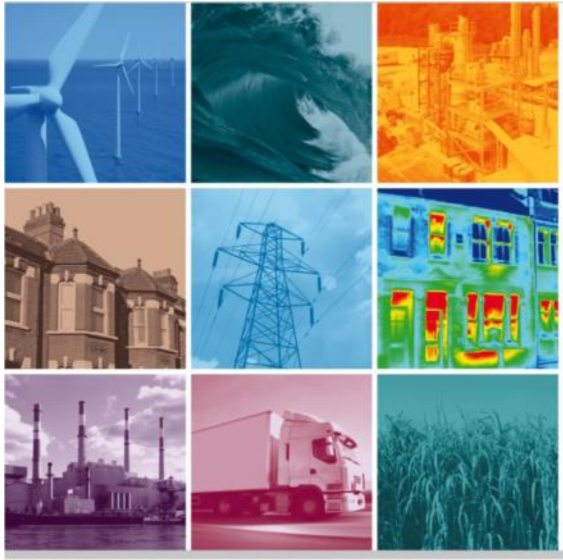


www.eti.co.uk

Innovation In Nuclear – Potential For Small Modular Reactors

A talk for the I Mech E Warwickshire Area at Benn Hall, Rugby - 2nd April 2019

Mike Middleton – Strategy Manager Nuclear

Presentation structure

- Introduction to the ETI
- Decarbonising the UKs economy
- Recap from previous publications October 2015 and September 2016
- Changes in UK nuclear context since 2015
- The ETI's nuclear cost drivers project
- Value of nuclear energy in a UK integrated energy system
- Realisation of benefits from innovation applied to nuclear energy
- Next steps
- Conclusions

Introduction to the ETI

- The ETI is a public-private partnership between global energy and engineering companies and the UK Government.
- Targeted development, demonstration and de-risking of new technologies for affordable and secure energy
- Shared risk
- Closing in summer 2019 after 12 years and a £400M technology programme

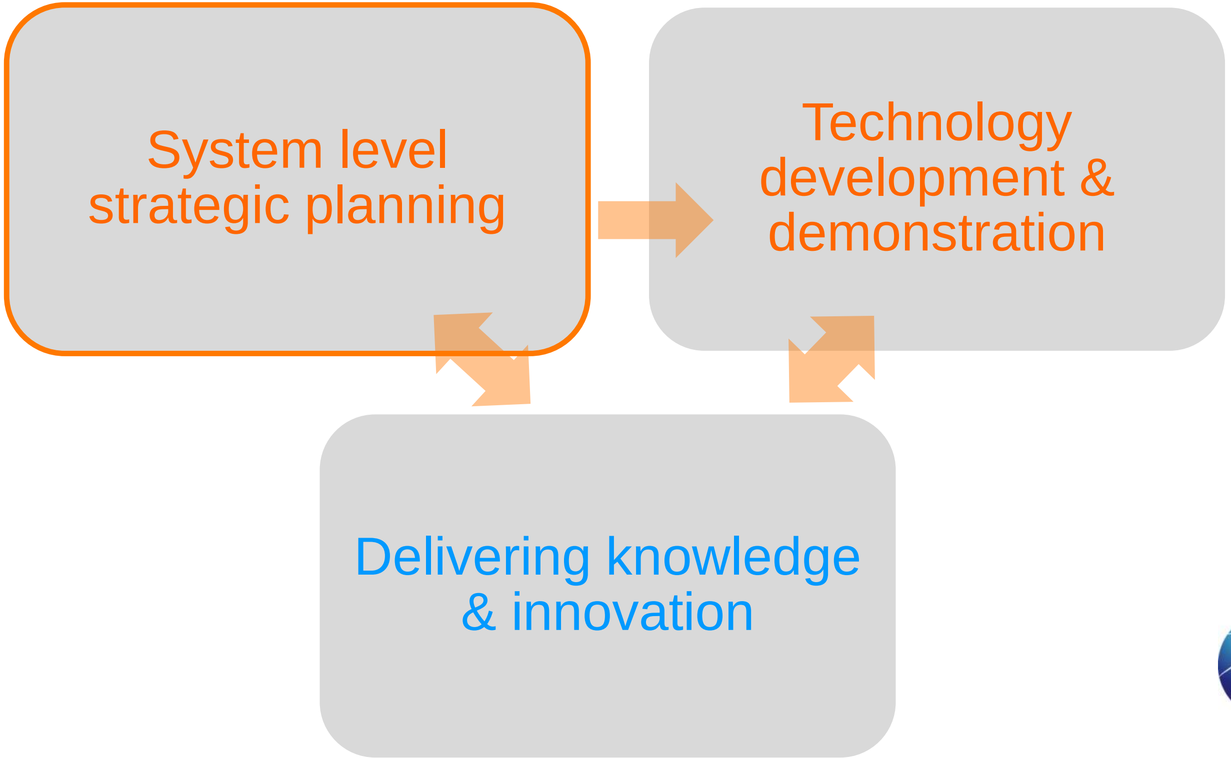
ETI members

bp
CATERPILLAR
EDF ENERGY
Rolls-Royce
Shell
Department for Business, Energy & Industrial Strategy
EPSRC Pioneering research and skills
Innovate UK Technology Strategy Board

ETI programme associate

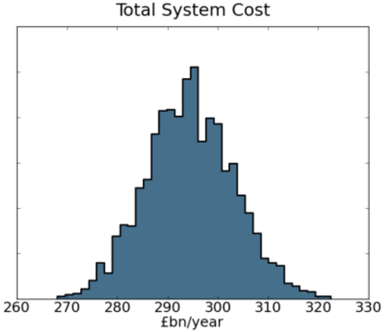
HITACHI Inspire the Next

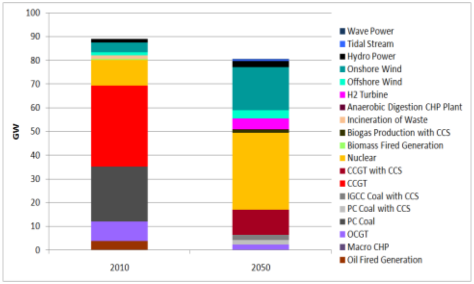
What does the ETI do?

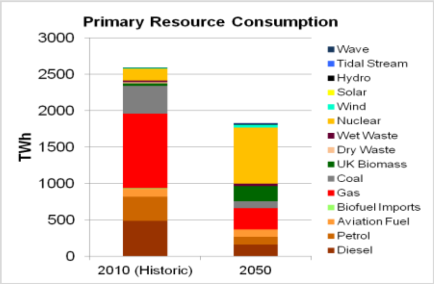


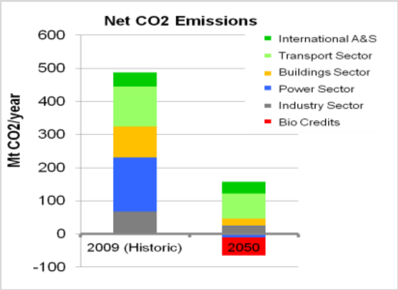
ESME – The ETI's system design tool

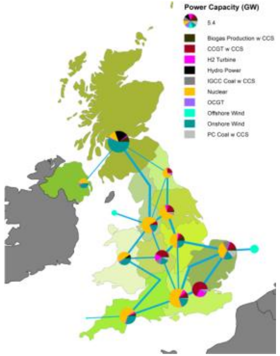
Integrating power, heat, transport and infrastructure
providing national / regional system designs

