Understanding the trade-offs between centralised and distributed recycle facilities

Edward A. Hoffman, Temitope A. Taiwo
Argonne National Laboratory
Argonne, IL, United States

Abstract

There are many possible variations of potential future nuclear fuel cycles. Some of them will involve the use of recycle facilities. Two primary approaches to the organisation of the fuel recycle facilities are the centralised and distributed approaches. In this study, an assessment of the attributes of the two approaches has been conducted for the purposes of discerning the advantages and disadvantages of the approaches.

Past studies have often had different objectives, priorities, and assumptions appropriate to the primary objective of the studies. This leads to completely different solutions to what appears to be the same underlying problem. Studies that involved centralised fuel recycle facilities often focused on minimising unit cost of fuel usually leading to large facilities taking advantage of economy of scale. The studies on distributed (collocated) recycle facilities sized to service one site often focused on proliferation resistance and minimising external cycle time by eliminating off-site shipments.

The objective of this trade study was to evaluate, identify, discuss and to the extent practical quantify the differences (trade-offs) in system performance resulting solely from variation of system architecture independent of technology. It focuses on system performance metrics in a broad range of areas including waste management, storage, transportation, economics, proliferation, resource utilisation and public perception.

This is a rather encompassing task focused on the fundamental differences between generic systems and not detailed differences of specific designs using specific technologies. The paper focuses on the driving assumptions, constraints, mass flow analysis and uncertainty that will drive the trade-offs between centralised and distributed recycle facilities. No conclusions about the preferred approach are made because even with sufficient data and precise analyses, each option will have its advantages and disadvantages which will have to be weighed by the decision-maker's subjective priorities.

Scenarios can be envisioned where either the centralised or distributed approach is favourable. Current results suggest that the uncertainties in cost, schedule, performance, etc., far exceed the calculated differences between the two approaches. The assumptions about the future are one of the primary differentiators. High growth and certainty favour the large investment to achieve low unit costs of the larger centralised facilities. Low growth and high uncertainty favour the reduced risk of smaller distributed facilities.

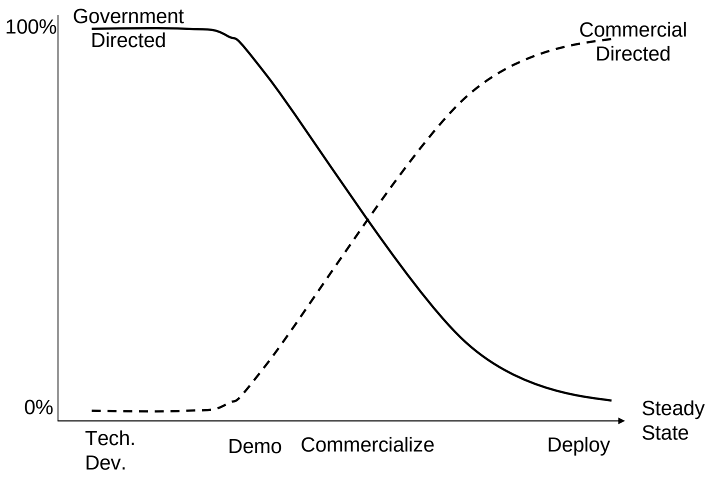
Introduction

A qualitative, technology-neutral assessments of the trade-offs between centralised and distributed recycle facilities (recycle systems) was performed. The transition from current commercial nuclear power enterprise to a quasi-steady state commercial operation in the future was considered. The transmutation system(s) could contain a wide range of technologies from existing to more advanced and exotic technologies, with diverse performance parameters. Therefore, idealised systems and facilities are considered in the evaluation to provide quantitative assessments of the significance of trade-offs. The intent is not to make recommendations but to present a balanced discussion on the advantages and disadvantages of centralised and distributed recycle systems.

