The University of Manchester
Dalton Nuclear Institute

Drivers for Reactor Choice

“Choosing a Reactor - Benefits and Challenges of Advanced Technologies”

. . or . . all these new systems are REALLY INTERESTING – but have they got a chance in the marketplace??’

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Choosing a Reactor - Benefits and Challenges of Advanced Technologies

- In all probability, all the AMRs that are put forward for regulatory consideration will be '*cheap as chips*', '*safe as houses*' and there will be no conceivable reason why they should not be '*on line by 2025*'
- Once a more realistic examination of a system is made, the benefits it offers and the challenges that it must surmount can begin to be compared with the factors that will be taken into account by those providing the finance to enable the reactor system to be brought into the power production market
- This presentation, which is based of work for DECC (now BEIS) seeks to examine the benefits and challenges offered by typical SMR/AMR

Choosing a Reactor - Benefits and Challenges of Advanced Technologies

- Most of the reactor designs (GWe or SMR) available for short term deployment are LWRs
- But many advanced systems are being proposed: all bring benefits, but also face challenges which must be met if they are to succeed in the market place
- ***Generic Feasibility Assessment*** looks at these benefits and challenges, and uses international work on ***Life Cycle Cost of Electricity*** to begin to judge system economics.
- This presentation reviews the methodology and makes some general observations on the challenges to various systems and their timescales.

Generic Feasibility Assessment - Development

NNL used their ORION fuel cycle model to analyse different future programmes with different systems

- ORION is a powerful tool, enabling all the inputs (uranium, thorium, enrichment, plant throughputs etc) and outputs (spent fuel, reprocessing products and wastes, waste/fuel radiotoxicity/heat output/volume etc)
- ORION also reveals (in marked contrast to some other UK assessments) whether the future programme is actually viable (enough Pu etc etc)
- As for other such tools, ORION essentially gives all the information of **WHAT** happens if a given future is pursued, it does not ask or answer the question **WHY?**

But which system is *The Best!!??*

NNL analysed all this ORION data for a large range of different systems using a Multi-Attribute Decision Analysis (MADA) technique based on the 42 metrics it had derived based on those used in the GENIV programme

- MADA gives giving ‘*marks*’ and ‘*weights*’ to each attribute, before combining all the marks and weights to give an “overall system score”
- The use of a MADA with the large number of 42 metrics makes the result very difficult to communicate meaningfully, even to committed stakeholders – there is often a shared understanding by ‘*those that were in the room for the analysis*’, which fails to be transferable to others.

Also the ‘weights’ (i.e. how *important* is this ‘score’) depend on the future being examined: every MADA ‘winner’ is a bet on a particular future, and is this future doesn’t materialise, the bet is lost - for example:

> “It uses 50x less uranium” – *but what if uranium stays below $50/lb U_3O_8 for 100 years? (*Since January 2019 the uranium spot price has so far been between $24.8 [10.01.2020] and $27.8/lb U_3O_8*)
>
> “It produces less waste” – *but are we* really *going to be limited by the availability of **geology** for Geological Disposal?*
>
> *“It makes the waste shorter lived and less radiotoxic” – but has anyone thought to tell the actinides which stick resolutely to the first molecule of clay they come across, or the mobile long-lived 129I, 36Cl, 14C etc etc – which seem to drive most GDF safety cases?*

So a MADA ‘Winner’ is easy to announce, but much less easy to explain or defend

* https://www.cameco.com/invest/markets/uranium-price

The **Generic Feasibility Assessment** methodology attempts to address the ‘why’, and poses the question

> ***“What are the attributes of a nuclear energy system which would justify investment in its future development with view to deployment in the UK?”***

- In the UK context, safety environmental and proliferation/security are all covered by well-developed regulatory regimes – so that reactor system deployment is not about “*how safe, secure, and environmentally benign*” a system is, or “*whether it can be licensed or not*” – but how much ***time*** and ***effort*** must be expended to allow the system to conform with regulation.
- This leads to a process with five High Level Discriminators

1. **How much time and effort will be required to achieve regulatory approvals to deploy this reactor system?**
2. **Is it likely that the reactor system is capable of being economically competitive with the reference (once-through LWR) system?**
3. **If this system was deployed . . . . . ? (covers fuel supply, waste disposal and reactor/fuel cycle siting issues)**
4. **Is there a credible path between state R&D investment now and private reactor system deployment then?**
5. **Can the system meet market demands?**

These High Level Discriminators lead down to 12 Strategic Attributes – and thence to the 42 Metrics used by NNL and the GenIV Project

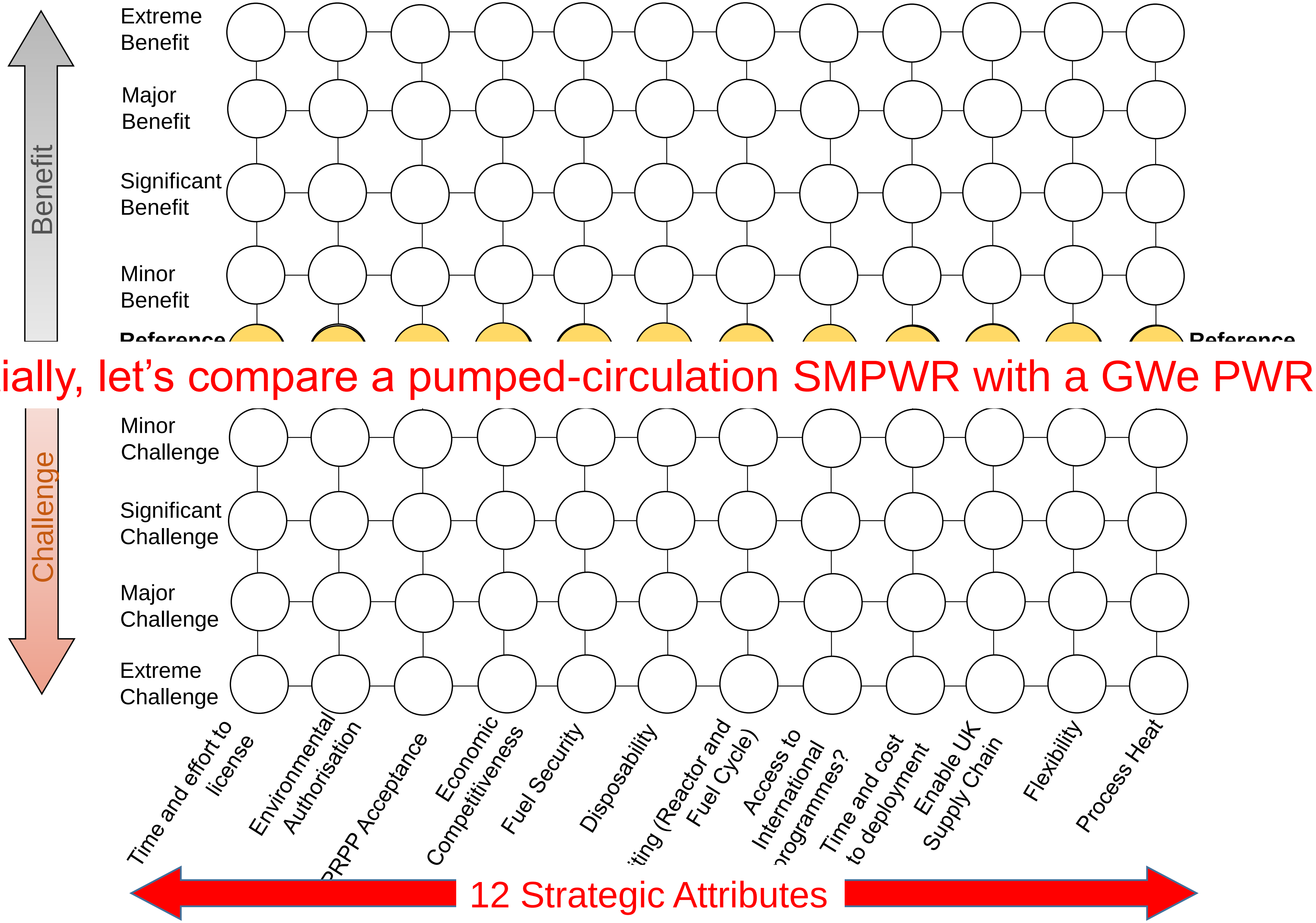
High Level Discriminators and Strategic Attributes

High Level Discriminator		Strategic Attribute		Metrics
1	Regulatory Challenges and Timescales	1	Safety and Licenseability	10
		2	Environmental Authorisation	1
		3	PRPP Acceptability	4
2	Competitiveness	4	Economic Competitiveness	9
3	Viable Deployment	5	Fuel Security	2
		6	Waste Storage and Disposal	6
		7	Siting	3
4	Development Route and Timescale	8	Access to International Programmes	0
		9	Time and cost to Deployment	3
		10	Enable UK Supply Chain	0
5	Meets Market Requirements	11	Flexibility	1
		12	Process Heat	2

The Generic Feasibility Assessment (GFA) Approach . .

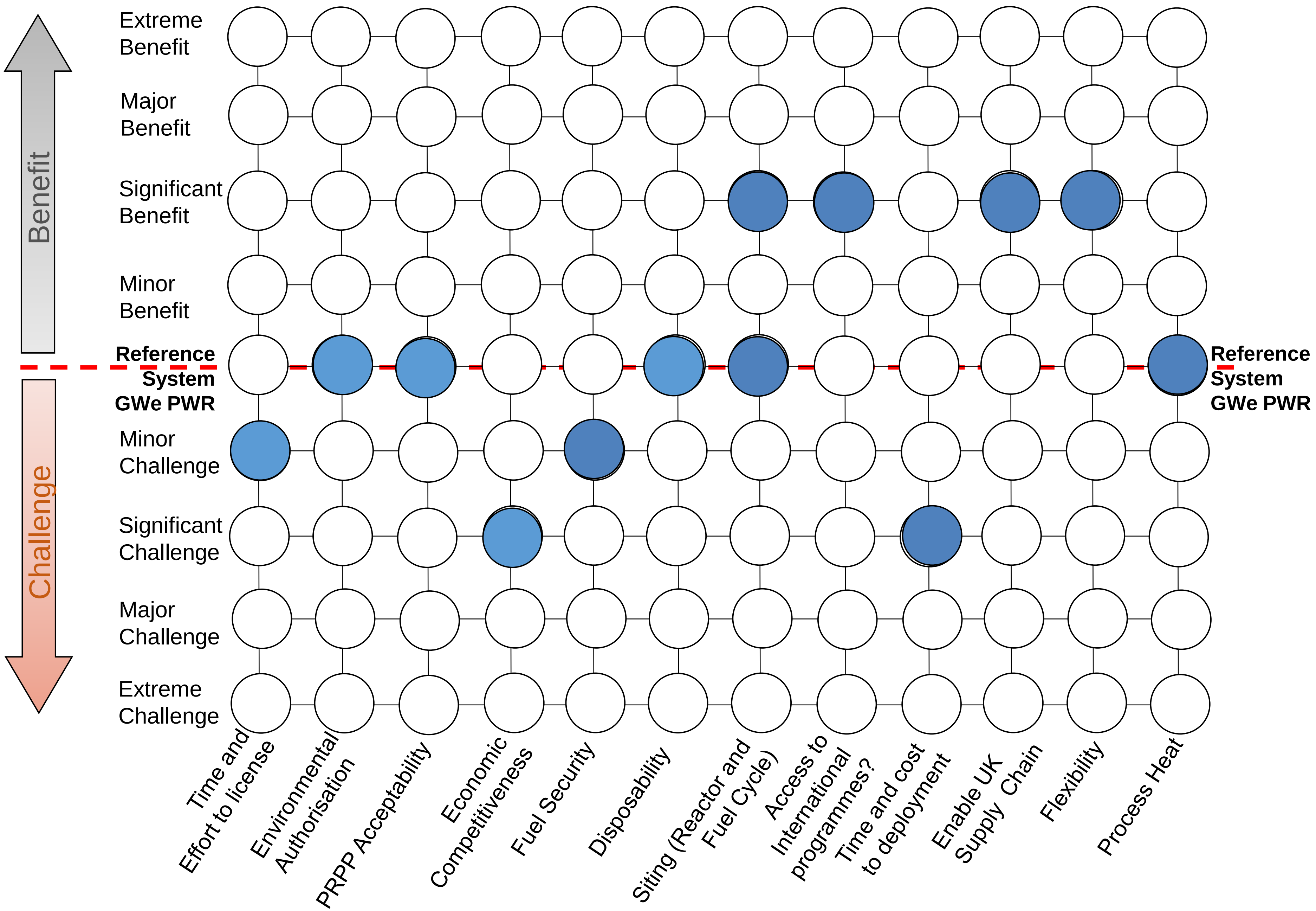
- Rather than use MADA, GFA assesses the smaller number of 12 'Strategic Attributes'
- These are compared with a 'Reference System', initially taken as '*once-through GWe-sized PWR*', whose characteristics are already well known.
- Crucially, the comparisons made are based on published data which can be referenced, linked, and made publically available. It is expected that as the body of assessments build up, it will provide a very significant and easily accessed database on reactor systems and their attributes. GFA assessments will change as technology advances – they will always be **Work in Progress**.
- It does not use 'scores', but asks the question *"does the system being examined offer benefits or challenges (compared to the reference system) on the attribute being considered, and how significant are these challenges/benefits"* - the outcome has been a visual presentation . . . .