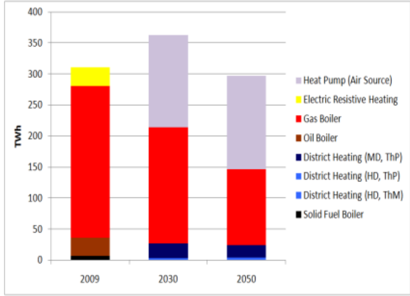












ESME
Energy System
Modelling Environment

ESME example outputs

Decarbonising the UK’s economy

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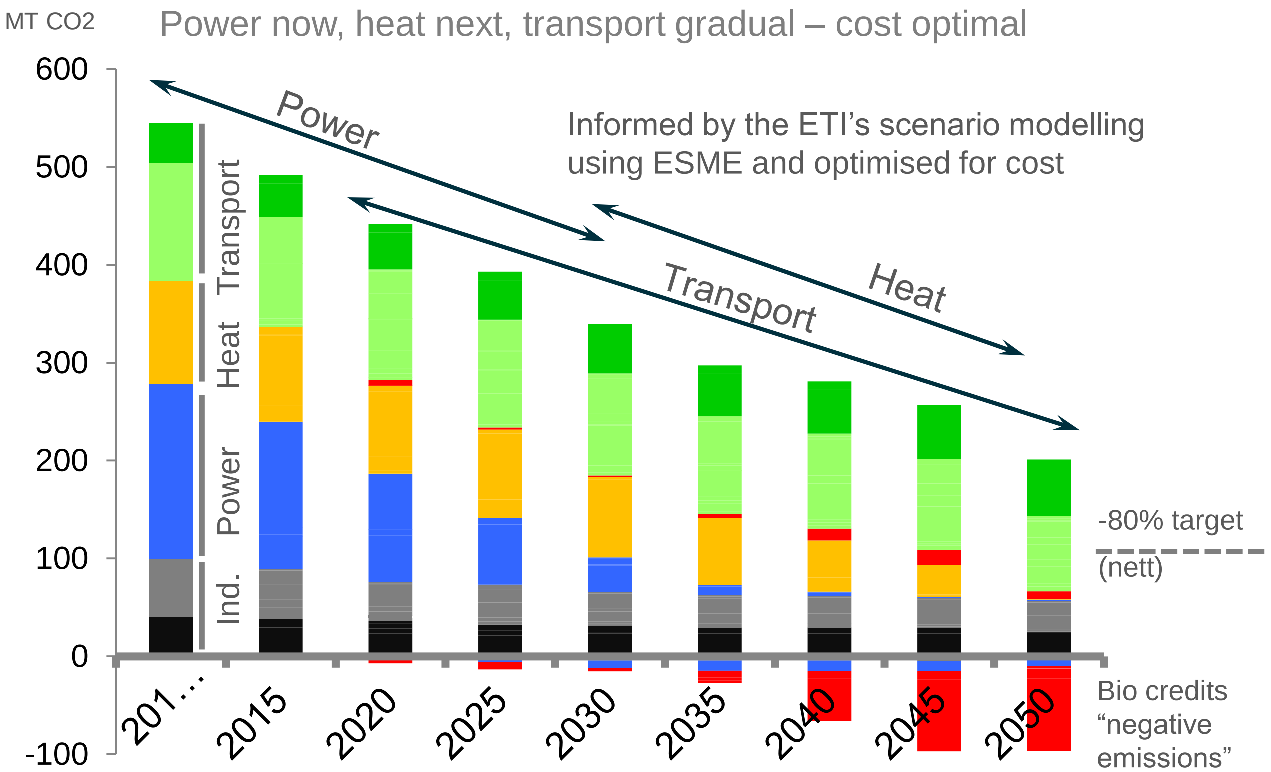
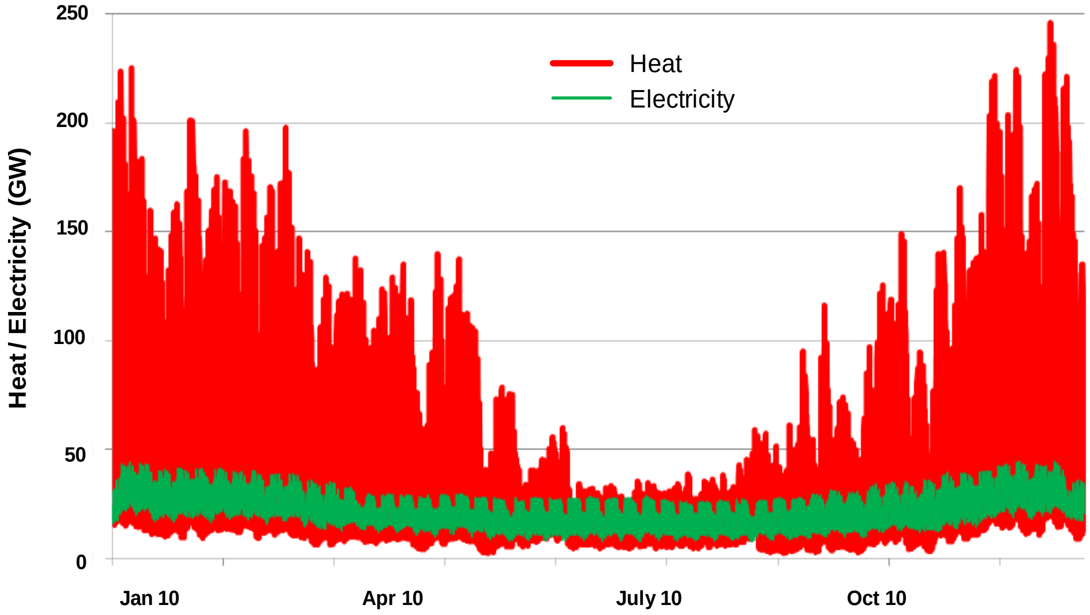
A trajectory for reducing the UK's carbon emissions



Decarbonising heat is challenging



Design point for a GB heat delivery system

Design point for a GB electricity delivery system

GB 2010 heat and electricity hourly demand variability - commercial & domestic buildings
R. Sansom, Imperial College

Unattractive to electrify it all

Economics matter - nuclear energy plants must be expected to be economically attractive

LCOE £/MWhr	Context	International Market Opportunity for Nuclear
Low	Price lower than other low carbon alternatives with predictable project delivery.	Very large with potential for growth in nuclear share internationally driven by SMRs.
Competitive	A viable choice depending on policy considerations and viable projects.	Large with potential SMR applications to complement large reactor deployment.
Not yet competitive	Cogeneration applications such as district heating supply or desalination improve project economic viability. Increase production volume to reduce reactor unit cost.	Small fraction of present international nuclear market.
High	Research and development plants. Remote communities off grid requiring heat and power. Embedded generation for providing heat and power.	Niche.

Notes: LCOE: levelised cost of electricity (an indicator to compare technologies but system costs are also important)

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Small Modular Reactors - definition

SMR is a small or medium reactor but not necessarily modular:

- Small - 10 to 300 MW (IAEA, DOE)
- Medium - 300 to 700 MW (IAEA)
- Excludes Large - 700 to 1700 MW (IAEA)

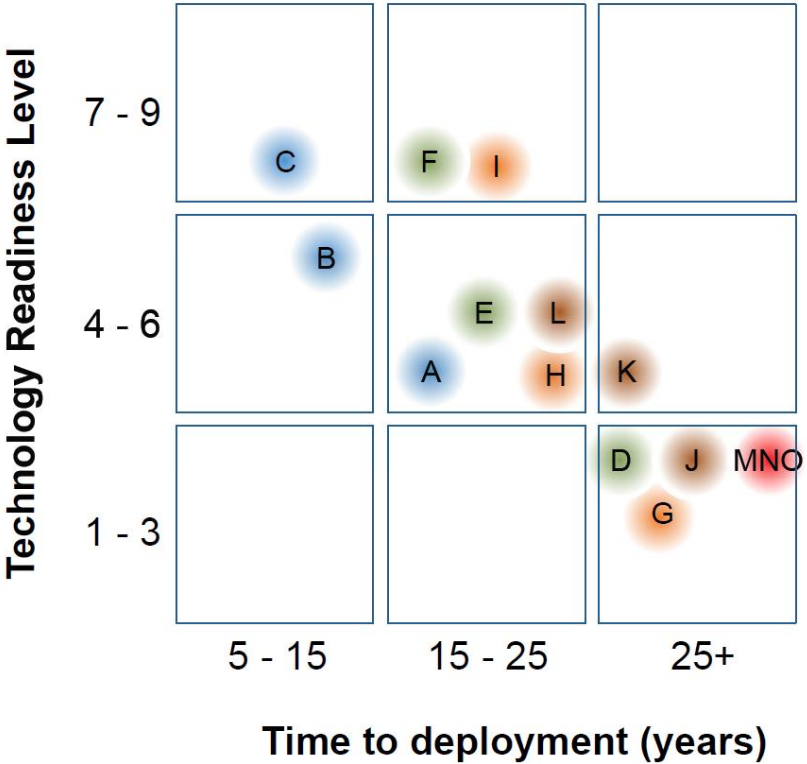
Modular in deployment:

- Modular – Multi-modular Nuclear Power Plant (NPP) on a common foundation base mat, with NPP modules added as needed
- <u>Not</u> power in a module to be returned to the factory for refuelling

Economic Advantage:

- Proponents aspire to use modern manufacturing and construction methods to reduce unit costs – the economies of multiples
- Innovation to overcome the dis-economies of scale of smaller units
- Individual projects may be more affordable compared with large reactors

NNL view (October 2016) of SMR technology readiness levels from assessments within project 3 of BEIS SMR TEA