Because of the free enterprise system practiced in the United States, it is unlikely that the commercial recycle facilities would ultimately be owned by the government. However, the United States government currently receives payment from the commercial nuclear industry for the purpose of removing used nuclear fuel (UNF) from the commercial nuclear power plants and managing the material. So, at least prior to the take-over of this function by non-governmental organisations, the US government must develop a plan for the management of the UNF.

The major objective of any commercial enterprise is to make sound investments where all risks are understood and justified by the expected rewards. The United States DOE will likely be intimately involved in the early development and commercialisation of the advanced fuel cycle technologies, even if at a minimum to provide incentives for the commercial sector. It might also have a need to direct resources and shape technology for the national interest and might remain the primary consumer of certain fuel cycle services (e.g. high-level waste disposal), due to the unique nature of the nuclear enterprise. Even if this enterprise is initially owned by the government, there might in the future be a transition to a greater proportion of commercial involvement which will also impact the trade-offs that must be made. The transition as depicted schematically in Figure 1 will impact the priorities at a given point in time and the overall trade-offs.

Figure 1: Conceptual transition to quasi-steady state



There are many ways of organising the advanced fuel recycle systems based on different technologies and different system objectives. In this study, a single-tier closed fuel cycle is assumed in which all of the UNF from the primary energy source, LWRs, is recycled in a single transmuter type and the UNF from the transmuter is recycled back into the same type of transmuter. The two primary approaches to the organisation of recycle facilities are the centralised and distributed (collocated) recycle systems as well as hybrid variations of these.

The impact of system optimisation on a study of this type cannot be understated. The optimisation goals and constraints applied will affect the conclusions. There is significant difference between optimisation of a component of the system and the entire system. This analysis does not address the many ways the system can be optimised and all the different options. The trade-offs are considered from the perspective that the system will eventually become fully commercialised and optimised based on constraints that are consistent with industrial practices.

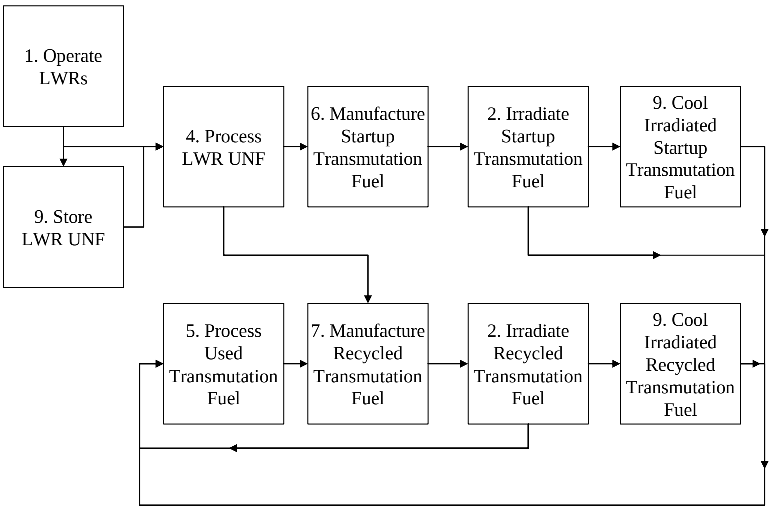
Scenario descriptions

A single-tier closed fuel cycle in which LWR will remain the primary energy source and all transuranic elements (TRU) arising from that enterprise will need to be fissioned (burned) to the extent practical for the purpose of minimising their environment impacts was considered in this analysis. It is assumed that a single type of transmuter will be used repeatedly for the continuous recycle of the TRU material. This fuel recycle scenario represents a realistic option that has been widely considered and adds enough complexity to identify the major differences between centralised and distributed recycle systems, while being simple to understand. In this study, the different scenarios considered are assumed to have the same objectives and to use similar technologies (as possible) with the primary variable being the system architecture. In practice, there might be different technologies that could perform better for different architectures and different organisations will have different priorities, but this study has identified those trade-offs and drivers related solely to differences in system architecture for otherwise identical systems.

