Nuclear Cogeneration: Workshop

25th September 2019

THE ROYAL SOCIETY

Welcome

Dame Sue Ion FREng FRS

Chair of Royal Society Science, Industry and Translation Committee

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Royal Society
Low carbon energy programme

The programme aims to consider how transformational science and technology can help the UK move to a low carbon future, whilst pursuing an active industrial strategy that creates growth and jobs in the short and medium term.

Comprises of short projects encompassing

- Workshops
- Policy briefing reports

Providing a rapid and authoritative synthesis of the current evidence for use by government, Parliament and stakeholders.

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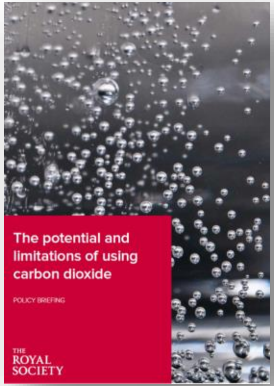
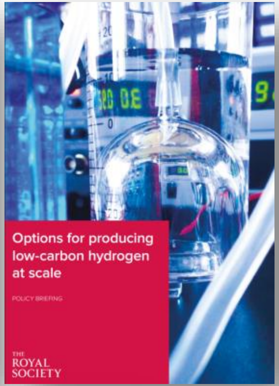
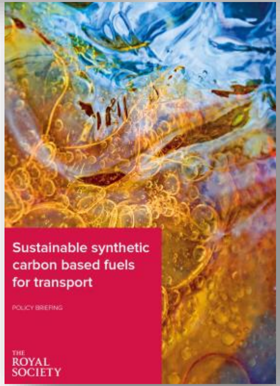
Projects







1. Battery storage workshop
2. Policy briefing on ***The potential and limitations of using carbon dioxide***
3. Policy briefing on ***Options for producing low-carbon hydrogen at scale***
4. Policy briefing on ***Sustainable synthetic carbon based fuels for transport***
5. Policy briefing on green ammonia – due December
6. Policy briefing on nuclear cogeneration – due January

Reports available at

https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme

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Royal Society Policy Briefing: Nuclear Cogeneration

Professor Robin Grimes FREng FRS
Project Chair
Imperial College London

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Agenda

09:30	**Coffee and Registration**	
10:00	**Introductions**	
	Welcome and introduction to the Royal Society's low carbon energy programme	Professor Sue Ion DBE FREng FRS, Chair of Royal Society Science, Industry and Translation Committee
10.10	Nuclear Cogeneration – the purpose, scope and aims of the workshop	Professor Robin Grimes FREng FRS, Chair of the Royal Society Nuclear Cogeneration Project
10.25	UK's pathway to net-zero by 2050, Committee on Climate Change	Baroness Brown of Cambridge FREng FRS
10.40	Nuclear in the UK (future?) including current view on cogeneration	Craig Lester, Deputy Director, Department for Business, Energy and Industrial Strategy
11.00	**Applications for nuclear cogeneration**	**Chairman Bill Lee**
	Introduction to cogeneration including use for Medical Isotopes and desalination	Professor Bill Lee FREng, Imperial College London
	Hydrogen production	Alan Woods, Rolls Royce
	Combined heat and power including district heating	Sam Friggens, Mott MacDonald
	Thermal energy storage	Professor Phil Eames, Loughborough University
	Thermal process heating	Mark Brennan, former Cavendish Nuclear
12.15	**LUNCH**	

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12.15	**LUNCH**	
13.00	**Break out session 1 - Nuclear cogeneration today**	
	• Have we missed any technologies? • Which technologies are most relevant to the nuclear power in the UK now and which in the future? • Where is nuclear cogeneration in operation around the world? • Where the expertise in the world is and what expertise does the UK possess?	Attendees discuss within six pre-allocated groups.
13.50	Feedback from breakout groups and discussion	Chair: Kirsty Gogan, Energy for Humanity
14.20	**TEA BREAK**	
14:30	**Break out session 2 - The future of nuclear cogeneration**	
	• What are the main technical and regulatory barriers to cogeneration systems? • What are the economic and socioeconomic considerations? • What are the main research needs? • What does the UK need to do to develop the skills necessary to implement nuclear cogeneration? • What are the practical timescales for implementing nuclear cogeneration?	Attendees discuss within six pre-allocated groups
15.20	Feedback from breakout groups and discussion	Chair: Craig Lester, BEIS
15.50	**Closing remarks**	**Professor Robin Grimes FREng FRS** **Professor Sue Ion DBE FREng FRS**
16:00	**Close**	

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The path to Net Zero

Baroness Brown of Cambridge FREng FRS
Committee on Climate Change

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Committee on Climate Change

25th September 2019

The path to Net Zero

The UK's contribution to stopping global warming

Julia Brown, Vice Chair of the Committee on Climate Change

Committee on Climate Change

Net Zero Report: summary recommendations

- **The UK should legislate as soon as possible to reach net-zero greenhouse gas emissions by 2050**. The target can be legislated as a 100% reduction in greenhouse gases (GHGs) from 1990 using the existing Climate Change Act procedures.
- The target should cover **all sectors of the economy, including international aviation and shipping**.
- The aim should be to meet the target **through UK domestic effort**, without relying on international carbon units (or 'credits').
- Now is the right time to set a net zero target. It is **technically possible, based on current consumer behaviours and known technologies**, with prudent assumptions over cost reduction.
- **An earlier date should not be set at this stage**. Some sectors could reach net zero earlier, but for most sectors 2050 appears to be the earliest credible date, to give time to develop speculative options as alternatives for any shortfalls. Avoiding the need for early capital scrappage or punitive policies.
- **The target is an appropriate contribution to the Paris Agreement**. The UK can benefit from the international influence of setting a bolder target, using it as an opportunity for further positive international collaboration.
- **Wales should set a target for a 95% reduction in emissions by 2050 relative to 1990.** Wales has less opportunity for CO_2 storage and relatively high agricultural emissions that are hard to reduce. On current understanding it could not credibly reach net-zero GHGs by 2050.
- **Scotland should aim for net-zero greenhouse gas emissions by 2045.** Scotland has proportionately greater potential for emissions removal than the UK overall and can credibly adopt a more ambitious target. Interim targets should be set for Scottish emissions reductions (relative to 1990) of 70% by 2030 and 90% by 2040.

