Aims of the Supporting Document

Overview and Purpose

The purpose of this supporting document is to complement the economics section of the presentation, particularly given the limitations of time and the inability to delve into detailed calculations during the presentation itself. Recognizing these constraints, it's essential to have a resource that not only offers further details on the calculations but also serves as a reference point for figures mentioned in the original presentation. This document, therefore, serves as a crucial companion to the presentation, ensuring that the audience has access to the necessary depth and substantiation of the economic aspects discussed.

Scope and Limitations

It is important to note that this document will not delve into the foundational aspects of how the High-Level Waste (HLW) Simulation model was built. Although it will touch upon the main ideas, a comprehensive explanation from scratch is beyond its scope. For those interested in the detailed mechanics of the model, the source code has been made available on GitHub. This approach ensures that the document remains focused and concise, while still providing avenues for deeper exploration.

Who Pays for High-Level Waste Disposal?

Funding Mechanisms

Understanding the funding mechanisms for HLW disposal is crucial before engaging in any detailed economic analysis. While this aspect was not covered in the presentation, due to its assumed familiarity to the Net Zero committee, it gives the explanation for the benefit of other potential listeners. In the UK, the responsibility for the disposal of HLW primarily falls to the government, through the Nuclear Decommissioning Authority (NDA). The NDA is funded by the Department for Business, Energy and Industrial Strategy and receives annual approval for its budget.

Government and Commercial Funding

An interesting aspect of this funding model is the initial reliance on government funds, primarily sourced from taxpayers, followed by a strategic shift towards maximising income from commercial operations. In 2021/22 for example, the NDA's planned expenditure was £3.494 billion, with £2.530 billion coming from the government and the remaining £0.964 billion generated through commercial activities like spent fuel management and transportation services[0]. This approach of blending government and commercial funds is seen as a sustainable model for future decommissioning projects.

Understanding High-Level Waste (HLW)

Definition and Initial Treatment

HLW predominantly refers to used nuclear rods from reactors, characterised by their high levels of radioactivity. Before these can be transported to storage facilities, they must undergo a cooling period in water pools, which typically lasts between 2 to 5 years, depending on the reactor type the waste came from.

Composition of Spent Fuel

The composition of spent fuel is generally consistent, with variances based on the reactor type. Taking a light-water moderated reactor (LWR) as an example, the spent fuel composition includes uranium (around 93.4%, with approximately 0.8% being U-235), fission products (5.2%), plutonium (1.2%), and minor transuranic elements (0.2%)[1]. It's important to mention that while uranium 238 (U-238) is a significant component, the real concern in terms of radioactivity comes from the fission products. Despite them constituting a smaller percentage of the waste they contribute to the 95% of the total radioactivity produced by the waste[2].

Assumptions for Waste Simulation
When simulating waste, a key assumption is that the mass of fuel inputted into the reactor is equal to the mass of HLW produced, disregarding the energy released (as per E=mc^2) due to its negligible impact on mass. This assumption simplifies the modelling process. Furthermore, while there are exceptions, the majority of reactors use UO2 fuel[3], and for the sake of this model, all reactors are assumed to do so.

Density Calculation of HLW
An important factor in predicting the volume of HLW is its density. Given the high densities of heavy metals (HM) involved, discussions typically revolve around cubic meters of HM. The calculated density of HLW, taking into account the different components and their respective densities, is approximately 18,400.72 kg/m3. This figure is critical for accurately estimating the volume and thereby the storage requirements for HLW.

Author's Suggestion: To enhance the credibility and utility of this document, it may be beneficial to include a section that addresses frequently asked questions or common misconceptions about HLW disposal economics. This could serve as a quick reference for readers and provide additional clarity on complex topics.

- HLW Density = (0.934×19.1)+(0.052×7)+(0.012×19.86) = 18.40472g/cm3 => 18404.72kg/m3 ~ 18,400 72kg/m3

Reactor Types in the UK

Current and Future Reactor Technologies

As of now, the United Kingdom predominantly operates Advanced Gas-cooled Reactors (AGRs)[4], each with a typical burn-up rate of 18 GWd/tHM[5]. It's crucial to understand that 'burn-up' measures the extent to which uranium is consumed in the reactor. A key point to note is that higher burn-up rates result in more fission products, thus leading to more radioactive HLW[6].

