Market and Technical Assessment of Micro Nuclear Reactors

80755/REP/001/C
Date: 31st March 2016
A report produced for DECC

www.nuvia.co.uk

Revision details:

Issue	Reason for re-issue	Date of re-issue
A	Issued to DECC for review and comment	15th March 2016
B	Re-issue after comments addressed	24th March 2016
C	Final issue after acceptance by DECC	31st March 2016

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EXECUTIVE SUMMARY

Work to date has indicated that small nuclear reactors could have the potential to provide significant benefit to the UK, in terms of energy supply and cost, speed of deployment as well as potential economic and commercial opportunity. Micro Nuclear Reactors (MNRs) are a distinct class of small reactor systems, typically of under 30MW electricity and 100MW thermal output, which are expected to occupy distinct and different market niches, in comparison to larger Small Modular Reactors (SMR's). This desk study was commissioned by DECC to provide a high level technical, economic and market assessment of this distinct class of reactor, looking at potential markets both in the UK and overseas. The study was conducted using publically available information only.

Although some MNR designs have evolved from LWR technology, MNRs are typically not water cooled or water moderated. They use a compact reactor and heat exchange arrangement, frequently integrated in a single reactor vessel. They are designed to be factory manufactured in large functional units largely eliminating the need for costly and complex nuclear critical assembly work on site. MNRs are generally designed to require no operator intervention in the case of emergency shutdown; on-site presence during operation can be minimised. The size of MNRs may enable them to be removed from site and taken to a specialist facility for decommissioning, with minimum onsite dismantling. There are a number of MNR designs currently in development, although only a few are actually operating or in construction.

Due to their size and unique characteristics, there are a number of potential market opportunities for MNRs. A potential global accessible market of up to 2850MW (equivalent to 570 units of 5MW each) has been estimated by around 2030. This covers both the UK market and internationally accessible markets (notably remote islands and desalination plant). The largest immediate market is likely to be nuclear power plant standby, with other markets starting on a much smaller scale, with the potential for longer term growth. The application size for NPP standby has been estimated as 10MW, making it ideally suited to a reactor of MNR scale.

Due to the early design stage of many of the MNRs, there is little publically available financial information. However, a number of factors can be identified which will affect likely cost and potential revenue. One of the key considerations will be the extent to which the learning curve will result in subsequent units being less expensive than the first as lessons are learnt and techniques are standardised. A clear advantage of the MNRs is their small size and simplicity, which allows for demonstration plant to be constructed relatively simply allowing theoretical aspiration to be tested.

One of the key uncertainties surrounding MNRs is the timescale and cost associated with the regulatory process. By definition the reactors are simpler, smaller scale and have a greater level of passive safety than large reactors. All these factors should be of benefit in the regulatory assessment process, however uncertainty remains and clear regulatory guidance will be required.

This study concludes that MNRs are feasible and have a potential market in the hundreds by 2030. MNRs could also bring significant economic benefits to the UK but must be decisively supported as they will only proceed with clear support and facilitation of political, regulatory and financial factors. The study also concludes that, whilst there are differences with the larger SMRs, no specific cut-offs have yet been identified in technical, financial or regulatory factors. However, further investigation may yield more definitive differentiators depending on the regulatory and market requirements of specific countries.

GLOSSARY OF TERMS

BWR	Boiling Water Reactor
CHP	Combined Heat and Power
GDA	Generic Design Assessment
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
LCOE	Levelised Cost of Energy
LMR	Liquid Metal (fast cooled) Reactor
LR	Large Reactor
LWR	Light Water Reactor
MNR	Micro Nuclear Reactors
MSR	Molten Salt Reactor
MWe	Mega Watt of electricity
MWt	Mega Watt of thermal energy
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
PWR	Pressurised Water Reactor
SAP	Safety Assessment Principle
USP	Unique Selling Point

TABLES

CONTENTS

1 INTRODUCTION

Work to date [1] has indicated that small nuclear reactors could have the potential to provide significant benefit to the UK, in terms of energy supply and cost, speed of deployment as well as potential economic and commercial opportunity. To this end, the UK Government has been undertaking a programme of assessment of small modular reactor systems of under 300 MWe in order to inform any policy decisions on the development and deployment of such systems in the UK. This work has revealed a distinct class of small reactor systems, typically of under 30MWe and 100MWt output and these are classed as Micro Nuclear Reactors (MNRs).

MNRs are expected to occupy distinct and different market niches, in comparison to larger Small Modular Reactors (SMR's). To ensure that MNRs are considered appropriately in any future Government policy decision on the development and deployment of nuclear energy within the UK, DECC commissioned a high level desk study to provide additional technical, economic and market assessment of this distinct class of reactor, looking at potential markets both in the UK and overseas.

Nuvia Limited, together with Parsons Brinckerhoff and Atomic Acquisitions, were awarded a contract to perform this work under Energy Technical Specialist Framework (TRN 906/10/2014).

The aim of the study was to bring together available information on the MNRs and assess the implications of this information for potential future development in this area. It is not intended to look in detail at areas already being covered by the main SMR study [1] but to look at the specific implications of the "micro" systems, answering the questions:

- What reactor technologies are available?
- What markets are there for this type of reactor?
- How will other factors will affect their deployment, for example cost or regulatory factors?

Information has been derived primarily from publically available sources, to allow for its open publication. Discussions were also held with the authors of the main SMR report and other interested parties to gather information and knowledge but no formal programme of engagement with potential MNR vendors was undertaken.

2 TECHNOLOGY

2.1 Introduction to technology

There is a range of scale and diversity of MNR designs but they nevertheless share certain defining characteristics which are outlined in Table 1 below:

Table 1 MNR Characteristics

Characteristic	MNR definition	Comparison to other reactors
Capacity	Up to 30MW electrical output and up to 100MW thermal power.	The larger Small Modular Reactors (SMRs) have a capacity in the range 30-300MW, whereas the planned new build Large Reactors (LR) have a capacity in the range 1100-1700MWe (currently generating LRs are 500-1200MWe).
Reactor technology	Typically, but not exclusively, high temperature gas reactors, liquid metal cooled fast reactors or molten salt reactors. MNRs generally employ the more efficient Generation IV concepts[1] that are currently at a lower level of technology readiness (although a few designs still rely on the Generation III concepts).	MNRs diverge from the SMRs closest to market which use Generation III+ technology (pressurised water reactors similar to Hinkley C). LR technologies are also light water reactors using PWR or BWR technology.
Design	Uses a compact reactor and heat exchange arrangement, frequently integrated in a single pressure vessel to minimise the risk of large loss of coolant accidents. Primary coolant may be a molten metal or salt, again avoiding the risk of large loss of coolant accidents.	The small scale of the MNRs reduces the need for additional complexity in safety systems, for fuel handling or for the power cycle offering significant simplification compared with large reactors and some further simplification relative to SMRs.
Construction	Designed to be factory manufactured in large functional modules which may be skid mounted (e.g. reactor with primary heat exchanger, secondary heat exchanger, turbine and generator), largely eliminates the need for costly and complex nuclear critical assembly work on site. Installation of the reactor is frequently below-ground to increase safety.	These are also features of SMRs but for MNRs the smaller scale allows a higher level of off-site assembly with greater access to the benefits of production line manufacture.

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[1] Generation I reactors were the early prototypes, Most currently operating, or soon to be operating, reactors are Generation II or Generation III. Many SMRs are Generation III+, an evolution of the current Generation III. Most MNRs are Generation IV technology, which is largely still under development.

Characteristic	MNR definition	Comparison to other reactors
Safety features	Generally designed to require no operator intervention in case of emergency shutdown, designed to reduce risks of aerial impact, avoid major vulnerabilities such as large loss of coolant and to incorporate inherently passive post-trip cooling. The small core size and the use of high integrity fuel designs, such as the ceramic TRISO type[2], are widely applied to minimise the source of any escape of nuclear material in a worst case accident scenario. Based on core thermal power it is estimated that MNRs could have a detailed emergency planning zone[3] as little as 25m radius, but unlikely to exceed 250m.	Many of the safety features will also be present in SMRs but differ from current generation large reactors. In particular, the smaller scale of MNRs permits passive post-trip cooling to be employed which is not feasible for the larger SMRs or LRs.
Refuelling	Whole core replacement as the refuelling strategy is typical for MNRs. The refuelling interval is generally longer than two years and in some cases the same as the life of the plant. Fuel enrichment often exceeds 5% to maintain reactivity in a small core over the longer refuelling cycle.	The small reactor core results in reduced neutron efficiency so that fuel utilisation will be lower than for larger reactors, including SMRs. Large Reactors (LRs) require more frequent refuelling.
Operation	Potential for minimal site manning is typical for MNRs, with some design concepts allowing for remote unattended operation, although this is not expected to be the case for first generation MNRs due to regulatory and safety factors.	This feature is in contrast to the manning levels required for a large nuclear reactor and is a further step beyond that proposed for SMRs. This presents challenges to the management of security and proliferation risks which will need to be addressed.
Decommissioning	Decommissioning concepts for MNRs are not yet developed. However, the smaller scale of MNRs may permit large components, possibly up to the scale of the reactor pressure vessel, to be removed from site, after a sufficient 'cooling-off period', to a specialist facility for decommissioning. Such a process could reduce complexity and cost, with potentially a smaller environment impact.	LRs need to be decommissioned in situ.

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[2] TRISO fuel is made of balls of Uranium covered by carbon and silicon carbide. Its spherical shape means the fuel retains strength and integrity, including under accident conditions.

[3] Estimate based on ONR assessment of Sizewell B under the Radiation (Emergency Preparedness and Public Information) Regulations 2001.

2.2 Available technologies

Of MNR's entering the market there are many vendors and technologies at differing stages of development. This section focuses on those technologies which are in the process of being marketed as technology development opportunities, albeit at a conceptual design stage in most cases. This early stage of development means that there is limited availability of robust data supported by independent evidence. For this reason the numerous research based technologies have been excluded.

The International Atomic Energy Authority (IAEA) defines small and medium reactors in terms of Evolutionary and Innovative, and this framework has been adopted in the assessment of MNRs [82]. Evolutionary is regarded as having been adapted from parent technology and hence does not involve large quantitative or qualitative changes in design. Innovative, however, represents quantitative changes in design and a step change in technology. Both types are discussed in more detail below, with current designs summarised in Table 3.

Evolutionary Designs

The reactor designs classed as evolutionary are derivatives of existing larger units. These Generation-III designs are an evolution of the current light water reactor (LWR) technology and are closest to actual deployment. Types include water cooled and water moderated MNR's which have been updated to include more passive safety features such as integral vessel configuration [83]. These evolutionary designs are able to draw on existing supply chains.

The designs already operating or closest to deployment are based on Russian technology and have been adapted from existing military units. Units are in operation at the Bilibino Nuclear Power Plant, although this design is not expected to be deployed in the future. There are two demonstration units under construction; the KLT40S in Russia (based on an icebreaker design), and the Carem-25 in Argentina.

Innovative Designs [65]

Often classed as Generation IV these designs include a range of technologies. The only commonality is that they are not light water reactors. Many of these designs originate from the 1960's, from designs abandoned when the US settled on light water reactors as its preferred choice of reactor for deployment. The Generation IV designs are summarised in Table 2.

Table 2 Innovative reactor types

Reactor types	Characteristics
High temperature reactor	Generally graphite moderated and mostly gas cooled. They can have a high thermal efficiency compared with LWRs due to higher operating temperatures. Currently there are two prototypes in operation the HTTR in Japan and the HTR-10 in China with larger units under development. The only UK design being developed for the MNR market is the U-Battery developed by Urenco which is at a concept stage.
Molten salt reactors	These reactors dissolve the fuels in molten salt mixtures, or use molten salts for coolant. These have many safety features, and have the potential to deliver higher efficiencies than an LWR. There is one operating molten salt design in operation (CEFR) and one prototype under construction (TMSR), both in China. Other designs are at various stages of readiness but development has slowed due to a lack of financial backing.
Liquid Metal Reactor (LMR)	This is a reactor design that is cooled by liquid metal, totally unmoderated. The technology has the capability to "breed" fuel, because it can be arranged to produce fissionable fuel during operation due to neutron capture. The small scale and role of MNRs may mean that this capability is not worth exploiting. These reactors function at a similar thermal efficiency to a thermal power plant.

Although experimental demonstration plants do exist, the innovative designs that are on fast track to commercialisation include Chinese gas and salt cooled reactors and salt-cooled thermal rectors. Other designs are at various stages of readiness from concept to detailed design. Table 3, overleaf, shows the differing reactor designs being considered for commercialisation. A glossary of terms is given below:

Type of reactor	LWR= Light Water Reactor PWR = Pressurised Water Reactor (a type of light water reactor) BWR = Boiling Water Reactor (a type of light water reactor) HTR = High Temperature Reactor LMR = Liquid Metal Reactor MSR = Molten Salt Reactor
Development status	Stage of development of reactor, from initial concept through design phases to construction, demonstration or operation. Concept design represents an early stage of development.
Power output	Maximum electricity output of the MNR. Given in MW of electricity. Values are given per unit (MNRs can also run as banks of 2 or more units).
Thermal output	Maximum thermal output of the MNR. Given in MW thermal. Values are per unit. A unit may produce electricity, thermal output or a combination of the two but will not produce the maximum value of both concurrently.
Circulation	Forced or natural circulation? Forced cooling relies on a continued power source to work whilst natural circulation requires no intervention

Safety	Active or passive safety systems. Passive systems require no intervention in the event of an incident
Reactor size	Physical dimensions of reactor unit in metres, height followed by diameter.
Refuelling	Number of years before unit will need to be refuelled.
Coolant	Substance being used as the reactor coolant.

The information given below has been obtained from a number of publically available sources, as specified within the tables. Whilst every effort has been made to ensure it is correct, it has not been possible to verify the technical validity of all data from a number of sources.