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Summary recommendations

- **Net zero target is only credible if policy to reduce emissions ramps up significantly**
  - The target can only be delivered with a strengthening of policy to deliver emissions reductions across all levels and departments of government. This will require strong leadership at the heart of Government. Delivery must progress with far greater urgency.
  - Policies must be designed with businesses and consumers in mind. They must be stable, long-term and investable. The public must be engaged, and other key barriers such as low availability of necessary skills must be addressed.
  - Report emphasises previous CCC recommendations for: Heating buildings; CCS; Electric vehicles; Agriculture; Waste; Low Carbon Power.
  - With new recommendations for stronger approaches to: Industry; land use; HGVs; aviation and shipping; and GHG removals.
- **Overall costs are manageable, but must be fairly distributed.** Rapid cost reductions during mass deployment for key technologies mean that net zero can be met an annual resource cost of up to 1-2% of GDP to 2050, the same cost as the previous expectation for an 80% reduction from 1990.
- **HM Treasury should undertake a review of how the transition will be funded and where the costs will fall**. It should develop a strategy to ensure this is, and is perceived to be, fair. A broader strategy will also be needed to ensure a '**just transition'** across society, with vulnerable workers and consumers protected.

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Reaching net-zero emissions in the UK
How UK net-zero scenarios can be delivered

	2020s	2030s	2040s
Electricity	Largely decarbonise electricity: renewables, flexibility, coal phase-out	Expand electricity system, decarbonise mid-merit/peak generation (e.g. using hydrogen), deploy bioenergy with CCS	
Hydrogen	Start large-scale hydrogen production with CCS	Widespread deployment in industry, use in back-up electricity generation, heavier vehicles (e.g. HGVs, trains) and potentially heating on the coldest days	
Buildings	Efficiency, heat networks, heat pumps (new-build, off-gas, hybrids)	Widespread electrification, expand heat networks, gas grids potentially switch to hydrogen	
Road Transport	Ramp up EV market, decisions on HGVs	Turn over fleets to zero-emission vehicles, cars & vans before HGVs	
Industry	Initial CCS clusters, energy & resource efficiency	Further CCS, widespread use of hydrogen, some electrification	
Land Use	Afforestation, peatland restoration		
Agriculture	Healthier diets, reduced food waste, tree growing and efficiency on farms		

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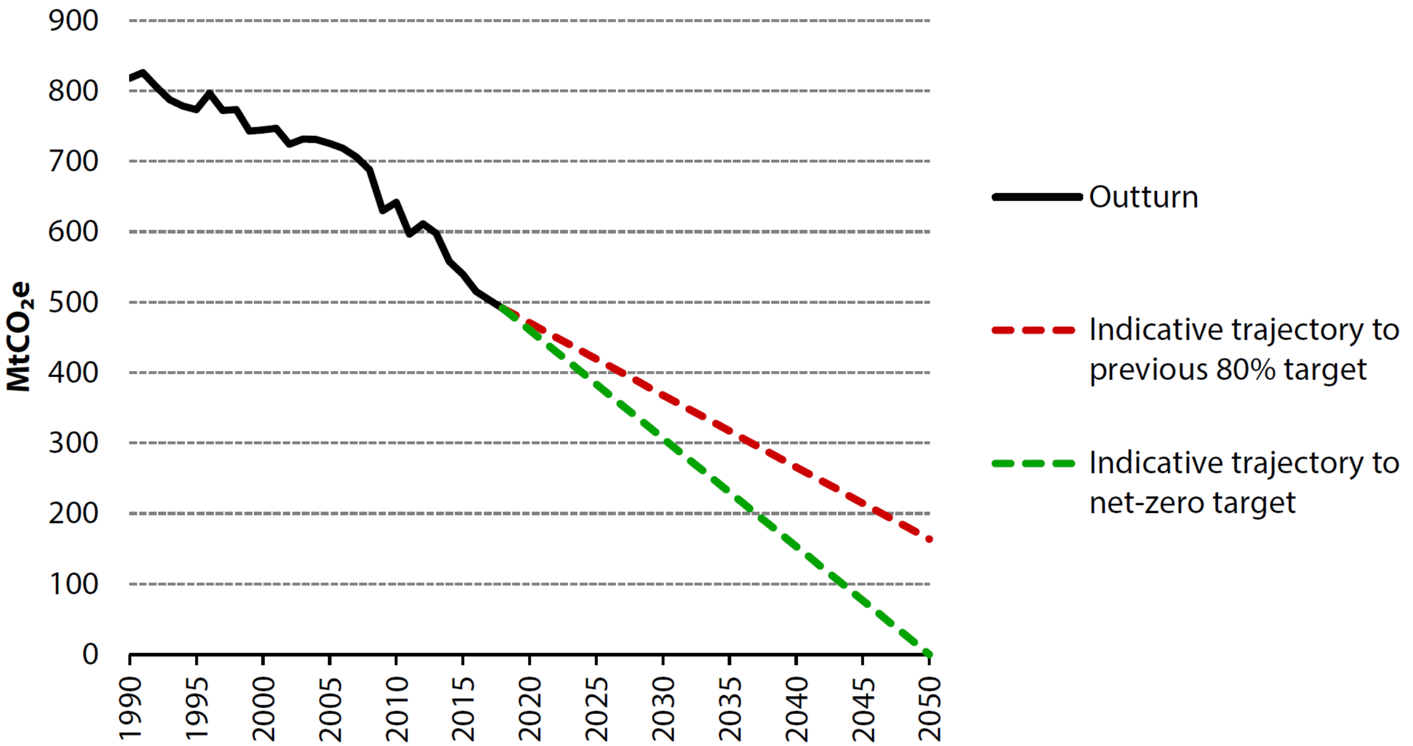
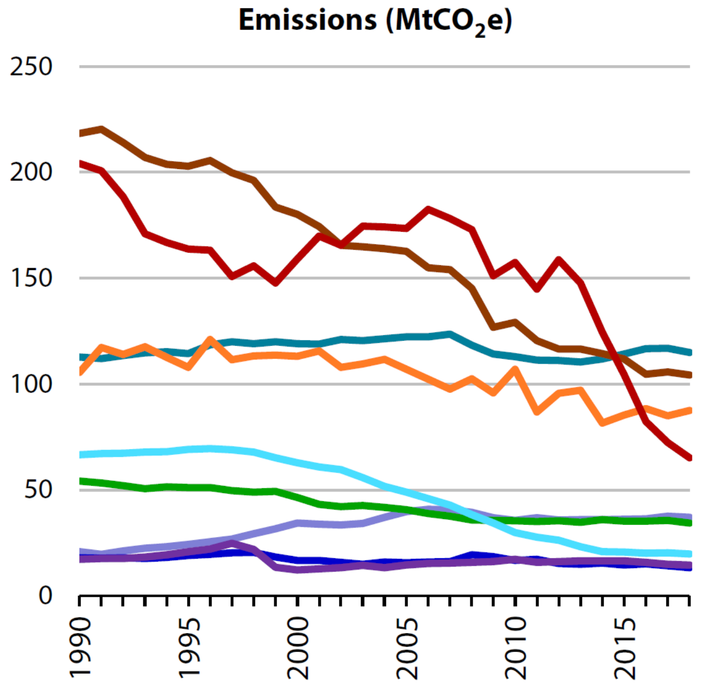
Reaching net-zero emissions in the UK
How UK net-zero scenarios can be delivered