Focusing on fuel consumption, we can estimate that a 1GW AGR power plant would require approximately 54 tonnes of fuel annually, based on specific calculations.

- (15/18)*65 => 54 tonnes / year of fuel.
- + Table and explanation

Upcoming EPR Reactors

The UK will soon introducing new reactor technology with the construction of Hinkley Point C and the planned Sizewell B plant, both of which are European Pressurised Reactors (EPRs). These reactors typically have a burn-up rate of 60 GWd/tHM[6], similar to Light Water Reactors (LWRs). Thus, for a 1GW EPR reactor, the estimated fuel requirement is around 16.7 tonnes annually.

- So, we can estimate the fuel requirement by doing (50/60) * 20 = 16.7 tonne

However, to calculate total fuel consumption, one must adjust for the reactor's capacity.

- Though it is important to note that these values are for 1GW reactors, so to calculate the total fuel consumptions you would do:
- Fuel / year = (1GW reactor fuel / year) * capacity / GW

Calculation of Uranium Consumption

Assuming the fuel comprises 95% Uranium-238 Oxide (238UO2) and 5% Uranium-235, this translates to roughly 89% uranium content. Therefore, the annual uranium requirement is calculated as 0.89 times the annual fuel requirement, scaled according to reactor capacity.

- Assuming the fuel is 95% $^{238}UO_2$ and 5% ^{235}U this will mean that the fuel is: $[Ar(U)/Mr(UO_2)]*0.95+0.05$ = 89% uranium
- Hence, Uranium / year = 0.89 * fuel per year * capacity

Reactor type	Typical burn-up (GWd/tHM)	Annual discharge of spent fuel (tons)
LWR (light-water moderated)	50	20
CANDU (heavy-water moderated)	7	140
RBMK (graphite moderated)	15	65

Table 1. Annual discharge of spent fuel for three common reactor types. This assumes a reactor of 1 GWe operating at 90% capacity. GWd/tHM is the amount of thermal energy (heat) in gigawatt-days released per metric ton of heavy metal (HM) in the fuel.

Operation Times of UK Nuclear Plants

Data Sources and Plant Lifespan

Information regarding the operational times and closure dates of current UK nuclear power plants has been sourced from the World Nuclear Report[7]. This data is fundamental in modelling the generation of HLW in the near future.

Implications and Future Analysis

A significant observation is that most of these plants are scheduled to decommission by 2025. Consequently, a more thorough analysis is required to predict the HLW generation from new reactors that will be constructed in this decade. This approach will provide a more realistic forecast of future waste generation (see SMRs section).

Interim Storage of High-Level Waste

The Economics of Interim Storage

One of the core aspects of the presentation is to highlight how the costs of interim storage accumulate over time, suggesting that these could be mitigated through committed HLW management. However, accurate data regarding the capacities of various storage facilities is scarce, given their differing natures.

- There is not a lot of information about the capacities of the storage facilities due to the fact that each of them is different.
-

Estimating Storage Capacities

Due to the varied nature of storage facilities, there's a lack of uniform information about their capacities. This section attempts to estimate these values based on available data. However, for a more accurate assessment, we suggest utilising data accessible to the NetZero committee from government sources.

Storage Capacity Calculation

From Figure 1[8], we observe that HLW is stored in pools, with each pool holding approximately 10 in width and 25 in length to give a total of 250 canisters. Each canister, as seen from Figure 2[9], contains about 25 rods, leading to a maximum of 6250 rods per pool. The volume of an Advanced Gas-cooled Reactor (AGR) rod is roughly equal to the volume of a hole in a Boiling Water Reactor (BWR) canister, calculated as

- (4.835-0.2)*(1.05/6)^2 = 0.142 m^3
- Hence 1 pool can contain a maximum of ~6250 * 0.142 = 887.5 m^3 of HLW

Total Storage Capacity in the UK

With 13 interim storage sites identified by [8], six of which are dry storage facilities, it was assume that the dry facilities store half the amount of HLW as the pools. Thus, the equivalent of six dry facilities is three pools, leading to a total of approximately 10 pools. Therefore, the overall storage capacity in the UK is around

- 887.5 m^3 * 10 = 8875 m^3 ~ 9000 m^3 which is the maximum storage facility of HLW in the UK.