Table 3A Summary of Evolutionary Designs

Reactor Characteristics	**Light Water**							
TYPE	**PWR**	**LWR**	**BWR**	**PWR**	**PWR**	**PWR**	**PWR**	**PWR**
Name	KLT-40S	EGP-6	VKT12	ABV-6	CAREM-25	MRX	UNITHERM	SHELF
Development Status	Construction	Operational not to be deployed in future	Shelved at conceptual stage	Detailed design	Construction	Conceptual design no recent activity	Concept design	Concept
Power output MWe	35	11 to 12	12	6	25	30	6.6	6
Thermal output MWt	150	62	Information not available	38	100	100	20	28
Fuel material	Uranium	Information not available	Uranium	Uranium	Uranium oxide	Uranium oxide	Uranium oxide/ Zirconium oxide	Uranium oxide
Fuel enrichment	<20%	Information not available	<5%	19.7	3.4	4.3	19.7	<20
Circulation	Forced circulation	Information not available	Information not available	Natural circulation	Natural circulation	Natural circulation	Natural circulation	Forced and natural circulation
Safety	Active and passive safety features	Information not available	Information not available	Passive safety features	Passive safety features	Passive safety features	Passive safety features	Active safety features
Reactor Vessel size (Height/ Diameter) m	4.8/2	Information not available	2.4/4.9	6/2.4	11/3.2	3.7/9.7	9.8/2.9	Information not available
Refuelling interval (years)	3.5	Information not available	10	10	1.5	3.5	17	5
Coolant	Light water	Boiling water	Water	Light water	Light water	Light water	Light water	Light water
Company	OKBM Afrikantov	Teploelectroproekt	OKBM Afrikantov	OKBM Afrikantov	CNEA	Jaeri	RDIPE	RDIPE
Country	Russia	Russia	Russia	Russia	Argentina	Japan	Russia	Russia
References	6, 7, 8, 9	2, 4, 5, 6, 10, 12	10	6, 8, 10, 13	8, 14	15, 16	17, 10	8

Table 3B Summary of Innovative designs – High temperature reactors

Reactor Characteristics	High Temperature				
TYPE	**HTR**	**HTR**	**HTR**	**HTR**	**HTR**
Name	HTTR	HTR-10	Ubattery	MHR-100	MTSPNR
Development Status	Operational	Operational	Conceptual design	Conceptual Design	Concept, quiet since 2010
Power output MWe	N/A	3	4	25	2
Thermal output MWt	30	10	10	Information not available	48
Fuel material	Uranium oxide	Uranium oxide	Uranium	Uranium	Uranium
Fuel enrichment	6	17	<20	<20	20
Circulation	Natural circulation	forced circulation	Forced circulation	forced circulation	Forced circulation
Safety	Passive and active safety	Passive and active safety	Passive safety	Passive and active safety	Active safety
Reactor Vessel size (Height/ Diameter) m	13.2/5.5	25/5.7	5/1.8	16.8/5.2	Not stated, unit is truck Mounted
Coolant	Helium	Helium	Helium	helium	gas/air
Company	JAERI	INET	URENCO	OKBM Afrikantov	NIKIET
Country	Japan	China	UK	Russia	Russia
References	18	19	20, 21	8	10

Table 3C Summary of Innovative designs – Fast reactors and molten salt reactors

Reactor Characteristics	**Fast reactor**							**Molten salt**		
TYPE	**LMR**	**LMR**	**LMR**	**LMR**	**LMR**	**LMR**	**LMR**	**MSR**	**MSR**	**MSR**
Name	Sealer	Gen4	4S	RAPID	ANGSTREM	CEFR	SSTAR	TMSR	IMSR	MARS
Development Status	Concept design	Concept design	Concept design	Concept design - no recent information available	Concept design	Operation	Concept design	Prototype under construction	Conceptual design	Conceptual design
Power output MWe	3 to 10	25	10	5	6	20	20	2	29	6
Thermal output MWt	Information not available	70	30	200Kw	Information not available	65	45	Information not available	80	Information not available
Fuel material	Information not available	Uranium nitride	Uranium Zirconium	Uranium nitride	Uranium oxide	Uranium Oxide (MOX planned)	Uranium nitride	Thorium/ Uranium	Uranium tetrafluoride	Uranium
Fuel enrichment	10 to 30	19.75	20	Information not available	Information not available	Information not available	Information not available	Information not available	32	Informantion not available
Circulation	Forced circulation	Forced circulation	Natural circulation	Natural circulation	Natural circulation	Forced circulation	Natural circulation	Natural circulation	Forced circulation	Natural circulation
Safety	Passive and active safety	Passive and active safety	Active safety	Passive safety	Passive safety	Active safety	Passive safety	Passive safety	Active safety	Passive and active safety
Reactor Vessel size (Height/ Diameter) m	Not verified	2.4/1.5	2/0.68	6.5/2	Not verified	not verified	18.3/3.2	not verified	not verified	10.0/ 4
Refuelling interval (years)	Not verified	10	30	10	30	30	20	not verified	7 (sealed for life)	15 or 60
Coolant	Lead	Lead bismuth	Sodium (lead Bismuth in development)	Lithium	Lead bismuth	Sodium	Lead	Molten flouride	Salt mixture	Fluoride-based salts
Company	Lead Cold Promation Nuclear Safetech	Gen4Energy	Toshiba	CRIEPI	OKB Gidropress	China Nuclear Energy Industry Corporation	Argonne National Laboratory	sinap	Terrestrial Energy	Kurchatov Institute
Country	Sweden	USA	Japan	Japan	Russia	China	USA	China with US DOE collaboration	Canada	Russia
References	19	8, 24	25, 26, 27	28, 29	10	8, 33	80	30, 31	31, 32	10

2.3 Technology barriers

Each MNR technology faces its own unique set of technical challenges to development. These include:

- High Temperature Reactors, whether thermal or fast, require materials in the reactor core that can withstand high temperatures. Some new reactor designs are targeting higher temperatures in order to utilize Brayton cycle turbines, which offer higher thermal efficiency than the conventional Rankine cycle.
- Fast reactors need core materials and cladding that can withstand high levels of neutron bombardment.
- Metal fuels suitable for many fast reactor designs require fuel fabrication and cladding able to withstand void swelling and deformation.
- TRISO fuel used in High Temperature Reactors is currently only produced on a small scale. Large scale production facilities will need to be developed for commercial MNRs. [34]
- Gas and molten salt thermal reactors use graphite-clad ceramic uranium fuel pebbles. Again larger scale production of this fuel needs to be developed.
- Current molten salt reactors circulate molten salts with fuel dissolved in them. This presents challenges in operation of the reactor as it results in the whole salt circulation becoming radioactive so that maintenance of any components in contact with the salt can only be conducted in remote operational facilities.
- Security of nuclear materials, at potentially remote and unmanned locations, is a challenge for all MNR types; a regulatory and political challenge as well as a technical one.

Each of these challenges must be addressed through research and development, involving potentially considerable financial investment; a difficult commitment to make unless clearly identifiable market and customers are available.

The development programmes for several reactors are on hold but this does not appear to be due to insurmountable technical challenges, rather due to an uncertain future industry environment making the business case for further investment difficult to justify.

2.4 Indicative schedule to Deployment

The diverse MNR technologies are at a range of different stages of development. However it is important to understand the likely earliest date at which MNRs could provide the option of commercial deployment. Figure 1 illustrates the steps and potential timescale for progress from a near-complete MNR conceptual design in 2016 to commercial deployment. This is not based on a particular reactor or regulatory regime but indicates the likely processes and their timescale.

The key observation is that the earliest likely date for first commercial orders is shortly before 2030, with earliest commercial operation in the mid 2030’s. Although this is dependent on a number of factors, including the regulatory regime, and could be expedited if extra resources were available.

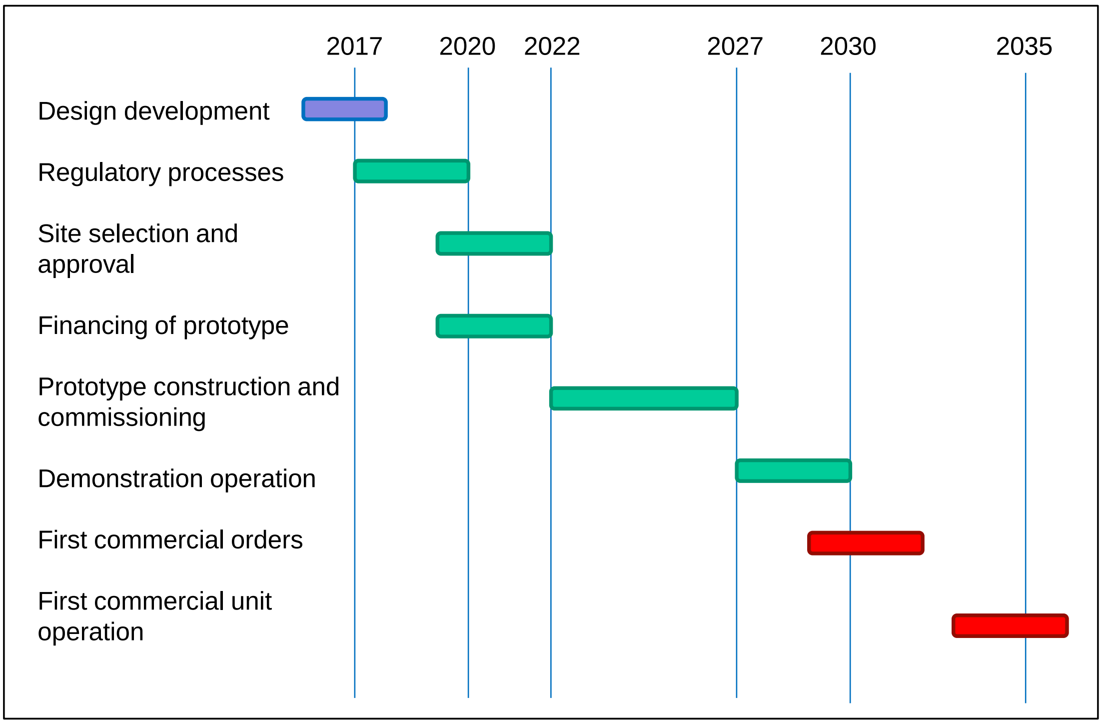


Figure 1 Illustrative Schedule for Earliest MNR deployment

3 APPLICATIONS AND MARKETS

3.1 Unique selling points MNRs

There are a number of Unique Selling Points (USPs) for MNRs which differentiate them from established large nuclear plant (and to a lesser extent SMRs) and from other non-nuclear energy sources such as gas turbines, wind generation etc. These selling points define the market and potential applications.

Table 4 Unique Selling Points

USP	Characteristics	Comparison with SMR characteristics
Scale	Opens up applications unsuitable for larger reactor types; can operate as part of a grid or stand alone	Similar to an SMR but permits smaller scale installation and potentially application within electricity distribution networks
	Simplifies design for manufacture, construction, operation, maintenance and decommissioning	MNRs offer increased opportunity for these benefits to be derived compared with SMRs due to their smaller size
	Allows a simpler design and safety provision which enhances reliability to levels potentially comparable with the best thermal plants	Some additional simplification beyond SMRs can be expected, such as passive cooling

USP	Characteristics	Comparison with SMR characteristics
	Potentially eases regulatory approval for sites closer to users	Smaller scale may further ease regulatory approval
Economy	Offers energy at a known cost through life, largely independent of fuel prices unlike gas and oil powered generation	Same benefit as SMRs, but may offer this benefit to a wider group of users
Autonomy	Supplies power for long periods independent of fuel deliveries	Similar to SMR, although some technologies offer longer periods between refuelling than those reported for SMRs
Flexibility	MNRs can supply power only, power and low grade heat or high grade heat (with loss of power output)	Similar to SMRs, but again applicable at a smaller scale which may extend the potential market access
	MNRs offers much greater rates of change of output than larger nuclear plant easing their application in supplying variable power demands	Likely to be better than SMRs as this feature is a consequence of smaller capacity and reactor technology
Environment	Low carbon supply of electricity and heat	Same characteristics as for SMR
	Continuous supply rather than less predictable intermittent as with solar and wind power	Same characteristics as for SMR
	Smaller sites with minimal environmental impact for construction	MNR sites can be expected to be smaller than SMR per reactor
	Minimal operational discharges	Depends on reactor technology, at least as good as SMR
	Low post-decommissioned impacts	Depends on reactor technology, at least as good as SMR

Potential markets can be divided into two areas; existing markets and potential future markets.

3.2 Existing markets

There are opportunities in existing markets for displacement of other technologies supplying electricity and heat. The following segments of the existing market have been identified for the potential installation of MNRs; each segment has been divided into specific applications for analysis:

Table 5 Existing market segments

Market segment	Purpose	Potential application
Secure Energy Supply	Provide reliable autonomous power source for critical infrastructure	• Nuclear power plants • Data centres • Military sites • Oil and Gas Terminals
Remote and off-grid locations	Provide power to isolated facilities	• Mining facilities • Remote islands
Dedicated heat and power	Autonomous facility for major energy user to avoid supply cost and reliability risks	• Steel works • Large commercial sites • Large chemical site • Desalination

3.3 Potential Future Markets

The future markets for MNRs are generally similar to those for larger reactors, although their smaller scale potentially allows their use with smaller scale applications, such as:

- Geographically distributed baseload power - potentially embedded in electricity distribution networks or supplying isolated consumers
- Flexible load following of power and heat – either for baseload, grid support or industrial/ commercial users

Compared with SMRs, these markets reach a smaller scale. Hence MNRs could be embedded in electricity distribution networks at lower voltages offering greater benefits to network capital and operating costs or supplying smaller critical demands or smaller groups of isolated consumers.

3.4 Considerations in assessment of potential applications

For each application, the following aspects have been considered to determine the suitability of using an MNR.

