has always been envisaged to achieve closed fuel cycle operation and the feasibility has been demonstrated, applying fast reactor technology *[16]*. The UK has followed this approach too, which led to the industrial reprocessing of SNF at Sellafield and the demonstration of fast reactor technology in the Dounreay fast reactor (DFR) and the prototype fast reactor (PFR). However, closure of the fuel cycle has never been achieved on an industrial scale leading to a stockpile of separated Pu as leftover of the successful reprocessing without having the required fast reactor technology established. The driver for the closure of the fuel cycle had disappeared after the oil crisis had been resolved, the uranium prices decreased, and the growth rate of the nuclear reactor programmes slowed worldwide after the Three Mile Island accident. Fast reactor technology as well as the required fuel cycle technologies, specifically the production of the required Pu bearing mixed oxide fuel, has been shown, to be much more complex to be operated than expected.

With the view on long term sustainability, the challenges of the final disposal, and the demand for a massive growth of the nuclear power as one of the most attractive low carbon technologies, we propose to revive closing the fuel cycle but in contrast to the historic approaches now by applying new, demand driven, tailored technologies.

We will consider the idea of closing the nuclear fuel cycle using a molten salt fast reactor operating on SNF which will neither require a supply with new, fresh fuel nor create additional waste to the already existing SNF. In comparison to today's strategy, see **Figure 3**, there are significantly fewer steps and fewer specific demands. The most significant of which is that a fast reactor demands a significantly higher amount of fissile material in the core than in a thermal reactor. This forms the need for some additional fissile material for the start-up, either by enriched Uranium or by Plutonium originating from historic reprocessing operation like it is available in the UK. The additional fissile material is only required for the start-up phase, during operation sufficient new fissile

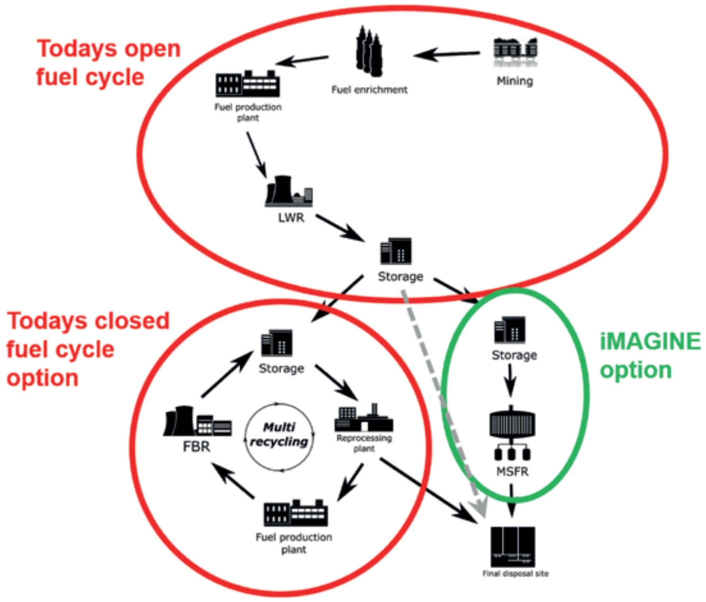


Fig. 3.
Todays fuel cycle and fuel cycle options for the future closing of the fuel cycle.

material will be bred from the fertile U-238.

The feasibility of operating purely on SNF has been demonstrated using advanced modelling & simulation (M&S) *[18, 19]*. The inserted SNF (~95% Uranium, ~1% Plutonium and ~4% fission products) will be transformed into vast amounts of energy and a clean stream of fission products, partly out of the salt clean-up system, partly appearing in the off-gas scrubbing system. Both streams have to be conditioned in an appropriate way to limit the source term under accidental conditions. Compared to the existing process, considering spent nuclear fuel as waste, the mass of waste will remain the same, while the short term activity will clearly increase due to the proportionality between the amount of fission products and the amount of energy produced out of the fuel. The energy 'squeezed out' from the SNF will be increased by a factor of 20 which will lead to the increase of short term activity (up to 500 years) while the long term activity will be significantly reduced due the burning of all TRUs.