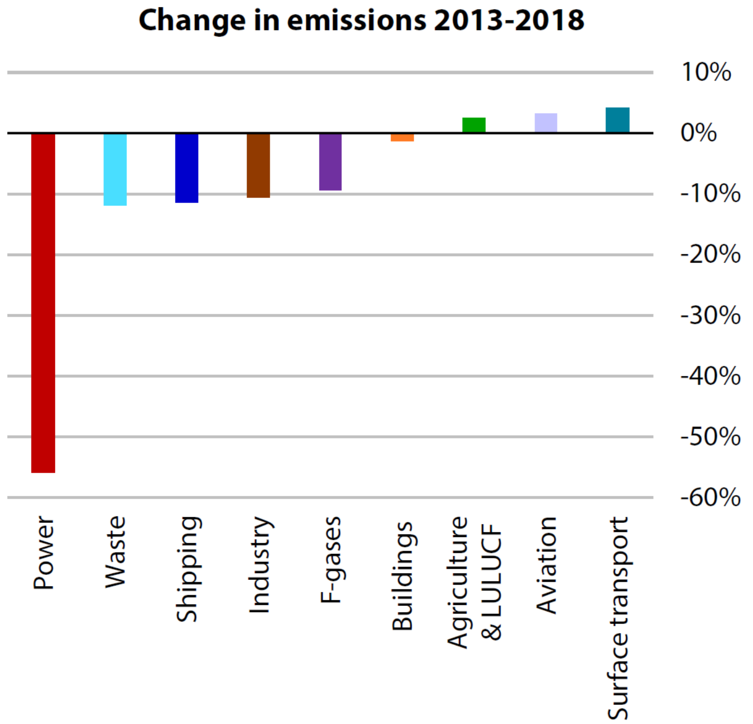
	2020s	2030s	2040s
Aviation	Operational measures, new plane efficiency, constrained demand growth, limited sustainable biofuels		
Shipping	Operational measures, new ship fuel efficiency, use of ammonia		
Waste	Reduce waste, landfill ban for biodegradable waste	Limit emissions from combustion of non-bio wastes (e.g. some use of CCS)	
F-Gases	Move almost completely away from F-gases		
Removals	Develop options & policy framework	Deployment of BECCS in various forms, demonstrate direct air capture of CO_2, other removals depending on progress	
Infra-structure	Industrial CCS clusters, decisions on gas grid & HGV infrastructure, expand vehicle charging & electricity grids	Hydrogen supply for industry & potentially buildings, roll-out of infrastructure for hydrogen/electric HGVs, more CCS infrastructure, electricity network expansion	
Co-benefits	Health benefits due to improved air quality, healthier diets and more walking & cycling Clean growth and industrial opportunities		

27th June 2019 legislated change from 80% to 100%



The journey so far





The impact of innovation on the costs of achieving carbon targets

Innovation and falling technology costs mean that the UK's 80% emissions target could be met at a lower cost than estimated in 2008 – under 1% of GDP in 2050, rather than 1-2% of GDP.

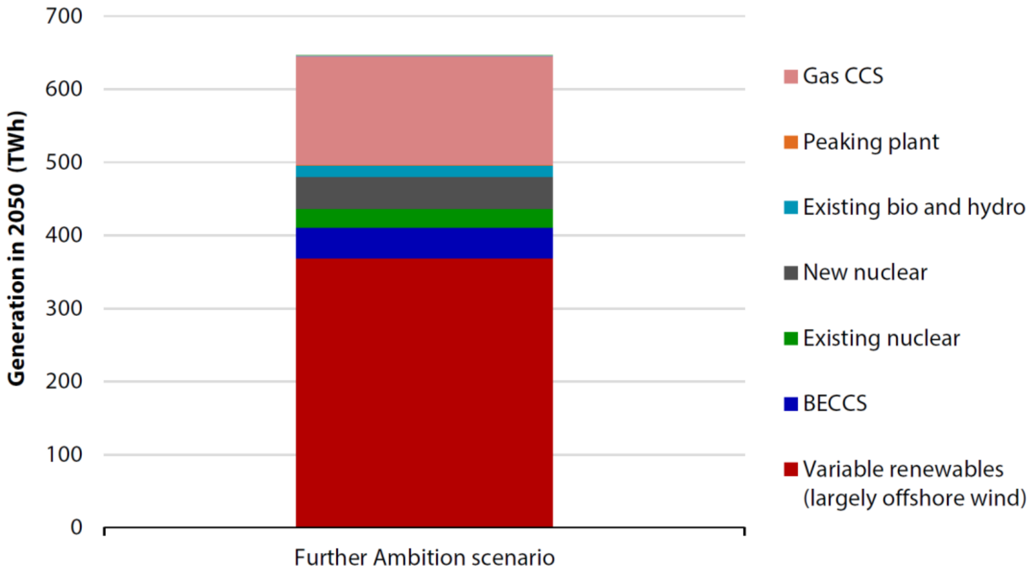
Changes in cost estimates for long-term emissions goals