Scale of the application

The size of a single MNR ranges from 4MW to 30MW of power production and up to 100MW of available heat. Since the costs of an MNR are primarily capital costs, economic considerations mean that these reactors are optimally operated continuously at maximum output (base load). Flexible operation is possible, although may not be as economically attractive, while MNR dynamic performance is not expected to be as good as comparable conventional thermal plant.

For the purposes of this study, it is assumed that applications need to have a demand of at least 5MW for over 7,500 hours per year to enable an MNR to operate in baseload to maximise its viability. A combination in number and/or capacity of MNR can be used to supply power to larger applications. This study has assumed that the capacity of a representative MNR unit is 5 MW. For SMRs the capacity of a representative unit would be considerably higher.

Economy of energy supply

Studies have indicated that the cost of energy from an MNR is likely to be comparable with that for a larger reactor, see Section 4.2 for further details. Whilst, without support (such as carbon pricing), such cost levels are not currently competitive with alternative generation of baseload power into developed transmission and distribution systems, they may be competitive where the costs of conventional power generation are much higher due to the smaller scale or local high cost of delivered fuel.

Remote location

Applications located away from access to large scale electricity grids or reliable fuel supply are candidates for MNR application. MNR units can supply local base load power demand continuously and reliably with the benefit of minimal and infrequent fuel deliveries compared with fossil fuels. Renewable energy sources offer the benefit of minimal fuel deliveries but cannot readily offer the continuous delivery of base load power. SMRs offer similar benefits but only where the baseload power demand is high enough.

Autonomy

MNRs, like SMRs, provide a high level of autonomy; once in place and operating there is no requirement for the delivery or long term storage of large quantities of conventional fuel. For some applications this will be a key benefit.

Fuel availability and fuel cost risk

Typical applications require a reliable and economic supply of fuel, often a liquid fuel such as diesel. Users and power systems that rely on such fuels require regular deliveries and large tanks for storage. Fuel supplies are then vulnerable to price fluctuations and unreliable deliveries in case of adverse weather or road conditions. Even where fuel delivery is less of an issue, such as where pipeline gas is available, longer term fuel price and availability may remain a significant uncertainty.

The cost of fuel for an MNR represents a small part of the cost of production so the forward costs of energy are certain for long periods of time. In addition, a typical refuelling cycle is four to five years so the risk of interruption of the delivery of fuel affecting production is further reduced. These benefits are similar for SMRs, although the refuelling cycle may be shorter.

Flexibility in energy delivery – heat and power

MNRs offer the possibility of supplying both heat and power. Thermodynamics dictates that all thermal power generation technologies reject a significant proportion of their input heat as lower grade heat. This heat may be used for other purposes; internationally such heat is used for warming large scale greenhouses or warming roads to avoid icing. Generally however, such low temperature heat has limited value. Higher temperature heat can be supplied by many MNR types but there is then a trade-off with power production as the energy available for power production is reduced. Where high temperature heat (e.g. over 500^{o}C) is used, the electrical output would be reduced much more significantly than for lower temperatures. The loss of electricity production per unit of heat offtake is fixed for a given plant design. This also fixes the relationship between the value of electricity sacrificed and the production cost of heat. This allows the minimum economic price of heat for a combined heat and power application to be calculated.

Flexibility in operation

The smaller physical dimensions of MNRs mean that the stresses imposed on materials under conditions of temperature change are reduced, permitting greater rates of change of power than larger reactors. This offers the prospect of using MNRs to follow demand variations. While this is technically feasible, the economics of such operation are unattractive as the costs of power from an MNR are dominated by the capital costs. Significant flexible operation must reduce the total power produced over a period of time, which can only increase the cost per unit or extend the payback period for the investment, either alternative degrading the investment case for an MNR, requiring a revenue premium to maintain the investment case.

One situation where flexibility will be valuable is the application of MNRs for power generation in systems with large contributions from renewable generation. The intermittency of wind and solar generation mean that it could be appropriate to install renewable capacity in excess of demand. Generation from these intermittent sources will generally be less than demand, requiring baseload and peaking plants to make up the shortfall. However, at times, such as midday early in summer when solar production will peak but demand will be lower, the renewable contribution could exceed demand for a short period. In conventional power markets this would result in negative wholesale prices on an integrated network. The flexibility of an MNR to run back rapidly and then quickly recover to full output would be valuable in this case, avoiding the penalty of negative prices but maximising revenues. Larger reactors, including SMRs, would not be so agile, incurring greater losses of production or risking life-limiting fatigue stresses in key components.

Power displacement

Applications where MNRs provide secure power may also have a grid connection for diversity of supply. In this case any excess of MNR power production above the immediate local demand may be exported to the grid, offering an additional potential source of revenue. For example, an industrial facility may have variable electricity requirements throughout a 24 hour period. The MNR could generate 24 hours a day and feed any excess electricity into the grid.

Political stability and security

Assessment of the potential scale of application internationally has excluded countries where particular constraints apply:

- *Security.* Where an MNR installation would face uncertain security or where the risk of breaching non-proliferation obligations would be too great.
- *International relations*. Where policy is to exclude foreign technology imports to protect local development.
- *Social and political opposition*. Where the application of nuclear technology is blocked by policy or legislation.

3.5 Discussion of potential applications

Potential specific uses of MNRs are discussed below together with an estimate of potential market size. Further discussion on these markets and the basis on which figures were derived can be found in Appendix 1 and in References 35-64. Market size has been considered in two ways; overall likely total market and potential take up of units by 2030-2035.

Nuclear Power Plant (NPP) standby power: Large scale nuclear power stations require emergency power generators to permit a safe shutdown in case of an emergency such as grid blackout. These generators are critical for the safety case of the plant, supporting cooling systems for the reactors and providing the power required for proper supervision and control of the plant. MNRs may be used to replace convention power generators to provide a safer continuous delivery of power. Market size has been assessed based on 364 operating or in construction NPPs in 23 countries [35] (excluding those with security or political concerns), and taking a proportion of these to determine a potential market of 472 MNRs (8 per reactor), half of those could be by 2030.

Data centres: Data Centres are major electricity consumers. Power supply is critical for these service providers whose business model depends on extreme reliability. The use of uninterruptible power supplies and backup diesel generators is necessary to avoid service failures that can result in financial and reputational penalties. These may be replaced by MNRs. However, the capital cost of MNRs and hence the long payback period, is likely to be prohibitive given the short life of typical data centre systems. Therefore the maximum number of units is estimated at 500, with fewer than 50 by 2030-2035.

Military sites: Military bases for which an MNR would be suitable would generally be long-term strategic installations such as operational headquarters, naval dockyards and major airbases. Such sites would be characterised by intensive activity and sustained energy consumption. Security of electricity supply is critical for this type of installation where current practice would be the use of multiple utility supplies and/or self-generation using multiple diesels or gas turbines. Limiting markets to NATO countries suggests a market size of 1200 units, with actual deployment probability limited to only the key sites (20%). 25% of those may be accessible by 2030-2035 given a potential take up of 60 units.

Mining: Mining industry requires large amounts of energy for mineral processing. These sites are located adjacent to the mineral deposits and are often in remote locations where it is difficult and costly to supply conventional fuels or electricity. This is something they are actively looking at in Canada. Although the potential market size could be for up to 240 MNRs, the proportion which are both remote enough and have sufficient remaining life to justify the investment would be no more 25%, leaving a potential take up by about 2030 of 60 units.

Remote islands: Many communities in the world live on islands with an independent electricity grid. These small systems have to supply daily power demand subjected to cyclic variations as for larger grids. Since these systems are generally quite small they rely on smaller conventional power generation technologies such as diesel engines. A number of MNRs could offer baseload generation complemented by conventional technology to meet peak demand and provide back-up in case an MNR unit was out of service. The potential MNR market is assumed to consist of islands with populations of less than 500,000, typically with an average demand of 500-750MW. For larger populations, SMRs or other reactor types may be more appropriate for fulfilling baseload demand. Security and political considerations are important in determining potential market size, which has been estimated at around 500 MNRs, with an assumed short term uptake of up to 10% (50 units).

Steelworks: Steel production is energy intensive. However, steelworks frequently use the process by-product gases to supply their own heat and power generation, often supplemented by imports from the grid. MNRs could provide an alternative to this and the potential market size in Europe has been estimated at 1700 units. However, unless the economic arguments are compelling any long term investment is unlikely given the current vulnerable nature of the steel industry in Europe.

Oil and gas terminals: Oil and gas terminal facilities are critical infrastructure for the exploitation of offshore oil and gas production. These sites treat the oil or gas to condition it for onward export to refineries or the chemical sector and to the national gas grid. The processing is energy intensive with site electricity and heat consumption reaching hundreds of megawatts. However, the facilities generally consume lower value components and by-products of oil and gas processing to supply their own energy needs and hence there appears to be no viable MNR market in this area.

Large commercial: Commercial installations such as shopping centres and office buildings require large amounts of energy for air conditioning, heating, ventilation, lighting, escalators and lifts and similar services. Large complexes are usually located in or near to urban areas and have good connections to the grid. In this application the adoption of MNR technology would be purely driven by economics. Only the very largest developments would be able to justify the investment in an MNR and it is unlikely that one would be installed in any existing complex with limited life remaining. Therefore a theoretical market of up to 200 sites a year in UK accessible markets has been assumed, with actual take-up probably far lower given economic considerations, likely siting constraints and public acceptability challenges.

Large chemical: Large chemical plants such as Grangemouth in the UK are major energy consumers. The characteristic of each site depends on the nature of the products, but in general they are relatively low value products with a high proportion of costs resulted from energy consumption. Total power and heat demands within the UK are estimated at over 1000MW electricity and 3000MW of heat, although much of this is met by existing plant fuelled, in part at least, by waste streams. Residual markets are considered to be about 600MNRs, but unlikely to be accessible due to the large investment required.

Desalination: Water scarcity due to population growth has resulted in the application of many desalination plants internationally. There are two classes of technology for desalination; thermal and membrane. The more robust thermal technologies have been widely employed in the Middle East. These use heat to distil fresh water from saline. However, the generally preferred future desalination route is using membrane technologies requiring electricity. The project growth in desalination requirements indicates the potential opportunity for approaching 500 MNR units. However, if the case is primarily economic, they will be adopted only where electricity prices are high, leaving only perhaps 5% of the theoretical market, 25 units.

Contribution to bulk power generation: The opportunity to contribute to bulk power generation will be determined by economic competitiveness, ease of siting and flexibility, but is not currently considered to be a primary market for MNRs. Subject to achieving such competitiveness, demand statistics suggest a potential market of 1000 units, i.e. 5,000MW of capacity, [85] whilst maintaining near baseload operation, although the increasing market penetration of intermittent renewable generation decreases the UK baseload opportunities. Given realistic limitations of siting and economics, only 10% of the potential market can be considered realistically accessible by 2030 – 2035.

3.6 Market assessment conclusions

Table 6, overleaf, summarises the reasons for adoption and potential scale of the deployment of MNR technology. Overall, a potential global accessible market of up to 2850MW (equivalent to 570 units of 5MW each) has been estimated by around 2030-2035. This covers both the UK market and internationally accessible markets (notably remote islands and desalination plant). It should be noted that this capacity is only equivalent to less than two new large reactors, illustrating the relatively small size of the short-term market.

Table 6 shows that the largest immediate market is likely to be nuclear power plant standby, with other markets starting on a much smaller scale, with the potential for longer term growth. The application size for NPP standby has been estimated as 10MW, making it ideally suited to a reactor of MNR scale.

Table 6 Reasons for adoption and potential scale of MNR application in each case.

Application	Main reason	Application Scale MW	Potential justifications							Market Scale capacity (MW)	Potential take-up 5MW units 2030-2035	Comment
			Economy	Remote-ness	Autonomy	Fuel risks	Heat & Power	Flex opn	Power disp			
NPP standby power	criticality	10MW			X				X	2360	230	
Data Centres	criticality	10MW	X		X				X	2500	50	
Military sites	criticality	20MW			X	X			X	1200	60	
Mining – high value	criticality	5-20MW		X	X	X				1200	25	
Mining – lower value	economy	10-40MW	X	X		X				1500	30	
Remote islands	economy	10-50MW	X	X		X				2500	50	
Steelworks	economy		X			X	X			8500	0	Self-generated fuel, challenging economic environment
Large commercial	economy	5-15MW	X				X			200	0	Short payback requirement
Oil & gas terminals	criticality	10-100MW	X		X					-	0	Self-generated low cost fuel
Large chemical sites	economy	10-100MW	X				X			3000	0	Short payback, challenging economic environment
Desalination	economy	10-50MW	X							2500	25	Only on remote islands
Flexible baseload generation	economy	10-50MW	X			X		X		5000	100	Distributed flexible generation

4 ECONOMIC DRIVERS

This section outlines key characteristics that drive the economics of investment in MNRs. These, and the accompanying commentary, have been derived from publically available information, including information comparing Large Reactors (LR) and Small Modular Reactors (SMR) as there has been limited analysis of MNRs.

It should be noted that, LRs and SMRs address different markets and there are many market related factors favouring one versus the other, and similarly SMRs and MNRs address different markets and have factors favouring each.

Publically available cost and pricing data has been included as an indication of claimed pricing and capital costs however no analysis of the comparability, validity or integrity of the data has been undertaken. Most of the designs are in concept or basic design stage and cost estimation has been carried out on a top down basis using criteria derived from LRs and SMRs. Actual cost data is generally not publically available for MNR units even for prototype MNR units in Russian, China and Argentina which are under construction or operating. The IAEA and Russian nuclear research institutes have published information on estimates of potential cost reductions achieved from volume manufacture and there are a number of academic papers also considering cost reduction from volume manufacture [65-72].