This proposed innovative nuclear system will require a complete redesign of the nuclear chemistry applied in the salt clean-up based on the principles described in *[19]* using the inter-disciplinary optimization potential described in "Demand driven salt clean-up in a molten salt fast reactor – Defining a priority list" *[20]*. There are further challenges to be considered on the development path. Challenges on plant structural integrity will need to be addressed either through clever design or operational procedures. Control systems will also need to be developed to manage plant throughput against the strong thermal feedback effects that would occur in such a reactor system which is an essential part of the general safety approach which has to be developed among the other challenges *[21]*. We would be expect to be able to exploit a range of technical innovations drawn from outside of the nuclear sector. Digitalisation and industry 4.0 are delivering digital twin solutions that create a high degree of confidence in our ability to effectively operate such a plant.

The consequences of the proposed approach on the fuel cycle, see **Figure 3**, are massive since the whole concept of the complex closed fuel cycle will be replaced by a really slick process with promised lower complexity, less proliferation concern, and because of this reason, cost reductions can be realised across the industry.

Based on the calculations that have been performed to date the overall performance indicators of a closed fuel cycle based on the molten salt fast reactor are impressive. The neutronic feasibility study indicated that a classical 3 GWth reactor (roughly equivalent in scale to Sizewell B) could be operated for 60 years on 130 tons of SNF and ~ 17 tons of plutonium *[18, 19]* for the start-up. Thus the UK Pu stockpile of 140 tons in 2020 *[22]* would be sufficient to start 8 reactors and the currently stored 8000 tons of SNF (6000 t AGR fuel, 2000 t LWR fuel *[23]*) would be sufficient to operate these 8 reactors for more than 930 years each.

Taking a view into the UK approach to build several new light water reactors and the opportunity of increasing the number of reactors by splitting the salt of operating reactors, it gets clear that this reactor system could be a long term available, reliable, and sustainable low carbon electricity source.

The process of developing a new, innovative nuclear energy system

This journey will be started with a glance into the historic steps and time scales of, at that time, new reactor developments. It will be followed by a short description of each process step for a state of the art development plan to get a deeper understanding what would have to be done to make a new, disruptive nuclear energy system real. This will lead at the end to a short closing remark on the role of the government required for success.

A Glance into History

The analysis of the historic development of UKs MAGNOX technology gives insight into the time scale as well as the process of a new reactor development, even when it has taken place in the middle of the last century. **Figure 4** shows the timeline of the development with several zero power facilities GLEEP (Graphite Low Energy Experimental Pile) in 1947 to Windscale-1 in 1952 *[26]*, which have been used to get first insight into the considered technology and to create the skilled workforce for the next steps. This first phase was followed by a small scale experimental reactor Calder Hall (180 MWth), and after several intermediate steps the full scale demonstrator, with the Hinckley Point power stations achieving almost 1000 MWth. The application of modern, digital M&S technologies will not avoid all real world experiments, but has definitively the

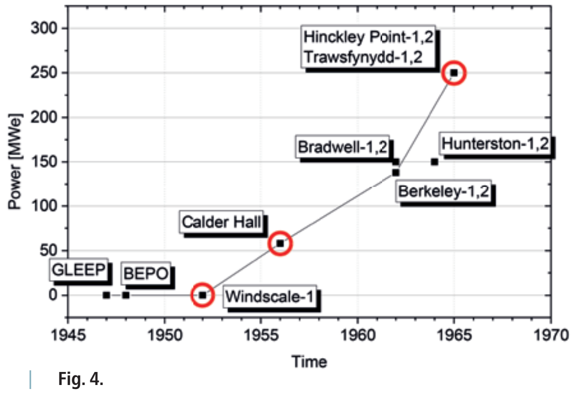


Fig. 4.
Magnox development timeline as described by the Electric Power Research Institute *[26]*.

potential to reduce the number of steps as well as to improve the confidence in choosing the right/ideal settings for the still required experiments. It seems essential to operate at least in a three step approach producing real life facilities as marked in **Figure 4** above by the red circles.