Strategic Attributes Versus Reference System



Initially, let’s compare a pumped-circulation SMPWR with a GWe PWR . . .

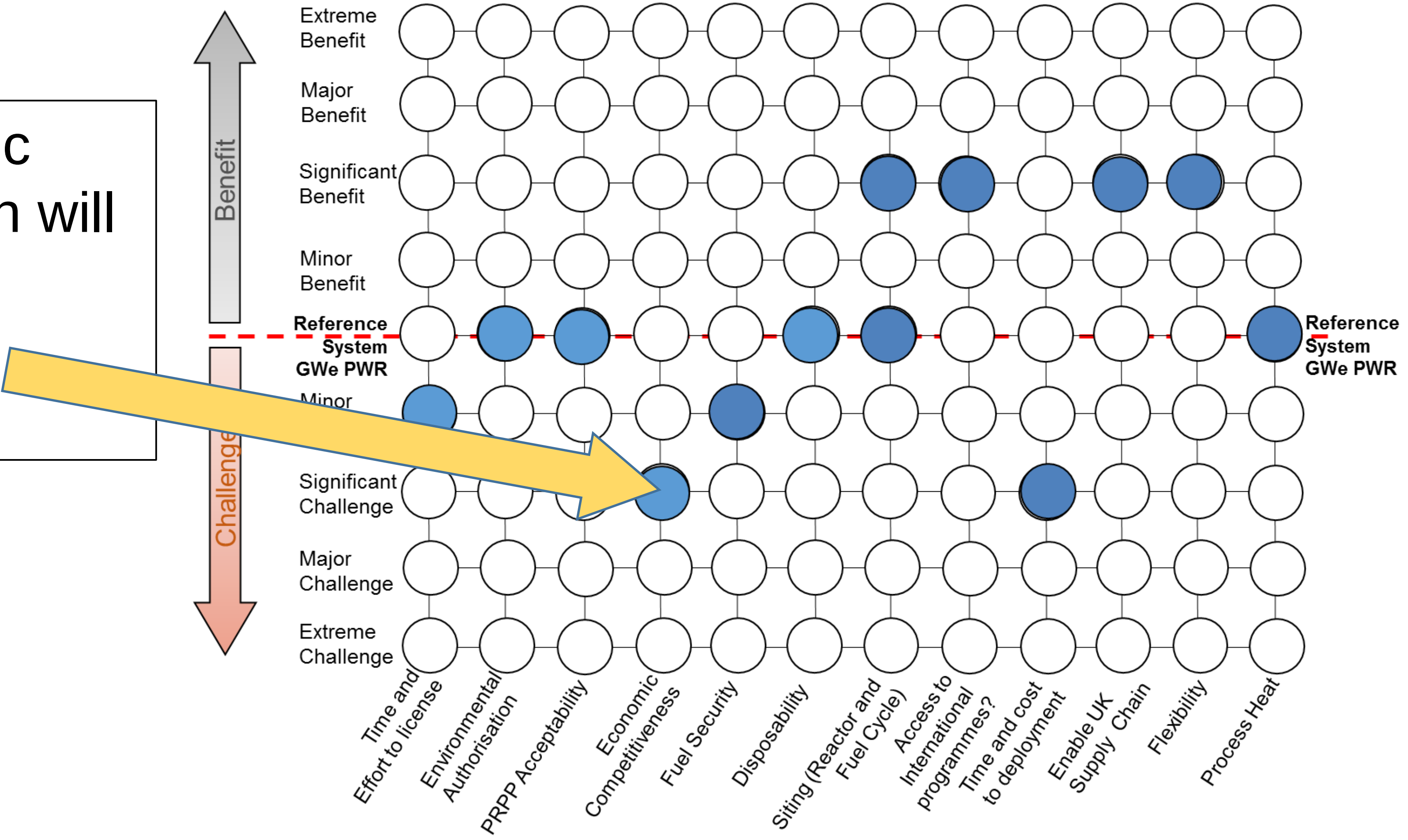
GFA Subject System: Pumped SMPWR. Reference System: GWe PWR *– Work in Progress*



Small Modular compared to Gwe-sized Reactors

A similar assessment to this will underlie the comparison between all SM-sized and GWe-sized version of most systems, for example

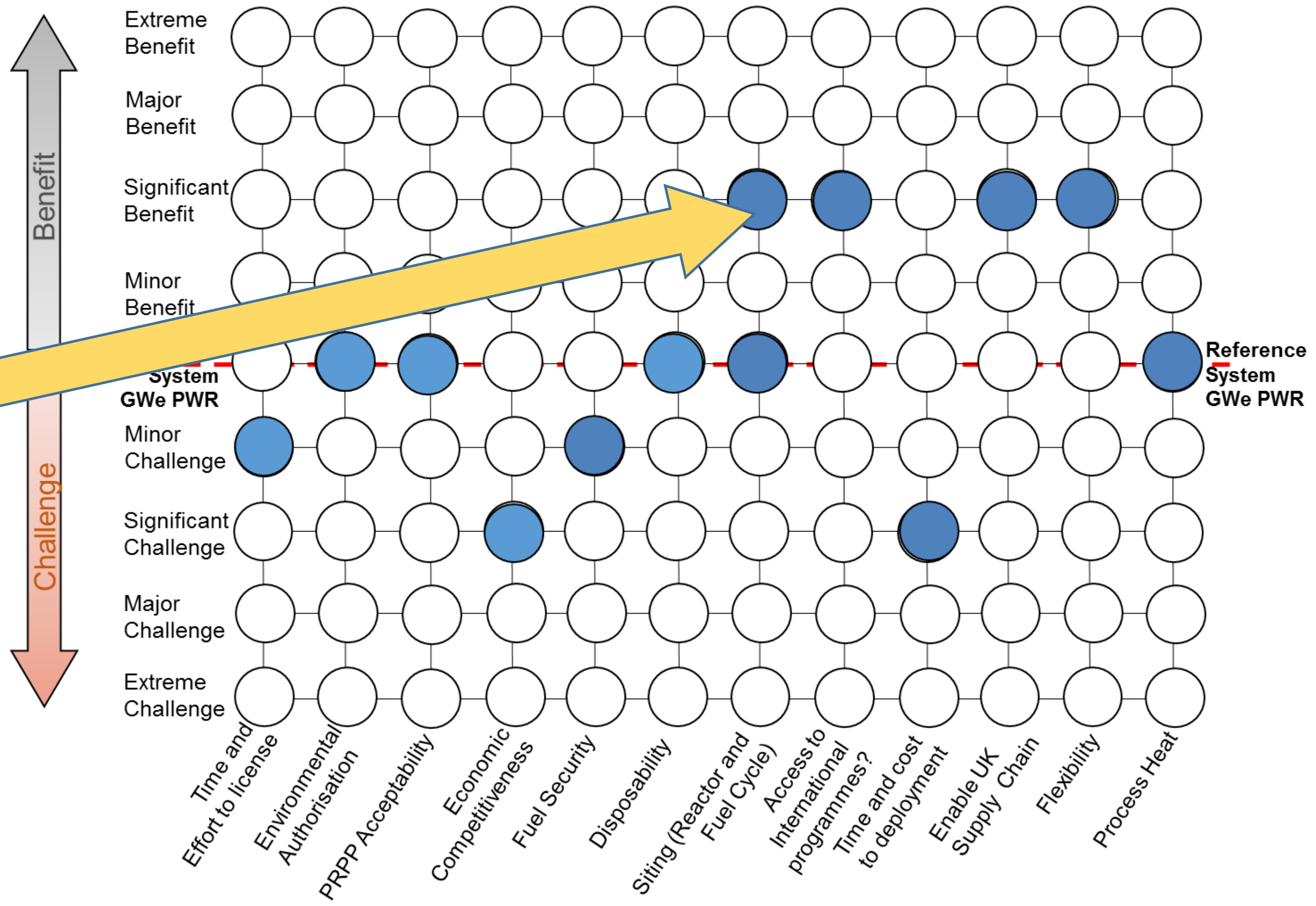
A challenge on Economic Competitiveness – which will be met if ‘Economies of Number’ can overcome ‘Economies of Scale’



Small Modular compared to Gwe-sized Reactors

A similar assessment to this will underlie the comparison between all SM-sized and GWe-sized version of most systems, for example