The economics of MNRs are driven by two factors, the revenue that may be received and the cost (both capital and operating costs). The drivers behind the two factors are discussed in the sections below, together with a summary of available cost data and an identification of potential advantages MNRs have the highest flexibility to be deployed in a range of locations. SMRs will also have characteristic, although available sites may be more limited due to their increased size, increased exclusion zone etc. There is very limited flexibility in the location of LRs.

Energy Production Flexibility

Price premiums are paid for heat and power at times of high demand. The small output of MNRs provides additional flexibility, compared to LRs, to meet demand. Nuclear Power Plants (NPPs) have been seen conventionally to only provide baseload heat and power, however technical and operational innovations may enable MNRs to provide a flexible source of energy (as discussed in Section 3). This characteristic may become more valuable as an increased proportion of baseload starts to come from solar and wind power, which has only very limited flexibility to meet demand. Therefore, MNRs have been ranked high for energy production flexibility. SMRs will demonstrate some of this flexibility but may not be as agile as the MNRs due to their larger reactor size. LRs run as baseload.

Heat / power split (Cogeneration)

MNRs offer the possibility of supplying both heat and power, which provides flexibility and two potential income streams. In common with all thermal power generation technologies MNRs reject a significant proportion of their input heat as lower grade heat, which could be used for other purposes, although this heat generally has limited value. Additionally, many MNR types have the capacity to generate higher temperature heat although there is then a trade-off with power production as the energy available for power production is reduced. Whist both MNRs and SMR have the potential for supplying power and heat, the larger heat output of an SMR makes the potential applications more restricted and hence MNRs may have a higher potential for generating revenue from this market.

Delivery Time

Shorter time to construct and deploy generation units provide an opportunity to add value through better cashflow and possibly price premiums. For example, in a market where a short fall of baseload capacity is forecast in the short term, sources of power that can provide capacity earlier than others can charge a premium (diesel generator manufacturers exploit this at present). SMRs are based on the concept of high levels of factory manufactured parts, short supply chains and short construction times. MNRs claim to further exploit this concept maximising factory manufacture, short supply chain and very short construction times (skid mounted modular units with prefabricated civil units). The result should be quicker deployment and predictability when designs become commercial. Therefore, although the differences are not likely to be extensive, it is possible that MNR delivery times will be shorter than for SMRs.

In order to exploit the above revenue drivers for MNRs, like SMRs, the IAEA provided 'an approach to economic assessment models to guide SMR design development and deployment approaches preferable for targeted applications' [65], which will be relevant to future applications.

4.1 Analysis of Costs

There is little data published on MNR costs. The limited amount publically available is summarised in Table 7, below. Overnight costs have not been considered as sufficient data is not available in the public domain.

Table 7 Indicative costs of electricity

Reactor	Information source	Estimated cost per MWh as quoted	Approximate cost in £
U-battery	Reference 20	€100/MWh	£78/MWh
Carem-25	Reference 77	$42/MWh	£29/MWh
ABV	Reference 77	$120/MWh	£84/MWh
Toshiba 4S	Reference 77	$130-290/MWh	£91-203/MWh

At this stage of development the differences in potential electricity costs should not be taken as an indicative of relative costs as the basis of the estimates is likely to differ significantly. Of more relevance is the fact that several of the figures are quoted under £100/MWh which is comparable to the administrative strike prices quoted [81] for onshore wind (£140-155/MWh), offshore wind (£90-95/MWh and solar (£100 - 120/MWhr)

Over the past 50 years cost modelling has maintained that NPPs that have increased size and number of units installed will produce cost reduction from economies of scale and learning curve effects and has followed the general argument that there is an increase in efficiency with size. The NNL SMR Feasibility Study [1] indicates that cost models show LCOE and capital costs increase for smaller MW sized SMRs (as described in the OECD data in their 2011 report). However there is controversy as to whether LRs have, overall, increased in LCOE over time or whether they show economies for size or learning economies from standardised unit construction [78, 79]. Whichever view is correct it appears the gains, if any, are modest for this size of reactor.

4.2 Factors affecting cost

Recent studies [65 and 69] of cost modelling for smaller reactor sizes have identified factors that can be exploited to counter the increasing cost for smaller reactor sizes shown in the earlier models.

The parameters in the detailed cost models, described in the IAEA 2013 Report 'Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors', have been used to identify the key characteristics of MNRs that drive lower costs. This approach is adopted as the characteristics that drive for lower costs for SMRs are claimed by MNR designs to make MNRs as, and in some applications, more attractive than SMRs.

Design Simplification

MNRs are recognised to be able, in principle, to have simpler designs than SMRs (As discussed in Section 2). This is partly due to the reduced size of the reactor core energy which increases the inherent safety of the design, and therefore reduces the cost of safety systems. As the volume decreases the surface area to volume ratio increases, the consequence being that for the same energy density a core will be able to cool quicker if is smaller [84]. It is also maintained by some designers (e.g. U-Battery) that fuel and other innovations enable increased design simplification. As a consequence complexity is reduced, reducing licensing, manufacturing and construction time and cost.

Design Standardisation

Standardising design enables cost reduction through exploiting the learning curve in manufacturing and construction. See discussion under factory and high volume manufacture.

Factory Manufacture

Both SMRs and MNRs benefit from the economics of factory manufacture. However, of all the sizes of reactor, MNRs may be best able to exploit the advantages from factory manufacture to gain the maximum cost reduction, due to their smaller size and relative simplicity. Design concepts have proposed manufacturing the plant on transportable skid mounted units and prefabricating into modules including much of the buildings and other civil works. This approach takes maximum advantage of the ways factory manufacture can reduce cost. For example, in a factory environment quality standards are cheaper to maintain, systemized learning can reduce cost more quickly, lower cost specialized manufacturing techniques can be used, site work is reduced so site construction cost and time and overrun risk can be reduced.

With their compact simplified designs, MNR's lend themselves to factory fabrication and automation. The production line manufacturing environment has additional benefits in terms of, faster more reliable quality control, cost predictability and lower human intervention due to automation, all of which should lead to a standardised product which can be applied consistently to the range of sites. In other industries this approach has given significant benefits as production line techniques are well understood and benefit from greater integration with suppliers through planning and collaboration leading to lower costs. Therefore, in Table 7 MNRs are considered to have the highest potential to take advantage of factory manufacture, followed by SMRs.

High Volume Manufacture

Volume production and installation of MNR enables cost reduction from learning to take place more rapidly throughout the supply chain. Specialisation of supply and construction can drive down costs and reduce time. Volume production and installation can reduce cost through spreading one off costs, such as design and regulation, over larger numbers of generators [70]. Larger volumes enable lower cost through full utilization of manufacturing production plant. This can be considered analogous to the FOAK (first of a kind) Formula 1 car being typically ten times the cost of a limited edition high end production sports car (NOAK – nth of a kind).

Figure 2 below shows the impact on unit cost of various rates of learning over cumulative numbers as an illustration of the cost reduction that could be achieved from volume production of components. Section 3 concluded that the potential market was for several hundred units which would enable significant benefits to be realised from the learning curve. Figure 25 of the DECC SMR Feasibility Study [1] shows learning rates range from 3% (coal fired power stations) to 26% (Combined Cycle Gas Turbines).

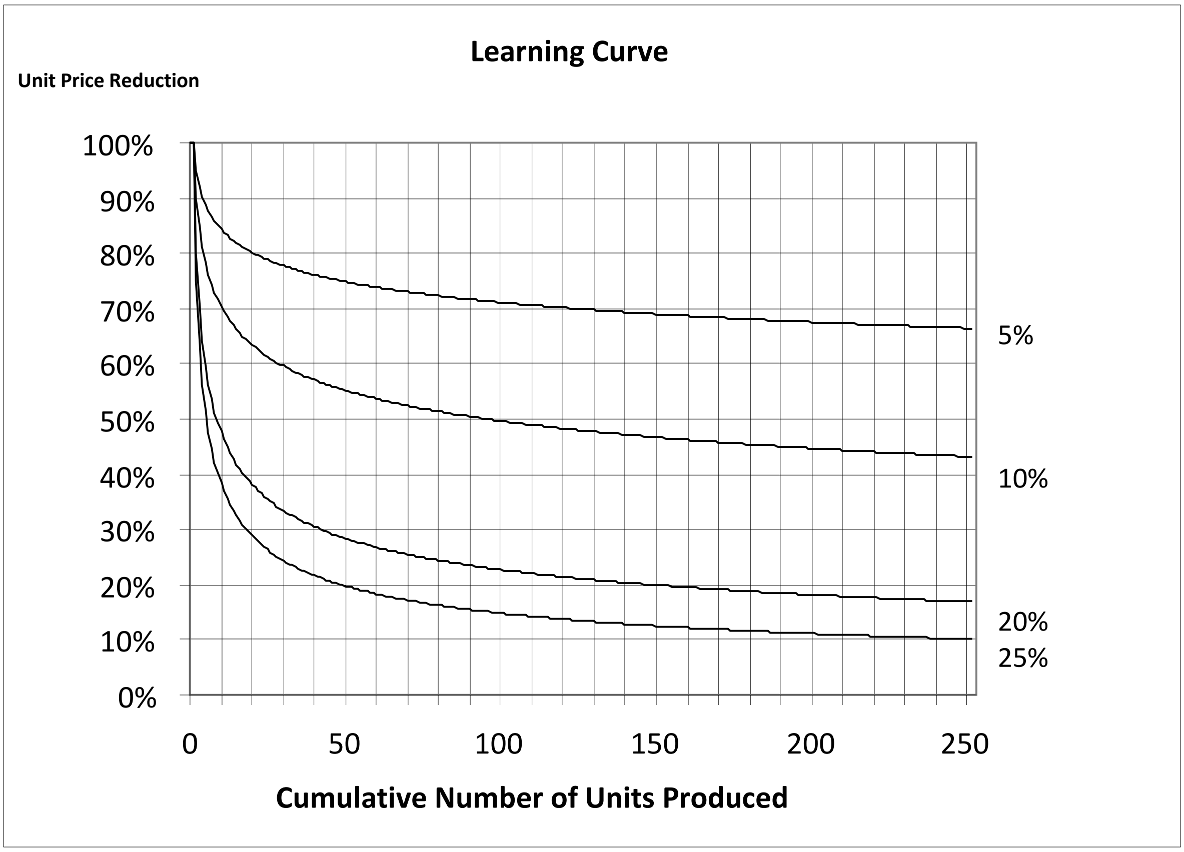


Figure 2 Illustrative Learning Curve Reduction

The significance of these curves cannot be overstated, as they will determine the long term financial viability of MNRs. The illustrative example that follows demonstrates how realising an appreciable learning rate will affect the overall financial cost. However, it should be noted that this is an illustration based on the aspirations of the vendors following academic research. Until further development of MNRs has taken place it is not possible to determine the accuracy of the illustration which introduces a significant risk to the development process going forward. It is here that MNRs have an advantage over larger reactors, including SMRs, as it will be relatively inexpensive to actually develop and construct an MNR, enabling the theoretical aspirations to be tested.

Assuming that the first-of-a-kind specific cost of an MNR was twice that of an established LR, the specific cost of the 100th unit can be read off the relevant curve for the learning rate. If a learning rate of 10% was assumed, typical of a moderately well understood technology or process, then the

100th unit would have a specific cost of 50% of the FOAK, i.e. equal to the LR cost, and the 250th unit would have a specific cost of 85% of the LR cost. If a learning rate of 25% was assumed, more typical of a developing technology under competitive pressures, then the 100th unit would have a specific cost of 15% of the FOAK or 30% of the LR. At 250 units the specific cost would be 10% of the LR.

The actual learning rate for an MNR is uncertain but is likely to be at least 10% due to the immaturity of the implementation of the diverse concepts. Providing the learning rate exceeds 10% then MNR capital costs will fall below those for LR at or before 100 units, i.e. an installed capacity of 500-1000MW. Other costs for the MNR for operation, maintenance and decommissioning are anticipated to be comparable or lower than those for an LR so the LCOE should fall rapidly below that for an LR, even before the equivalent cumulative capacity of a single LR unit is reached.

The comparison in Table 7 below, shows MNRs with the highest score as they have the highest volume manufacture and therefore, theoretically, may have the greatest potential for learning curve savings. However, as discussed above this is an uncertain area which cannot be verified until manufacture is underway.

Technical Innovation

Technical innovations to lower cost or improve performance can be adopted more rapidly due the lower development cost of smaller plants and lower financial barriers to entry. With simpler designs, changes driven by technical innovation can be proven and made with less time and expense than larger more complex designs. The ranking in Table 7 is based on the greater potential to use prototyping and demonstration plant (due to lower cost) making technical innovation easier to progress than for the larger SMRs.

Operating Innovation

The low output, modular nature, simplified design and inherent safety features of MNRs provide a basis to enable innovations in operating regimes to be explored, potentially lowering costs or raising revenues, e.g. load following, reducing staff recruitments, etc. It may also be possible to reduce operational costs due to fuel innovations that reduce the frequency and duration of refuelling for MNRs. However, these potential innovations are likely to be longer term aspirations and not likely to result in short term cost reductions. Therefore all reactor types are considered to have low potential for operating innovation in the short term.

Financing Costs

MNRs have a number of potential advantages when financing compared to LRs and, to a lesser degree SMRs, with the principal ones listed below [69, 71]:

- Reduction of risk premium due to the portfolio effect i.e. some risks are spread over multiple units (e.g. plant failure, construction overrun, operating and fuel cost increase, etc.).
- Reduction of risk premium through knowledge learnt from each incremental unit.
- Reduction in financing costs can be achieved through reduced interest charges during construction due to shorter construction times and hence time to operation, when compared to LRs. This advantage will also apply to SMRs.
- More financing competition as there is a larger number of investors due to reduced absolute total scale of financing per unit (total capital cost) required before electricity generating.

Table 7 below summarises the key differences between LRs, SMRs, and MNR in terms of their potential to take advantage of the economic factors discussed above.