A. LWR1
B. LWR2
C. LWR3

D. HTR1
E. HTR2
F. HTR3

G. SFR1
H. SFR2
I. SFR3

J. MSR1
K. MSR2
L. MSR3

M. GFR1
N. SCWR1
O. LFR1

Source: NNL presentation at the London Nuclear Power Symposium 24th October 2016

Technology Group	Abbreviation	Neutron Spectrum
Very high temperature gas reactors	VHTR	Thermal
Molten salt reactor	MSR	Thermal
Supercritical water cooled reactors	SCWR	Thermal
Gas cooled fast reactor	GFR	Fast
Sodium cooled fast reactors	SFR	Fast
Lead cooled fast reactors	LFR	Fast

Developing SMR technologies and markets

Country	Technology	Notes
China	HTR – PM high temperature gas reactor (pebble bed core)	Construction start 2012 of demonstration plant at Shidaowan in Shandong province. Operations were forecast from 2017 but delayed? Coal combustion replacement?
China	ACP100 integral PWR	IAEA safety review complete April 2017. Demonstration plant at Changjang. Commercial operations forecast 2025. District heating?
USA	NuScale integral PWR	Commenced NRC review Jan 2017. First potential customer UAMPs within Idaho Nuclear Laboratory site. Commercial operations forecast 2026.
Canada	Open and technology neutral	Canadian Government and regulatory support for nuclear technology development at Canadian Nuclear Laboratories site at Chalk River with SMR demonstration by 2026.
Japan	HTGR – high temperature gas reactor (prismatic core)	HTTR test reactor operating since 1998. Recent periods of continuous hydrogen production using sulphur iodine process. Next step technology demonstrator (2025) Intended to use gas turbine for power conversion.
UK	?	Start of 2019; UK AMR competition phase 1 complete; announcements awaited for phase 2. UK consortium lead by R-R seeking Govt support for light-water SMR design

This table is illustrative; the list of markets and associated technologies here is not exhaustive
A range of fusion technologies are in development; all are yet to demonstrate “gain”

Conclusions From ETI Nuclear Insights (1) October 2015

energy technologies institute

10 YEARS TO PREPARE for a low carbon transition

Nuclear is part of the mix in an affordable low carbon transition

potential roles for both large nuclear and small modular reactors (SMRs)

Large reactors are best suited for baseload electricity production

upper capacity limit
site availability of

35 GWe

Actual deployment will be influenced by a number of factors and could be lower

Future nuclear technologies will only be deployed if there is a market need

and these technologies provide the most cost effective solution

SMRs could fulfil an additional role in a UK low carbon energy system by delivering combined heat and power

a major contribution to the decarbonisation of energy use in buildings

using district heating infrastructure

SMRs offer more flexibility with deployment locations that could deliver heat into cities via hot water pipelines up to

30 km
in length

Assessed deployment capacity of at least

21 GWe

Flexible power delivery likely to be required

A decision is required now regarding

10 years

of enabling activities for a first commercially operated UK SMR with earliest operational date around **2030**

A strategic approach to reactor siting together with public consultation

will be important for both large nuclear and SMRs

ETI's nuclear insights and supporting project reports are available at: www.eti.co.uk

Conclusions From ETI Nuclear Insights (2) September 2016

A credible integrated schedule for a UK SMR operating by 2030

depends on early investor confidence

The Government has a crucial role to play

in delivering a policy framework which supports SMR deployment and encourages investor confidence

If SMRs are to become an integral part of a 2050 UK energy system, deployment should address future system requirements including

power

heat

flexibility

SMR factory production can accelerate cost reduction

PREPARING FOR DEPLOYMENT OF A UK SMALL MODULAR REACTOR BY 2030

UK SMRs should be designed and deployed as "CHP ready"

Extra costs are small and potential future revenue large

UK SMRs should be designed for a range of cooling systems

including air cooled condensers

There is economic benefit in deploying SMRs as CHP to energise district heating networks; this depends on district heating roll out

There is a range of sites suitable for early UK SMR deployment

Including options for the UK first of a kind site

Changes in UK nuclear context since 2015

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Changes In UK nuclear context since 2015

These include:

- Hinkley Point C now in construction informed by the learning from
  - EPRs operating in Taishan
  - EPRs at Olkiluoto and Flamanville yet to enter commercial operation
- Westinghouse AP1000s in operation in China but
  - Cost over-runs at Vogtle and VC Summer bankrupted Westinghouse
  - NuGen’s project for 3 AP1000 units at Moorside now closed
- Hitachi has suspended further UK investment in their ABWR projects
  - Horizon projects at Wylfa and Oldbury now “paused”
- CGN’s export reactor design progressing GDA; potential deployment at Bradwell
- Private sector investment in advanced nuclear technologies
  - BEIS AMR competition with 8 contractors completing phase 1

Nuclear increasingly perceived as difficult, risky and expensive whilst deployment of renewables led by offshore wind and solar grows and costs fall

The ETI's Nuclear Cost Drivers project

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Project purpose - ETI cost drivers project

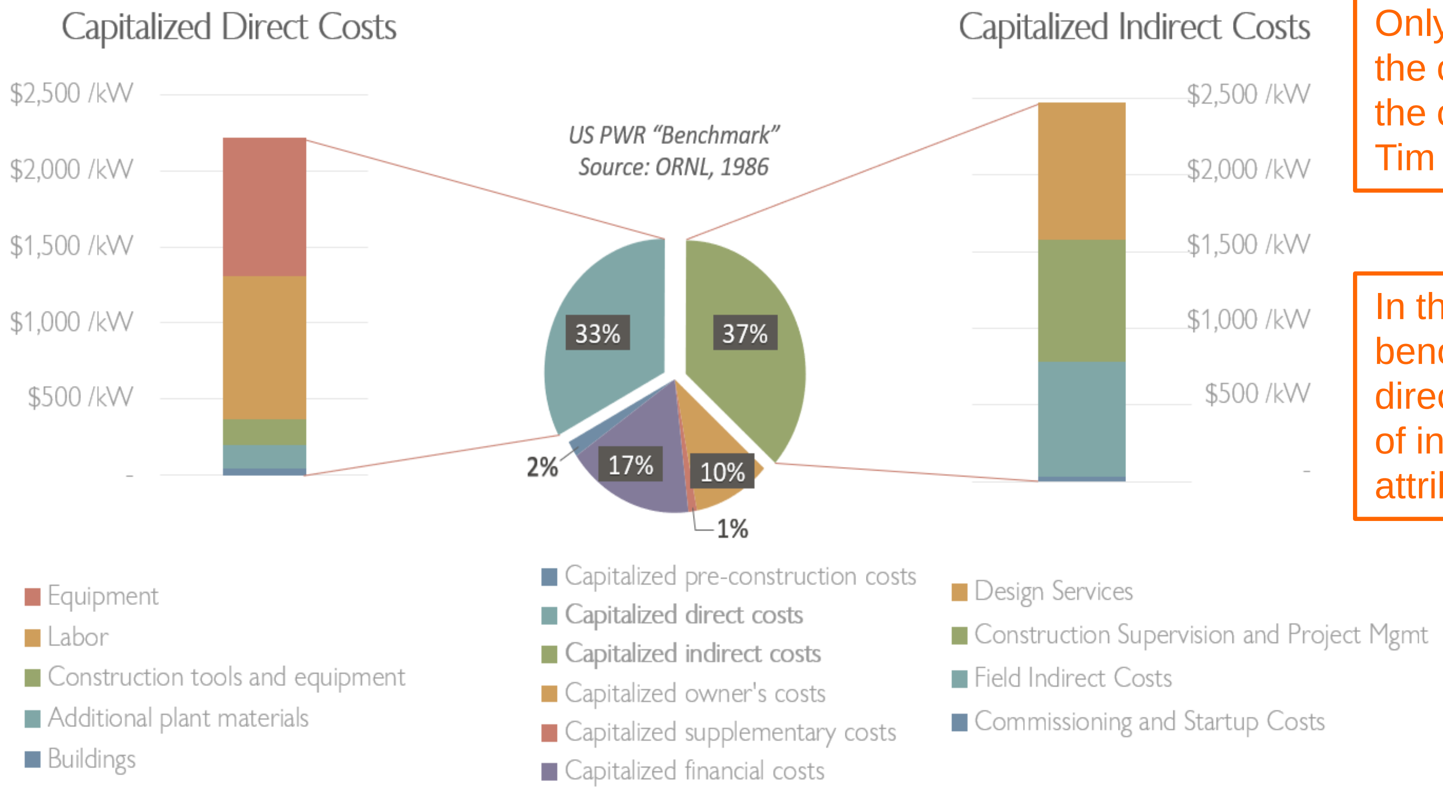
To identify the cost drivers within historic, contemporary and advanced reactor designs.