GHG emissions reduction target (relative to 1990)	Year and report	Cost range estimated for 2050
60% reduction in CO_2 (~55% reduction in GHG)	2003 - *Energy White Paper*	0.5-2.0% of GDP
80% reduction in GHG	2008 - *Building a low-carbon economy – the UK's contribution to tackling climate change*	1-2% of GDP
100% reduction in GHG	**2019 – Net Zero Report**	**1-2% of GDP**

Assumed costs and cost reductions

Technology	Cost in 2025	Cost in 2050	Percentage cost reduction
Power generation		<40 (£/MWh)?	>42%?
Offshore wind	69 (£/MWh)	~~51 (£/MWh)~~	26%
Solar PV	47 (£/MWh)	41 (£/MWh)	13%
Nuclear	98 (£/MWh)	71 (£/MWh)	28%
Gas CCS	79 (£/MWh)	79 (£/MWh)	0%

Illustrative Net Zero power scenario



Source: CCC analysis based on the capacity and generation mix in the "Hybrid 10 Mt" scenario of Imperial College (2018) *Analysis of alternative heat decarbonisation pathways.*

Notes: The role of gas CCS in providing firm power is illustrative and could be replaced by nuclear power or alternative renewable technologies, reducing residual emissions.

How big? In the next 30 years...

- Electricity system x2 to x4
- Offshore wind 10 GW to 75+GW
- Hydrogen production 27TWh to 350TWh
- CCS 0 to 180 Mt CO_2
- Afforestation 10,000 to 50,000 hectares pa
- 29 million existing homes installed with low carbon heat
- Major changes in agriculture and land use
- Zero carbon new car registrations from 2.5% to 100% by 2030

All at the same time

Issues for nuclear

- Cost vs current alternatives
  - Offshore wind

- Cost vs future developments
  - Offshore wind + hydrogen
  - Gas CCS
  - Tidal current

Nuclear in the UK

Craig Lester
Dept. for Business, Energy & Industrial Strategy

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UK Nuclear and Co-generation: Policy Perspectives Craig Lester

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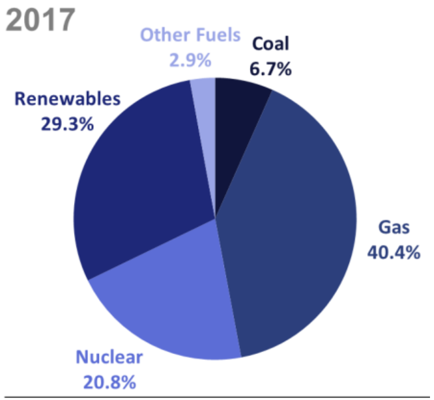
UK Nuclear Landscape

- Powering homes and businesses for over 60 years
- 20% of the UK's electricity needs
- **40% of UK low-carbon electricity**
- Low-carbon, secure and reliable base-load power
- Reduction in UK's CO2 emissions – Net Zero
- Diversifying local economies
- Steady public/cross party support

UK Energy Mix

- Net Zero means "more of everything" (including CCUS for Gas)
- Need to meet much higher electricity demand as we decarbonise energy, transport and heat
- Need to go "beyond the grid" into industrial process and hydrogen production/use
- VfM important – but will be a range of costs (not just cheapest)

Shares of electricity generation by fuel



Source: DUKES

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UK Clean Growth Strategy

Not just about decarbonisation – also about economic growth

Some key policies:

- Accelerate clean growth – develop world leading **Green Finance** capabilities.
- Accelerating the shift to low carbon **transport**.
- Rolling out low carbon **heating** - phase out the installation of high carbon fossil fuel heating in new and existing homes.

= Delivering clean, smart, flexible power.

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Why Nuclear?

- Currently provides around 40% of UK's low carbon electricity
- Reliable baseload power complements the growing renewable portfolio
- UK Nuclear sector is an economic powerhouse currently equivalent in scale to the aerospace manufacturing industry
- Provides highly-skilled, long-term employment for 87,000 people and is a driver of regional growth
- **Scope for co-generation** (and other positive uses)

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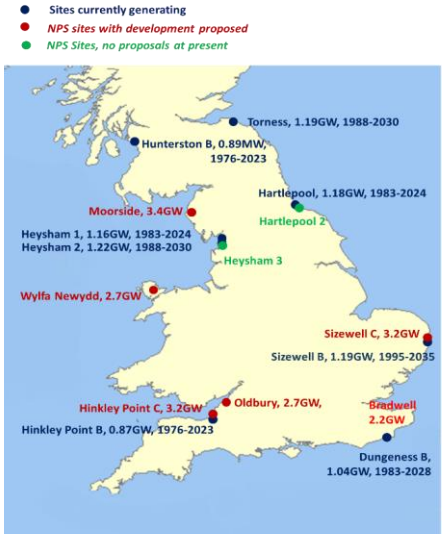
How Much Nuclear?

- Current 40% of UK’s low carbon electricity is reducing both in absolute terms and as a % as reactors retire and demand grows
- **Scenarios of 15-50GWe, not including co-generation**
- No GWth estimates
- But assumes more hydrogen



Principles for New Nuclear: Sustainability

- Nuclear has an important, *complementary* role to play in the UK's energy future as we transition to a low carbon economy
- Emphasis on value for money for consumers and taxpayers – 30% cost reduction in new build by 2030
- The Government looking at alternative funding models to finance large-scale new nuclear projects to reduce the costs of capital and therefore costs to consumers.
- Consulting on the Regulated Asset Base (RAB) model as a sustainable funding model that can attract significant investment for new nuclear projects.
- Sustainable funding mechanisms are key.

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Nuclear Pipeline 1#

- Hinkley Point C
- Sizewell C
- Bradwell B

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Nuclear Pipeline 2#

- Wylfa?
- Moorside?
- Oldbury
- Hartlepool
- Heysham

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Nuclear Pipeline 3# ??

- Trawsfynydd?
- Sellafield?
- NDA land?
- MoD land?
- Coal power stations?
- Industrial sites?

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What next?