Table 7 Differences in Economic factors between different reactor sizes

Factors	Large Reactors	Small Modular Reactors	Micro Nuclear Reactors
Revenue Premium			
Low Carbon Electricity	**High**	**High**	**High**
Incremental Volume requirements	**Low**	**Medium**	**High**
Location Flexibility	**Low**	**Medium**	**High**
Production Flexibility	**Low**	**Medium**	**High**
Delivery time	**Low**	**Medium/High**	**High**
Cost Reduction			
Design Simplification	**Low**	**Medium**	**High**
Factory Manufacture	**Low**	**Medium**	**High**
Volume production and installation	**Low**	**Medium**	**High**
Technical Innovation	**Low**	**Medium**	**High**
Operating Innovation	**Low**	**Low**	**Low**
Financing Costs Reduction	**Low**	**Medium**	**High**

4.3 Risks

The attractiveness of financing for MNRs is affected by a number of risk factors which are summarised below.

Political risk	The political environment and level of commitment in relation to MNRs is uncertain. There is a high risk that commitment may change before industry has the chance to develop competitive products in the long term.
Public acceptability risk	One of the key benefits of MNR deployment is the potential to locate them much closer to population centres. There is a high risk that this will not be publically acceptable in the short term.
Regulatory risk	There is a risk that projects may be stalled due to prohibitive cost of regulation. The cost of regulation is currently uncertain.
Monetary risk	The direct risks associated with financing should be lower for MNRs as the total amount of investment needed, and the timescale for income to be generated, will be lower.

4.4 Attractiveness of developing an MNR industry in the UK

The development of an MNR industry in the UK may be beneficial for the UK for the following reasons [65]:

- The UK may be able to utilise and grow its existing nuclear knowledge and supply chain into a new product line. Growing the economic benefit from high value added jobs and manufacture and leveraging existing intellectual and physical assets. [U-Battery Market Report, [76].

- A potential MNR industry could enable the UK to grow indigenous civil nuclear reactor manufacturers gaining Intellectual Capital at low entry cost. At present this core part of the civil nuclear supply chain is not provided in the UK.
- MNR development could foster innovation leading to Generation V at a lower development cost than other reactor types (due to scale)
- MNRs could provide flexible low carbon solutions to heat and power generation in the UK and export markets.
- Longer term, the implementation of MNRs could allow structural changes in electricity generation market; for example, less transmission infrastructure would be required.

5 REGULATORY FACTORS

5.1 UK Regulatory Process

The principal of the UK nuclear regulatory process, in common to other countries for example Canada, employs a risk informed methodology. This form of nuclear regulation is, however, different to that employed in the US where regulation is more prescriptive and is dictated by guidelines and procedures issued by the Department of Energy.

The regulation of a new nuclear facility may be undertaken in two phases. Phase 1 is the Generic Design Assessment (GDA), which looks at the design independent of siting, and Phase 2 is the site licensing process which takes account of site specific factors. The GDA process is a four step process undertaken by the Office of Nuclear Regulation [86], with steps 2-4 being an incremental and interactive review period.

Step number	Description
Step 1	Preparation of the design, safety case and security submissions by requesting party
Step 2	Fundamental design safety case and security claims overview
Step 3	Overall design safety case and security claims review
Step 4	Detailed design safety case and security evidence assessment

The estimated overall review period is currently 4 years for large reactors. It is currently uncertain how long it would take for MNRs, although an indicative 3 years has been assumed in Section 2.4.

5.2 Application to MNRs

Historically the UK licencing process has been focused on larger nuclear reactors. Regulation and demonstration of the Safety Assessment Principles (SAP) have been approached by developing complex computer codes (i.e. models) that extrapolate from realistic scale experiments and other evidence. However, the SAPs are actually indifferent to the size of the nuclear installation being considered and would also be applied to SMR or MNR operations through the GDA (General Design Assessment) Process.

Features of MNRs which may help to simplify the regulatory process compared to large reactors are:

- Simplicity of design
- Smaller in scale with reduced foot print
- Greater level of passive safety

MNRs eliminate the need for many critical safety systems, consequently the whole regulatory process should be focussed on a few failure modes and exploring their behaviour, although this will depend on the regulatory regime in place. One of the key requirements, if a worldwide market is to be developed, is to develop a design which can be licensed under multiple regulatory regimes. The reduced scale and complexity of MNR's implies creating computer models is also simplified, and direct physical modelling to test specific features or behaviour is feasible, even at full scale, through the use of suitable test facilities.

Therefore, the GDA process for MNRs may be, in theory, be simpler than for other reactor types. However, this remains a key uncertainty until the process has actually been applied in practice.

In Canada consideration is already being given to the licensing of SMRs and MNRs and the approach being taken may be of use to the UK. The Canadian regulator categorises issues affecting the MNR designs in three distinct groups as illustrated below [79]:

First group – Issue not likely a problem	- Existing requirements and guidance already address the issue
Second group: Issue requires some clarification. Short to medium lead time to resolve	- Clarification may be needed around application of the graded approach or the basis of the requirements needs to be more clearly expressed. Can be addressed in pre-licensing engagement discussions (e.g., vendor design reviews)
Third group – Issue requires significant regulatory analysis to understand potential risks and mitigation approaches. - Long lead time to resolve. - The Challenges: •Not sure if or when the issue might be proposed in an application •May be technology dependent	- The Canadian Regulator will consider proposals in developing regulatory positions based on science and engineering practices. - Public consultations and discussion papers, will help to further establish regulatory positions prior to developing or modifying requirements and guidance - Issues may also benefit from international discussion through regulatory cooperative arrangements

The Canadian regulator recognises the issue of smaller simpler designs and estimates the timeline from initial application to granting of a non-commercial operating licence would be in the range 9 years for large SMRs and 6-7 years for MNRs.

To ensure design and regulatory definition an experimental demonstration plant may be the most expedient path to commercialisation of a unit. This is the path adopted by both the Argentinian Carem-25 and the Russian KLT40S units currently under construction. In China a larger version of the HTR-10 High Temperature Designs is also being constructed.

5.3 Site Regulation and site deployment

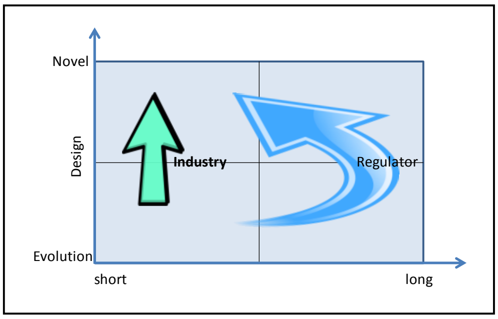
From the broader perspective of regulation of the reactor units, much of the site licence conditions already cover the manufacturing process. Reactor fabrication is no different to supply chain management in the nuclear sector. It will be the site licence holder who will be responsible for verifying quality and regulatory compliance during fabrication and take on the liability of operating a nuclear facility. Where MNRs may be located outside current nuclear licensed sites the responsibilities would need to be clearly defined.

In considering FOAK (First of a kind) MNR deployment in the UK, exiting nuclear licensed sites offer advantages as the regulatory infrastructure is met by the Site Licence Company. However, commercial deployment of NOAK (Nth of a kind) unit outside exiting nuclear sites may prove a greater challenge to public opinion.

5.4 Regulatory challenges

In general, issues that affect licensing timelines can be categorised as follows:

- Completeness of licence application
- Stakeholder support
- State of completeness of design
- Outstanding safety issues
- Novel features or approaches
- Supporting R&D (material tests etc.)



The novelty of the MNR designs introduces uncertainty into the application of the regulatory process. Current regulatory experience is primarily been based on large designs and due consideration need to be given as to whether the regulator will assess the new batch of designs from a starting point of a large reactor and whether different expertise is required.

For a commercial organisation operating in a free market economy, the uncertainty over the cost and timescale of regulation could result in business cases becoming quickly untenable. Vendors are attempting to identify potential bottlenecks in advance. However this doesn't guarantee certainty or early resolution and predictability through the regulatory process.

Global regulatory standardisation may be an option however legal jurisdiction and legislation vary from country to country which makes one universal regulatory framework difficult to sustain. However, for the UK, the first step is possibly to issue a definitive consultation guideline for MNR/SMR specific nuclear licence similar to that which is currently in progress in Canada. This will enable vendors to move forward.

6 CONCLUSIONS

The key advantages of MNRs are:

- The simplicity of the design, including safety systems
- The potential ease of construction through factory construction
- Smaller overnight cost of each unit (compared to other reactor types) resulting in ease of financing
- The possibility of placing reactors in remote locations as they do not require transmission and distribution infrastructure opening up niche markets
- Technology enables greater operational flexibility than LRs

The small scale of the MNRs also means that full scale demonstration facilities can be constructed relatively easily enable concept to be developed and proven with less reliance on complex computer codes and theoretical calculations.

Technology - There are technological challenges to be overcome before more reactors design can reach operation, as many are still at a concept stage. However, it is not the technology, per se, which is the limiting factor. The development programmes for several reactors are on hold but this does not appear to be due to insurmountable technical challenges, rather due to an uncertain future industry environment making the business case for further investment difficult to justify.

Market Analysis - The market analysis has shown that there are a number of potential markets for MNRs, some displacing existing power generation and some opening up new markets. There is significant evidence of interest and investment in MNRs outside the UK. Further investigation and engagement would be required to better understand the nature of the potential market.

Cost - The assessment of the economics of MNRs has shown that the vendors believe the revenue opportunity is sufficiently attractive and the cost can be managed to attract investment. Initial estimates of the cost of generating electricity suggest it will be broadly comparable to other low carbon sources. MNRs have, and are able to develop, features that may attract higher revenue premiums than other reactors.

Technological, market and cost considerations are all generally favourable to the development of MNRs, however for deployment to move forward at a faster rate two major uncertainties need to be addressed.

1. Uncertainly in how the regulatory process will apply to NMRs
2. Uncertainty in long term political commitment to manage a predictable nuclear industry environment

Further work is required to understand the industrial environment which will enable MNR development to move forward. This includes defining policies and a structure enabling the industry to develop. This may be similar to that deployed for the development of wind and solar power.

The overall conclusion of this study is that MNRs are feasible and have a potential market in the hundreds by 2030-2035. MNR learning rates may result in costs undercutting LRs and potentially SMRs before the capacity of one LR has been installed. MNRs could bring significant economic benefits to the UK but must be decisively supported as they will only proceed with clear support and facilitation of political, regulatory and financial factors.

The study also concludes that, whilst there are differences with the larger SMRs, no specific cut-offs have yet been identified in technical, financial or regulatory factors. However, further investigation may yield more definitive differentiators depending on the regulatory and market requirements of specific countries.

APPENDIX 1
MARKET ANALYSIS

1. Nuclear power plant

Large scale nuclear power stations require emergency power generators to permit a safe shutdown in case of an emergency such as grid blackout. These generators are critical for the safety case of the plant, supporting cooling systems for the reactors and providing the power required for proper supervision and control of the plant.

Conventional emergency back-up power systems are based on multiple independent diesel generators. These need to demonstrate reliable automatic starting in case of an incident and require a secure supply of fuel. Both of these needs create regulatory requirements to demonstrate regularly that these essential systems will operate correctly on demand. An alternative based on the use of normally operational micro nuclear reactors would offer a secure independent supply of power that continuously demonstrates its availability for use in case of an emergency. The MNRs would supply power to the plant electrical auxiliary system in parallel with normal supplies, displacing auxiliary consumption in normal operation, while being able to supply the required emergency power at any time.

APPLICATION	DOES IT BENEFIT FROM MNR?	COMMENTS
Scale of application	Yes	Multiple MNRs would be needed to support a single large reactor
Remote location	No	
Fuel unavailability	Yes	Dependency on conventional fuel supply and secure storage would be eliminated
Security	Yes	Large nuclear plants are already subject to security provisions
Fuel price sensitivity	No	Emergency diesel fuel consumption is a very minor operating cost
Power displacement	Yes	MNR supplies would reduce auxiliary consumption so that a large proportion of the capacity of the main plant would be exported

This study has identified 23[4] potential countries where potential application of MNRs with operational nuclear power plants or those under construction would be possible. There is a wider community of nations with nuclear programmes but a number of countries have been excluded due to the closure of their nuclear programmes, security risks or difficulty in market penetration.

In these countries 339 nuclear reactors are in operation with 25 under construction. [35] According to the US Energy Information Administration, the average age of US commercial reactors is 35 years. Since the US led installation of commercial nuclear reactors it is likely that the average age of the worldwide fleet is a little lower. It is considered unlikely that plants at the middle or end of their life would invest in additional nuclear power equipment. Consequently, only a proportion of the operational reactors could be considered as a potential market for auxiliary MNR installation.
It is estimated that that 10% of the existing plants and all the plants under construction would be candidates for the installation of auxiliary MNRs. This represents a total of 59 large nuclear reactors.

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[4] The 23 countries are: Belgium, Brazil, Bulgaria, Canada, Czech Republic, Finland, France, Hungary, India, Japan, South Korea, Mexico, Netherlands, Romania, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, UAE, UK and USA

Conventional practice is for each nuclear reactor to be supported by three to eight emergency diesel generators. Assuming eight MNR at 5 MW each are needed for each reactor, this application represents a potential market of 472 MNR reactors. Only a proportion of new reactors would adopt auxiliary MNRs so the realistic capacity would be limited to less than half this number, established largely in line with new build programmes, representing about 230 units by 2030.

2. Data Centres

Data Centres are major electricity consumers. Power supply is critical for these service providers whose business model depends on extreme reliability. The use of uninterruptible power supplies and backup diesel generators is necessary to avoid service failures that can result in financial and reputational penalties.

The high dependency on electricity makes these centres sensitive to energy cost variations. If MNR technology can meet data centre demand at a price similar to import from the grid, the additional advantages of long-term price security and autonomy of supply may make investment in an MNR attractive. Conventional standby generators would need to be retained for fallback supply in any case.