Principal outcomes to be improved understanding of:

- the cost drivers within contemporary UK nuclear new build projects and the identification of areas of potential innovation which can support cost reduction;
- the cost drivers within advanced reactor technologies and the identification of areas of potential innovation which can support cost reduction; and
- the relative differences in cost base between contemporary and advanced nuclear reactor technologies and the potential to achieve a step reduction in the cost of generating electricity.

Project examined a sample of 33 relatively recently completed (or nearly completed) projects and compared them in a standardised way alongside a historic US PWR benchmark described in the 1986 Oak Ridge National Laboratory cost study which was also treated in the same standardised way.

Traditional nuclear power plants – What drives the cost of electricity



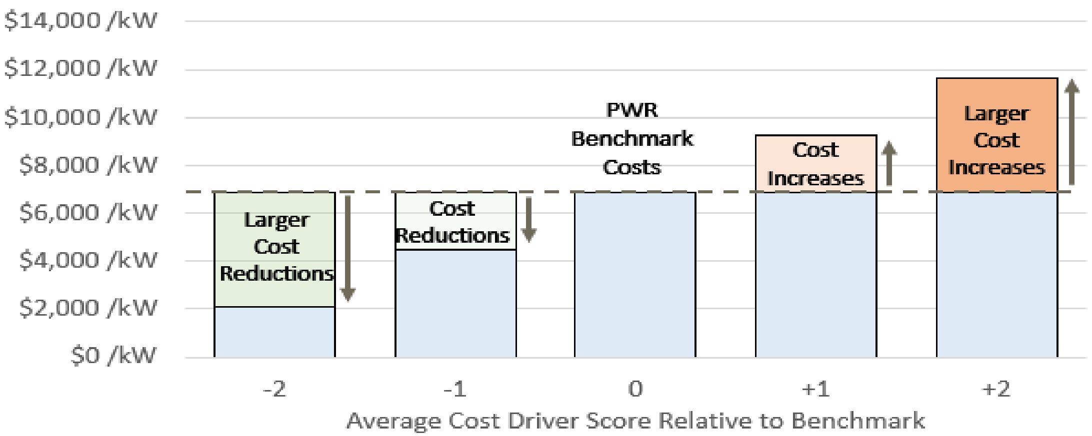
Only two costs matter; the capital cost and the cost of capital – Tim Stone CBE

In the ORNL benchmark, 50% of direct costs and 80% of indirect costs are attributable to labour

Source; the ETI's Nuclear Cost Drivers Project Summary Report

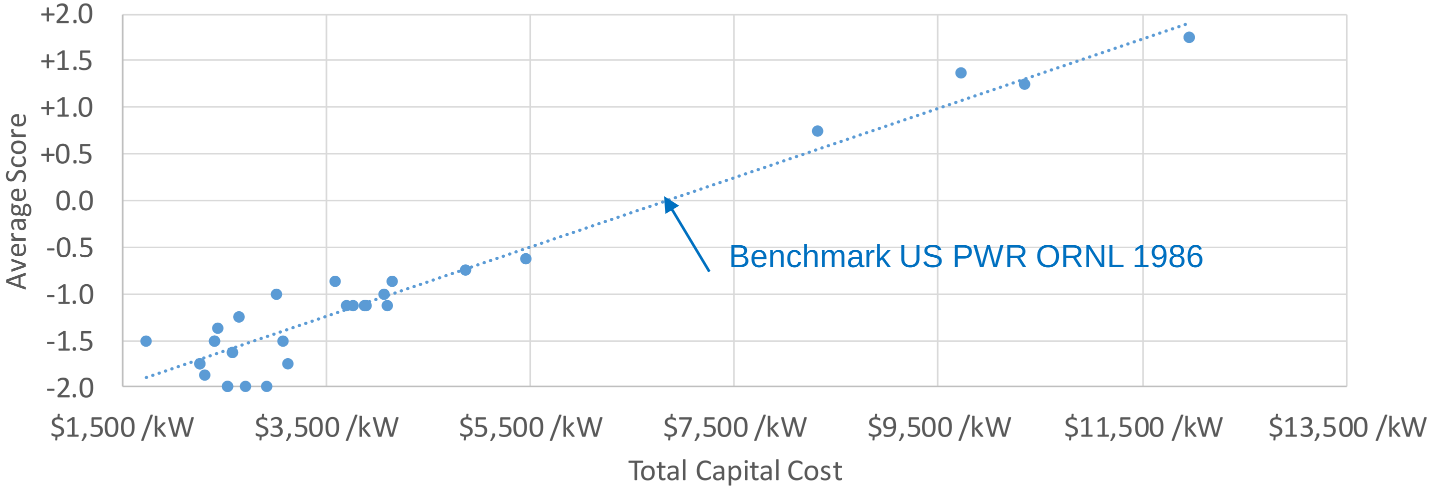
Project methodology

Cost Driver	Owner
Supply Chain	Vendors
Labour	EPC
Project Governance and Project Development	Government
Construction Execution	EPC
Political and Regulatory Context	Government
Equipment and Materials	EPC/Vendor
Vendor Plant Design	Vendor
Operations	Operator



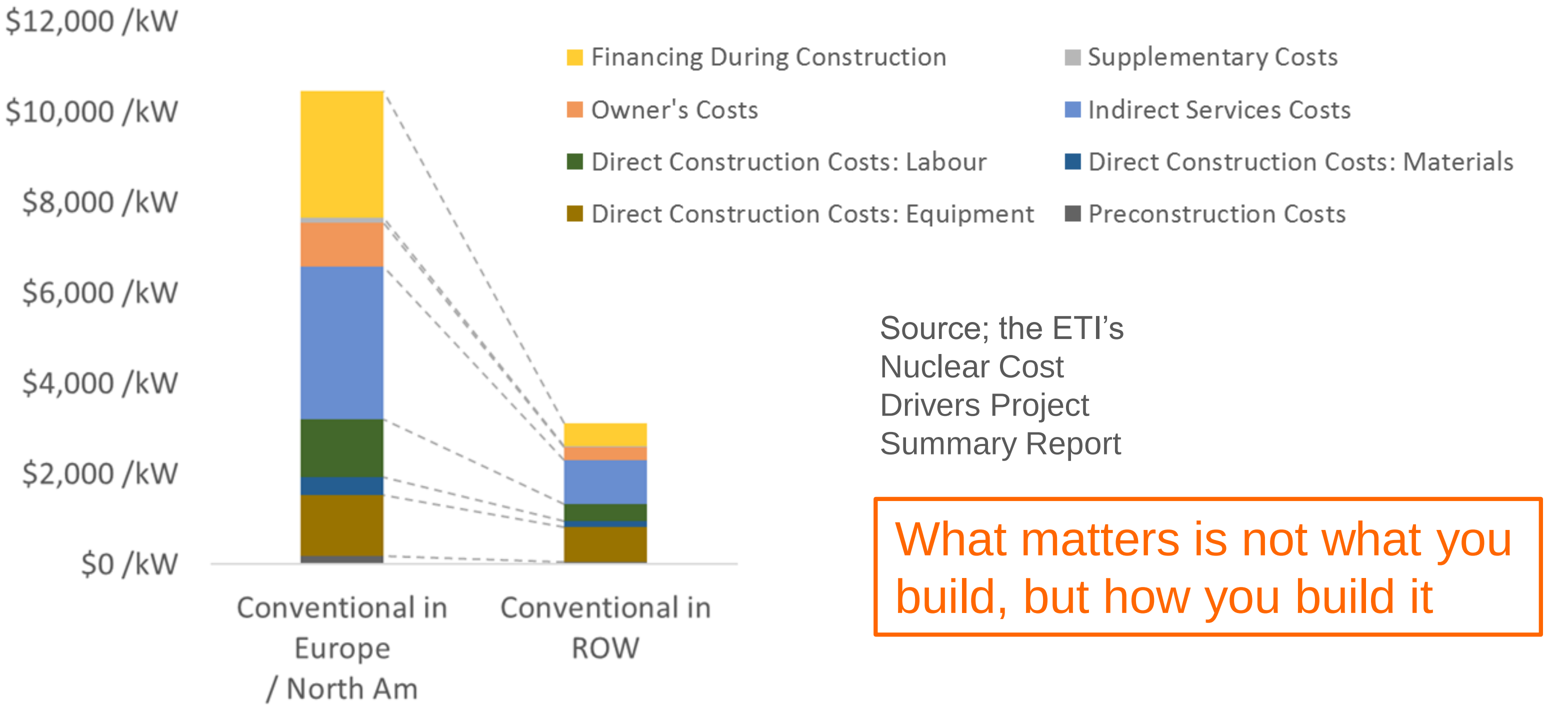
- 8 cost driver categories with associated actors/owners identified through discussion with experts
- Specific indicators developed to categorise performance within each category with range -2 to +2
- Over 150 hours of structured scorecard interviews with senior personnel involved in the projects
- US PWR benchmark from ORNL cost study treated in the same standardised way and set as datum