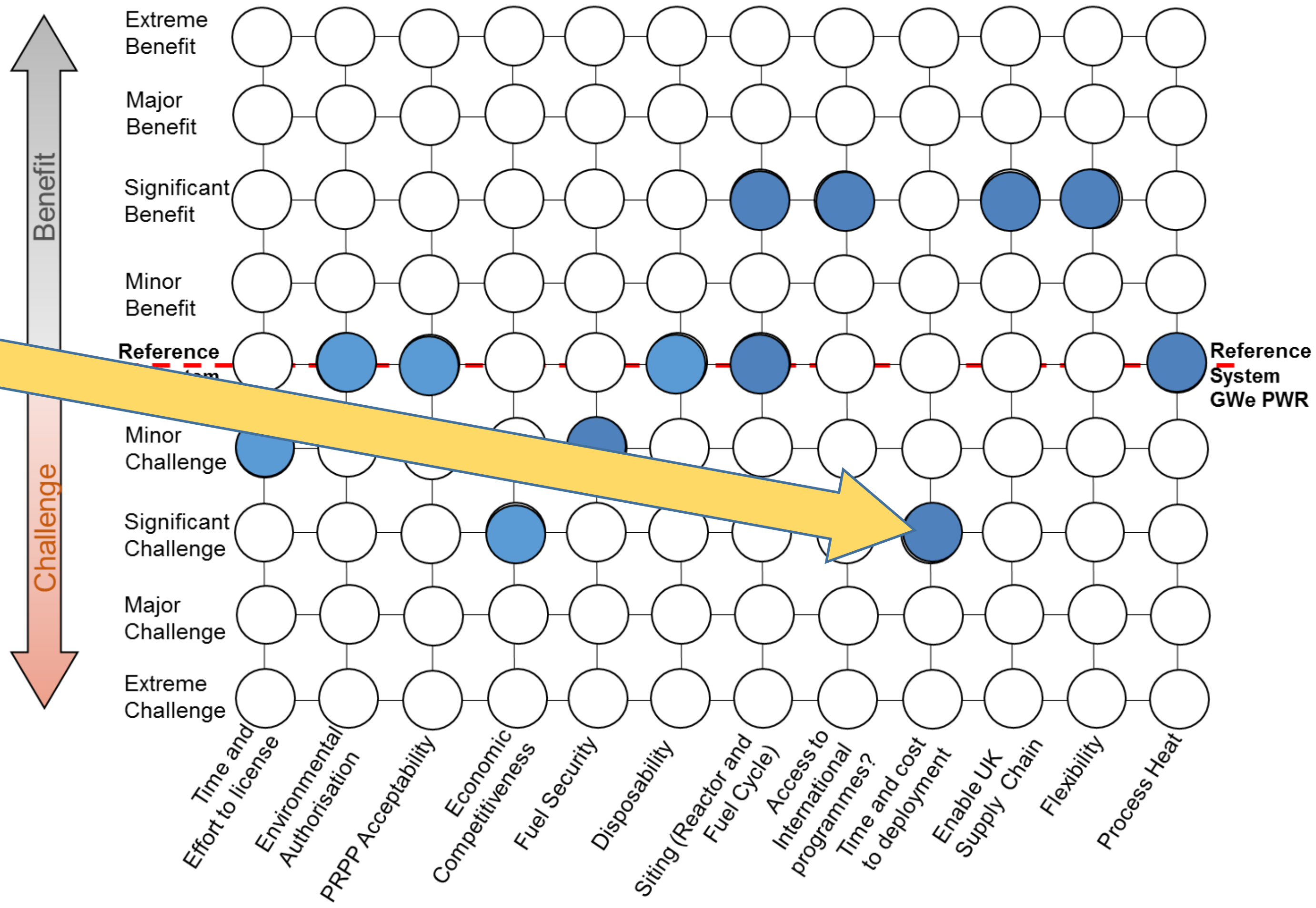
A benefit on Siting if reactors are sited individually or in small groups, which will be lost if GWe-sized groups are contemplated



Small Modular compared to Gwe-sized Reactors

A similar assessment to this will underlie the comparison between all SM-sized and GWe-sized version of most systems, for example

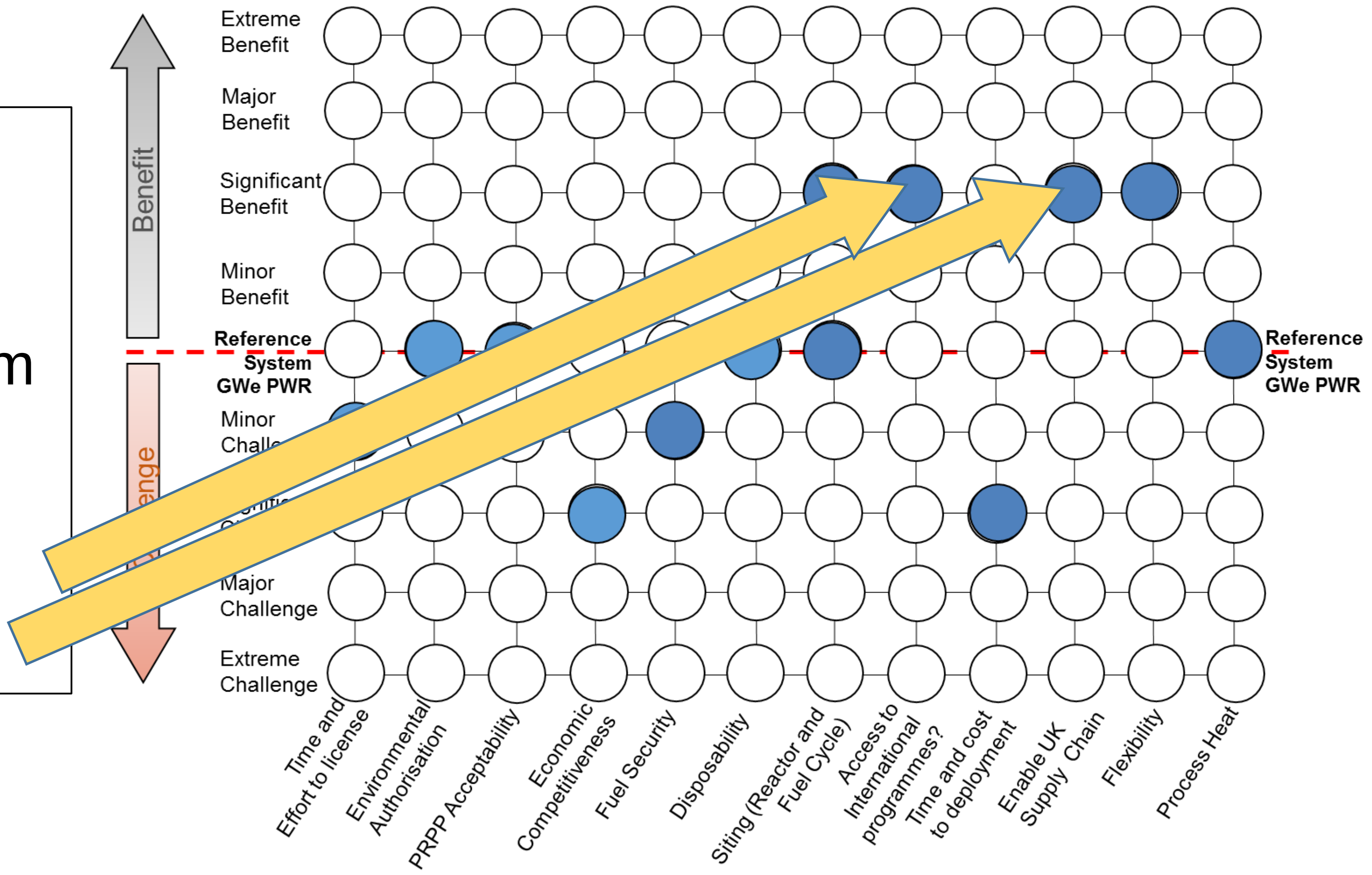
An overall challenge in Time and Cost to Deployment – GWe reactors are here, now. SMRs estimated on-line UK by ~2030



Small Modular compared to GWe-sized Reactors

A similar assessment to this will underlie the comparison between all SM-sized and GWe-sized version of most systems, for example

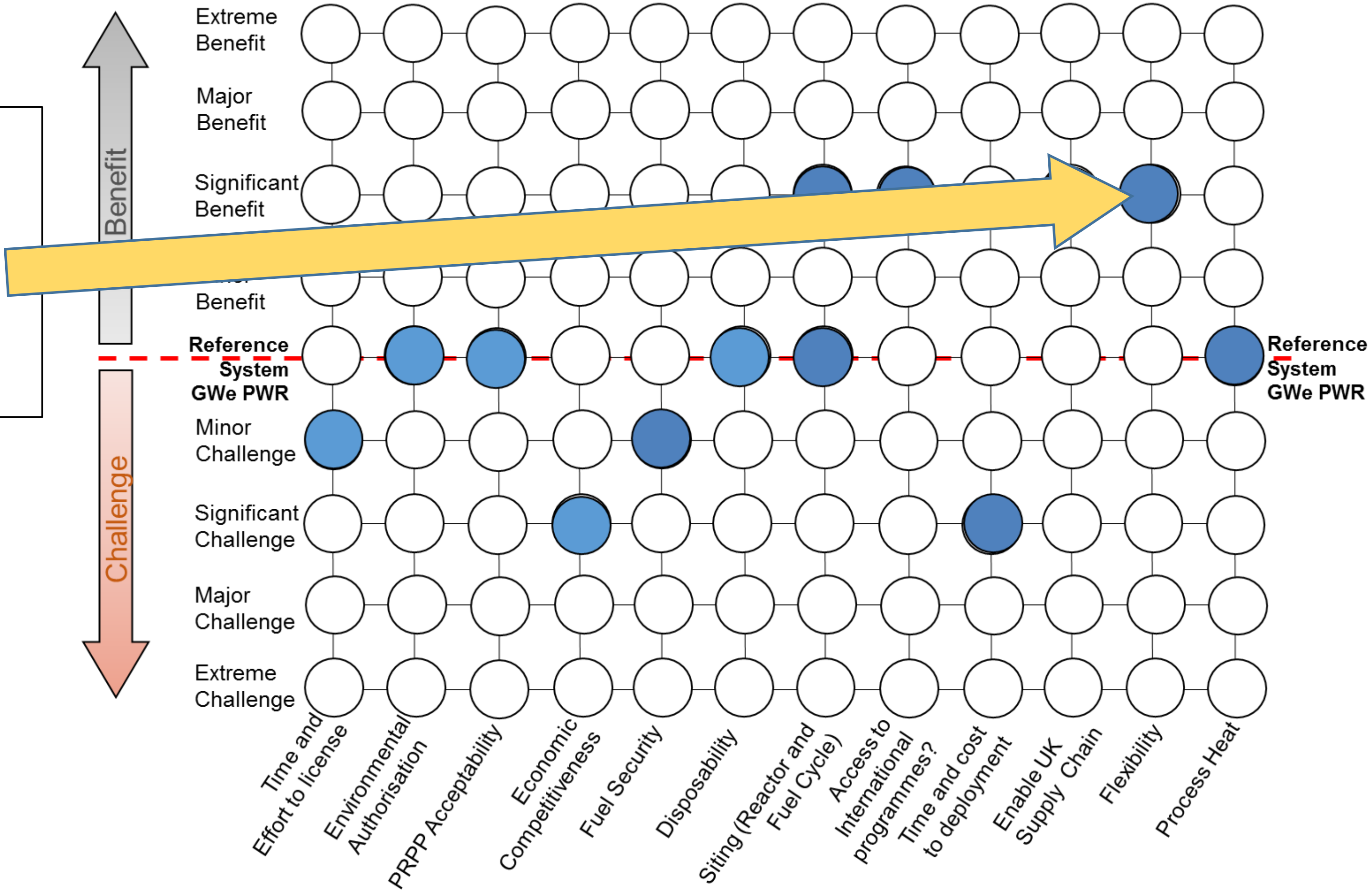
A benefit to the UK in that a general lower level of development can lead to opportunities for benefits from UK participation in international programmes – and improved prospects for the UK Supply Chain



Small Modular compared to GWe-sized Reactors

A similar assessment to this will underlie the comparison between all SM-sized and GWe-sized version of most systems, for example

A benefit in flexibility – either from greater unit flexibility or from the shut-down of smaller increments of power



Generic Feasibility Assessment

GFA tells you which attributes of a system offer benefits (in comparison to the Reference) and which offer challenges

What GFA does **NOT** tell you is whether those benefits or challenges are likely to become significant drivers for any future choice of reactor system

For this, we have used **Levelised Cost of Electricity** studies to examine the contribution of the various sources of expenditure to overall power cost.