There is the argument that the MAGONX development is from a time that is too distant to be relevant today (1947 to 1956). Instead, let's compare it with a more modern case, one of the last developments of a really new nuclear power technology in the west, the pebble bed high temperature reactor technology in Germany (see **Figure 5**). Even then, this was over 3 decades ago (1966 to 1983). The process still indicates the three major steps, even if the order seems surprising – the small scale technology demonstrator AVR before the zero power experiment. This approach was the result of a very efficient planning based on the experience with the graphite moderated reactor technology in the 60ies, specifically our previous case the MAGNOX programme, and the follow up AGR programme which was an evolution of the MAGNOX technology. Even with this experience of graphite technology, a skilled workforce, and experience with building reactors, the developers came back to the zero power experiment (the KAHTER facility) to gain a deeper insight into the mode of operation and the optimization potential before taking the step to the industrial demonstrator THTR-300.

In the development of the industrial demonstrator, the major arguments for the zero power experiment are the comparably low cost and the opportunity of rapid, flexible, very well instrumented tests to demonstrate and improve understanding of the system behaviour as well as to support licensing code validation, for example forthe pebble flow *[27]*. The benefits of the zero power experiment are an almost immediate accessibility after shut down, the significantly reduced shielding requirements during operation and the flexible operational envelop, allow significantly faster take up of a relevant set of experimental results. Experiments of this kind are almost impossible to implement in power producing systems (in this case the AVR) with high operational temperature, high neutron flux, and a high radiation level due to fission products and material activation.

- How can we use this experience for the planning of a new, disruptive system? What are the arguments for the initial step, an own zero or low power experiment in the UK for new developments?
- Many arguments have been given in the last paragraph why a zero power experimental facility is of high importance for the development of a disruptive, new reactor technology. However, there are two questions remaining: Could we make progress relying on M&S without an experiment at this stage? Can we just go and 'order' some experiments for validation in another facility?

The massive use of M&S will help to create a much better overview of the opportunities and thus to optimize the nuclear system but it cannot replace the experience in experiments completely. Experimental data is at a minimum required to establish model credibility through a process of validation, especially since the performance characteristics of any novel system are to an extent unknown. M&S will help to get the best possible outcome and reduce the number of costly experiments via a down selection process.

There are clear reasons why the start of a nuclear programme is often associated for with the first significant reactor experiment, see the GLEEP experiment in the MAGNOX process given in **Figure 4**. The decision for a low power experiment requires:

- a real commitment to kick off a serious programme for building and operating the facility and the formation of a team of specialists which is able to develop the project
- development and production of the first key components, e. g. the fuel with governmental agency support needed to cover licensing and proliferation of nuclear materials
- the establishment of a supply chain, bringing in Small and Medium Sized enterprises and cross organisation agile delivery
- the close interaction with the regulator to get the experiment licensed
- strong links to nuclear innovation programmes, which will supply the innovative methods and partnerships to undertake our mission

Thus, the zero power experiment will help the UK to create/re-create the essential skills basis in designing, licensing, building, commissioning, and operating an innovative reactor of a completely new type. In addition, an experiment will

- help creating international recognition as basis for future collaboration
- give an opportunity for necessary safety demonstrations in the regulatory process of the next step
- leverage cost saving opportunities by reducing the uncertainty margins in the following design steps
- create a business opportunity by providing financed reactor experiments for other MSR developers with their own designs who cannot collaborate due to sensitivities over sharing of IP.
- serve as a case study and collaborative R&D platform for linking with international partners who want to access the UK market.

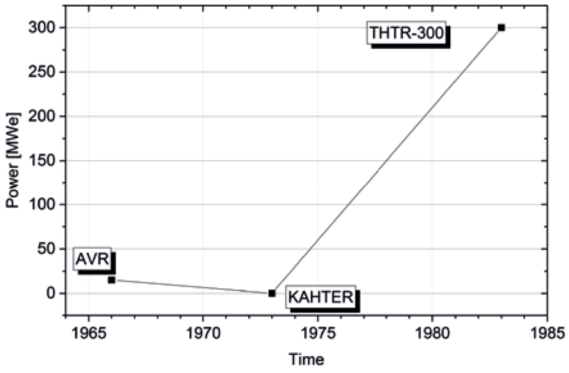


Fig. 5.
Timeline of the pebble bed reactor development in Germany.