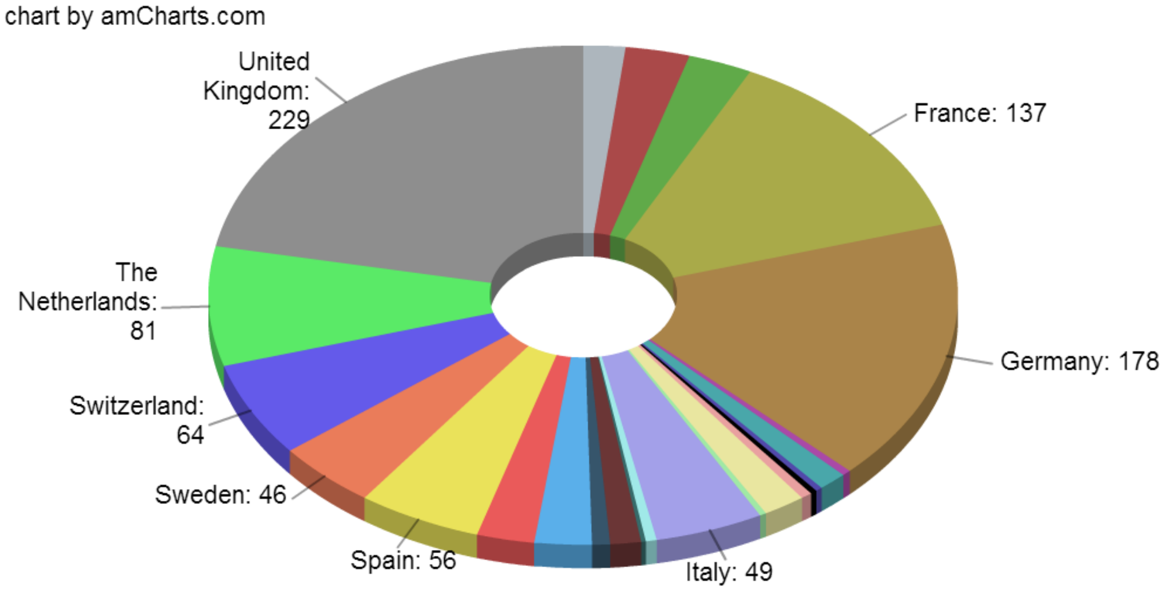
The life of MMRs is expected to be similar to that for existing nuclear reactors at about 60 years, while the life of data centres and their computing facilities is significantly shorter. This may mean that such an investment would be less attractive as end of life costs of the MNR would be incurred at a time when large costs for a replacement data centre were incurred. Alternatively the MNR would need to be sold to a utility or other investor to operate as a supplier to the grid, where feasible.

The main benefit of using MNRs for data centre power supply would be economic with the additional benefit of long terms stability in energy costs. The disadvantage of such an investment would be the additional capital cost with long payback for the MNR which would contrast with the large investment with short life typical of data centre systems.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Larger data centres are estimated to consume up to 10MW that can be supplied with 2 MNR
Remote location	No	These sites are normally located close to populated areas
Fuel unavailability	Yes	This is the case if the data centre include a generation set as part of the facility
Security	Yes	Data centres have strong physical security
Fuel price sensitivity	Yes	Data centres rely heavily on electricity supply, and therefore price variations have a significant impact on them
Power displacement	Yes	As the data centres are often connected to the grid it is possible to export any excess of electricity generation

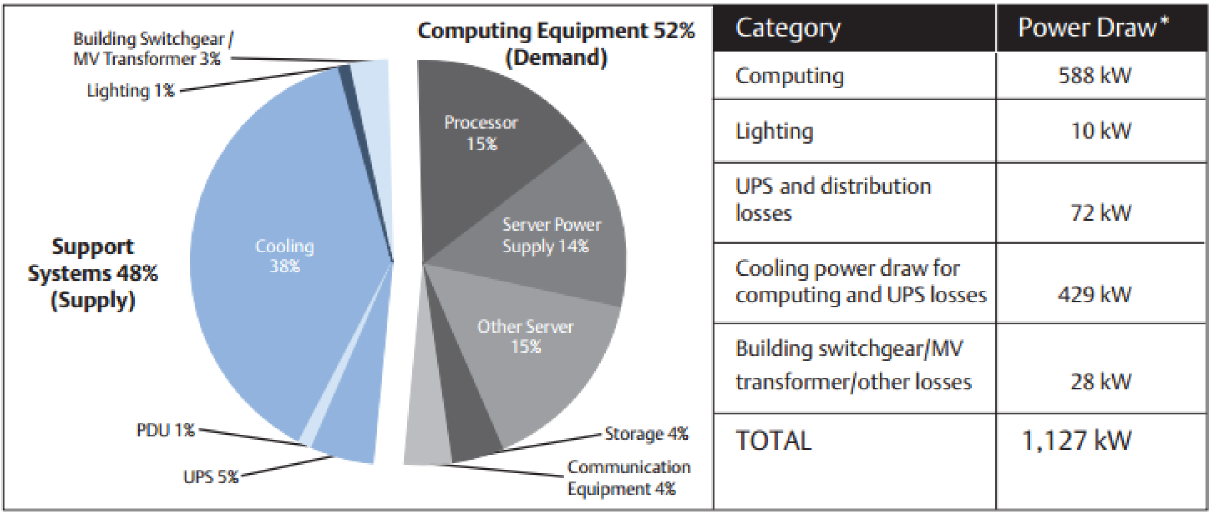
A total of 3,790 data centres have been identified in the world. At the moment 40% of data centres are in the USA while about 27% are in Western Europe [36, 37].

Currently there are 1048 data centres from 24 countries in Western Europe.



It is estimated that about 80% of data centres are located in countries where power could be supplied by UK supplied MNRs.

Consumption breakdown for a typical 5,000 square-foot data centre. [38] Total capacity is 1,127 kW



Category	Power Draw*
Computing	588 kW
Lighting	10 kW
UPS and distribution losses	72 kW
Cooling power draw for computing and UPS losses	429 kW
Building switchgear/MV transformer/other losses	28 kW
TOTAL	1,127 kW

The demand of each individual site is not reported, however this can range from 1MW to 10MW with the average reported for the US being around 7MW

Since the economic advantages of MNRs in this application are balanced by significant issues associated with the capital cost, rate of return and mismatch with the asset life of the data centres, access to this market will be limited. Given the challenge of MNR investment in this application it is estimated that a maximum of 10% of data centres would consider an MNR. This would represent a potential market of 250 sites, each with two units, a total of 500 MNRs. However the realistic take up would be likely to be around 50 by 2030, although it is possible that the sector would not adopt the technology at all.

3. Military Sites

Military bases for which an MNR would be suitable would generally be long-term strategic installations such as operational headquarters, naval dockyards and major airbases. Such sites would be characterised by intensive activity and sustained energy consumption. Security of electricity supply is critical for this type of installation where current practice would be the use of multiple utility supplies and/or self-generation using multiple diesels of gas turbines.

MNR technology appears to be an appropriate option to supply base load demand for large military bases due to its high reliability, continuous and stable generation and independence of significant fuel deliveries. Any concerns about proliferation or physical security would be minimised by the conventional high level military provision for such strategic installations.

The life time of an MMR at about 60 years is also consistent with the longevity of strategic military sites so that the investment would be assured of long term exploitation. The use of MNR is only considered likely for military sites based in the home country and long term strategic bases overseas e.g. US bases in Europe or Asia.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Average major US naval base consumes over 9MW, major army and air force bases are likely to be similar.
Remote location	Some facilities	Strategic military installations may be located in remote areas or closer to cities e.g. naval base at Farslane
Fuel unavailability	Yes	Autonomy of energy supply is attractive compared with multiple supply connections or diesels with fuel deliveries.
Security	Yes	Strong military security is assured
Fuel price sensitivity	No	Fuel cost is not a primary consideration for military sites
Power displacement	Yes	Where a connection to the local grid is available export of any excess power would be feasible

The limited amount of information publicly available for military sites worldwide limits estimation of the potential military market for MNRs. Published data on US bases identifies over 300 sites [39]. The published consumption data suggests that average demand would exceed 9MW [40]. It is anticipated that no fewer than two units would be installed per site to provide secure supplies.

Limiting likely military application to NATO countries and assuming that the US represents half the number of bases would suggest a market size of the order of at least 1200 units. The strategic justification for an MNR would be limited to key sites, probably those with the largest demand. It is therefore estimated that the actual potential for military application is around 20% of this figure, i.e.240 units. It is unlikely that this level of penetration would be achieved before 2030.

4. Mining Facilities

Mining industry requires large amounts of energy for mineral processing. These sites are located adjacent to the mineral deposits and are often in remote locations where it is difficult and costly to supply conventional fuels or electricity.

Conventional energy supply for many mineral processing sites is by multiple diesel engines using fuel tankered or flown from the nearest port, pipeline or railhead. Delivery of the large quantities of fuel to the

remote sites is expensive and vulnerable to interruptions due to weather conditions. In some circumstances large scale local storage of fuel may be difficult due to the adverse climatic conditions.
In this application an MNR offers the possibility of producing the necessary energy locally with a high level of autonomy and potentially at a lower price compared with liquid fuels that bear high transport costs. In addition, large fuel storage tanks are not necessary and the small quantities of fuel for the MNR can be readily delivered and stored to guarantee reactor operation for extended periods of time.

One disadvantage of an MNR in this application is that the life of an MNR unit is likely to be longer than the life of many mines. The implication of this would need to be evaluated for each potential application.

The significance of energy supply for mineral processing sites depends on the value of the product. There are two groups of applications which have significantly different considerations; those where interruption of supply incurs high costs due to loss of production and those where the cost of energy represents a high proportion of production costs. Gold mining is representative of the first group [41] while copper mining and processing is typical of the second.

The first application to high value minerals is summarised below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Big mines require large amounts of power for mechanical processes e.g. to separate gold from ore
Remote location	Yes	Many large mines are located off-grid in remote areas
Fuel unavailability	Yes	Sites are vulnerable to interruptions of fuel supply incurring costs of up to £100k/ hour in case of lost production
Security	Yes/marginal	High value mineral processing has robust security to limit theft but may not be at the levels necessary to minimise proliferation risks, particularly in third world countries
Fuel price sensitivity	No	Fuel costs are not significant compared with the value of the product
Power displacement	No	Sites are generally remote

The second application, where energy costs are a high proportion of product cost, is typified by copper production [44-46] . The characteristics of this application are tabulated below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Production has high energy consumption representing typically one third of the value of the product.
Remote location	Yes	Many mines are located off-grid in remote locations
Fuel unavailability	Yes	Sites are vulnerable to interruptions to fuel supply, but losses are limited to less than £1million per day
Security	Marginal	Lower value mineral processing has lower levels of security but this would not be at the levels necessary to minimise proliferation risks, particularly in third world countries
Fuel price sensitivity	Yes	Electricity costs may represent over 25% of production costs. Variations in energy price have a major impact on cost of production

		so that predictable longer term energy costs are likely to be advantageous where fuel prices are volatile[5]
Power displacement	No	Sites are generally remote

In 2014 North America, Canada, Australia and Chile were reported to have produced 783 tonnes of gold [42] which represented about 1,600 MW of running electricity consumption. 75% of the gold mines in Australia were reported to produce more than 100,000 ounces per year, equivalent to 5MW electricity consumption. If a similar proportion of the mines identified above consume in excess of 5MW then there would be a potential market for 240 MNRs. Since only a proportion of mines will have sufficient remaining life and are remote enough to suffer from excessively unreliable fuel deliveries it is estimated that the likely market take-up would be limited to 25 MNRs by 2030.

The combined copper production of North America, Chile, Europe and Australia represents about 75% of worldwide production of 15 million tonnes [44]. Based on published average consumption data for facilities in Chile this is equivalent to a continuous demand of 6,400 MW. Only a small proportion of mines would be likely to adopt MNR power generation as few will be large enough, have a long enough remaining life and suffer sufficiently high energy costs to justify the investment. If the technology proves cost effective and reliable, a market of up to 300 MNR could be foreseen with a take up of fewer than 30 by 2030.

5. Remote Islands

Many communities in the world live on islands with an independent electricity grid. These small systems have to supply daily power demand subjected to cyclic variations as for larger grids. Since these systems are generally quite small they rely on smaller conventional power generation technologies such as diesel engines.

Fuel supply to these locations is often costly and requires the maintenance of large stocks of fuel to assure supply between deliveries and when adverse weather conditions restrict fuel deliveries. Installation of one or more MNRs could secure base load production at relatively low cost with reduced dependence on fuel stocks for security of supply. The key to this market would be simplicity, reliability and low levelised cost of power.

The life of an MNR is expected to be about 60 years which would offer the benefit of a longer period for recovery of the investment.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Appropriate for islands with populations between 50,000 and 500,000 which generally offer sufficient base load demand
Remote location	Yes	Islands or communities not connected to a larger power system
Fuel unavailability	Yes	Currently these communities have a high dependency on fuel imports
Security	Marginal	Security provision appropriate to non-proliferation requirements would need to be established

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[5] Copper price currently reported to be ~$2/lb http://www.infomine.com/investment/metal-prices/copper/

Fuel price sensitivity	Yes	Variations in world market oil price have a large impact on electricity cost and island economies. Increased long term stability in pricing would be beneficial
Power displacement	No	

The energy intensity of consumption on remote islands varies according to their level of development. The developed economies are reported to consume an average of 1-3 kW per inhabitant, comparable to mainland communities. Demand variations during the day limit the cost effective role of an MNR to the continuous base load duty. Conventional power plant such as existing diesel facilities would need to be retained to meet the shorter term variations in demand.