There is a clearly defined set of major system functions that need to be performed for this type of scenario. These functions can be allocated to sites and facilities in a variety of ways to produce a wide range of scenarios. The system scenarios considered are modelled as a combination of the above major functions. Each function can be performed by a wide range of technologies at many types of facilities and sites. The intent is not to focus on technology choices, but to make the study as technology neutral as possible.

Figure 2 shows the general functional flow of the system to be analysed. The off-site transportation functions could occur along any line an arrow exists depending on the architecture. The waste management functions are not shown in this figure, as they are assumed to primarily flow from the used fuel processing functions. However all functions will handle nuclear material and produce some quantities of radioactive waste.

Figure 2: Functional flow diagram



There are many ways of organising the physical architecture of the advanced fuel recycle systems based on different technologies and different system objectives. In this study, a single-tier closed fuel cycle is assumed in which all of the UNF) from the primary energy source, light-water reactors (LWR), is recycled in a single transmuter type and the UNF from the transmuter is recycled back into the same type of transmuter.

For the purpose of discerning differences between the centralised and distributed (collocated) recycle approaches, six fuel recycle configurations (called scenarios) were considered. These were the:

- Fully Integrated Transmuter Site (ITS) – primary distributed option similar to what has been envisioned for the Integral Fast Reactor, but could apply to any transmuter technology.
- Centralised LWR Reprocessing/Distributed ITS – consolidation of the reprocessing of the large mass of LWR UNF which support an ITS-based system that recycles the more radiologically challenging transmuter fuel without offsite shipments.
- Centralised LWR Reprocessing with Collocated Transmuter Fuel Fabrication/Distributed ITS – expands the centralised capabilities to include production of transmuter fuel which eliminates shipment of separated materials. It allows transmuter operation to begin prior to investment in the collocated recycle facilities, while still precluding shipment of the radiologically challenging irradiated transmuter fuel.
- Centralised Integrated Fuel Recycle – the centralised equivalent of the ITS where all fuel recycle activities are integrated on centralised fuel recycle sites supplying multiple transmuter sites.
- Mini-centralised Integrated Transmuter – addresses a fundamental criticism of distributed ITS concepts by utilising the excess LWR UNF recycle capacity at a traditional ITS concept as a mini-centralised recycle centre to start up additional ITS that would not require excess LWR capacity resulting in improved overall system efficiently utilising the available LWR separation capacity.
- Fully Centralised/Industry Specialisation – completely centralised system where all major fuel recycle functions are performed at separate centralised sites.

Performance metrics

A broad spectrum of system performance measures was considered in order to provide understanding of the trade-offs that will result from the choice of centralised or distributed fuel recycle facilities. Since this study was a technology-neutral evaluation of the broad question of trade-offs between centralised and distributed fuel recycle, the evaluation of specific metrics with numerical values was not the goal, but data from past studies on single-tier closed fuel cycle over a broad range of conversion ratio was used to represent the mass flows for a broad range of potential systems [1,2]. The study evaluated the broad system performance differences in a qualitative manner to provide understanding of differences and should be a useful basis for more focused future trade-off studies. The measures of system performance differences were defined broadly, and grouped into seven major areas: waste management; fuel storage; proliferation resistance and physical protection; resource sustainability; economics; safety, licensing and public perception; and transportation.

General impacts

The results of the analysis show that many of the performance measures will be highly sensitive to the technology choices and far less sensitive to the system organisation. Some measures are additionally sensitive to the embedded assumptions. Many of the performance measures show

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time-dependent impacts during the transition period from the current state of enriched uranium fuelled LWR to the quasi-steady state fully-deployed advanced fuel recycle system. Optimisation of the system can often significantly reduce the importance of differences in system organisation. This makes specific conclusions about the general trade-offs in system architecture challenging to defend on technical grounds without a lot of specific caveats.