1950s - Present

1st to 3rd Generation nuclear reactors

2030s

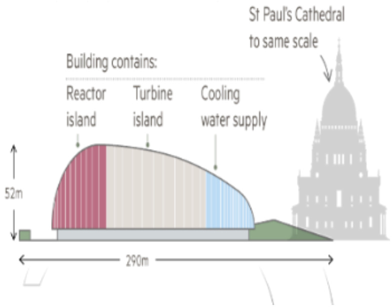
Small Modular Reactors (SMRs)

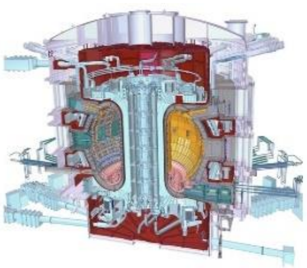
2040s

Advanced Modular Reactors (AMRs)

2050s +

Nuclear Fusion





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Nuclear Pipeline 4#

- Small Modular Reactors – enabling framework, ISCF
- Advanced Modular Reactors – AMR competition
- Fusion - platform
- Advanced Manufacturing & Construction programme:
  - digital engineering execution & assurance
  - modular & advanced construction

Innovation (1)

- **Provides up to £56 million** for R&D for advanced nuclear reactors to develop feasibility and detailed studies
- **Provides £86 million** for a National Fusion Technology Platform at UK Atomic Energy Authority's Science Centre in Oxfordshire – UK looking to compete for £1bn of international contracts for fusion technologies
- UK an active member of the **Generation IV forum** to explore areas of mutual interest and international collaboration in the development of next generation of nuclear reactors

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Innovation (2)

- Setting out a new framework to support the development and deployment of **Small Modular Reactors (SMRs)** in the UK & innovative technologies that support them
- Developing policy for siting SMRs and supporting the upskilling of UK regulators
- **Innovation key to driving export growth:** UK government will work with civil nuclear sector to develop co-ordinated global campaign for promoting the UK's nuclear expertise overseas to maximise future export orders across the nuclear life cycle

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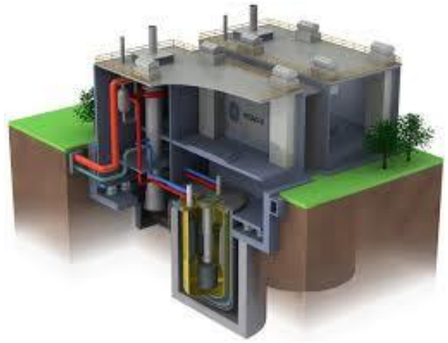
Co-generation possibilities/speakers

a) Process heat
b) Hydrogen production
c) District heating
d) Thermal Energy Storage
e) Seawater desalination
f) Medical isotopes



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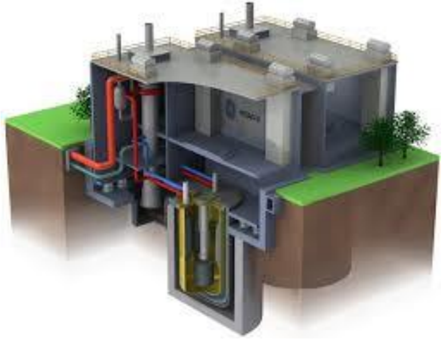
Co-generation possibilities

- **(a) Process heat**

➢Temperature vs materials

➢Co-location risks

➢Not for oil extraction?



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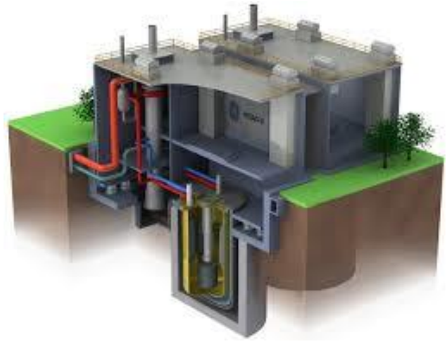
Co-generation possibilities

- **(b) Hydrogen production**

➢Production method?

➢Total carbon footprint?

➢Co-location risks



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Co-generation possibilities

- **(c) District heating**

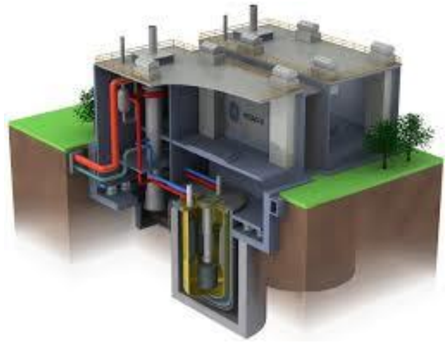
➢ Fragmentation of current DH schemes

➢ Framework/Coherent policy for long term future

➢ Regulation

➢ Balancing Stakeholder needs (Users, Investors, Value chain)

➢ Costs



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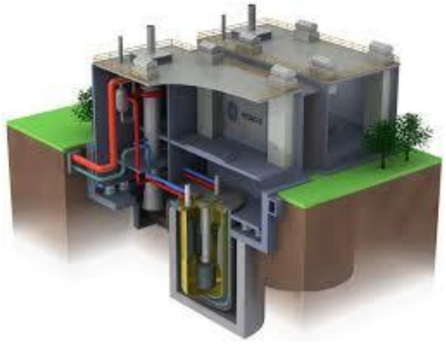
Co-generation possibilities

- **(d) Thermal Energy Storage**
  - Maximises SMR/AMR commercial case
  - Lessons from Solar
  - Where is the further work?
  - Getting beyond “batteries”



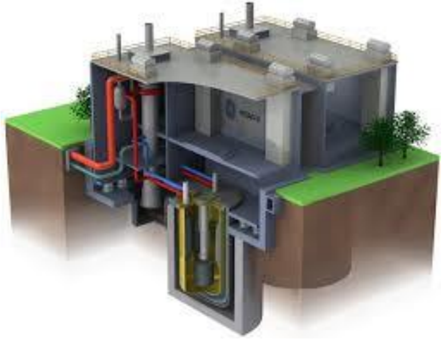
Co-generation possibilities

- **(e) Seawater desalination**

➢The next crisis…water?

➢What price water?

➢Export or Aid?



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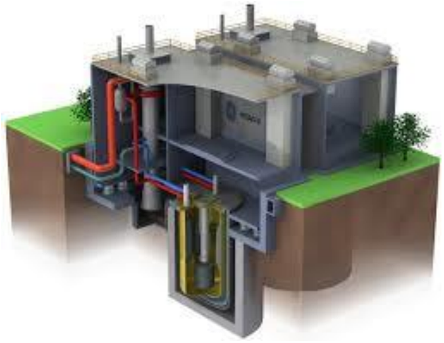
Co-generation possibilities

- **(f) Medical isotopes**
  - Growing demand/innovation
  - Unfinished business from 2008 shortage
  - Live issue – BREXIT and beyond, ageing reactors
  - UK Make or buy?