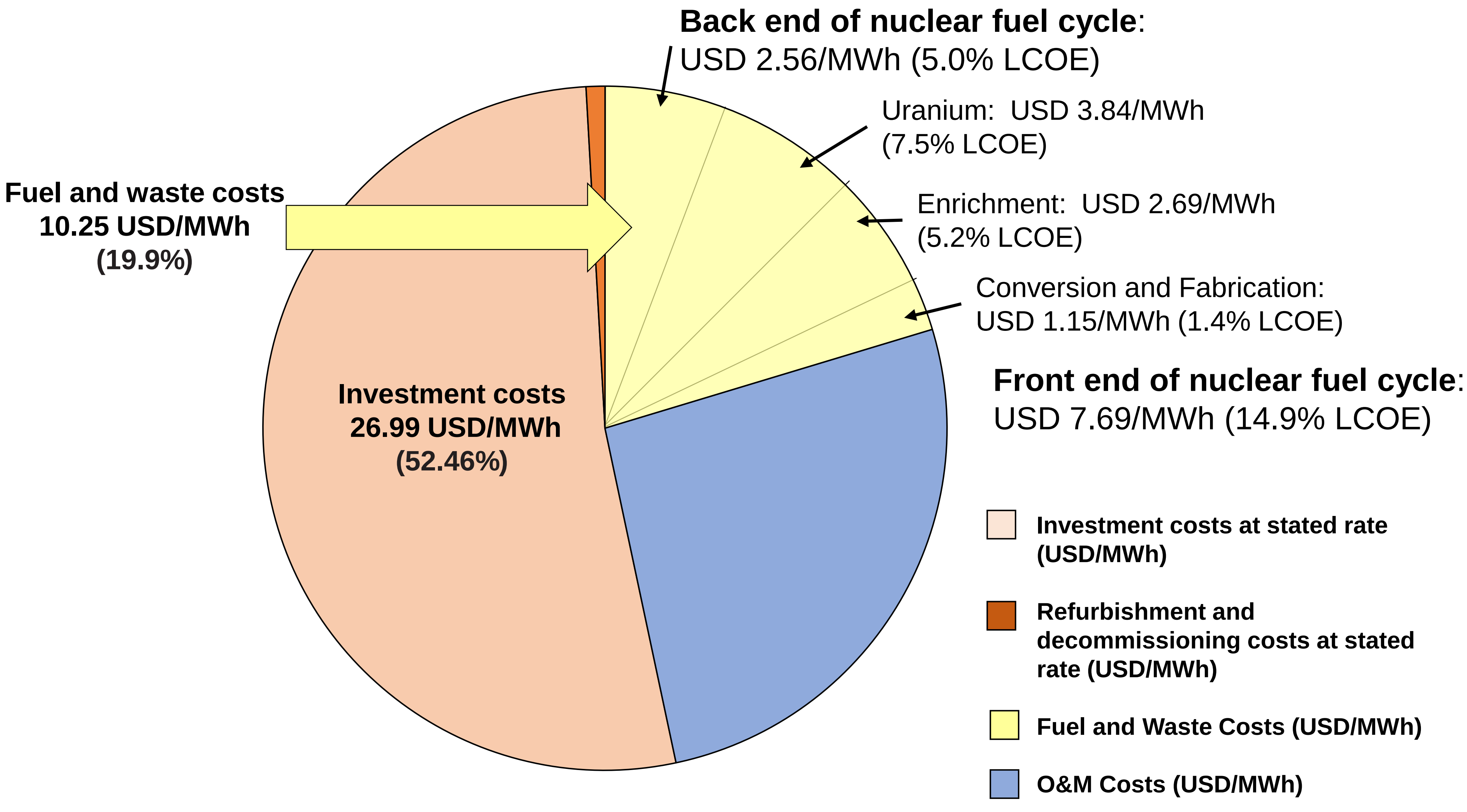
In particular, we have used the 2015 NEA-IEA study "*The Projected Cost of Producing Electricity*" *(still current)*. This examines a number of different GWe-sized LWRs from various countries, and we have used an average of their results.

Levelised Cost of Electricity (LCOE)

LCOE gives the cost (in US dollars) of a MWh of electricity generation across the reactor’s lifetime, taking into account the discount rate to be applied.

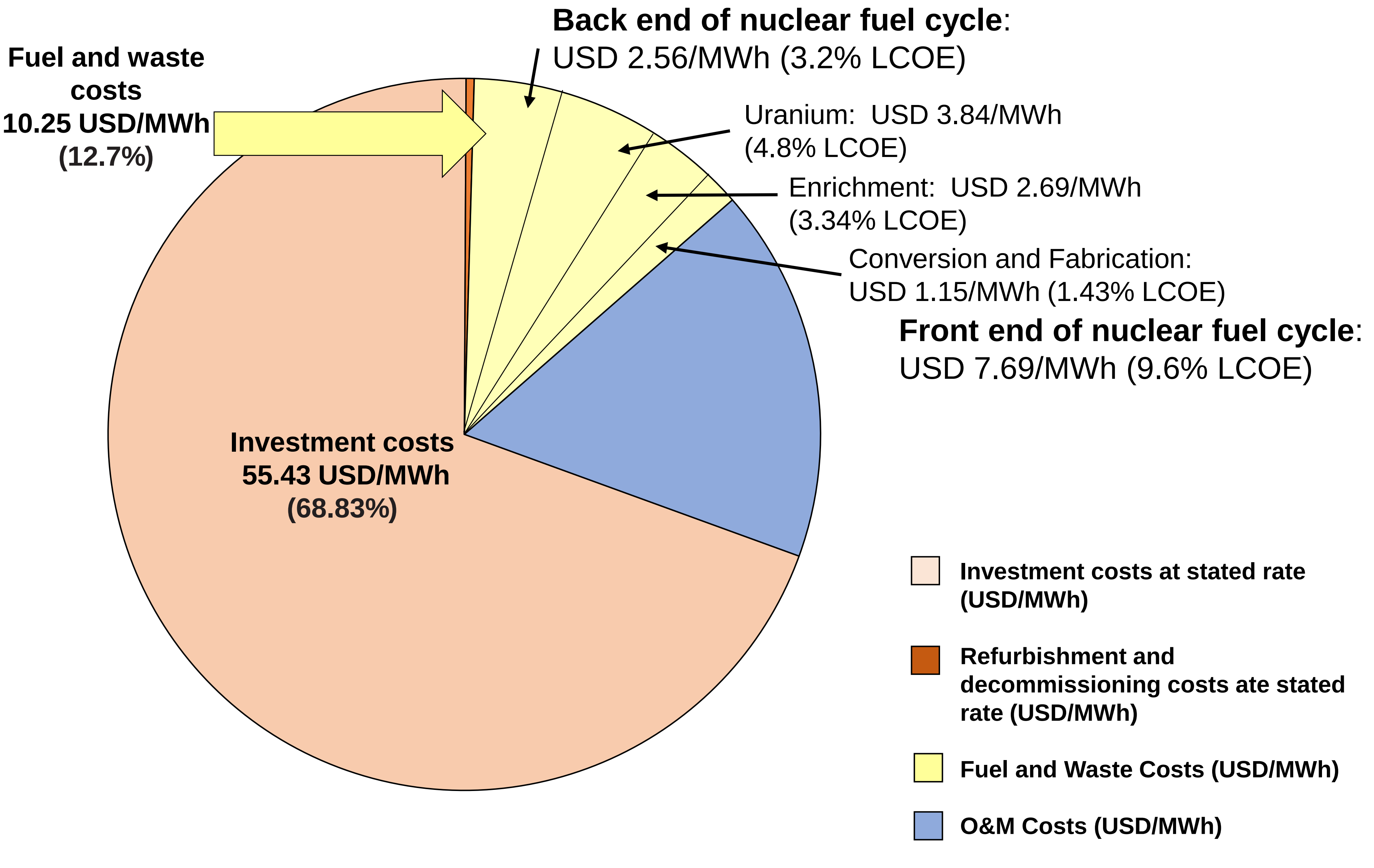
The most striking feature is the high percentage of LCOE taken up by the initial capital expenditure and financing charges, the comparatively small contribution from fuel cycle costs, and the miniscule effect of decommissioning.

The results change markedly with Discount Rate as shown by the following slides.