Since the same amount of material will ultimately be processed, the waste management figures of merit are relatively insensitive to the system architecture. They are however very sensitive to any technology differences that may be driven by system architecture differences.

There may be significant differences in the quantity and types of material in storage during the transition period. These differences are likely to be less once the quasi-steady state operation is established. Storage metrics will be sensitive to technology which may impose significantly different constraints on the system. At the quasi-steady state, the material in storage would likely be highest as the system is more centralised because additional cooling time would be needed in order to ship the irradiated materials more efficiently.

Proliferation resistance and physical protection are very difficult to quantify or even qualify in a meaningful way without detailed analysis. The primary difference between the distributed and centralised recycle systems arise from materials in storage and transport, where the less outside of reactors and the less handling, the better. Most of the proliferation resistance and physical protection (PRPP) metrics are technology and design sensitive. The material types are also very important. Any system that involves the shipment of significant quantities of weapons usable materials would present additional challenges to material safeguards. The Fully Centralised/Industry Specialisation scenario assumes that there is a separation between the material recovery and fuel manufacturing activities and the shipment of separated materials, which would make PRPP of greater importance. Other variations of centralised schemes that could involve shipment of significant quantities of separated materials would also make this a much more important consideration. Shipment of fresh transmuter fuel would represent a significant PRPP consideration, especially considering the wide range of possibilities for these plutonium-bearing fuels. The only scenario that does not ship any materials beyond the used LWR fuel is the Fully Integrated Transmuter Site. However, this approach would involve the most sites with separations and fuel fabrication technology, which might be a disadvantage due to the spread of nuclear technology knowledge to a greater number of operators, which may be significantly reduced by industry consolidation.

Public perception has variable behaviour depending on the metrics considered. Some metrics suggest there could be significant benefits while other metrics for the same scenario suggest significant disadvantages.

Transportation requirements provide a clear distinction between the centralised and distributed recycle systems. The more the system contains collocated facilities, the less shipping that would be required. Transportation is heavily related to environmental impacts (potential for release near urban areas), safety (traffic accidents), and public perception (facilities can be sited where public supports them, but transportation crosses many diverse jurisdictions).

Since all scenarios are assumed to do the same thing, namely recycle all used LWR fuel and transmute it to the same degree, there is negligible impact on very long term resource utilisation. However, some scenarios may permit a more rapid expansion of the transmuter fleet by compressing the external cycle time for recycle of the used fuel. This will not impact the amount of material that will ultimately be fissioned, but will impact the timing. For example, more LWR, and therefore more uranium, will be needed to produce the same level of nuclear power if transmuters are delayed while the used fuel is cooling prior to recycle. This also could reduce the total nuclear power level, which would require other sources such as coal to meet the total energy demand. In that way it could have substantial impacts on sustainability and environmental metrics outside of just the considerations within the nuclear energy system.

Economic impacts

There are many economic differences that will be important beyond just the levelised cost [3-5]. The economics trade-offs are quite substantial with the range of scenarios considered, showing advantages and disadvantages between the systems and the sensitivity of economic indicators during the transition versus equilibrium periods. Early on in the transition period, there will be significant technological risk because of immature technology leaving large uncertainty in cost, performance, uncertainty, supply chain, demand, etc. Once all these technological uncertainties have been resolved and the system is in a quasi-steady state, then most of the benefits of adaptability and flexibility become evident and the risk premiums could be eliminated which will change the balance of the economic trade-offs and likely give much greater importance to the economy of scale advantage of large centralised facilities compared to mitigation of risk.

A number of potentially significant factors that could have large economic impact were identified. These generally were not inherently related to system organisation and were found to be more important during the initial transition period and stem from the assumption that centralised fuel recycle facilities will be large relative to the distributed facilities. Past fuel recycle facilities have often had limited demand for their products resulting in significant under-utilisation and/or delays between production and consumption. Both of these are economic risks that must be balanced with potential economy of scale benefits. Nuclear facilities can have very substantial learning curve benefits. Limiting the size of the initial facilities is one way to reduce investment in the more expensive first-of-a-kind facilities and then leverage this learning with economy of scale to produce more economical facilities over time. There are also concerns that too large of a facility would create a natural monopoly and the potential for a large disruption in the fuel supply if it were to become inoperable.