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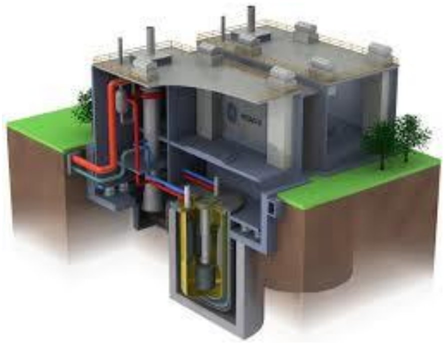
More Co-generation possibilities

- **(g) Waste treatment?**
  - Shorter, easier storage/disposition?
  - Recycling not reprocessing?
  - “Nuclear will eat itself”



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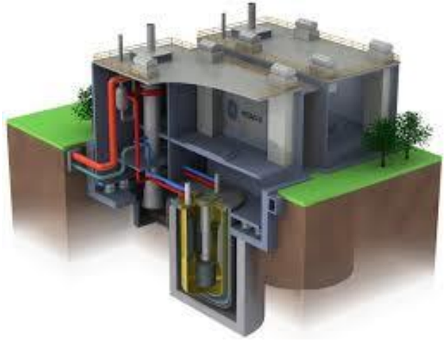
Even More Co-generation possibilities

- **(i) Hydrocarbons?**
  - Another process heat idea
  - Feedstock not fuel?
  - Products eg carbon fibre
  - Transition for communities



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Introduction to Nuclear Cogeneration

Professor Bill Lee FREng
Imperial College London

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Undeb Ewropeaidd
European Union

Llywodraeth Cymru
Welsh Government

Cronfa Datblygu Rhanbarthol Ewrop
European Regional Development Fund

Prifysgol Bangor University

HISTORICAL NUCLEAR CO-GENERATION.

"WE'VE BEEN THERE BEFORE"

Bill Lee FREng, Michael Rushton,
Simon Middleburgh and Tim Tinsley*

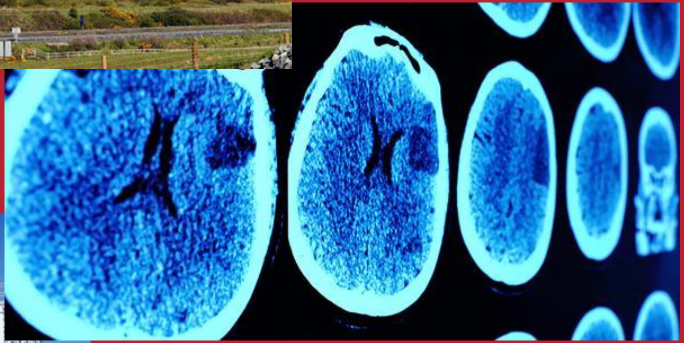
Nuclear Futures Institute, Bangor University

*National Nuclear Laboratory, Central Laboratory, Sellafield.

Sept 25th 2019

Outline

- What is Co-generation?
- Historical case studies
  - Anglesey Aluminium
  - Calder Hall and Chapelcross
  - Nuclear Steelmaking
  - Lessons learned.
- Medical Isotopes
- Waste
- Desalination
- Conclusions



"Atoms for peace"
Atoms for survival

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Nuclear Co-generation.

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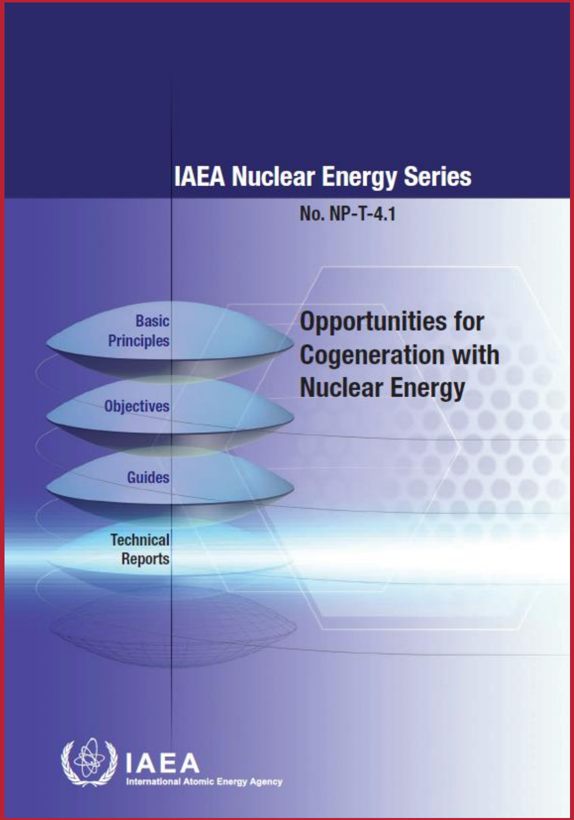
- Defined by IAEA (2017) as "integration of nuclear power plants with other systems and applications. The heat generated by the NPP can be used to produce a range of products such as cooling, heating, process heat, desalination and hydrogen."
- But just using the heat generated ignores using the radiation e.g. for medical isotope production.
- Options available depend on reactor type e.g. hydrogen production needs >800ºC so limited to High Temp Gas Reactors (HTGR) or fusion.



Historical Example: Atomic Smelters 1971-2009.