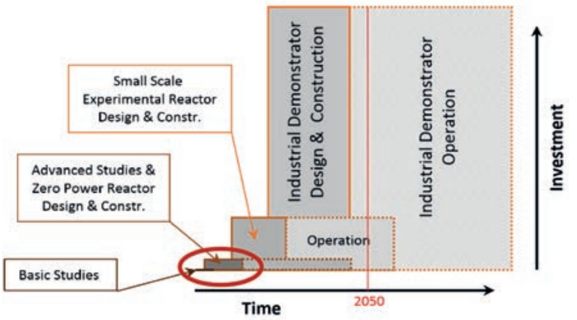


Fig. 6.
Time and investment scales for the development of a disruptive nuclear system

The 4 Steps in the Process

Based on the already proposed reduction of the number experimental facilities a 4 step process will be developed with a rough description what should be achieved in each step. The 4 steps will have different time requirements and will be interlinked. The given timescales are based on the future plan of the BEIS (Department for Business, Energy & Industrial Strategy) nuclear innovation programme with the aim to have a market ready, in industrial application demonstrated product in 2050. **Figure 6** gives a qualitative overview on the time scales (construction and operation) and the required investment for the different steps. From the figure it already gets clear, that the development of a new, disruptive nuclear system does not require large investments in the first years (step 1 and 2, see red mark), which opens the opportunity to work on different systems in the early stages to down select the options before the first large investment for the small scale demonstrator is to be made. Current UK strategy for AMR's could provide a route to kick-start the necessary R&D.

Basic Studies

The basic studies of a new nuclear technology is the time to form a first consortium with academic partners, national laboratories, and industrial players to exploit the proposed disruptive approach and demonstrate its feasibility. It will provide attraction to the industry due to new long term IP creation, and provide scientific underpinning to their own proprietory designs and ideally create public belief and trust in the innovative capacities of nuclear research, 'we are solving the problems of the future'. The necessary modern digital M&S tools will be created and a pool of experts will be formed. They will identify possible deficiencies on M&S basis to work out the challenges and shape the future requirements in more detail. Basic studies will make use of the traditional strength of the country to leverage from recent governmental investments. New capabilities will be built up in subject areas where currently strength is missing by leveraging from international networking, working with supra-national institutions, and attracting specialists from abroad.

Experiments can be used in order to establish fact (validation) or to understand the characteristics of critical components/processes of the system – proof of principle as well as to validate models using basic experiments that examine separate effects *[25]*. In general, large scale modelling does not by definition mean fewer experiments as the number of experiments could increase. But these will be smaller in scale – separate effects – and more numerous, and can be delivered at a lower cost per experiment.

The basic studies step will create the first interaction with the regulator to develop an understanding of a reasonable safety approach and the definition of supporting experiments required for licensing. It will lead to international recognition which can be supported by establishing international research collaborations. This step will support the UK strategic vision for the nuclear 2020 target to establish the capabilities & collaborations necessary for a collaborative research programme across industry and research organizations.

Advanced Studies

In this stage new technology approaches (e. g. salt clean-up) have to be developed and demonstrated using existing infrastructure leveraging past investments. For the scale up a hot salt laboratory for thermal-fluid dynamics and material interaction studies as well as a fuel lab for salt clean-up studies and fuel production (for the zero power experiment) has to be established. Advanced studies will leverage the traditional strength to create innovative approaches and can foster the development of IP within the industry support base. Within this step, the zero power reactor will be a key stage to form a consortium and develop the skilled workers for the next step. Ideally, the zero power reactor can be based on refurbishment of a recently shutdown facility like it has been shown in the GUINEVERE experiments in Belgium. This approach has shown to create significant cost and time savings. As already mentioned a zero power reactor will create the international collaboration opportunities and can serve with experiments for money for industrial players. A comparable approach is offered, e. g. by the IPPE in Russia using the BFS facility for fast reactor technology.