The major challenge of this type of analysis is that economics is very sensitive to scale; timing, time delays, dynamic behaviour and past experience; uncertainty in performance and future demand; system organisation; ownership, organisational knowledge, experience and resources; as well as other factors that are likely sensitive to system architecture and the state of development; and the specific technology deployed. These are likely to be impacted by the choice of system architecture, thus affecting a variety of economic metrics.

Most of the economic trade-offs are unrelated to the traditional cost analysis that assumes risk and other economic factors are the same and therefore the low cost solution using the same cost of money is the economically preferred alternative. There are very substantial differences in the economics of the centralised and distributed systems that are unrelated to the unit cost calculations and there is likely to be very different costs of money between the different facilities and technologies. It seems quite likely that the relative values of the metrics will change substantially as the system transitions from the current state to the future quasi-steady state conditions.

Even though the total quantity of fuel, reprocessing, electricity, etc., in an integrated fashion will be very similar for consistent scenarios, the relationship in time will be different between the centralised and distributed scenarios. This will be as important as the variation in overnight capital cost with the scale of the facilities.

Simplified evaluations with idealised models and assumptions were used for analysing the relative values of the economic metrics. The high degree of sensitivity to the assumptions makes the economics evaluation the most highly uncertain and requires future definitions of very specific scenarios with sufficient detail. For every scenario, there are many alternative approaches. One of the important underlying assumptions in this assessment is that the centralised facilities will be large monolithic facilities, but this is only one alternative. There is certainly nothing that precludes the centralised facility to be installed in a modular fashion at the same scale as the distributed options or any other appropriate scale that optimises performance. This would reduce some of the economy of scale advantages, but mitigate the diseconomy of scale issues. This would eliminate much of the economic difference save for the smaller difference related to transportation costs and costs/savings associated with an integrated site assuming the collocated site.

Economy of scale is a well understood concept. By utilising common facilities, common workforce, less than linear increase in construction costs with size, specialised labour, specialised equipment, and other factors, the unit cost of production at full capacity is reduced as the maximum capacity of a facility is increased. This suggests that bigger is better. The general assumption is that centralised facilities are bigger because they will support multiple transmuter sites while the facilities collocated with the transmuters will be sized to support just that one site. So an advantage of the centralised system is the potential benefits from a larger scale.

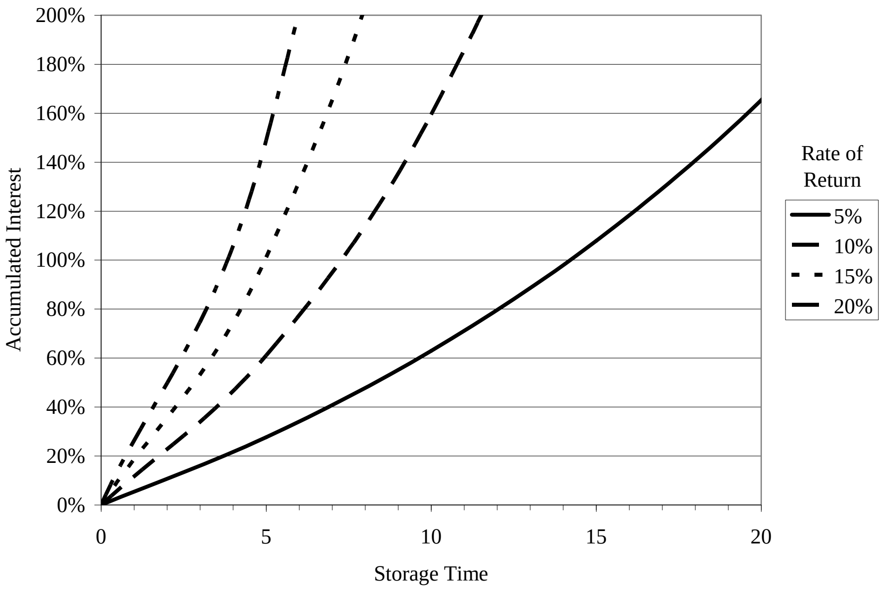
However, there are a lot of embedded assumptions in the bigger is better approach and many of them boil down to the question of whether or not there is a market to purchase that product at a price that is not reduced because of the increase in supply resulting from this new production. There are many other factors that can be diseconomies of scale that can be specific to the nuclear company, such as organisational efficiency or available capital, or region specific, such as sufficient infrastructure.