Data suggests two project groupings



Genre	Number of Units in ETI Database
US PWR Benchmark	*1*
North America & Europe	*5*
Rest of World	*28*

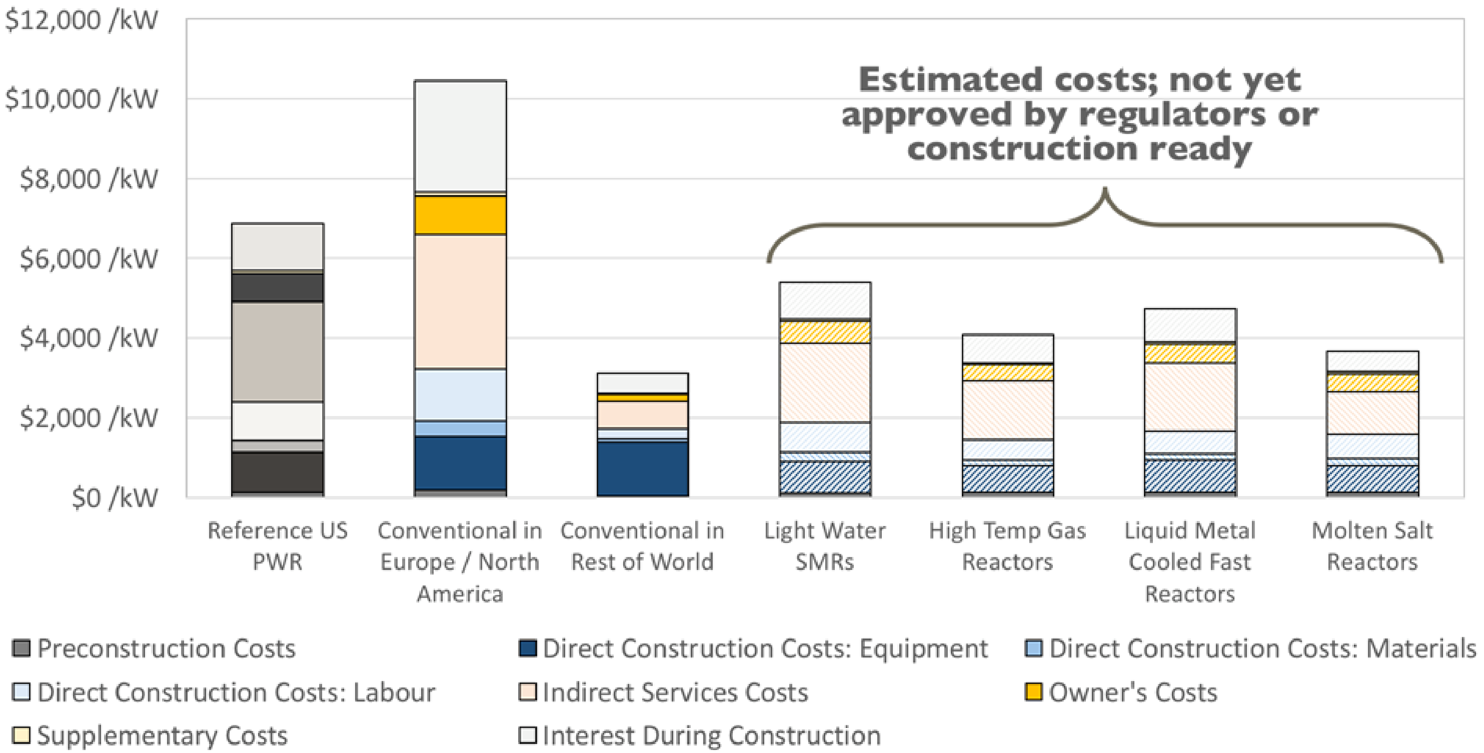
ETI NCD project – comparison of 2 "genres" "Europe/North America" vs "Rest of World"



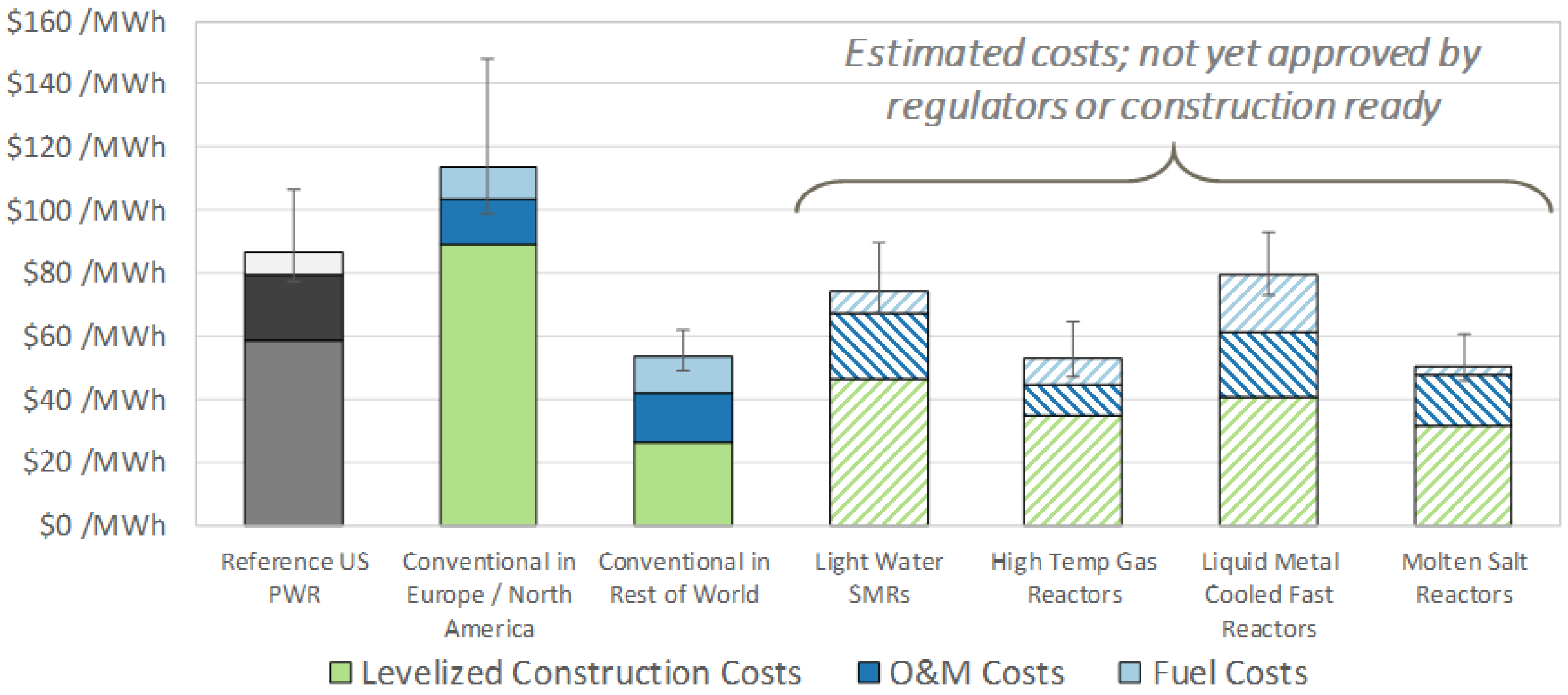
Source; the ETI's Nuclear Cost Drivers Project Summary Report