Experimental Reactor

The experimental reactor is typically the small scale technology demonstrator and the first step into a power producing unit. However, it could be used later on as demonstrator for a small size reactor for remote siting. However, this dual approach will require a disruptive development in the process of establishing a reactor system. In our case, the experimental reactor could be initially designed without salt clean-up, operating on enriched uranium (smaller and cheaper) serving a market niche like the Akademik Lomonosov for remote site electricity production *[28]* or for propulsion. The system will be of small size with a power of 10 to 50 MWth even if the demonstration of the self-sustained operation on SNF will not be achievable in a such small size system. To limit and stretch the initial investment requirement the salt clean-up step could be added offline in a second development stage to demonstrate the new technologies. Detailed design, licensing, construction, and commissioning will create the future skilled workforce for the full scale industrial demonstrator. Close technological and financial collaboration with industrial partners will be a key to create innovative solutions in the supply chain as well as possibly a system integrator for the next step. At this point two approaches are possible, a collaboration driven approach for international innovative reactor development, or a more commercially driven approach. The historic boiling water reactor development shows that both approaches can even be followed in parallel *[26]*.

In our case, the experimental reactor will deliver the first operational experience with a liquid fuelled system since the molten salt reactor experiment at Oak Ridge National laboratory in 1965 to 1969 [29]. A key point for a rapid application of the disruptive innovation will be starting with a conservative approach with reduced temperature level and low power density followed by a successive process of stretching the operational envelop to improve the economy performance based on the operational experience and detailed observation of the material behaviour. The experimental reactor is the first opportunity for material testing under real operational conditions involving high temperature, corrosive environment and high radiation level. Taking the step into the experimental reactor early will provide the developer with a steeper learning curve in a new technology and thus an earlier success, but sure on the cost of taking a higher risk. Taking leadership will give the developers the early lead in an innovative technology resulting in excellent market opportunities.

Full Scale Industrial System Demonstration

In this stage industrial demonstration of economic, reliable, sustainable, and safe power production using a new technology for the national as well as the international market is the essential function. The functionality of the entire nuclear system from fuel production over reactor operation as well as salt clean-up and off-gas treatment as one unit has to be demonstrated, thus the application of a new highly sustainable low carbon technology. By providing the first industrial demonstrator since generations, the UK will demonstrate industrial leadership and create the related market opportunities required to achieve a significant market share. The industrial demonstrator can/should already be owned by a commercial operator and should be supported by the government in critical components like the nuclear island and the fuel as well as in the licensing. In the UK currently, this approach is consistent with current policy of supporting industry through the Advanced Modular Reactor programme and is in-line with recent NIRAB recommendations to the UK government.

The IP generated during the development and operation of an industrial scale demonstrator will serve the specific purpose of lowering the technical and commercial risk of licensing and operating a novel reactor technology. Commercial solutions will share some of the underlying technologies, though with additional privately held IP in order to differentiate one commercial design from its competitor.

By no means, the full scale demonstrator need to be a short term operating prototype. Based on massive use of M&S it should be a well-developed, M&S supported, ideal experiment which will be a first of class and thus go into full production for a significant time. There is history for this – the Calder Hall reactor, see **Figure 4**, operated for decades but it was also the full scale demonstrator. It powered Sellafield site (a large town in scale) *[30]*, and was comparable to EBR-II at the Argonne-West site in US *[31]*.

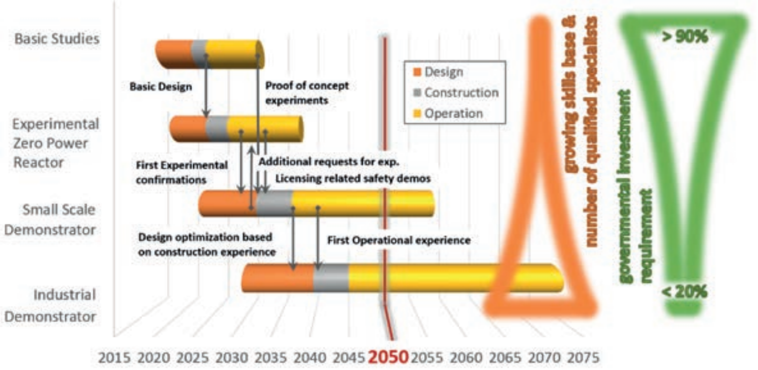


Fig. 7.
Interlinked development processes required for establishing an innovative.