- This sounds reasonable due to the fact that there were 2 HLW recycling facilities that would produce enormous amounts of High Activity Liquor, HAL, which is fission products in nitric acid. Over time HAL can be conditioned (remove water + add glass to turn liquid into a viscous material making it less hazardous) to reduce its volume by 2/3[10], however conditioning facilities do not have big capacities and so high amounts of HAL had to be stored.
- Therefore, rough approximation of the maximum interim storage capacity indicates that no urgent interim storage facilities should be build to meet the demand of the nuclear industry which is supported by [8] that states that no new storage fascilites are planned to be built. We will also ignore the decommissioning process (some storage facilities going out of service due to end of operation time) due to the fact that new pools will be build for each new big powerplant.

Importance of Sensitivity Analysis in Interim Storage Cost Estimation

Due to the inherent complexities and the multitude of assumptions required in estimating interim storage costs for HLW, a significant limitation of our current analysis is the absence of a sensitivity analysis. Sensitivity analysis is a crucial tool that quantifies the uncertainty in the outcomes of a model in response to variations in its input variables. It helps in understanding how changes in key assumptions—like construction costs, operating expenses, or facility lifespans—can significantly impact the projected costs of interim storage.

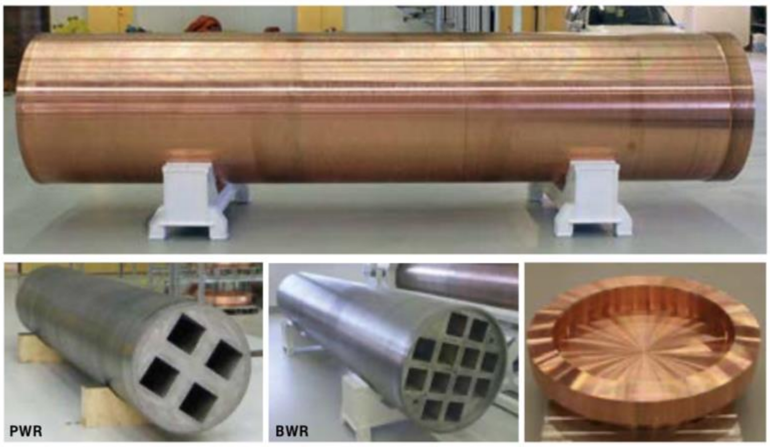
While time constraints prevented the incorporation of this analysis in our current model, it's highly recommended for future studies, especially considering the limited data available for our estimates. The NetZero committee, with access to more comprehensive and detailed data from government sources, is in a prime position to conduct this analysis. By doing so, they would not only refine the cost estimates but also enhance the reliability of the economic projections for HLW interim storage.

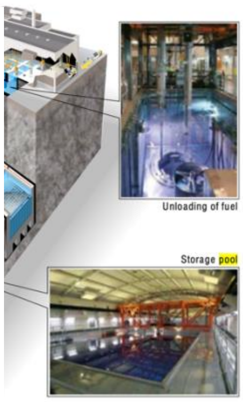
Interim Storage Costs Calculation

For the construction of a 12m deep pool, the approximate dimensions of the Sellafield pools can be derived as 25×10×12 m, equating to a 3000 m pool. The estimated construction cost, including safety inspections, is around £1.5 million, with decommissioning costs in the lower billion range, approximately £2 billion. Operating costs are estimated at around £2 million annually.

Assuming a lifespan of approximately 50 years for these facilities, the cost per cubic metre of storage per year is calculated as

- (2 bill + 1.5 mill + 2 mill)/(900m^3*50) = £45,000 / m^3 stored for 1 year.
- This value is used in the simulation
- £30k /18400 = £2.4 / kg of HLW per year (to use later in the recycling section)





ent nuclear fuel, Clab.

Figure 2-8. *Copper canister with inserts of nodular cast iron for PWRs and l* Figure 2

canister's length, diameter and copper thickness are 4.835 metres, 1.05 metres

A Figure 3 *which the copper weighs 7.4 tonnes, the*

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Geological Disposal Facilities (GDFs)

Introduction to GDFs

Geological Disposal Facilities (GDFs) are secure repositories designed for the long-term underground storage of nuclear waste. As will be detailed in the presentation, GDFs are crucial for ensuring the safe and secure disposal of nuclear waste for many years.