In terms of the suitable range of demands for this application a minimum of 50,000 inhabitants have been assumed, representing an average demand of 50MW or more. Larger islands are likely to rely on a combination of different generation technologies including larger conventional plants and even combined cycle gas turbine power plant. If nuclear technology was cost effective it is likely that above a population of 500,000, representing an average demand of 500MW, SMR technology would prove more economic than MNR.
If nuclear technology was to be applied in candidate remote islands the technology would require suitably skilled staff to operate and maintain the facility. Some of these could be ex-pat workers, but a high proportion would need to be local staff, implying the provision of significant levels of education and training.

A further consideration in this application is potential political instability and potentially weaker security against proliferation risks. These issues would be less significant in the offshore islands of nuclear experienced countries such as the UK, France, the Netherlands and the US.

Using the Caribbean as an example region, there are 13 islands of an appropriate size [47, 50, 53]. Of these six are offshore dependencies of the UK, France, Netherlands or the US. The total population of these islands is around 1.1 million, equivalent to an average electricity demand of 1,100 – 2,200MW [48, 49, 51, 52]. Base load would be expected to be around 50% of this, 550-1,100MW, corresponding to 110-220 5MW MNRs. Assuming that the Caribbean represents half the potential remote islands a maximum market size of around 500 MNRs can be foreseen.

Take-up in this application will be determined in part by economics and in part by politics. It is considered that only 10% of the potential, i.e. 50 MNRs, would be likely to be exploited quickly with further application dependent on success and public acceptance.

6. Steel works

Steel production is energy intensive; however a high proportion of this energy input is delivered by fuels necessary for the reduction of iron. Currently no electricity intensive process for iron production is available. Steelworks frequently use the process by-product gases to supply their own heat and power generation, often supplemented by imports from the grid.

Steel processing from remelting to rolling mills is also energy intensive and in this case electricity is the primary energy source. In Europe steel mills report that they are losing competitiveness due to higher energy costs. Reliable electricity supplies are available but the cost to industrial consumers appears to be too high. There is therefore potential for MNRs to be used to supply power to these large consumers if the life cost of power is significantly lower than current market levels.

There is a theoretical possibility of supplying heat to steelworks from an MNR. However, the temperatures required for the numerous physically distributed steel processes are in the region of 800-900ºC, beyond those foreseen to be available from any MNR, even local to the reactor. So there is no potential for an economic benefit from heat in this application.

The characteristics of this potential application are summarised below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Steel works power demand ranges up to 200MW
Remote location	No	Steel mills are generally located in industrial sites with good access to the gas and electricity grids
Fuel unavailability	No	Process by-products represent a major fuel source on some sites; elsewhere good import connections are installed.
Security	Marginal	While steel production is generally conducted in politically stable countries, the physical security for an MNR would be at a higher level than typically provided in the steel industry.
Fuel price sensitivity	Yes	Energy prices are a major factor for the competitiveness of the sector and uncertain and volatile future prices undermine confidence for new investment
Power displacement	Yes	Steelworks are generally well connected to export any surplus generation

The UK steel industry has a reported energy demand of 480MW [57, 54, 55, 56], offering the potential to install about 96 MMR units (5 MW each). In the European Union, assuming a similar split of iron production and steel processing and comparable energy intensity to the UK, an average power demand of 8,692 MW would be expected for the annual steel production. This capacity offers a theoretical potential of 1,738 MMR units (5 MW each). Realistic constraints on the industry which is vulnerable, competing with much larger producers in Asia, are that any long term investment is currently unlikely and investment in MNR technology is even more unlikely unless the levelised cost of electricity produced is radically below current market levels. Since this is not expected to be the case no MNRs are likely to be applied in the European steel industry.

7. Terminal facilities

Oil and gas terminal facilities are critical infrastructure for the exploitation of offshore oil and gas production. These sites treat the oil or gas to condition it for onward export to refineries or the chemical sector and to the national gas grid. The processing is energy intensive with site electricity and heat consumption reaching hundreds of megawatts.

Conventionally these facilities consume lower value components and by-products of oil and gas processing to supply their own energy needs. This simplifies the energy supply and permits a high level of independence of local infrastructure which reflects the criticality of these sites to the host country. The life of such a terminal site is determined by the life of the oil and gas fields supplying the raw products. Typically fields are managed to be depleted over a period of 25-30 years.

While these facilities would benefit from the autonomy of energy supply offered by an MNR it is considered that the availability of fuels at minimal or even negative cost would be a significant disincentive to the application of MMR in this application. If carbon emissions were to be minimised it is considered that carbon capture would be likely to be a lower cost investment as long term storage of the carbon dioxide in depleted oil or gas fields connected to the facility would minimise such costs.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Big energy consumers
Remote location	Yes	
Fuel unavailability	No	Significant amounts of low value products or by-product fuels available
Security	Yes	Terminal facilities are strategic assets subject to stringent security provision.
Fuel price sensitivity	No	
Power displacement	No	Major sites are often remotely sited and not grid connected.

Due to the limited benefits of MNRs in this application and the low cost of energy sources accessible to oil and gas terminals it is considered that this application does offer a significant market opportunity.

8. Large Commercial Buildings

Commercial installations such as shopping centres and office buildings require large amounts of energy for air conditioning, heating, ventilation, lighting, escalators and lifts and similar services. Large complexes are usually located in or near to urban areas and have good connections to the grid. In this application the adoption of MNR technology would be purely driven by economics.

Seasonal energy demands represent a significant demand of large commercial buildings. In many regions heating is required in winter and cooling in summer. The opportunity to use low grade heat from an MNR is reasonable, but temperatures would conventionally need to be in the range 75-90ºC. It would be possible to use heat at 55-70ºC although larger heat exchangers would be required. The former temperatures would require some sacrifice in power output of the MNR, while the lower temperatures could be supplied by High Temperature Reactors with minimal penalty.

The life of a large commercial complex is unlikely to exceed 30 years, considerably shorter than the economic life of an MNR. In addition, the rates of return expected of such investments are not consistent with those for power plant of any type unless support reduces the levelised cost of electricity or increases the cost of alternatives. The characteristics of this application are summarised below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	No	Few complexes have a high enough power demand for an MNR to be required; heat demands are potentially much higher but would be highly cost sensitive
Remote location	No	
Fuel unavailability	No	
Security	Yes	Commercial centres have limited security and separate and much stronger security would be needed for the MNR
Fuel price sensitivity	Yes	This application is highly sensitive to energy costs
Power displacement	Yes	Good connections with the grid would allow excess power to be sold into the network, but this would only be viable if the levelised costs was competitive with market rates

In 2010 the commercial sector electricity consumption was 4.54 quads, equivalent to 547.77x10^6 MW. Assuming this is proportional to the office space, commercial buildings over 500,000 square foot had an average consumption about 7.52MW. However, commercial buildings consume most of the electricity during working hours with about half of the energy consumed for space heating, cooling and ventilation. If a MMR unit would be installed to supply electricity to one of these buildings it is likely that most of the day, outside working hours, the generator would need to export a large amount of power into the grid. In addition, the number of sufficiently large commercial buildings in the USA in 2003 was 8,000 out of a total of 4,859,000

Consequently, this application is not considered viable.

In order to recognise the global market and the diverse climatic conditions for commercial buildings statistical data for US buildings were used to inform this element of the study [58]. The scale of the sector energy consumption is very large with average electricity consumption for commercial buildings in the US totalling 144GW in 2010. The larger buildings, i.e. those over 46,500m2, represented 11% of this energy consumption, 16GW, equivalent to an average of 2MW of electrical demand per building. A smaller number of extremely large buildings, numbering about 2,500, will have electricity consumptions in excess of 5MW.

The average heat demand of the buildings was reported to be approximately equal to the electricity consumption but would be concentrated in the colder seasons. It is estimated that the economic heat capacity for a CHP scheme would be about half of this capacity, i.e. about 2.5MWth for the largest buildings. This heat demand might be met by higher temperature reject heat from an HTR or by heat extracted from the thermal cycle with some reduction in generated power.

Retrofitting an MNR as energy source for a major commercial complex is unlikely to be feasible for existing buildings so any market would be for new buildings. Assuming a life of 30 years for large complexes, it would be expected that construction would at least maintain the number of such buildings, meaning that construction of 80-100 new buildings of this size per year would be necessary in the US. Globally the total figure for such new construction would be expected to be three to five times this number; although only half might be located in countries accessible to UK supplied MNRs.

The scale of MNR market for this application will be constrained by economic and practical issues. The investment cycle and expected returns on major buildings would only support the application of MNRs if the LCOE was significantly lower than alternatives. Physical constraints of siting, access and security of the MNR facility would also seriously limit the potential market. Finally confidence of investors is likely to limit the adoption of a new and very different energy technology. Hence although a theoretical market of up to 200 sites per year might be accessible, initial take up will be very slow and the ultimate penetration uncertain, but probably a modest figure less than ten per year.

9. Large Chemical Plants

Large chemical plants such as Grangemouth in the UK are major energy consumers [59]. The characteristic of each site depends on the nature of the products, but in general they are relatively low value products with a high proportion of costs resulted from energy consumption.

In many instances electricity and heat are supplied from generators burning by-products or supplemented by combined heat and power plants adjacent to these sites.

Similarly to the iron and steel sector, many large chemical sites in Europe have become less competitive with higher resource and energy costs. MNR technology could be viable in this application provided that the levelised cost of electricity was low enough.

Electricity cost is the main benefit that MMR would provide to these sites, although low cost heat could be valued, subject to the loss of electrical capacity that would result. These benefits would have the potential to increase competitiveness and reduce exposure to more volatile natural gas and electricity prices. In addition, chemical plants are generally embedded in the grid so it would be possible to export any excess generation to the grid, providing an additional revenue stream.

The key characteristics of this application are summarised below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	Big energy consumers, although part of it may be generated through by-products and their own fuels
Remote location	No	Most of them located in industrial areas
Fuel unavailability	No	Supplies generally available
Security	Yes	Large scale chemical sites have significant security provision, although enhancements to nuclear levels would be required
Fuel price sensitivity	Yes	Large consumers which are sensitive to energy costs in a strongly competitive market
Power displacement	Yes	Embedded in the grid and consequently can generally export excess power production

The electricity consumption of the refining and chemicals sectors in the UK is substantial, although heat demands are also significant [60]. Total power demand is over 1000MW with heat demands over 3000MW. However 70% of these demands are met from existing CHP plants fuelled at least partly by waste streams, leaving a very small accessible market

The refining and chemical sectors in the UK are declining due to the cost of raw materials being lower in other markets. As a result the appetite for investment in the sector is limited and the ageing asset base has a remaining life significantly less than an MNR. Elsewhere the refining and chemicals sector is stronger but highly competitive. Investment criteria are generally very demanding with short payback times being required for capital investments. These circumstances are unhelpful for a long term investment such as an MNR so a minimal market penetration is anticipated in this application.

10. Desalination

Water scarcity due to population growth has resulted in the application of many desalination plants internationally.

There are two classes of technology for desalination; thermal and membrane. The more robust thermal technologies are widely employed in the Middle East. These use heat to distil fresh water from saline. Membrane technologies use semi-permeable membranes to selectively separate fresh water. Reverse osmosis, the most advanced membrane technology, is now the preferred desalination process due to its lower capital and operating costs [62]. This technology consumes about 2 to 4 kWh/ m^3 compared with a similar electricity consumption for auxiliaries plus about 70kWh/m^3 of heat for the thermal processes.

Desalination plants are always located adjacent to the source of salt water, be it from the sea or an inland saline source and as close as feasible to areas of demand such as cities and industrial areas. Connection to the grid is not considered to be a constraint for most applications.

For this application, installation of an MNR for power production will be driven by economics and security of supply.

The characteristics of the application are summarised below.

APPLICATION	DOES IT BENEFIT FROM MMR?	COMMENTS
Scale of application	Yes	
Remote location	Possibly	Desalination plants are generally built within reach of consumers
Fuel unavailability	No	
Security	Yes	Security for water production is not sufficient to manage the safety and non-proliferation risks of an MNR
Fuel price sensitivity	Yes	As large scale energy consumers desalination plants are sensitive to energy costs
Power displacement	Yes	Possible where excess capacity is installed

In the Middle East water demand is growing quite rapidly – typically 4-7% per year, mainly due to population growth [61, 63 and 64]. Changing climatic conditions, growing population globally and rising standards of living are all driving increasing international water demand. In the Middle East alone water production is planned to grow by 7 million m^3/day by 2020 which represents an average increase in power demand of up to 1200MW. If this additional capacity was to be supplied by 5 MW MNR units it would require up to 240 reactors. Currently the Middle East represents half the installed global desalination capacity. Extrapolating the growth in desalination to the global market would suggest a potential opportunity for approaching 500 MNR units.

If the case for MNRs in this application is purely economic they will only be applied where the price of electricity is high, typically on remote islands and limited remote areas elsewhere. It is considered that the realistic market for MNRs in desalination will be limited to a maximum of perhaps 5% of the estimate above representing up to 25 units.