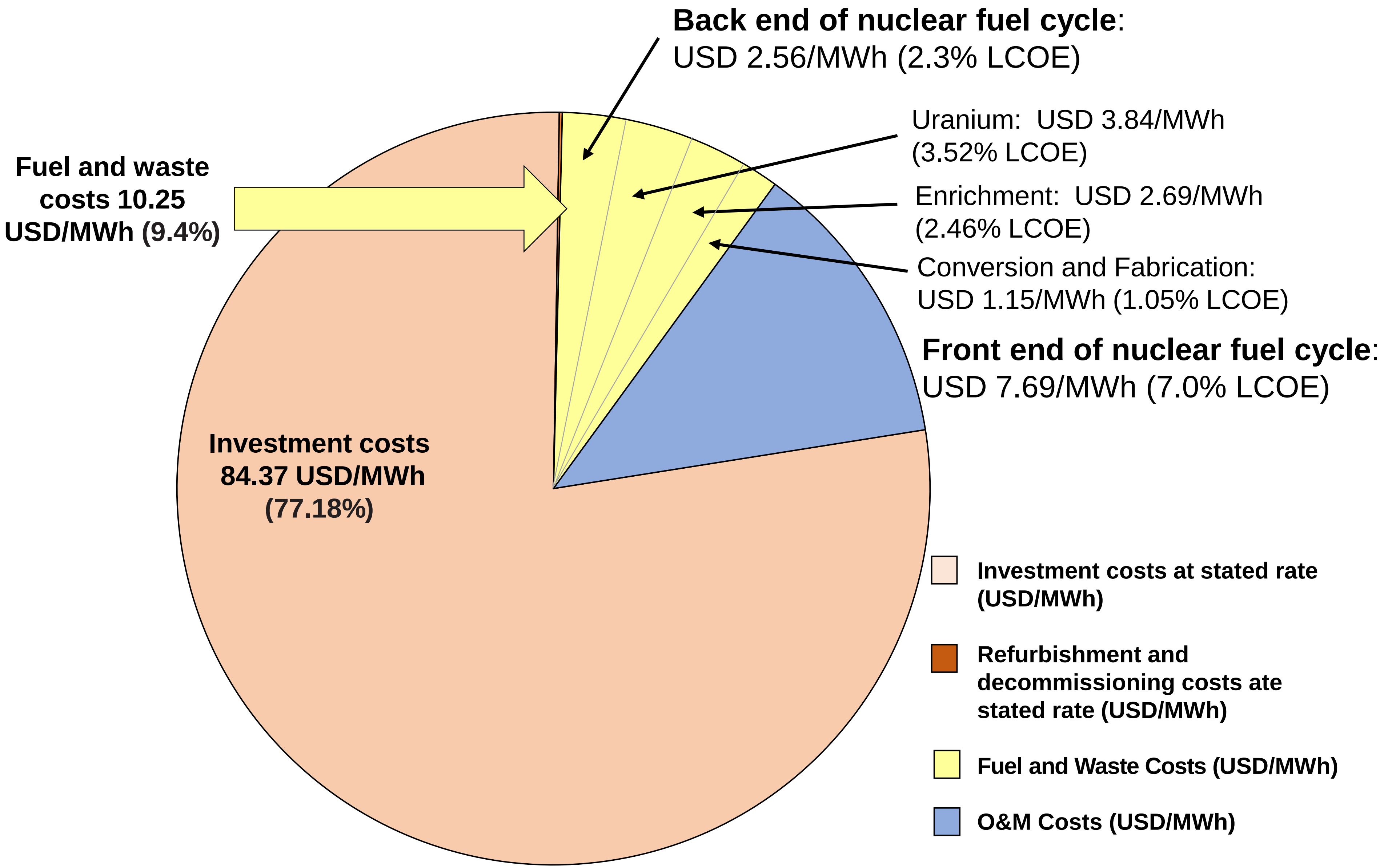
LCOE at 3% Discount Rate – 51.45USD/MWh

The Projected Cost of Producing Electricity, NEA-IEA, August 2015



LCOE at 7% Discount Rate – 80.53USD/MWh

The Projected Cost of Producing Electricity, NEA-IEA, August 2015



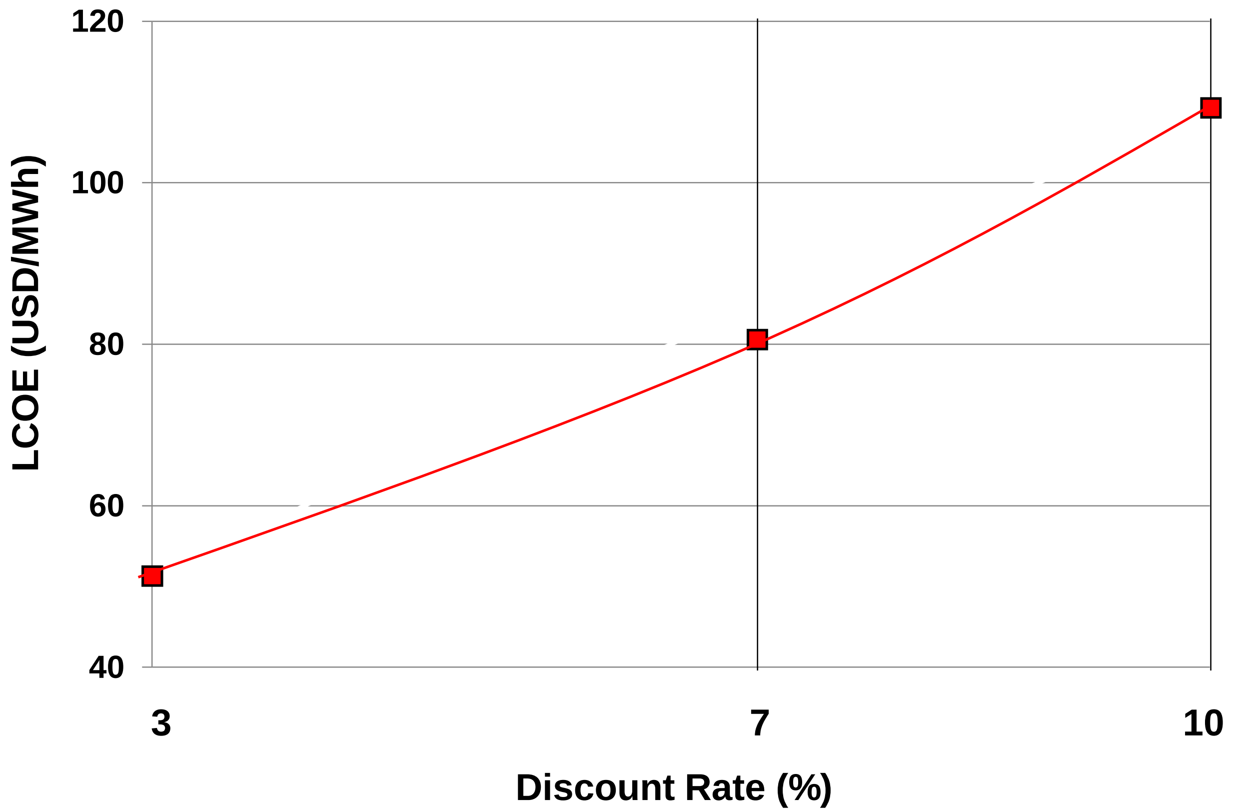
LCOE at 10% Discount Rate – 109.32USD/MWh

The Projected Cost of Producing Electricity, NEA-IEA, August 2015

Levelised Cost of Electricity (LCOE)

Immediate points to note are:

- The cost of uranium is between 3.5% and 7.5% depending on interest rate
- The entire back end of the fuel cycle accounts for 2.3% to 5.0%
- The whole fuel cycle cost is equivalent to the effect of around 1% increase in interest rate from 7%



*It is not too dramatic to state that the economic viability of '*nuclear in general*' and '*any nuclear system in particular*' could stand or fall on its ability to be financed at a reasonable rate*

Levelised Cost of Electricity (LCOE)

Many studies have used 20% LCOE as the difference between First of a Kind (FOAK) and Nth of a Kind (NOAK), and many have said variations on '*we've calculated the LCOE and it's 20% too high, but that'll come down as soon as we build some*'.

It's therefore instructive to look at how much change of 'front and back end' costs would be needed to give a 20% change in LCOE.

	Front end	Uranium	Enrichment	Conversion + fabrication	Back end	LCOE (USD/MWh) 7%
$/MWh	7.69	3.84	2.69	1.15	2.56	80.53
% of LCOE	9.55	4.77	3.34	1.43	3.18	
Factor rise for +20% LCOE	3.10	5.19	6.99	15.00	7.29	

So a 20% change in LCOE requires, for example:

- A 3-fold rise in the whole front end costs
- A 5-fold rise in the cost of uranium
- A 7-fold rise in the entire 'decommissioning and waste management' back end

Levelised Cost of Electricity (LCOE)

The outcome is that, on straight economic grounds,

- Increases or decreases in capital cost, interest rates and build time will be important
- Changes in uranium usage will have only a small effect on LCOE unless the U price becomes extremely high – *and note that as LCOE rises, so nuclear itself becomes less competitive!!*
- Disposal costs will need to be extreme to become economic drivers.

Also fundamentally, the UK regulatory system would not permit an 'advanced' reactor to be built unless and until the regulators have satisfied themselves that every system and every material in the candidate reactor is '*fully developed and ready to go*'.

Whether it is indeed ready can be assessed by examining the Technology Readiness Levels in the reactor system.

Technology Readiness Levels

Technology Readiness Levels (TRLs) are a method of estimating technology maturity of critical technology. TRLs are based on a scale from 1 to 9, with 9 being the most mature technology

They were originally developed by NASA in the 1970s and have achieved wide acceptance.

A typical definition of TRLs is used by the European Commission

Technology Readiness Levels

European Commission

Technology Readiness Levels

TRL 0: **Idea**. Unproven concept, no testing has been performed.

TRL 1: **Basic research.** Principles postulated and observed but no experimental proof available.

TRL 2: **Technology formulation**. Concept and application have been formulated.

TRL 3: **Applied research**. First laboratory tests completed; proof of concept.

TRL 4: **Small scale prototype** built in a laboratory environment ("ugly" prototype).

TRL 5: **Large scale prototype** tested in intended environment.

TRL 6: **Prototype system** tested in intended environment close to expected performance.

TRL 7: **Demonstration system** operating in operational environment at pre-commercial scale.

TRL 8: **First of a kind commercial system**. Manufacturing issues solved.

TRL 9: **Full commercial application**, technology available for consumers.

The Properties of Advanced Technologies

Perhaps the overriding conclusion to come out of our GFA studies on Advanced Systems is that:

"An Advanced System Marches at the Speed of its Lowest TRL"

- When an Advanced Reactor System goes to the regulators, all of a sudden a PowerPoint saying '*it's easy*' does not suffice.
- Regulators will require evidence, flowsheets, and demonstrable engineering experience to support licensing and permitting
- The fact that '*it worked OK in the US in 1983*' will cut but little mustard.

The Properties of Advanced Technologies

This means that challenges such as component corrosion by coolants, the specification of disposable wasteforms and the technology to produce them, fault analysis and response, maintenance procedures – all these must be to all intents and purposes at TRL9. If the smallest critical system or component is at TRL 5 – forget licensing until it's fully developed

Every developing system can therefore be viewed as a series of TRLs for various converging systems, components and materials – and the '*TRL 9 Critical Path*' will plot the earliest plausible deployment date of the system.

Widespread recognition of this fact might just curtail the current vogue for presentations of '*imminent new*' systems which should end with '*and then a miracle occurs*'

The Properties of Advanced Technologies

The most of the non-LWR technologies vying for attention both at GWe and SM sizes are covered by five technology groups:

- Sodium-cooled Fast Reactor (SFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Cooled Fast Reactor (MSFR)
- Molten Salt Cooled Thermal Neutron Reactor (MSThR)
- High Temperature Gas-cooled Reactor (HTGR)

- *Note that BEIS includes fusion as a group in their analysis of AMRs* * – *fusion is not included here.*