Closing remark

The link between the proposed 4 stages of the process, the required information exchange between the stages, and a proposed time scale is given in **Figure 7**, supported by a qualitative sketch for the national skills base and the requested shares of governmental investment.

The governmental share of the required investment is proportionally higher in earlier phases of the project where the driver is to develop the wider skills base. Later in the programme, the share of government investment is lower due to the fact that industry will be more able to attract the investment needed to commercialise the technology when it is demonstrated as an attractive investment opportunity.

Electric Power Research Institute (EPRI) has analysed the historic development of 4 different reactor types *[26]*. In all cases, the development activities have been carried out and financed by different partners in government and industry. The topic of the zero power reactor is typically in the hand of the government (not shown in **Figure 8** since the study was based on power producing systems), while the next steps are shared with increasing level of industry involvement correlated with the increasing maturity of the technology, see **Figure 8** *[26]*. A detailed analysis indicates that the nuclear island as well as the fuel fabrication and supply for the demonstrators are mainly in the hand of the government while other components are already delivered by the industrial partners. The main reason is that a new, innovative fuel supply has to be handled on governmental level due to proliferation concerns while the nuclear island is subject to supervision of the IAEA and the regulator.

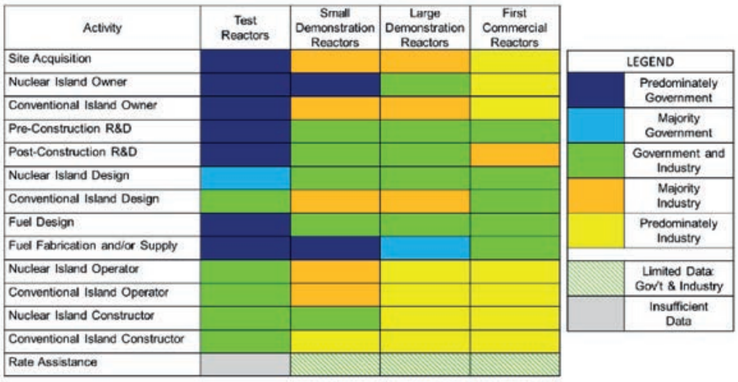
Based on the given arguments highly innovative reactor technologies without a planning for zero power reactor experiment lacks the seriousness which is required to start such an important endeavour. Thus, investing into a reactor physics experiment on an innovative technology will immediately give the UK a high profile in research and the connected international recognition.

Cost estimations given by insiders of the Indian fast reactor programme and the lead cooled fast reactor programme in Russia indicate an overall investment volume of ~10bn$ and 10bn€ respectively to achieve the level of the industrial demonstrator. Within the analysed historic US Programme the investment shares for the first of a kind reactor ranged between 8 % and 86 % governmental contribution with an average of ~ 40 % with higher industrial contribution for mature technologies. In some promising technologies industry has already taken a significant share in the small scale demonstrator (e. g. BWR technology) while in other high risk approaches even the industrial demonstrator has been supported by national governments.

Typically significant teams within a strong leadership in national programmes and research centres have been operated creating the required number of qualified experts and the essential skills level for designing, licensing, constructing, commissioning, as well as operating the 'new nuclear reactors' at that time.

Conclusions

The energy trilemma and the UN development goals form the key driving forces for all kind of energy research. Based on these requirements a universal vision for strictly demand driven strategic development has been worked out based on the key words: no resources requested, no waste produced while being highly economic, reliable, safe, and secure. Following this vision a mission for a future disruptive, demand driven nuclear energy system with the



Activity	Test Reactors	Small Demonstration Reactors	Large Demonstration Reactors	First Commercial Reactors
Site Acquisition	■	🟧	🟧	🟨
Nuclear Island Owner	■	■	🟩	🟨
Conventional Island Owner	■	🟧	🟧	🟨
Pre-Construction R&D	■	🟩	🟩	🟩
Post-Construction R&D	■	🟩	🟩	🟧
Nuclear Island Design	🟦	🟩	🟩	🟩
Conventional Island Design	🟩	🟧	🟧	🟩
Fuel Design	■	🟩	🟩	🟩
Fuel Fabrication and/or Supply	■	■	🟦	🟩
Nuclear Island Operator	🟩	🟧	🟨	🟨
Conventional Island Operator	🟩	🟧	🟨	🟨
Nuclear Island Constructor	🟩	🟩	🟨	🟨
Conventional Island Constructor	🟩	🟨	🟨	🟨
Rate Assistance	⬜	▨	▨	▨