Theoretically, there is no one optimum size and ultimately depends on the time, place and needs. Practically, there are only a limited number of sizes of nuclear facilities that will be licensed or pursue licenses because scaling is not a trivial matter and requires significant investment to license a different sized nuclear facility.

A mismatch between supply and demand is a large source of economic risk. Collocated facilities are sized for the expected demand at the site. For centralised facilities, the expected demand is from diverse consumers making decisions based on their best interest. A large increase in supply capacity will be brought on line in single discrete facilities in order to take advantage of the economy of scale. For example, if the future growth rate is 1% when 1.5% was assumed, the transmuter fleet will only be 75% of that anticipated at 60 years in the future.

Figure 3 shows the accumulated interest that would be added on top of the levelised cost for a given storage of the product. Levelised costs are typically calculated based on the assumed production being promptly consumed (sold). This figure shows that carrying charge as a fraction of the levelised cost calculated in the standard manner could more than double the levelised cost if inventory on average is retained for a significant time. For example, a 10% rate of return

Figure 3: Accumulated Interest from delay between production and consumption



would double the levelised cost at time of use relative to at the time of production if the average storage time is just over seven years. It is easy to conceive of scenarios where this would be true for large centralised plants built early in the transition period. Collocated facilities will also have significant carrying charges while the start-up inventory is being produced prior to the start of operation that will add to the overall levelised cost.

Since the storage time or reduced capacity is likely to vary over the life time of the facility, a more accurate levelised cost based on detailed production and consumption is needed. What this simple analysis shows is that delay between production and utilisation may be the dominant cost factor and will certainly be a significant cost component if there are any significant time between production and utilisation whether planned or unexpected, which is most likely early in the transition period.

Collocation will increase the capital-at-risk for a single site as more capabilities are incorporated at that site. Centralising the fuel recycle functions will reduce the capital-at-risk at the transmuter site, which will be a minimum when only the transmuter and necessary balance-of-plant facilities are onsite and highest for the fully integrated site.

The capital-at-risk is minimised when the size is smallest, which is typically a trade-off with unit cost of production. The smallest capital-at-risk for fuel recycle facilities likely occurs when collocated with the transmuter. This can also be managed through modular designs. However, collocation increases the total capital-at-risk for the entire transmuter site substantially because it is the sum of all the pieces.

The importance of capital-at-risk is tied very closely to the perceived risk. Other than the fully integrated transmuter sites, investors (private or government) must be found to create the other necessary facilities. It does not matter whether it is fuel cycle service investors requiring future transmuter investors or transmuter investors requiring future fuel cycle investors. The availability of consumers or suppliers for a service depends on the details of the market and where in the transition from the current state to the future quasi-steady state. Initially, there will likely not be a market for fuel cycle services making this a very risky investment, but eventually with substantial growth new capacity may be a small increase to a well established market with only the normal business risks. The transmuters will not have transmutation fuel without investment in fuel cycle services (centralised or distributed). Assuming the transmuters can run on uranium-based fuel, they will be, for practical purposes, a variation on the existing LWR until there is a supply of transmutation fuel. The ability to operate on uranium fuel seems like an important risk mitigation strategy early in the transition period by providing an alternative reliable fuel source and/or allowing the electricity (revenue) generating transmuter to begin operations prior to completion of the UNF recycle facilities. This is an argument for using LWR as the transmuter, but it applies to all transmuters.