11. Flexible Baseload Generation

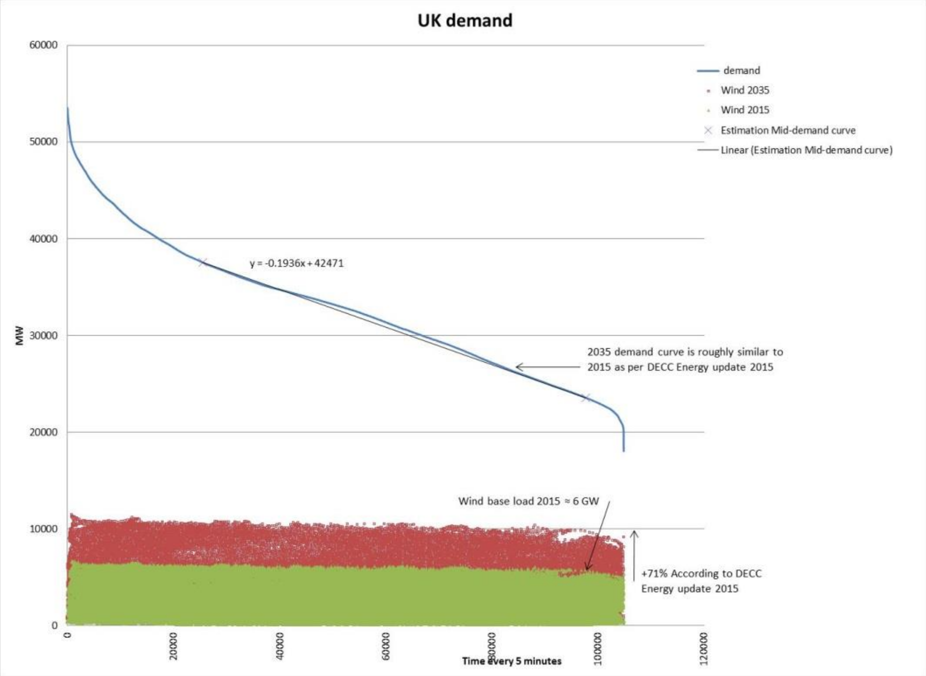
The opportunity for MNRs to contribute to bulk power generation will be determined by their competitiveness, ease of siting and flexibility. The competitiveness of the MNR is likely to depend upon the support provided and the reductions in cost that can be achieved through large scale production. Their siting will be in part determined by regulatory considerations and partly by public acceptability. If both of these become favourable, installation of significant numbers of MNRs embedded in the distribution network will become feasible. Such an application would result in reduced transmission network costs and hence potentially improved MNR economics.

However, wider application for power generation would require exploitation of the baseload duty that maximises the revenues for MNR investment. However, as the penetration of intermittent renewable generation from wind and solar PV increases, the baseload opportunity is reduced, being replaced by flexible generation to fill the gaps between renewable production and demand. The level of flexibility required will vary from operation for a few hours each week to nearly continuous operation with a few periods each week when output has to be reduced.

The figure below illustrates how the baseload operation has been reduced by intermittent generation. The green coloured region at the bottom of the graph is a dense scatter of wind operating points for each of the five minute intervals in 2015 that make up the load-duration curve. The red region is the same area scaled up to the 2035 level. This demonstrates the reduction in baseload duty and emphasises the opportunity for flexible operation close to baseload duty.

The duty close to baseload will include periods of output reduction to avoid exposure to the negative wholesale power price when renewable generation exceeds the net demand. Larger reactors inherently have lower rates of loading and unloading than MNRs due their scale and necessary thickness of vessels which need to avoid life-limiting fatigue damage due to temperature cycling. This difference in characteristics means that MNRs will be able to deload to avoid adverse wholesale prices and reload as the price recovers more quickly than other reactors, enhancing their economic viability.

The figure below suggests that up to about 5,000MW of MNR generation could be installed while maintaining near baseload operating conditions. This would be a potential market of 1,000 5MW units. Given realistic limitations of siting and economics, up to 10% of this number could be foreseen as part of a second wave of installation between 2030 and 2035.



APPENDIX 2
REFERENCES AND EVIDENCE MATRIX

No	Source	Comment	Use
1	DECC SMR reports Completed report: Ongoing work	Main SMR study to which the MNR study is a small companion study. Discussions were held with the authors of these reports, no specific data was provided but discussions were held to avoid overlap with the main SMR study scope	Background information, ensuring compatibility with main SMR study
2	https://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=467	Statistics for EPG-6	Information on EPG-6 for Table 3
3	https://books.google.co.uk/books?id=wRvFBAAAQBAJ&pg=PA526&lpg=PA526&dq=egp6+reactors&source=bl&ots=19JyHAHjG4&sig=wdzF4FXJ_BWCrpA5tL_I-U8ZrKw&hl=en&sa=X&ved=0ahUKEwjPjsb-6ebKAhVEUhQKHYLeDUEQ6AEILjAI#v=onepage&q=egp6%20reactors&f=false	Book on Nuclear Power in the Artic	Background information on development of Russian reactors in the Arctic for Technology section.
4	http://www.rosatom.ru/en/areas_of_activity/nuclear_power_division/power_generation/	ROSATOM webpage on power generation	Description and technical information of construction of Russian reactors – Technical Section
5	https://books.google.co.uk/books?id=lgKjQr4MZTMC&pg=PA115&lpg=PA115&dq=egp6+reactors&source=bl&ots=XXpJrTnfAL&sig=mhDnrdGntHsDz0IC_ADS-pD_V5c&hl=en&sa=X&ved=0ahUKEwjPjsb-6ebKAhVEUhQKHYLeDUEQ6AEIMDAJ#v=onepage&q=egp6%20reactors&f=false	Book- Technology & Soviet energy availability. Soviet power stations in operation	List of reactors p115 Technology Section
6	http://www.power-technology.com/features/featurethe-worlds-smallest-nuclear-reactors-4144463/	Power Technology.com web page The world's 10 smallest nuclear reactors	Identification of MNRs in world – Technology section details of KLT-40S, EGP-6, CEFR for Table 3

No	Source	Comment	Use
7	http://www.neimagazine.com/features/featureklt-40s-nuclear-barge-project-still-afloat	U enrichment level of KLT-40S	Used for information on KLT-40S in Table 3
8	Advances in Small Modular Reactor Technology Development, IAEA publication, September 2001 http://aris.iaea.org and 2012 update https://www.iaea.org/NuclearPower/Downloadable/SMR/files/smr-status-sep-2012.pdf	Provides summary of reactors	Covers Carem-25, ABV-6, KLT-40S, CEFR, 4S, Gen4, Shelf, MHR-100 for Table 3
9	https://www.iaea.org/NuclearPower/Downloadable/aris/2013/25.KLT-40S.pdf	Russian KLT-40S Reactor Diagram and Data	Description and technical information of construction of KLT-40S for Table 3
10	http://www.andrew.cmu.edu/user/ayabdull/Victor_RussianSMRs.pdf	Paper: Current Status, Technical Feasibility and Economics of SMRs in Russia 2014	Recent Information on Russian MNR status and deployment - Gives information on ABV-6, EGP-6, MARS, ANGSTREM, MTSPNR, VKT12 for Table 3
11	http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx	World Nuclear.org Small Nuclear Power Reactors	Recent Information on MNR status and deployment - Technology, Regulation and Economics section
12	https://books.google.co.uk/books?id=Swr9BTI_2FEC&pg=PA241&dq=%22world%27s+northernmost+nuclear+power+plant%22&hl=en&sa=X&ved=0CCoQ6AEwAGoVChMI76Tgj6znyAIVyzkaCh1A9g0D#v=onepage&q=%22world's%20northernmost%20nuclear%20power%20plant%22&f=false	Encyclopaedia of the Arctic: Bilibino NPP EGP 6	History of Bilibino NPP – Technology and Barriers Section Table 3
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14	http://www.uxc.com/smr/Library%5CDesign%20Specific/CAREM/Presentations/2009%20-%20Why%20CAREM.pdf	Presentation on Carem-25 INVAP Argentina	Technology Section – Carem-25 reactor information for Table 3
15	http://www.uxc.com/smr/uxc_SMRDetail.aspx?key=MRX	Information on MRX	Information on MRX for Table 3
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17	https://www.iaea.org/NuclearPower/Downloads/Technology/files/SMR-booklet.pdf	Summary of technologies	Information on Unitherm for Table 3
18	http://httr.jaea.go.jp/eng/index.html	JAEA web pages on HTTR	Technology Section – HTTR information for Table 3
19	http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx	World Nuclear Organisation Small nuclear power reactors updated March 2016	Information on HTR-10 for Table 3
20	http://www.u-battery.com/ De	Website for U-battery	Information on U-battery for Table 3.
21	The U-battery market analysis, Urenco, Taking the U-battery from concept to market, 10th April 2014	Presentation on U-battery	Information on U-battery for Table 3
22	http://htmr100.com/index.html	Website on HTMR	HTMR-100 information for Table 3
23	https://www.iaea.org/NuclearPower/Downloadable/Meetings/2015/2015-08-25-08-28-NPTDS/DAY1/7._The_HTMR-100_technology_and_economic_case.pdf	IAEA datasheet on the HTMR	HTMR-100 information for Table 3
24	http://www.gen4energy.com/	Gen4 website	Provides information on Gen 4 reactor for Table 3
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No	Source	Comment	Use
27	http://nordic-gen4.org/wordpress/wp-content/uploads/2014/09/Asano.pdf	Overview of fast reactor development ofToshiba – 4S and TRU burner	Provides information on the $s for Table 3
28	http://www.uxc.com/smr/Library/Design%20Specific/RAPID/Other%20Documents/RAPID%20Reactor.pdf	RAPID reactor information historical	RAPID reactor information for Table 3
29	http://atomicinsights.com/the-rapid-l-reactor-designed-by-japans-criepi-for-jaeri-is-getting-a-lot-of-blog-attention/	Review of RAPID reactor historical	RAPID reactor information for for Table 3
30	https://public.ornl.gov/conferences/MSR2015/pdf/10-China's%20TMSR%20programm_HongjieXu.%20pptx.pdf	Shanghai Institute of Advanced Physics presentation on: China’s TMSR programme	Information on the TMSR programme for Table 3
31	http://world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx	World Nuclear Organisation factsheet on molten salt reactors Molten Salt Reactors TMSR, IMSR	Information on molten salt reactors for Table 3
32	http://terrestrialenergy.com/	Website for the IMSR reactor	Information on IMSR for Table 3
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34	http://www.world-nuclear-news.org/ENF-Triso_fuel_triumphs_at_extreme_temperatures-2609137.html	Article describing TRISO fuel	Used to understand the potential safety gains of using TRISO fuel
35	https://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm	European Nuclear Society February 2016	Number of reactors in Europe and worldwide
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39	http://militarybases.com/	February 2016	Number of US military bases
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49	http://www.enemalta.com.mt/index.aspx?cat=2&art=5	Enemalta February 2016	Capacity installed in Malta
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51	http://www.nrel.gov/docs/fy15osti/62703.pdf	National Renewable Energy Laboratory February 2016	Capacity installed an population
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54	https://www.steel.org/~/media/Files/AISI/Public%20Policy/Member%20Map/NorthAmerica-Map2013/SteelPlant_NorthAmerica_AISI_version_June252013.pdf	American Iron and Steel Institute February 2016	Number of steel mills in North America
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56	https://www.worldsteel.org/statistics/crude-steel-production.html	Worldsteel Association February 2016	Crude steel production 2014-2015 by country
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66	http://www.sciencedirect.com/science/article/pii/S036054421401295X	Article: Load following with Small Modular Reactors (SMR): A real options analysis	and Economics Section
67	http://www.oecd-nea.org/ndd/pubs/2015/7279-proj-costs-electricity-2015-es.pdf	OECD/NEA Projected Costs of Generating Electricity 2015 Edition	Latest estimates of Electricity cost comparison – Economics Section

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68	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf	UK Government report Electricity generation costs 2013	Economics Section
69	https://www.iaea.org/INPRO/6th_Dialogue_Forum/session-4/2.sozoniuk.pdf	OECD/NEA Study on the Economics and Market of Small Modular Reactors	Economics Section
70	http://www.nuclearinst.com/write/MediaUploads/TR.pdf	Cambridge University presentation: Economies of Scale v Economies of Volume – LWRs	Economics Section
71	http://www.kns.org/jknsfile/v45/1-13-58.pdf	OECD/NEA study on the economics and market of small reactors	Economics Section
72	http://www.oecd-nea.org/ndd/pubs/2015/7195-nn-build-2015.pdf	OECD/NEA report Nuclear New Build: Insights into Financing and Project Management	Research on MNR's plans, barriers and financing, Technology, Regulation and Economics section
73	http://www.nei.org/CorporateSite/media/filefolder/Conferences/SMR/BloombergSMR2014.pdf	NEI Small Reactor Forum presentation: Findings from an Assessment of Baseload Generation Nuclear SMR compared to Natural Gas Combined Cycle	Assessment of baseload generation capacity
74	http://www.neimagazine.com/features/featureload-following-capabilities-of-npps	Nuclear Engineering article: Load-following capabilities of NPPs	Economics section
75	http://eprints.lincoln.ac.uk/16273/	Lincoln University: Load following with Small Modular Reactors: a real option analysis	Economics section
76	U-Battery Market Reports, Aorora Energy research, July 2015	Comparison of LCOE and Overnight Cost with conventional generation	Economics sections
77	https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf	Report on status	Provided cost estimates for economics section
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79	Paper – Historical construction costs of global nuclear power reactors, Jessica Lovering, Arthur Yip, Ted Nordhaus, 13th January 2016	Discusses whether learning curves have applied to large nuclear plant	Cost factors section
80	Paper - *SSTAR LEAD-COOLED, SMALL MODULAR FAST* REACTOR WITH NITRIDE FUEL by J. J. Sienicki, A. V. Moisseytsev, P. A. Pfeiffer, W. S. Yang, M. A. Smith, S. J. Kim, Y. D. Bodnar, D. C. Wade, and L. L. Leibowitz, *Argonne National Laboratory, Workshop on Advanced Reactors with Innovative Fuels,ARWIF-2005,Oak Ridge*	Information on SSTAR reactor	Information on SSTAR reactor
81	DECC Contract for Difference: Final Allocation Framework for the October 2014 Allocation Round – Updated 2 October 2014. Appendix 1	Contains agreed administrative strike prices for renewable energies	Cost information for Section 4.2
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Background Reading			
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90	http://www.oecd-nea.org/ndd/pubs/2015/7246-ned-2015.pdf	Nuclear Energy Data Données sur l’énergie nucléaire 2015. Latest OECD Data on Nuclear Energy,	Background information for Economics section
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