** explain*

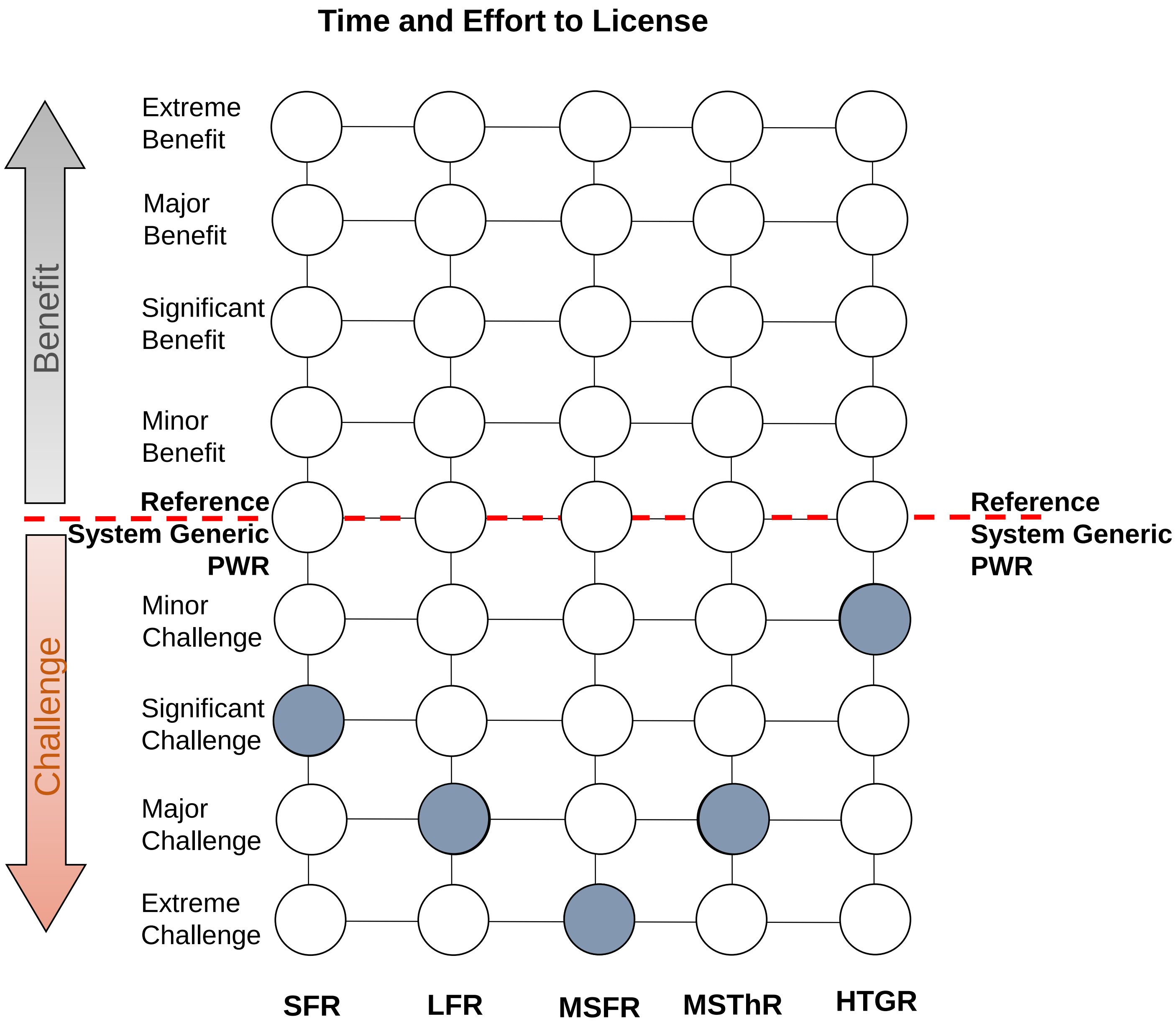
The Properties of Advanced Technologies

Work in support of the DECC/BEIS Techno-Economic Assessment of Small Modular Reactors performed a GFA assessment

- Initially comparing a once-through pumped-cooling SMPWR against a once-through GWe-sized PWR as the Reference System.
- Then comparing SMR versions of the five technology groups against a once-through pumped-cooling SMPWR as the Reference System

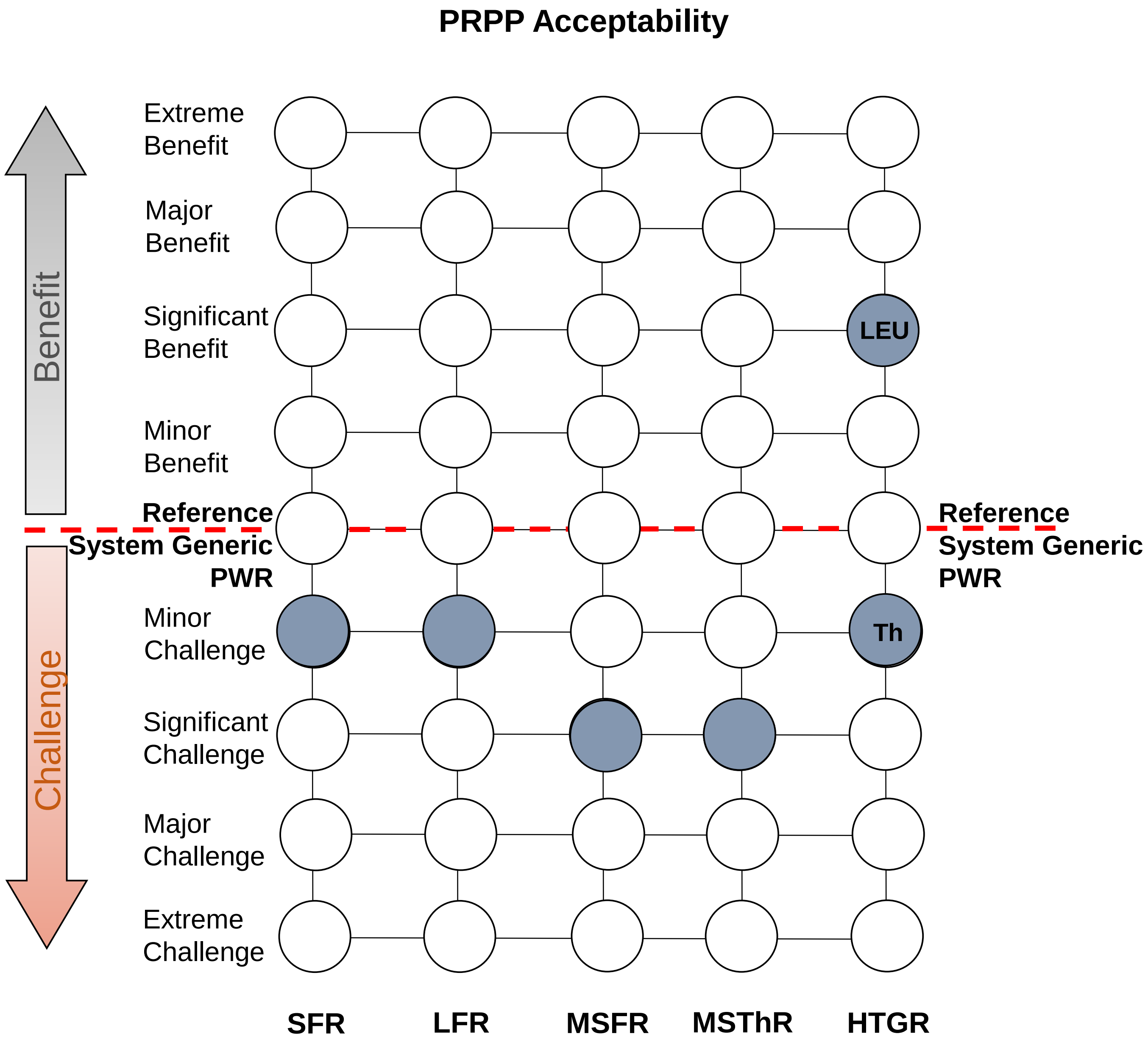
Note: the difference between 'SM' and 'GWe' reactors is the same for PWRs and for the 5 technology groups, so the GFA assessments will be the same for '*SM versus SM*' and '*GWe versus GWe*' comparisons.

A few cross-comparisons give a flavour of the preliminary results, which can be then viewed through the vantage point offered by LCOE.



All systems offer a challenge compared with the once-through LWR, which has the benefit of 60 years of continuous development and licensing

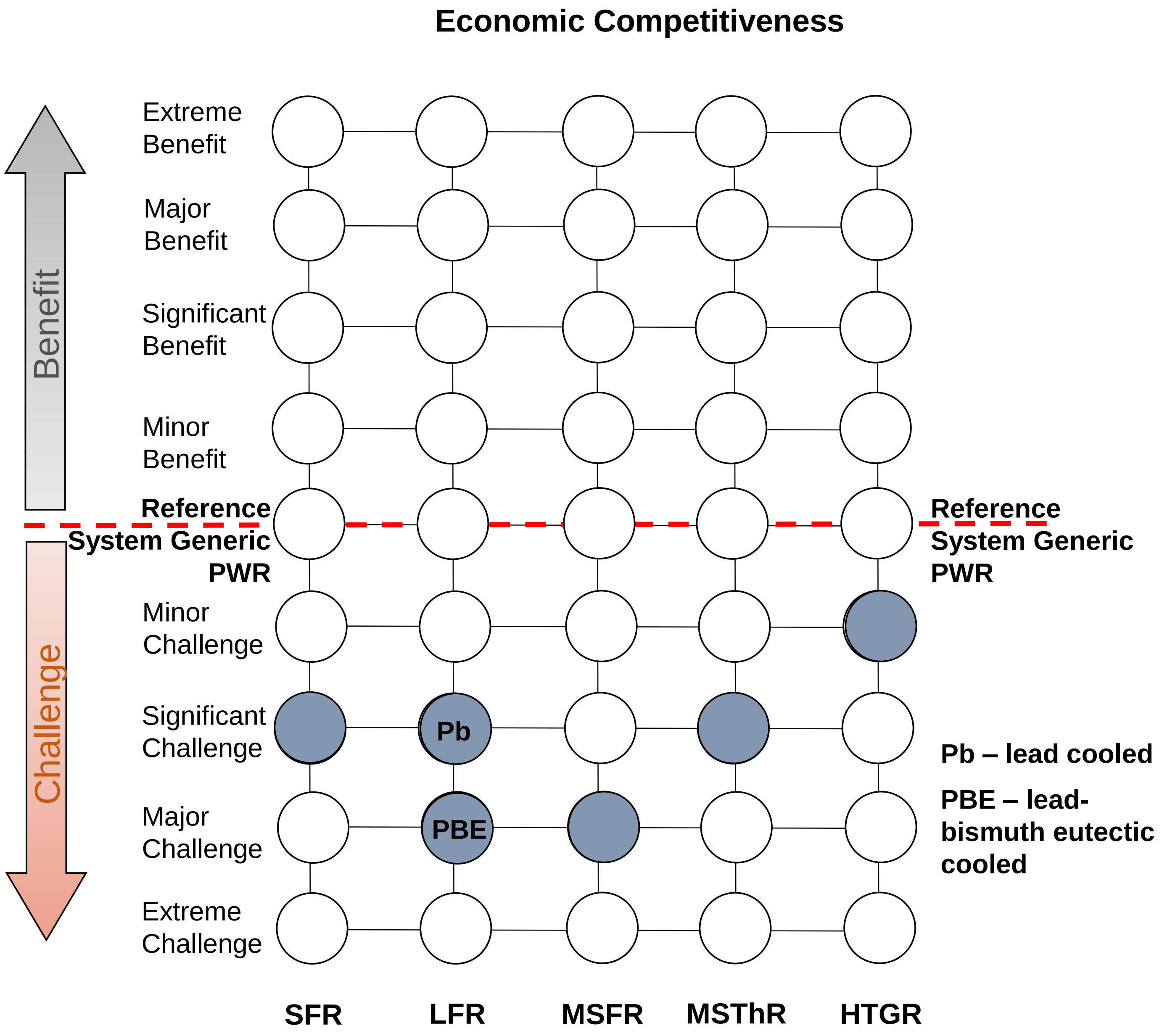
The resulting increase in time and effort would give a delayed deployment date and the probability of considerable up-front cost.



Recycling with Pu separation gives a range of challenge to Proliferation Resistance and Physical Protection

HTGRs on a once-through cycle using LEU fuel, avoid the production of weapons usable materials though using use a significantly higher enrichment than PWRs. They improve PRPP with very robust TRISO fuel and very low uranium concentrations in fuel element.