The concentration of supply chain, particularly to a sole source provider, is a significant system risk. It gives that provider monopolistic power over transmutation fuel which would require government regulation or a realistic alternative (e.g. UOX instead of MOX). It also creates a single mode failure. If there is an accident at a single monolithic facility, it could take the entire supply out of the market until a replacement facility can be constructed. For nuclear systems, particularly after such a significant accident, it will likely be a decade or more before it is replaced. These are all system risks that will need to be considered. The ITS are their own sole supplier, which puts the entire site at risk if the fuel recycle capabilities are lost and it is the only one with this capacity. However, this is a small incremental operational risk at a single site as there may be many sites at that time.

One of the trade-offs during the transition period will be learning versus economy of scale. The unit cost is assumed to decrease with increased size (economy of scale), but it is also assumed to decrease with repetition (learning). Large capacity will reduce the learning by reducing the needed number of repetitions. Once the Nth-of-a-kind is achieved, there is little or no learning required. There will be more learning benefits from building a larger number of smaller units at a given time during the transition period. Determining the optimum size to be deployed during the transition period will include a trade-off between economy of scale benefits and learning

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benefits. There are simple mathematical relationships that model these effects. They require information about the relationship between the unit cost of building a larger facility and building multiple facilities. In practice, there is a very wide range of expected behaviours. Some systems make significant cost improvements by increasing scale, while others are much less sensitive to scale. Some systems make significant cost improvements in each subsequent facility while others show much less benefit from learning. Results from a simple evaluation indicated that based on purely the trade-off of economy of scale and learning, the preferred alternative is not clear during the transition phase.

Conclusions

This report has provided a general understanding of the significant trade-offs likely to be driven by the choice of system architecture for the recycle of UNF. There are many ways of organising the advanced fuel recycle systems based on different technologies and different system objectives.

A broad spectrum of system performance measures was considered in order to provide understanding of the trade-offs that will result from the choice of centralised or distributed fuel recycle facilities. This study evaluated the potential system performance differences in a qualitative manner. This qualitative analysis provides understanding of those differences and should be a useful basis for more focused trade-off studies in the future.

The analysis shows that many of the performance measures will be highly sensitive to the technology choices and far less sensitive to the system organisation. Some measures are additionally sensitive to the embedded assumptions. Many of the performance measures show variations in the transition period from the current state of enriched uranium fuel LWR to the quasi-steady state of the fully deployed advanced fuel recycle system. Optimisation of the system can often significantly reduce the importance of differences in system organisation. This makes specific conclusions about the general trade-offs in system architecture challenging to defend on technical grounds without a lot of specific caveats.

The economics trade-offs are quite substantial with the range of scenarios considered, showing advantages and disadvantages. Some of the economics metrics show significant difference between the early transition and quasi-steady state periods. Once all these technological uncertainties have been worked out and the system is in a quasi-steady state, economy of scale will likely be a more dominant factor pushing the recycle system towards large centralised facilities.

A number of potentially significant factors that could have large economic impact were identified as a result of this study. However, these generally are not inherently driven by system organisation, specifically centralised versus distributed (collocated). Most of these factors are likely more important during the initial transition period, when technological, regulatory, deployment, and other uncertainties are the highest. Past fuel recycle facilities have often had limited demand for their products resulting in significant under-utilisation. Nuclear facilities can have very substantial learning curve benefits. Limiting the size of the initial facilities is one way to reduce investment in the more expensive first-of-a-kind facilities and then leverage this learning with economy of scale to produce more economical facilities over time. There are also concerns that too large of a facility would create a natural monopoly and the potential for a large disruption in the fuel supply if it were to become inoperable.

Acknowledgements

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