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- **Al production from bauxite ore is energy intensive (10-15 MWh/t Al).**
- **Wilson Government in 1960's decided to develop indigenous Al production including via "Atomic Smelters".**
- **Anglesey Al and Invergordon used nuclear from grid while Lynemouth used coal.**
  - **Invergordon closed in 1981 due to poor deal with SSEB, electricity price too high.**
  - **Anglesey Al ran successfully due to good deal with CEGB but closed in 2009 when NDA ran Wylfa (Magnox) reactor and were unable to supply electricity at reduced rates.**
  - **Lynemouth closed in 2012 due to the European Union's emissions rules under the Large Combustion Plant Directive.**
- **A hydro-electricity powered smelter at Loch-Aber in Scotland has been working since 1929 and is still operating.**

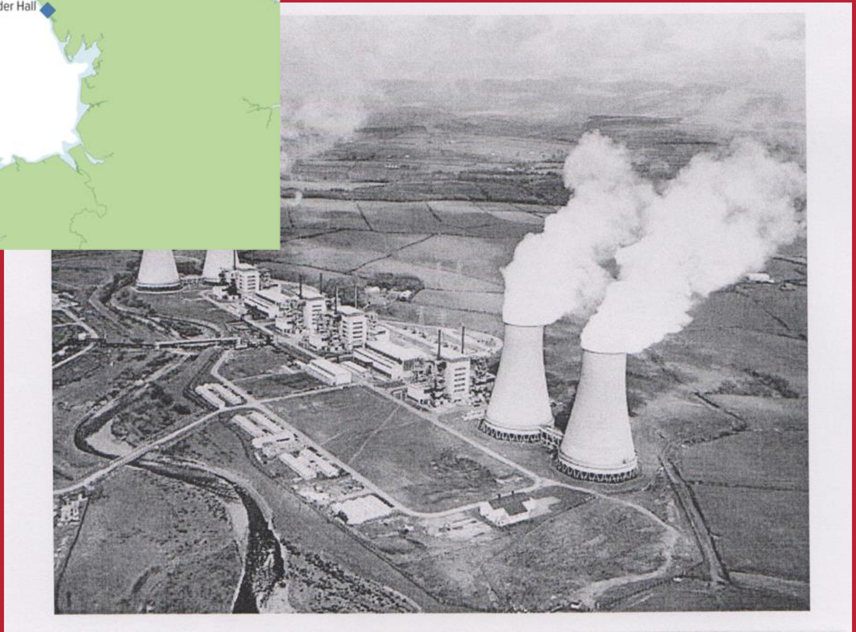
Lessons Learned from Al Co-generation 1971-2009.

Anglesey Al Smelter prior to closure, 400 employees and 100,000t/annum production

Al requires ~10-15 MWh/t Al (therefore Combined Cycle Gas Turbine produces >5t CO_2 per 1t of Al)

- Government, energy supplier and energy intensive user industry need to work together and have clear technical and business plan at outset.
- Spin-off benefits of geographical co-location and cogeneration e.g.
  - If grid fails smelter provides a large continuous load allowing NPP and smelter to avoid shutting down
  - Decouples need to do smelting in mountainous areas where there is HEP, can put the smelters near to demand.

Historical Example: Co-generation at Calder Hall, Sellafield (1956-2003) and Chapelcross, Dumfriesshire (1959-2004).



Fully operational Calder Hall in 1960’s.

- From 1959 each site generated ~200 MWe from 2 pairs of Magnox reactors with 4 cooling towers.
- Both sites had several cogeneration functions.

Co-generation at Calder Hall.

Calder Hall at Sellafield when fully operational.

- Pu for nuclear deterrent.
- Reliable site power supply e.g. for reprocessing plant and waste cooling.
- Low and high pressure steam for reprocessing, site industrial plant and building heating.
- Radio-isotopes for medical, industrial and research applications. e.g.
  - ^{60}Co radiotherapy, pest sterilisation (agriculture), thickness gauges, weld inspection and medical equipment sterilisation.
  - ^{238}Pu, Radioisotope Thermoelectric Generators for heart pacemakers and ocean navigational buoys.
  - ^{14}C for tracer studies in organic compounds in medical and biological research.

Lessons Learned from Co-generation Experience at Calder Hall and Chapelcross.

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Ability to:

- Generate reliable electricity to directly support industrial site.
- Generate secure steam (High and Low Pressure) to directly support industrial (e.g. reprocessing) site, including heating of buildings and process steam.
- Generate electricity for commercial sale into the UK national grid.
- Produce specialist radionuclides for medical and industrial applications, e.g. ^{14}C, ^{238}Pu and ^{60}Co.
- Provide a research test reactor for the future Magnox fleet, including testing of new fuel element designs.

First power reactors in the country
were versatile and enabled native progress

Historical Example: Nuclear Steelmaking

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- Another energy intensive industry – manufacturing 1 tonne of steel consumes 20.3GJ, accounts for 17% primary industrial energy use worldwide.
- Nuclear steelmaking considered seriously in 1970's, Finniston lecture, European Nuclear Steelmaking Club (ENSEC included UK, Italy, Germany, France, Belgium, Netherlands, Luxembourg) and similar initiatives in USA, Japan.
- Need high temps. (900-1000ºC) to reduce iron oxide and to convert natural gas to reducing hydrogen and CO gases by steam reforming.
- But programmes stalled with lack of commercialisation of HTGR's.
- Ongoing R&D into use of hydrogen in steelmaking rather than CO.

Proc. R. Soc. Lond. A. **340**, 129–146 (1974)
Printed in Great Britain

THE SIXTH ROYAL SOCIETY TECHNOLOGY LECTURE

Nuclear energy for the steel industry

BY H. M. FINNISTON, F.R.S.
British Steel Corporation

(*Lecture delivered* 5 *December* 1973 – *MS. received* 2 *April* 1974)

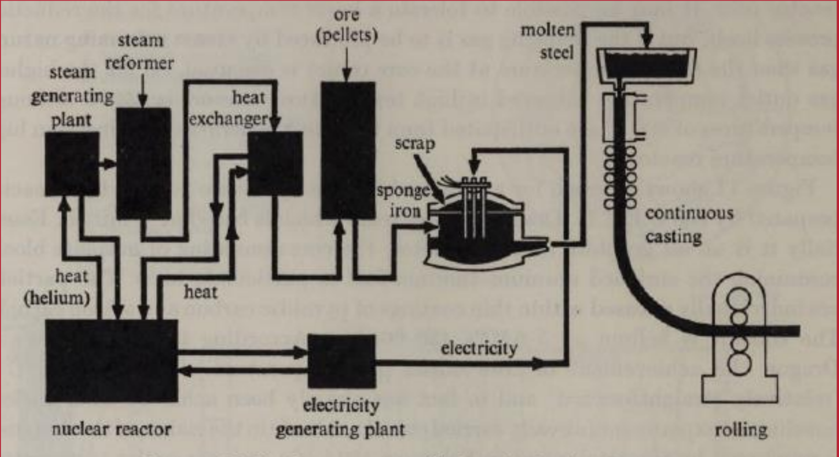

FIGURE 12. Nuclear power applied to the d.r./e.a.f. route.