LEGEND	
■	Predominately Government
🟦	Majority Government
🟩	Government and Industry
🟧	Majority Industry
🟨	Predominately Industry
▨	Limited Data: Gov't & Industry
⬜	Insufficient Data

Fig. 8.
Visualization of evolving government and industry roles in the design, construction and operation of test, demonstration and first commercial reactors as described by the Electric Power Research Institute *[26]*.

additional aim of solving the long term nuclear waste problem is developed. Key point for the massively improved sustainability indices is the operation in closed fuel cycle mode based on already existing spent nuclear fuel. Even if the advantages of closed fuel cycle operation are well known, the technology has never been established successfully due to the prohibitively high development cost and high commercial risk.

In the first part, we describe the requirement for a disruptive technology, an innovative molten salt reactor operating on already exiting SNF without extensive and expensive pre-processing. The side requirement is on developing an online salt clean-up, for online removing elements which prevent the reactor from long term operation. This approach will significantly reduce the proliferation risk, the radiation to human in fuel manufacturing, as well as the high reprocessing cost and the even higher cost of solid fuel production, while opening a massive optimization potential due to online linking of reactor and fuel cycle.

In a second part, we developed an innovative process to establish a new, disruptive nuclear system. In contrast to historic approaches, the new process consist only of 4 major stages supported by the massive application of modelling and simulation to reduce the number of required experimental facilities. The process is characterized by: basic studies, advanced studies and zero power experiment, small scale demonstrator, and finally the industrial demonstrator. The process gives a clear structure for innovative nuclear development with specific roles which have to be taken over by the government and industrial players with different shares. It indicates the requirement to involve different partners, but the reward of the successful development has the potential to give the world one of the most promising, sustainable, and reliable low carbon technologies.