Economies of Scale and Cost Efficiency

One of the primary advantages of GDFs is their ability to utilise economies of scale to reduce the cost per unit of waste stored. For instance, the GDF in Finland, which cost less than a billion euros (€818 million[15] or £710 million), did not fully benefit from economies of scale, resulting in a storage cost of £2.02 million per cubic metre of HLW. This calculation is based on the facility's total capacity of 6500 tonnes[16] and the previously calculated HLW density of 18,400 kg/m^3. In contrast, the proposed Swedish GDF, with an estimated cost of SEK 124.1 billion[17] (£9.5 billion) and a 12,000-tonne HLW capacity, has a projected cost of £1.46 million per cubic metre of HLW. While the proposed GDF in the UK, significantly larger in scale, is expected to reduce storage costs to approximately £500,000 per cubic metre of HLW.

Country	Status	Cost / £ bill	HLW capacity / m^3	£ mill per 1 m^3 of HLW
Finland	Completed	0.71[15]	353	2.02
Sweden	Proposed	9.5[17]	652	1.46
UK	Proposed	25-30	9, 980	0.570

Canisters in GDFs

Significance of Canister Design

The design of canisters is a critical component in the functionality of GDFs, as they are responsible for containing HLW and protecting it from the surrounding environment. The design of these canisters is particularly important to ensure the safe containment of HLW.

There are two main types of KBS-3 canister designs: Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR). The choice of design is dependent on the type of reactor and the toxicity of the waste produced. BWR canisters are suited for lower burn-up AGR reactors, while PWR canisters are designed to contain the more toxic waste from higher burn-up EPR reactors.

BWR Canisters for AGR

The BWR canister designed for AGR reactors has a diameter of 1.05 metres, which equates to approximately six holes for rods, giving a side length of 1.05/6 metres per hole. Assuming a square shape for each hole, the area for a single rod hole is (1/6)^2 m^2. With a total of 12 rods per canister, the total area is calculated as 12 \times (1.05/6)^2 = 0.3675 m^2. The volume of the canister is then calculated as 0.3675 \times (4.835-0.2) = 1.703 m^3, where 0.2 m accounts for the thickness from both sides.

It is noted that the rods do not occupy the full space of the hole, allowing room for clay, but this aspect was not included in the calculation. The volume of cast iron in the canister can also be calculated by subtracting the copper and HLW volumes from the total canister volume, which is π \times 0.55^2 \times 4.835 = 4.595 m^3. The resulting cast iron volume is 4.595 - 1.443 - 1.703 = 1.449 m^3. Therefore, each BWR canister has a total volume of 4.595 m^3, with 1.703 m^3 dedicated to HLW, 1.443 m^3 to copper, and 1.449 m^3 to cast iron.

Canisters

- Canisters is arguably the most important component in the GDF since it is this layer that will hold HLW and protect it from the surroundings. That's why a canister design is very important.
- There are two types of KBS-3 canister designs, BWR and PWR. This is because the higher burn-up reactors (EPRs) will produce a more toxic waste and will have to be isolated more thrilly.
- BWR will be used for a low burn-up AGR reactor while PWR will seal more toxic waste from EPR reactor.

BWR (For AGR)

- Diameter = 1.05, which is approximately 6 holes for rods, hence rod hole side length is 1.05/6 m. Since squares, the area of a single hole for a rod is (1/6)^2. There are total of 12 rods per canister, hence 12*(1.05/6)^2 = 0.3675 m^2 is the area. So, volume = 0.3675 * (4.835-0.2) = 1.703 m^3. (0.2 accounts for thickness from both sides)
- Note from the picture it is clearly seen that the rod doesn't take up the full space of the hole (cause there will be a clay), but this was ignored in this calculation
- It is possible to find the volume of a cast iron as well by doing:
    - Total cylinder volume – Copper volume – HLW volume = cast iron volume
    - Total canister volume = Pi * 0.55^2 * 4.835 = 4.595 m^3
    - cast iron volume = 4.595 - 1.443 - 1.703 = 1.449 m^3

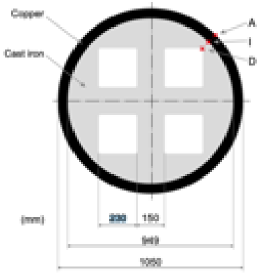

Figure 3-1. The canister configuration for the PWR fuel assembly from Guinan (2001). Points A, I and D are henceforth used in the calculations.