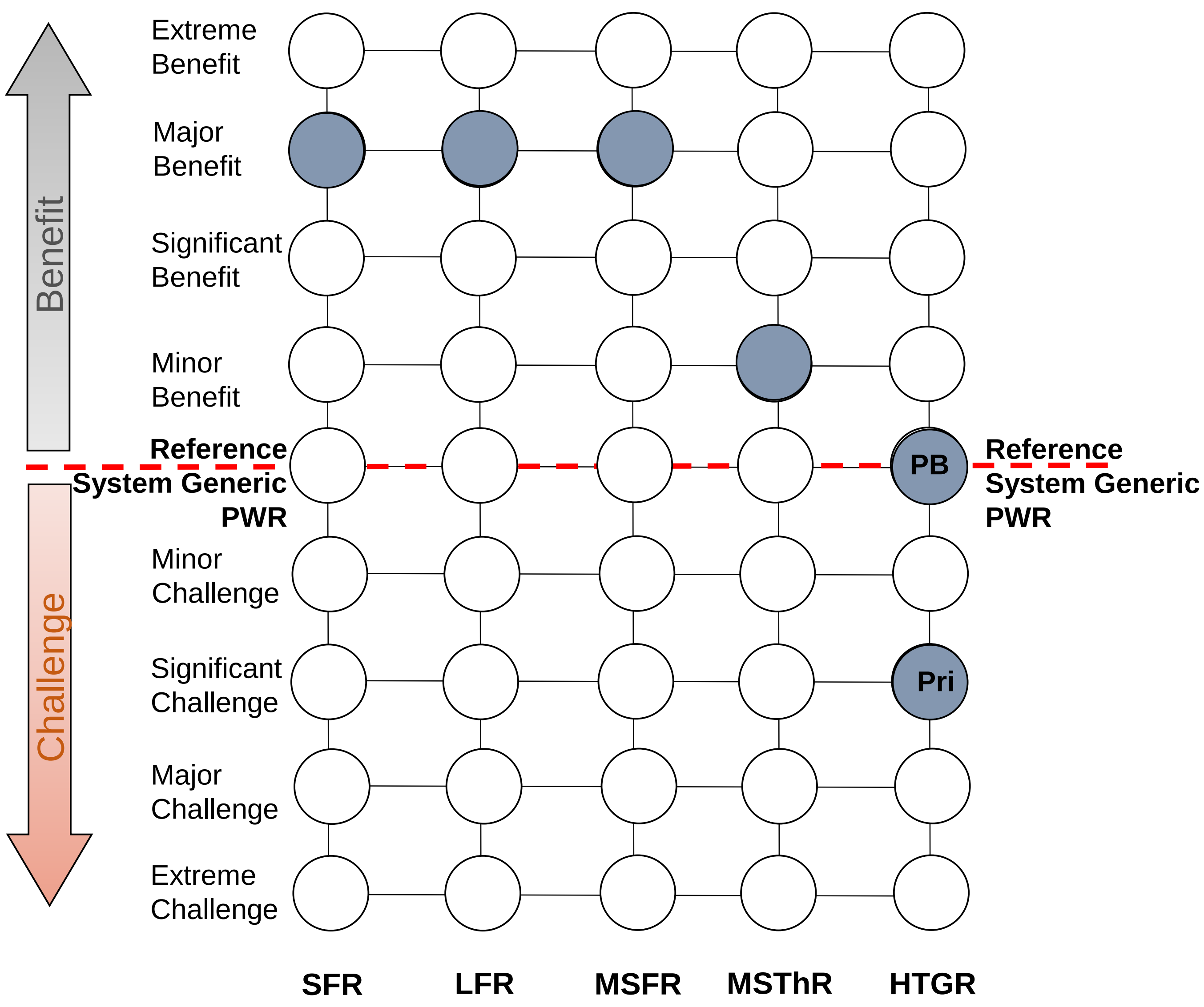
BUT, if thorium based fuels (e.g. thorium mixed with Pu) are used, the production of the fissile U233 isotope leads to a change in assessment to Minor Challenge.



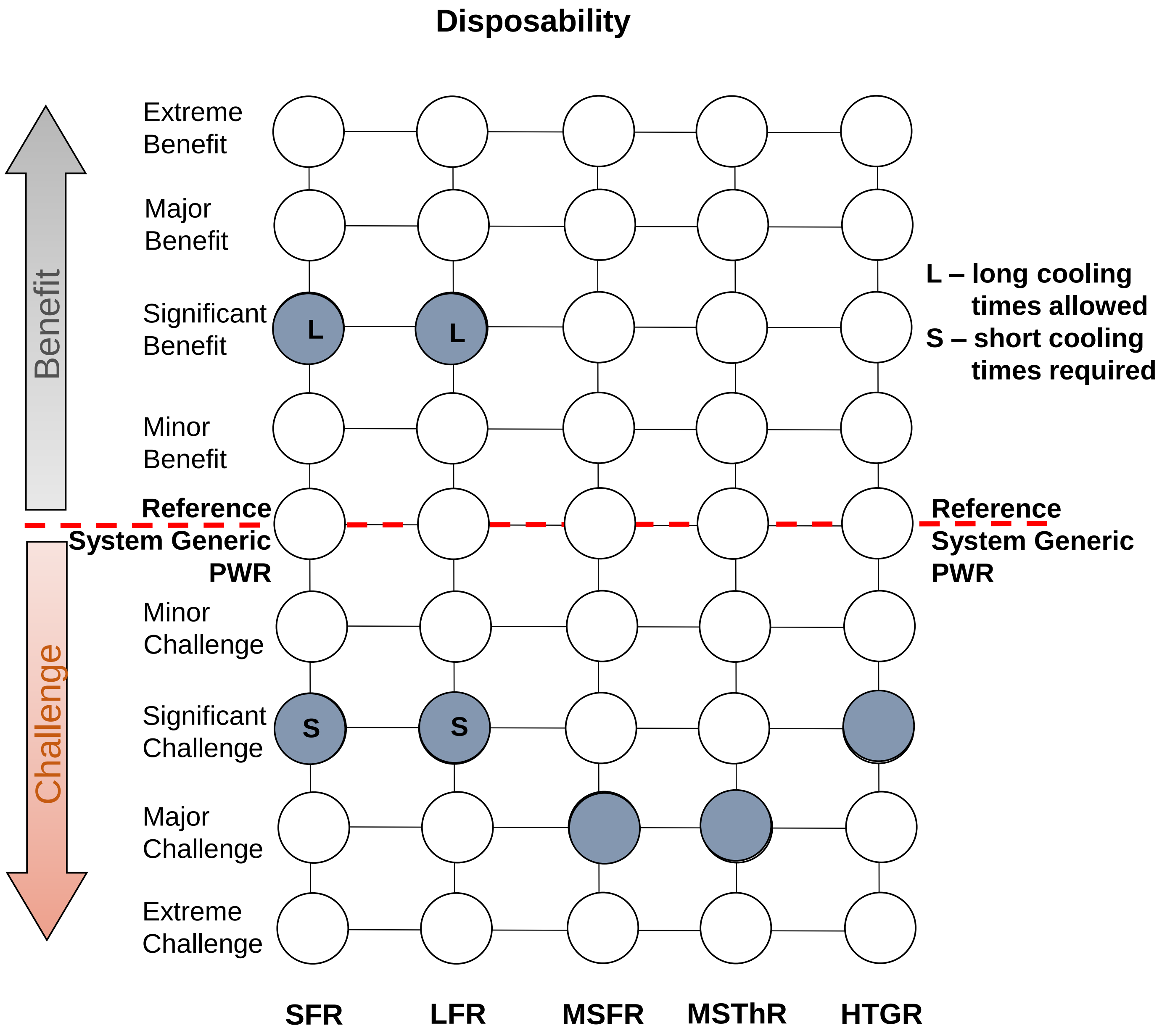
At their present state of development all emerging systems have '*ground to make up and much to prove*' compared with LWRs.

In particular, recycling systems must bear the recycling costs, which are likely to be considerable and in some cases/areas are at low TRL. Economic benefits for these systems (and those using thorium) will depend on a large rise in uranium cost and/or very high costs of (or problems with) waste disposal.

Fuel Security



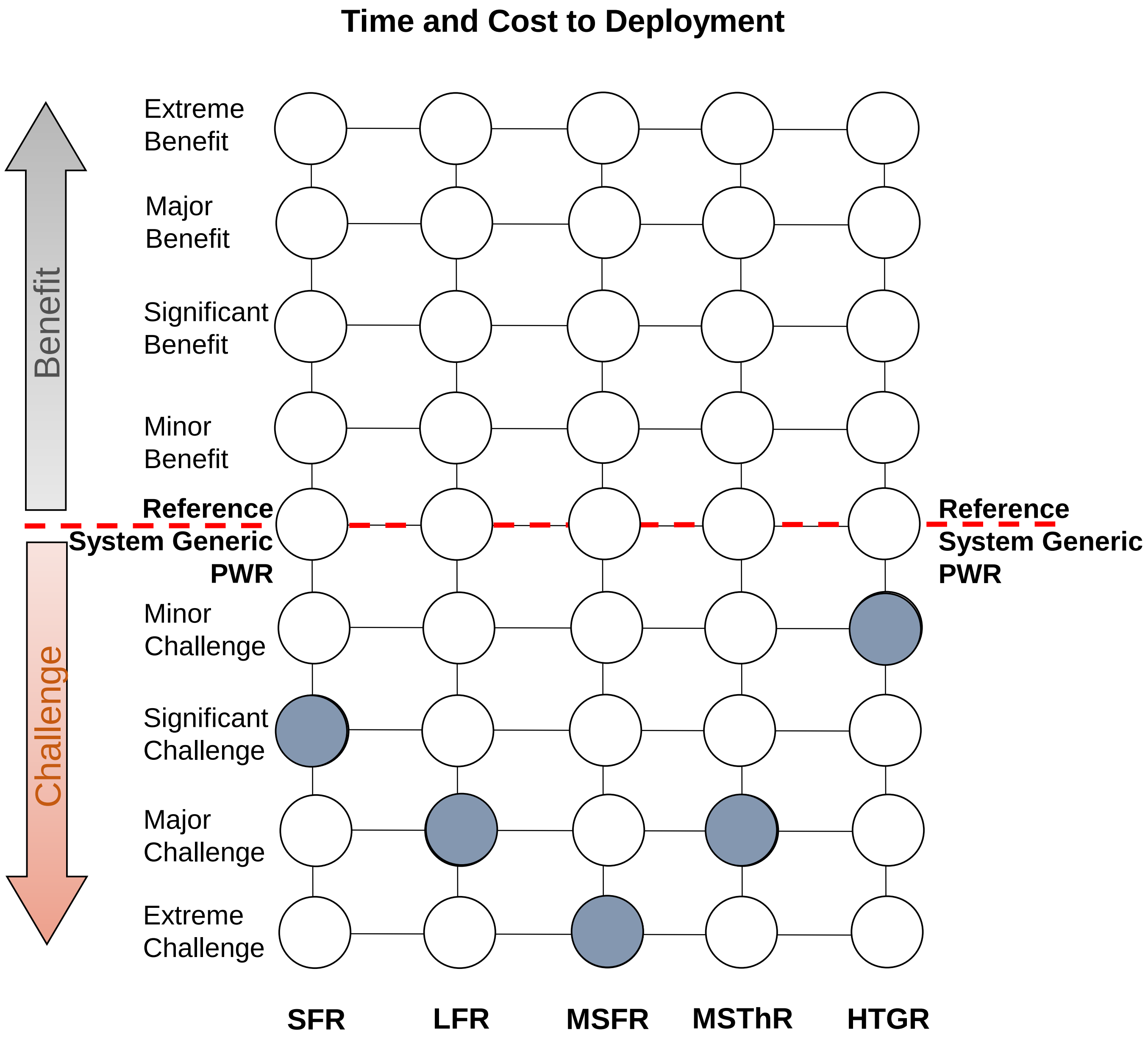
An area of major benefit for recycling systems, with factors of 50-60 in uranium usage. To translate this into overall economic advantage very considerable increases in U price would be required.