What matters is not what you build, but how you build it

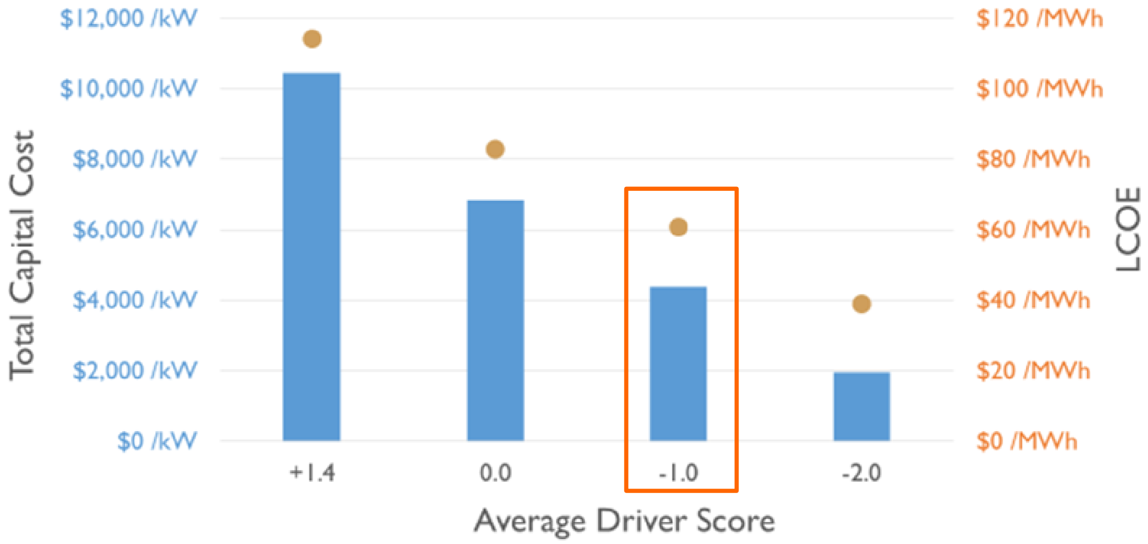
Comparison of capital costs across all genres



Comparison Of LCOE Across All Genres



Cost reduction scenarios for NA/EU genre



- Average cost driver score of minus 2.0 unrealistic in UK due to wage rates and handful of other factors
- Score of minus 1.0 might be a reasonable expectation supported by experience from Nuclear Electric's projects at Sizewell

Alternative Cost Scenarios with Other Rate Assumptions

Avg. Score	Capex/kW	Opex	7% Capex/MWh	7% LCOE	6% Capex/MWh	6% LCOE	9% Capex/MWh	9% LCOE
+1.4	$10,454 /kW	$25 /MWh	$89 /MWh	$114 /MWh	$75 /MWh	$99 /MWh	$123 /MWh	$148 /MWh
0.0	$6,826 /kW	$24 /MWh	$58 /MWh	$83 /MWh	$48 /MWh	$72 /MWh	$84 /MWh	$108 /MWh
-1.0	$4,386 /kW	$23 /MWh	$38 /MWh	$61 /MWh	$29 /MWh	$53 /MWh	$57 /MWh	$81 /MWh
-2.0	$1,946 /kW	$22 /MWh	$17 /MWh	$39 /MWh	$11 /MWh	$34 /MWh	$31 /MWh	$53 /MWh

Nuclear cost reduction in the UK

What matters is not what you build, but how you build it

→

If the 8 cost drivers are successfully addressed in the UK as elsewhere in the world then contemporary Gen III+ reactors can be cost competitive

Three questions:

- What is the aspirational average cost driver score (or LCOE) to be achieved in the UK after a sequence of plants?
- What is the shape of the potential UK nuclear cost reduction curve?
- How do different policy options impact the shape of the curve and ultimate LCOE?

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Nuclear In ESME whole system analysis

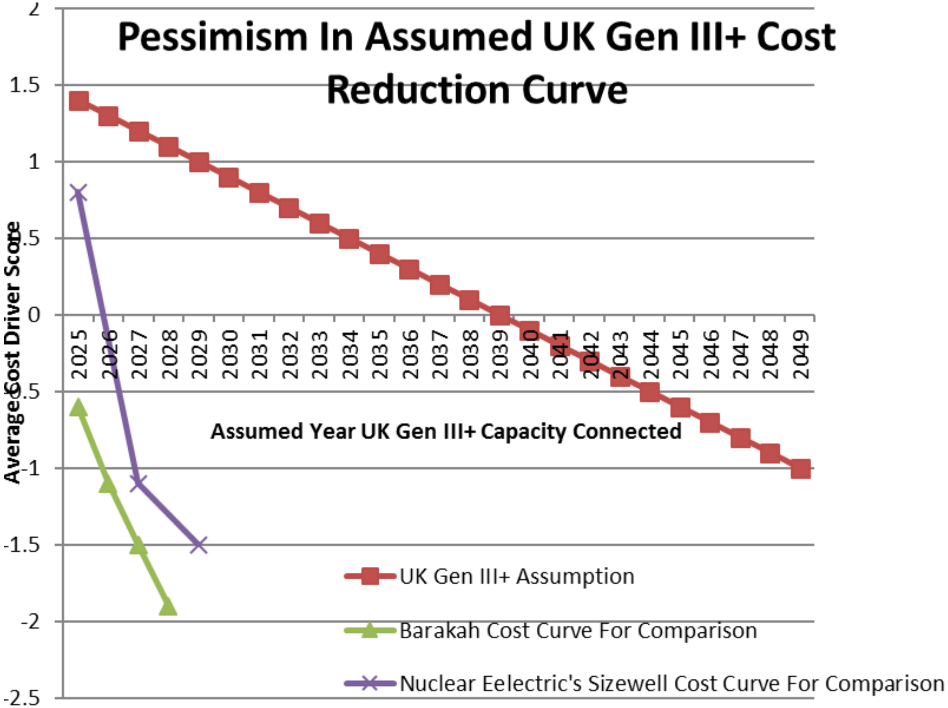
Nuclear technologies in ESME in 4 different data sets:

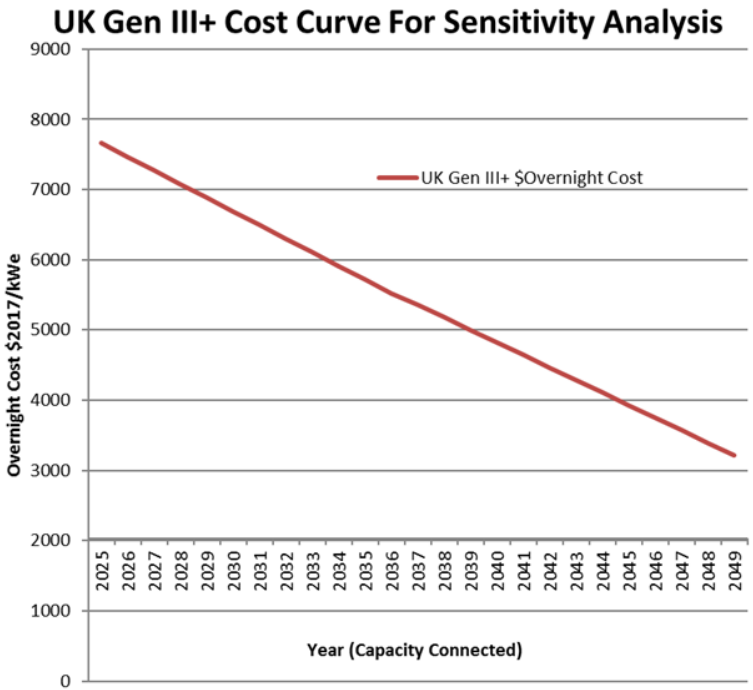
- **Legacy**; the existing UK Advanced Gas Cooled reactors plus the Sizewell B PWR all operated by EDF Generation
- **New build Generation III+** light-water reactors such as EDF’s Hinkley Point project and Horizon’s ABWRs (now “paused”)
- **SMRs** using contemporary light-water technology
- **Advanced** or Generation IV nuclear reactors

Initial Road-testing Of ETI NCD Data In ESME 4.4

Nuclear Technology	Context	Assumptions	ESME 4.4 Dataset	NCD Data Road Test
Legacy	EDF's existing reactor fleet	All currently scheduled to be shut down by 2035	Undeclared additional life extensions realised	No change
Contemporary Gen III+ projects	18 GWe new nuclear projects at various stages	Grid connections from 2025 onwards connecting 1.4 GWe/per year	Earlier DECC report and data on future cost of generation	Updated but conservative cost data
Light-water small modular reactors	Multiple studies; referenced in sector deal	Deployment not before 2030. Capable of power plus low grade heat for DH	From ETI alternative nuclear technologies project	Updated cost data
Advanced Nuclear Gen IV	Improved safety and proliferation resistance	Costs greater than Gen III+ & deployable from 2040	Costs greater than Gen III+	Cost and first deployment data for HTGR "Genre". 2035 deployment