- Total canister volume = 4.595 m^3
- 1.703 m^3 of HLW per canister.
- 1.443 m^3 of copper / container.
- 1.449 m^3 of cast iron / container

PWR (For EPR)

- This is the variation of a canister which utilises more cast iron to seal a higher radioactivity HLW.
- Very handy sketch from **(7 change to this document)** to estimate volume. Total HLW that can be in a single PWR canister is 4 * (0.23^2)* (4.835-0.2) = 0.981 m^3

- It is possible to find the volume of a cast iron as well by doing:
    - Total cylinder volume – Copper volume – HLW volume = cast iron volume
    - Total canister volume = same as before (4.595 m^3)
- cast iron volume = 4.595 - 1.443 - 0.981 = 2.171 m^3
- Total canister volume = 4.595 m^3
- 0.981 m^3 of HLW per canister.
- 1.443 m^3 of copper / container.
- 2.171 m^3 of cast iron / container
- Total metal mass intake = 8900x1.443 + 2.171*7300 = 30 tonne of metal
-

Recycling
- As you saw from the HLW section the composition of HLW is about 95% of unused uranium which can be got back via recycling.
- During recycling process you separate high radioactivity fission products from the uranium through electrolysis in nitric acid. At the end you get recycled uranium with HAL which was described earlier.
- The idea behind recycling is to get back the uranium and generated plutonium, it is a concept that purely works on the scarcity of the elements you are trying to get. At 60s it was thought that uranium was very scares and recycling technologies were developed. It is then everybody realised that there is more uranium on earth that everybody predicted.
- uranium is about 100 times more common than silver[15]
- So, the problem with recycling is that at current uranium price it is more expensive to recycle than to buy a new pile of uranium.
- The concept of break-even price is often use to assess the economic validity of the recycling.
- It can be calculated using the following equation:
- Burying fuel + interim storage = Recycling – Returned U + conditioning recycling waste + burying recycling waste.
- The lates recycling cost it was been able to found was from a 20 year old paper (~£2,850 per kg)[18]. The recycling price is very likely to went down a bit, however it will argued that this will be balanced by the more costly safety inspections due to rising safety standards over time as well as conditioning costs. So, these factors will not be included in the calculation.
- Hence the equation is:
- Burying fuel + interim storage = Recycling – Returned U + waste + burying recycling waste.
- 1kg of UO_2 fuel -> HLW -> U_3O_8 mass -> equivalent to 0.95*(8.9 * U_3O_8) mass that we don't have to buy. Assuming 95% of uranium is left. Also, 0.12kg of Pu
- $4400 / kg of Pu from reactor => 3530*0.12 = £424
- 2850 – 424-8.9*(128.7) = 1280 / kg
- 1 kg of HLW = (1 kg/18400 kgm^{-3}) * (£567000 / m^3) = 30 pounds
- 20 years of storage => £2.4 *20 = 48 pounds
- Canister = 65 / kg
- 1280 – 48-30 -65 = £1137 / kg of U you will pay more!
- 2,850 – 100 – 65 – 424 = 8.9 x

- X = £254 / kg
- Note that there was a mistake in the ES.

SMRs

- This section will show the thinking involved behind the future prediction of HLW
- The leading expert in SMRs is Rolls Royce, which is closely working with the government. Also, this is the only company that already proposed a technology with enough data to fit it into a model.
- Hence, we assume that all SMRs in the future by 2050 will be approximately the same as RR ones
- SMR – 470 MWe standard Pressurised Water Reactor (PWR), 60 years life time
- PWR => light water reactor => 50 GWd/tHM burn up => 20 tonnes pre GW => 9.4 tonne of U per year (or waste) => 1m^3 of waste per 2 years => but should produce more waste
- Refuelled every 18-24 month, 285 m^3 over lifetime **(19)** (refuelled every 2 years, but don't bother having some years with 0 uranium consumption). 285 /60 = 4.75 m^3 per year
- Need 24 GW of nuclear by 2050 **(20)**
- According to model By 2036 will be only 6.4 GW of energy (only 2 operational power plants), hence need 24-6.4 = 17.6 GW more
- Assume all of them will be from SMRs => 17.6 / 0.47 = 37.45 => 38 SMRs
- Set up in 4 years rather than decades **(21)**
- Production cost will be £1.8 bill / unit for 5^{th} unit **(21)**
- First SMR by RR will be by 2029 => assume 2029 **(22)**
- Assuming that the target will be hit, that Rolls Royce will be able to build 1-2 at a time

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