SFR and LFR fuel is considerably more challenging than the PWR Reference Systems, especially if the fuel is reprocessed at short cooling times (current reprocessing technologies generally not suitable). Once conditioned the wastes have benefits of lower heat generation.

Major challenge for MS systems based on need to develop reprocessing technology and waste conditioning.

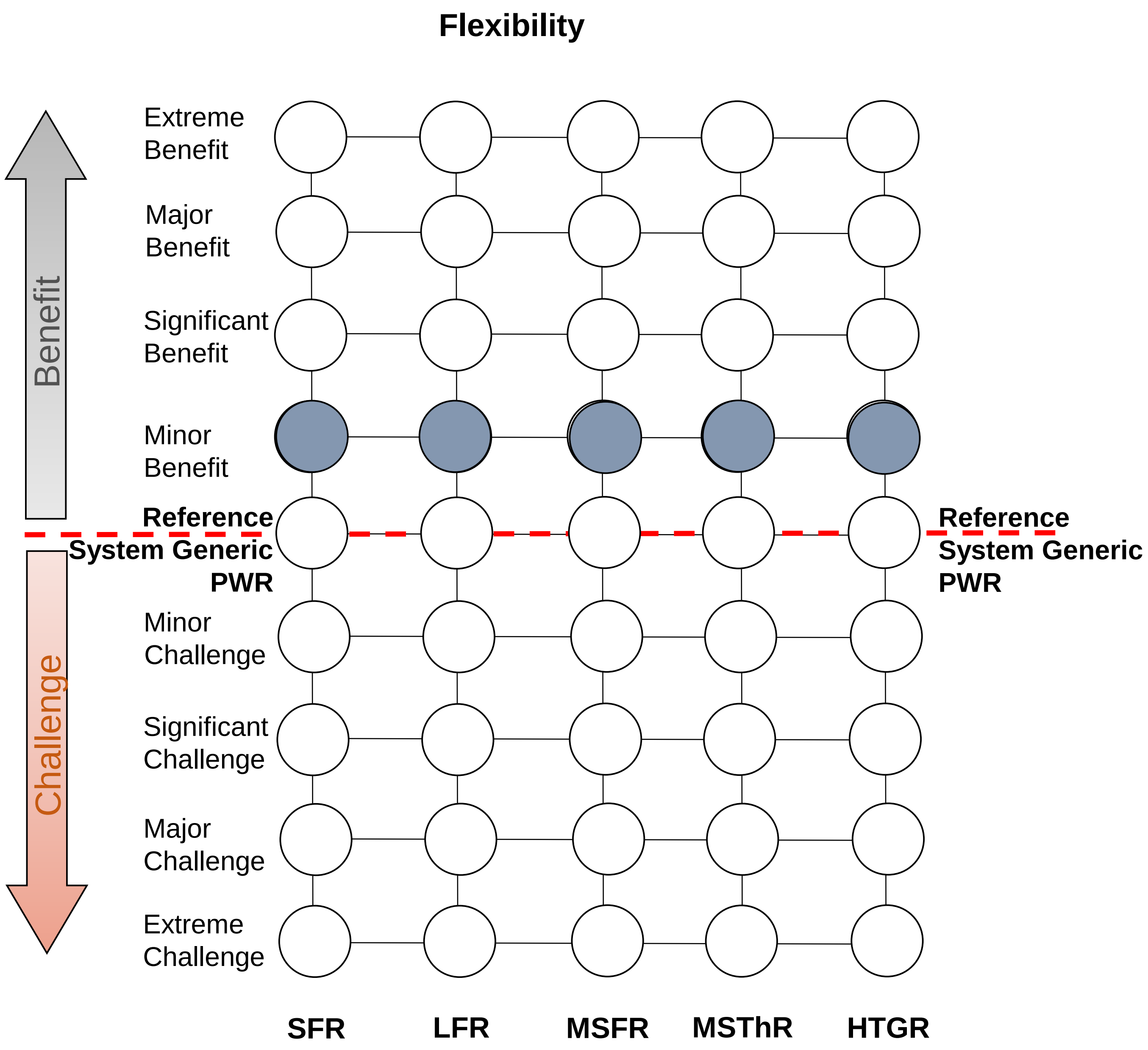
HTGR challenge is large volume and limited experience of graphite disposal



Cost largely mirrors perceived challenges in capital and development spends

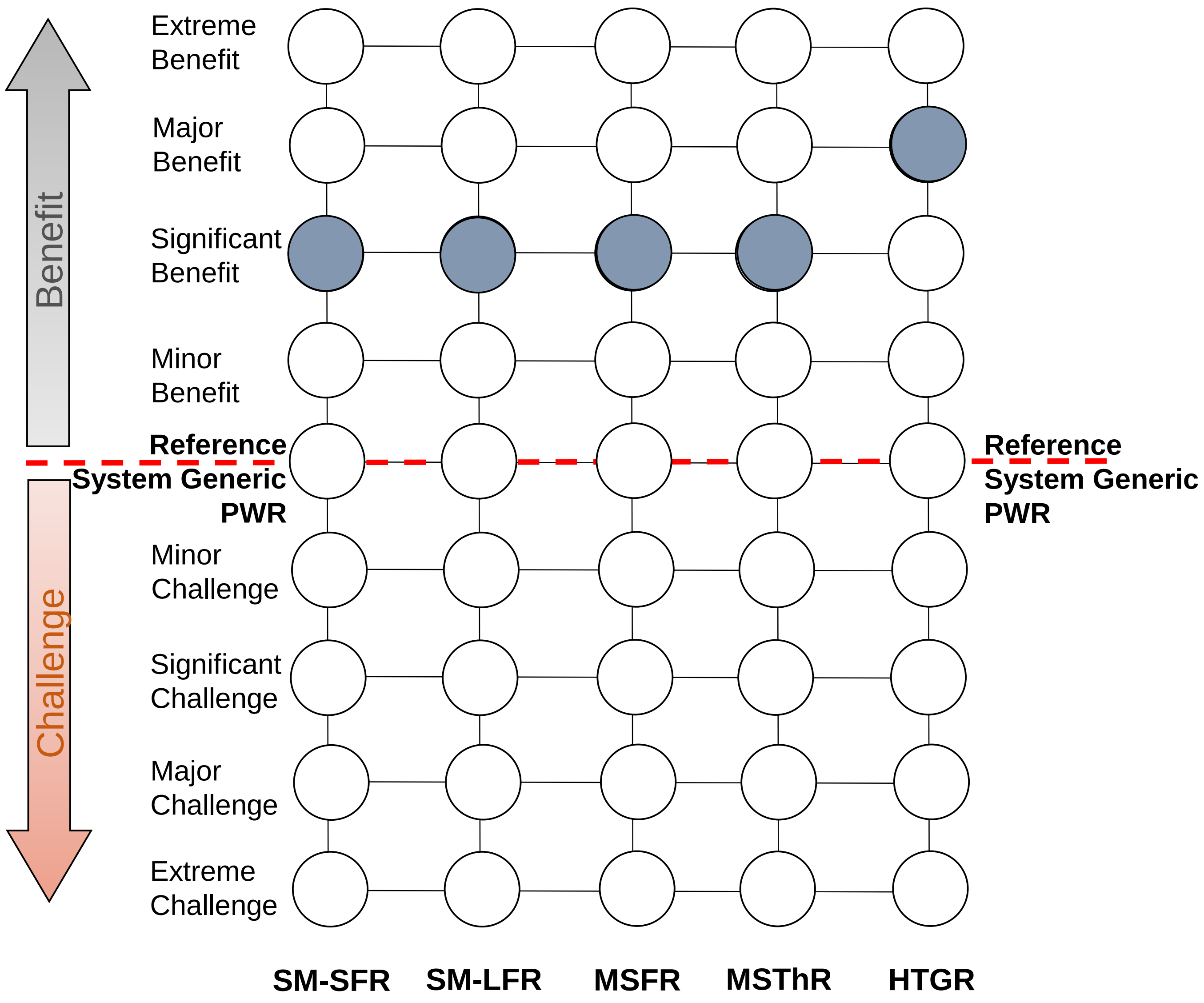
Time to deployment is challenging because of elements of low TRL in most of the advanced systems, with some systems requiring advances in both processes and materials

UK on-line deployment dates in the range 2035 to 2070.



All advanced systems appear to offer some benefit over LWRs, but key problem for all nuclear is high *cost* of flexibility – who pays??

Process Heat



All advanced systems operate at a higher temperature than LWRs, so can offer more useful process heat. HTGRs have highest temperatures and hence potential benefits.

Overall Picture?

- **Time and Effort to License** – unsurprisingly all ‘advanced’ systems demand more effort and time to deploy that existing systems with 60 years of continuous experience
- **PRPP Acceptability** – once-through systems like PWR are the benchmark, and any closed fuel cycle system offers challenges
- **Economic Competitiveness** – no ‘advanced’ systems offer a clearly defined economic advantage – even after a generaous FOAK-NOAK allowance
- **Fuel Security -** closed systems driven by offering U savings often present economic challenges in comparison to other low-carbon power options at the same high uranium prices – security of supply through non-deployment?

Overall Picture?

- **Disposability** – some closed systems can offer significant advantages in waste volume and heat generation – but it is very difficult to postulate the differences as game changing even when considering LCOE at zero discount rate.
- **Time and Cost to Deployment** – this ‘accumulated’ attribute shows little sign that most advanced systems can either make it to market in a reasonable time, and no compelling reason how they could compete once they get there
- **Flexibility** – one area in which many systems offer potential advantages – but the key question is ‘*how is nuclear flexibility to be paid for’*??

Overall Picture?

- **Process Heat** – the one area where virtually all ‘advanced’ systems offer the advantage of a higher operating temperature than LWRs. Here the use of nuclear heat for activities such as hydrogen production (and substitution for natural gas) could be both economic and offer a huge benefit in driving down carbon emissions. The HTGR technologies offer the highest temperatures, and are also good from a PRPP viewpoint. Watch this space!

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Note: this analysis derives from an assessment of Advanced SMR Systems for DECC (now BEIS) completed in March 2016. This analysis is now (since December 2017) at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/665274/TEA_Project_3_-_Assessment_of_Emerging_SMR_Technologies.pdf - authors as acknowledged for this presentation

Also note that, subsequent to the submission of this analysis, a meeting was held with regulators in January 2017, where they suggested various wording changes to the GFA ‘template’, though these did not affect the assessment. The actual GFA assessments (*though not the BEIS website paper)* have been reformatted reflecting these changes, and are made available as supporting literature.

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Thank You

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