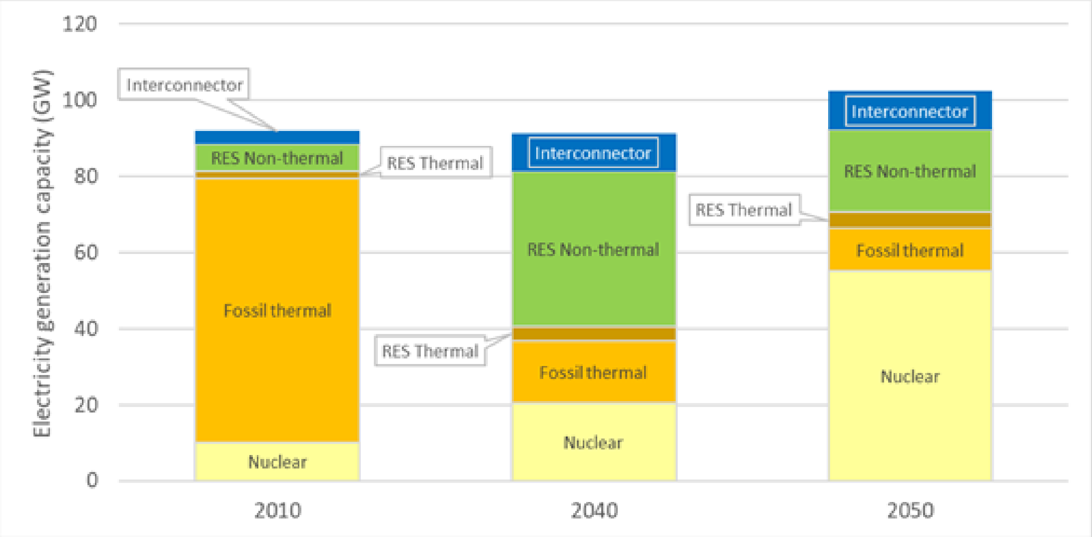
Derivation of updated Gen III+ cost data





Cost reduction curve grossly pessimistic; more work is required focussed on UK context and cost base

Results from initial road testing of ETI NCD data in ESME 4.4 sensitivity analysis



Caveats

- Deterministic analysis (non Monte Carlo)
- Inconsistent treatment of costs
- Advanced reactor offering limited to electricity generation only
- Avoid using the hard number (55 GWe) for 2050 nuclear capacity because of the collection of uncertainties in the limited sensitivity analysis

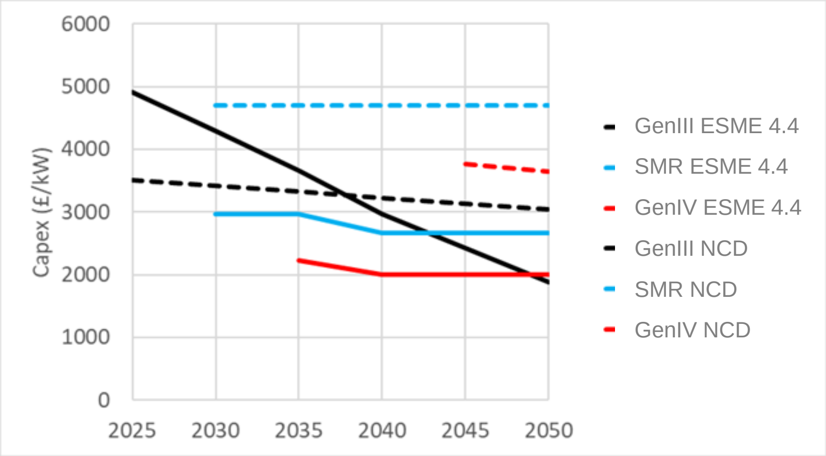
Observations

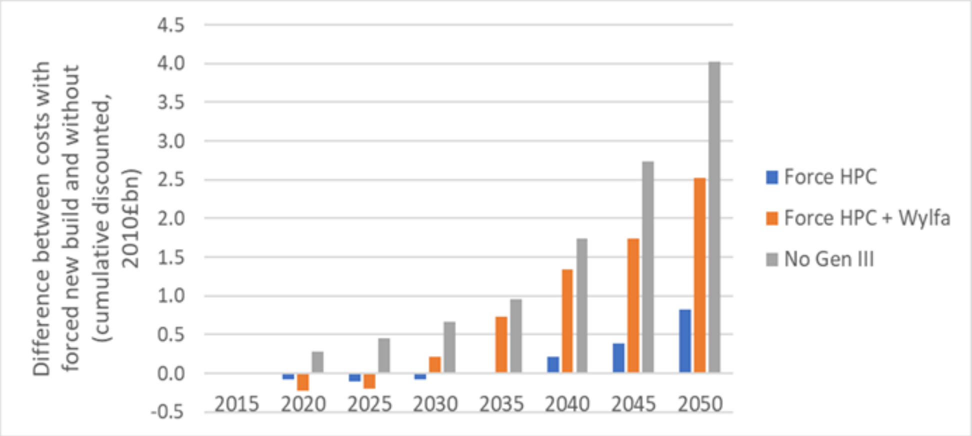
- ESME 4.4 Patchwork Scenario 2018 – nuclear limited to 8 Gwe
- ESME 4.4 Clockwork Scenario 2018 – legacy plus 16 GWe Gen III+ plus some SMRs

Conclusion

- Nuclear remains important in the mix in this sensitivity analysis. What has changed within the analysis?

What has changed in the analysis? Nuclear cost drivers data In ESME 4.4





- ESME technology overnight costs captured in 2010 pounds with universal 8% cost of capital
- Initial Gen III+ costs are now much higher but with much greater subsequent learner rate:
  - The high early costs with "forcing in" the first 2 plants still produce net system benefit
- SMR costs have fallen
- Gen IV (High Temperature Gas Reactor) costs have dropped and availability advanced

Learning from initial road testing of ETI NCD data in ESME 4.4 sensitivity analysis

Although the detailed numbers have changed from ETI Insight 1 (2015):

- There is a substantial potential role for large Gen III+ reactors connecting from 2025 until at least 2035, if delivered in the right way

- There is a further potential role for advanced technologies (SMRs and/or AMRs) deployed in numbers from 2035, if delivered in right way:

What matters is not what you build but how you build it

A UK energy system with high levels or intermittent renewables requires solutions providing:

- Power
- Heat (and hydrogen but not tested in ESME 4.4 sensitivity)
- Flexibility

Realisation of benefits from innovation applied to nuclear energy production

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Design optimisation for nuclear products large Gen III+ and SMRs for electricity generation

Design optimisation maximising productivity of direct labour and indirect services in product delivery

Improved delivery

Large reactors:

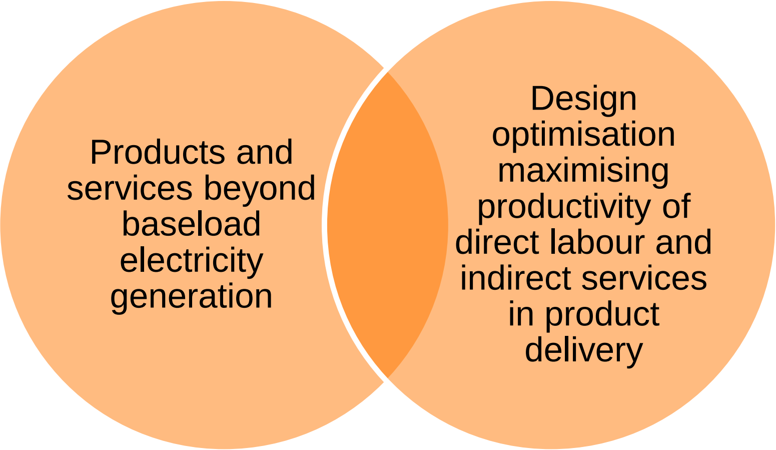
- Programmatic learning
- Site based module construction
- Digital design tools and construction records

SMR in addition:

- Factory based manufacture and module assembly
- New manufacturing techniques

Design optimisation for nuclear products - roles beyond baseload electricity production

Improve economics and grow potential market access and volume



Beyond traditional generation of baseload electricity:

- Flexible power
- Heat supply
- Hydrogen production
- Off-grid applications
- Air cooling options
- Isotope production
- Radioactive waste destruction

Large reactors:

- Programmatic learning
- Site based module construction
- Digital design tools and construction records

SMR/AMR in addition:

- Factory based manufacture and module assembly
- New manufacturing techniques

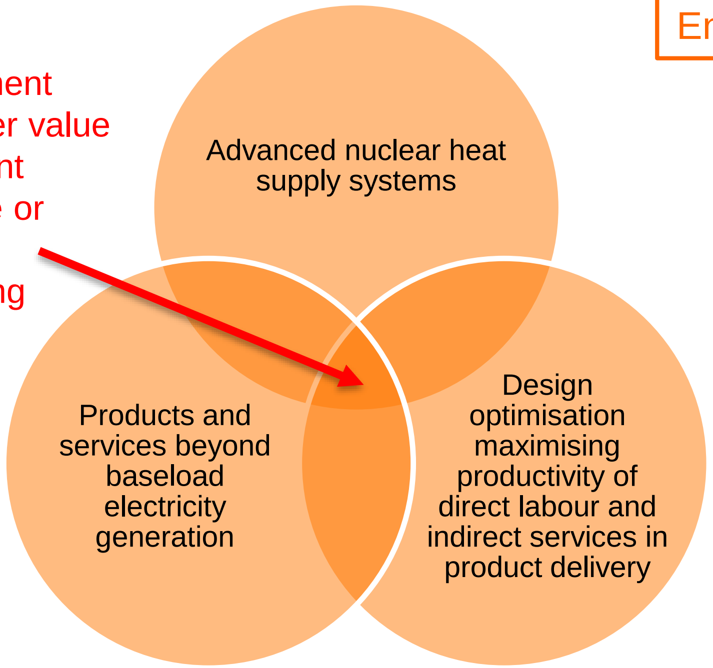
Design optimisation for nuclear products

Maximum economic value:

- Attractive designs for development
- Projects which deliver consumer value and attract developer investment
- Economic growth through more or better jobs
- Sustainable growth by accessing markets beyond the UK

Beyond baseload electricity:

- Flexible power
- Heat supply
- Hydrogen production
- Off-grid applications
- Air cooling options
- Isotope production
- Radioactive waste destruction



Enabling transformational costs

- HTGR
- Liquid metal cooled
- Molten salt
- Modular fusion

Large reactors:

- Programmatic learning
- Site based module construction
- Digital design tools and construction records

SMR/AMR in addition:

- Factory based manufacture and module assembly
- New manufacturing techniques

Suggested attributes for commercially viable advanced nuclear technologies

Transformational reduction in cost through relentless focus on design optimisation:

- Designed as products not infrastructure construction projects
- Harvest the benefits of simpler nuclear heat supply systems
  - Coolants that don't boil away and cores that don't melt in transients and accidents
- With simpler and more resilient nuclear heat supply systems
  - Minimise the scope of the plant subject to bespoke nuclear grade quality requirements
  - Maximise the scope of plant deliverable through multiple suppliers using standard specifications
- Drive out man hours required in manufacture, deployment, operation and maintenance
- Electricity is expected to be the most important market but attractiveness within the local or national energy systems will also be important to drive favourable developer economics and unit volume
  - Cogeneration with heat or hydrogen; flexibility to be compatible with intermittent renewables
  - Operable with a range of cooling systems/heat sinks to maximise deployment opportunities
  - Higher operating temperature of future nuclear technologies is a key enabler

- The development of advanced nuclear heat supply systems is an enabler not an outcome
- Success lies in design optimisation with modern deployment methods to drive out cost

Next steps

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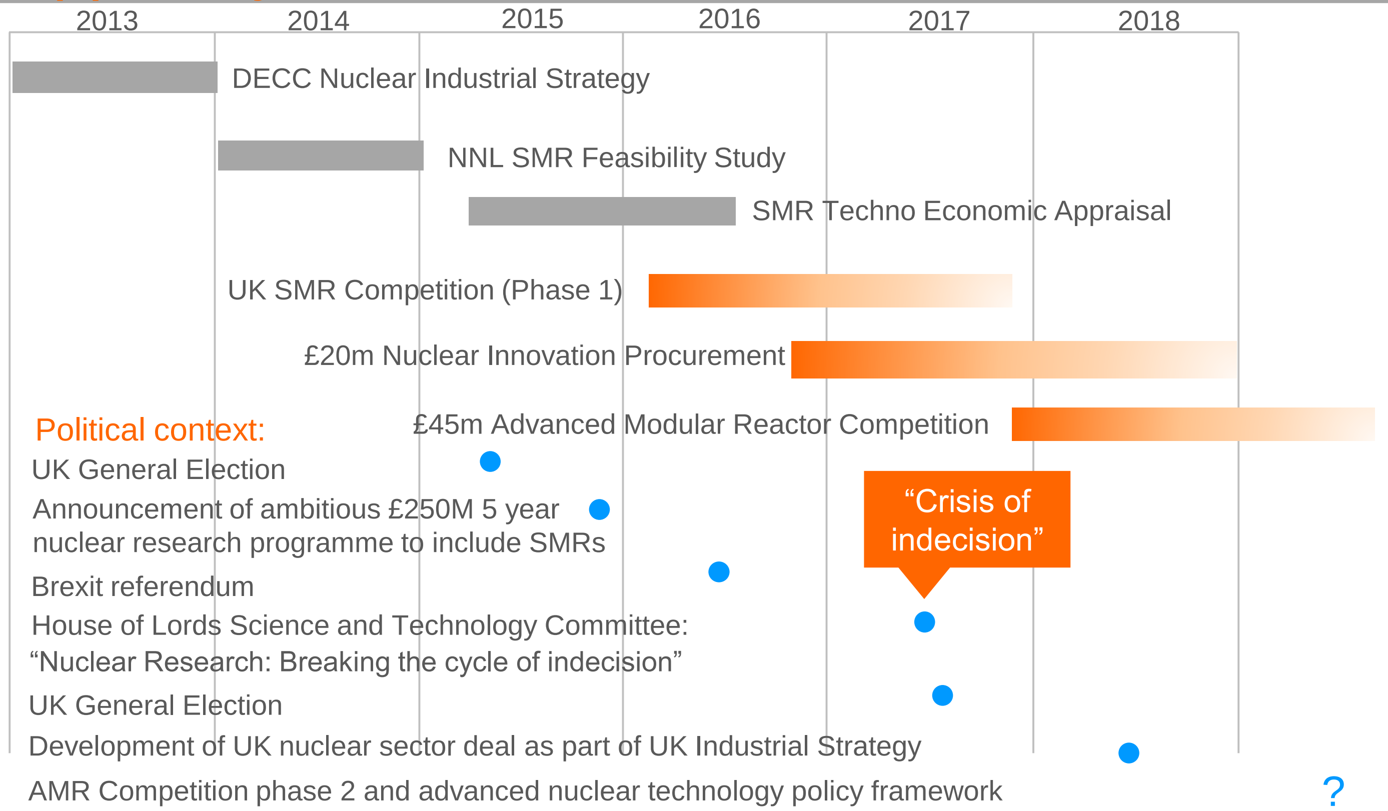
Some aspects of nuclear innovation support by Government since 2013



Opportunities for UK nuclear policy development

- Better understanding of the UK cost reduction trajectory of large Gen III+
- Better understanding of a range of UK Government policy options and their potential impact on this cost reduction trajectory
- Framing the policy and opportunity for SMRs or AMRs to help successfully drive UK industrial strategy and clean growth
- Continued analysis at the whole energy system level:
    - Reflecting continuing innovation and cost reduction
    - Beyond 80% GHG abatement towards carbon neutral
    - Triple optimisation of cost reduction, carbon abatement and clean air

Conclusions

- Introduction to the ETI
- Decarbonising the UKs economy
- Recap from previous publications October 2015 and September 2016
- Changes in UK nuclear context since 2015
- The ETI’s nuclear cost drivers project
- Value of nuclear energy in a UK integrated energy system
- Realisation of benefits from innovation applied to nuclear energy
- Next steps
- Conclusions

Conclusions

Large contemporary Gen III+ reactors to be operating in the UK from 2025:

- can be cost effective for UK baseload electricity generation if delivered in the right way
- evidence demonstrates that a programmatic approach rooted in project performance improvement and cost reduction successfully reduces project schedule, cost and risk
- the right policy framework is required to realise these benefits in the UK
- more work needed to better understand the UK cost base and potential Gen III+ cost reduction curve

Light-water SMRs could be developed to be operating in the UK from around 2030:

- may be lower cost and more investible as projects compared with large contemporary Gen III+ reactors which are either FOAK or not executed within a programmatic approach
- economics can be enhanced through cogeneration for district heating or desalination

Advanced Modular Reactors (with potential for some technologies to be operating in the UK from 2035):

- have potential to be cost transformational
- electricity generation still important, but system need for flexibility alongside low carbon heat & hydrogen
- successful designs are expected to have a total focus on optimisation to reduce costs; future cost uncertainty prevails because designs which deliver this are yet to come to market

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