References

1. https://www.worldenergy.org/work-programme/strategic-insight/assessment-of-energy-climate-change-policy/
2. environmental Scientist, The Journal of the Institution of Environmental Sciences Volume 23 No 1, 2014, available: https://www.the-ies.org/sites/default/files/journals/env_sci_feb_14.pdf, accessed 07/03/2019
3. https://unchronicle.un.org/article/goal-7-ensure-access-affordable-reliable-sustainable-and-modern-energy-all
4. http://www.cop21paris.org/knowledge-centre/reports/
5. The Emissions Gap Report 2017 A UN Environment Synthesis Report, UNEP available : https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf, accessed 13/07/2018
6. Long-term Nuclear Energy Strategy, HM government, available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/168047/bis-13-630-long-term-nuclear-energy-strategy.pdf, accessed 13/07/2018
7. https://www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c/about#timeline
8. http://www.hitachi-hgne-uk-abwr.co.uk/downloads/2017-12-14_uk_abwr_completes_regulatory_assessment.pdf
9. Argonne's Nuclear Science and Technology Legacy, Historical News Releases, available: https://www.ne.anl.gov/About/hn/news111220.shtml, accessed 07/03/2019
10. B. Merk et al.: The Current Status of Partitioning & Transmutation and how to develop an Innovative Approach to Nuclear Waste Management, ATE 5, 2019
11. End of reprocessing at Thorp signals new era for Sellafield, available https://www.gov.uk/government/news/end-of-reprocessing-at-thorp-signals-new-era-for-sellafiel, accessed 28/03/2019d
12. Generation IV International Forum https://www.gen-4.org/gif/jcms/c_9260/public
13. Malik, F. Strategy—Navigating the Complexity of the World; Campus Verlag: Frankfurt, Germany; New York, NY, USA, 2013.
14. V. Dekusar et al: "Comparative Analysis of Electricity Generation Fuel Cost Component at NPPs with WWER and BN-type Reactor Facilities, FR17 Yekaterinburg, Russian Federation, 26 – 29 June 2017, available: https://www-legacy.iaea.org/NuclearPower/Downloadable/Meetings/2017/2017-12-12-12-12-NPTDS-test/FR17_WebSite/papers/FR17-435.pdf, accessed 26/02/2019
15. A. Khaperskaya: Conceptual approaches and the main directions of R & D on partitioning and transmutation of minor actinides and long-lived fission products in the Russian Federation 15th IEM P&T, 30 Sept.3 Oct. 2018, Manchester Hall, Manchester, UK
16. Merk B, Stanculescu A, Chellapandi P, Hill R (2015) Progress in reliability of fast reactor operation and new trends to increased inherent safety, Applied Energy 147, 1 June 2015, Pages 104–116
17. WPFC Task Force on Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation (TFPT), https://www.oecd-nea.org/science/wpfc/index_pt.html
18. B. Merk, D. Litskevich, K. R. Whittle, M. Bankhead, R. Taylor, D. Mathers: "On a Long Term Strategy for the Success of Nuclear Power", ENERGIES, 8(11), 12557-12572. doi:10.3390/en81112328.
19. B. Merk, D. Litskevich, M. Bankhead, R. Taylor: "An innovative way of thinking Nuclear Waste Management – Neutron physics of a reactor directly operating on SNF", PLOS ONE July 27, 2017, https://doi.org/10.1371/journal.pone.0180703
20. B Merk, D Litskevich, R Gregg, AR Mount: Demand driven salt clean-up in a molten salt fast reactor–Defining a priority list, PloS one 13 (3), e0192020
21. acatech (Hrsg.): Partitionierung und Transmutation nuklearer Abfälle. Chancen und Risiken in Forschung und Anwendung (acatech POSITION), München: Herbert Utz Verlag 2014
22. N. C. Hyatt: Plutonium management policy in the United Kingdom: The need for a dual track strategy, Energy Policy, Volume 101, February 2017, Pages 303-309
23. David Hambley: Management of Nuclear Fuel in the UK: Past, Present and Future, INMM 32nd Spent Fuel Workshop January 10 – 12, 2017 Washington, DC USA, available: https://www.inmm.org/INMM/media/Documents/Presenations/Spent%20Fuel%20Seminar/2017%20Spent%20Fuel%20Seminar/Hambley_ManagementOfNuclearFuelInThe-UKPastPresentAndFuture.pdf, accessed 11/10/2018
24. https://www.britannica.com/topic/nuclear-proliferation
25. P. Peterson: Integral and Separate Effects Tests for Thermal Hydraulics Code Validation for Liquid-Salt Cooled Nuclear Reactors, NEUP Project No. 09-789, available: https://neup.inl.gov/SiteAssets/Final%20%20Reports/09-789%20NEUP%20Final%20Report.pdf, accessed 28/03/2019
26. Program on Technology Innovation: Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors: Historical Review and Analysis. EPRI, Palo Alto, CA: 2017. 3002010478
27. V. Drüke & D. Filges (1987) The Critical HTGR Test Facility KAHTER–An Experimental Program for Verification of Theoretical Models, Codes, and Nuclear Data Bases, Nuclear Science and Engineering, 97:1, 30-36, DOI: 10.13182/NSE87-A23493
28. Akademik Lomonosov Floating Nuclear Co-generation Plant, https://www.power-technology.com/projects/akademik-lomonosov-nuclear-co-generation-russia/
29. MSRE's 50th – The short-lived Molten Salt Reactor Experiment is far from forgotten, https://www.ornl.gov/news/msres-50th
30. First nuclear power plant to close, available: https://www.theguardian.com/uk/2003/mar/21/nuclear.world, accessed 28/03/2019
31. EBR-II Sixteen Years of Operation, available: https://inldigitallibrary.inl.gov/Reports/ANL-0001.pdf, accessed 28/03/2019

Authors

Bruno Merk
Dzianis Litskevich
University of Liverpool,
School of Engineering, L69 3GH,
United Kingdom

Bruno Merk
Dzianis Litskevich
Aiden Peakman
Mark Bankhead
National Nuclear Laboratory,
Chadwick House, Warrington,
WA3 6AE, United Kingdom