Lessons Learned from Nuclear Steelmaking.

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- Energy intensive industries may need development of a particular reactor type e.g. high temperature reactors.
- Global initiatives may be needed.

Medical Isotopes

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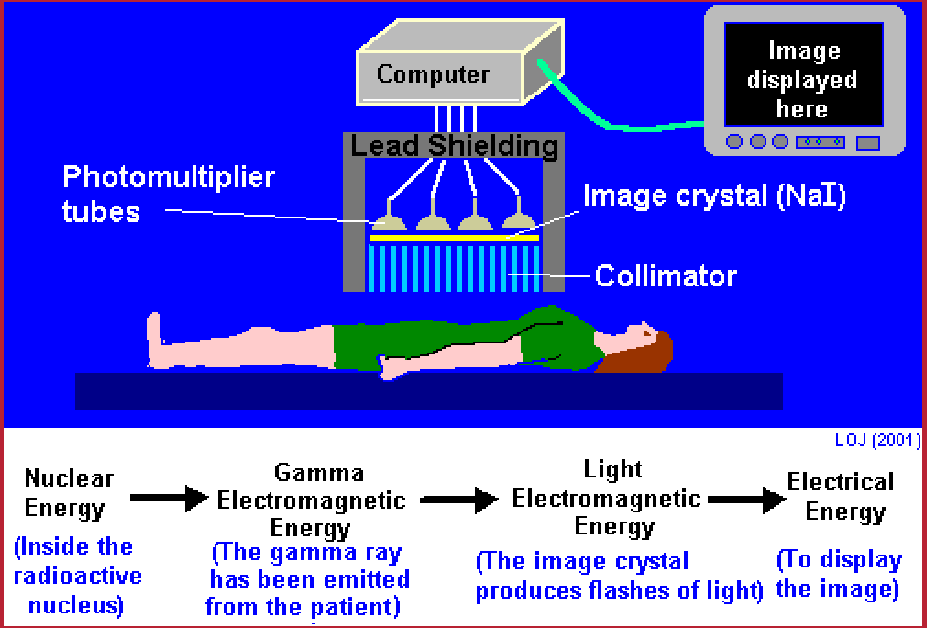
- **Nuclear medicine** defined as using radioactive isotopes for diagnosis and treatment.
- Radioisotopes attached to chemicals that have an affinity for particular organs, bones etc.
- Often inject a small amount as a tracer to follow a physiological process, find out where it goes using *emission* e.g. of γ rays.
- Differs from **radiology** where energy (X-rays, ultrasound, magnetic field) is passed through patient to interact with tissue so using *transmission*.

Radionuclide	Symbol	Physical half-life	Chemical Form	Diagnostic Use
Indium	^{111}In	67.4h	OncoScint	Colorectal or ovarian cancer
			ProstaScint	Prostate cancer
Iodine	^{123}I	13.3h	Sodium Iodide	Thyroid Function/ Imaging
Technetium	^{99m}Tc	6h	Sodium Pertechnatate	Imaging of brain, scrotum, kidneys, heart etc.
			Tetrofosmin	Cardiovascular Imaging
			IDA	Gall Bladder Imaging
Thallium	^{201}Tl	73.5h	Thallous Chloride	Myocardial Imaging

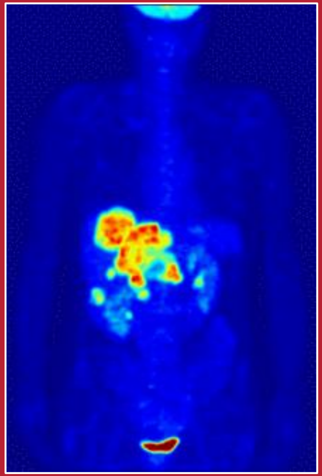
Positron Emission Tomography.

- Positrons = positively charged anti-electrons generated from radionuclide tracer injected in patient.
- Travel 0.001-1mm hit electron and annihilate, producing two 511 keV γ rays which are detected.



Schematic Gamma camera

Real PET Scanner



Whole body PET scan using ^{18}F – FDG.

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Medical Isotopes

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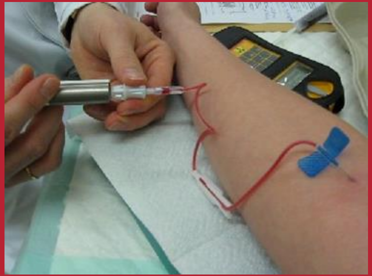
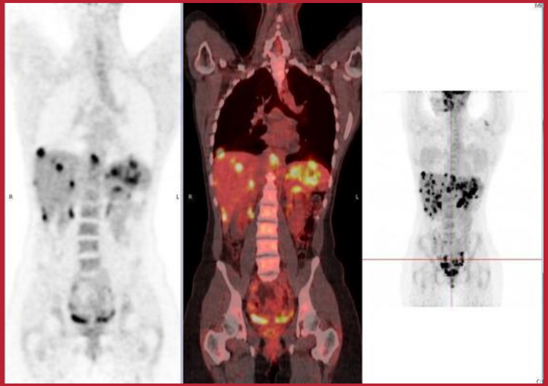
- Radio-isotope market supplied by research reactors which use neutrons to generate isotopes in Mo metal targets.
- UK (Harwell) supplied most of Europe in 1950’s while Amersham became important in 1960’s and due to its profitability was privatised by Thatcher Government in 1981.
- ^{99}Mo and ^{99}Tc become most important isotopes in 1970’s.
- Diminishing number of research reactors, and concentration of radioisotope industry led Nuclear Energy Agency of OECD in 2010 to criticise the “entire economic structure of the isotope market claiming it is biased, with the private sector not paying realistic production costs, and governments subsidising a sector that is not economically viable …”.
- Current global shortage of ^{99}Mo (and so ^{99}Tc) and due to short half lives UK relies on imports from EC.
- Hope that new reactors (PALLAS in Netherlands and MYRRHA in Belgium due to start production in 2025/26) can remove shortage (at least within the EC).
- US Congress appropriated $40M in 2018 and $20M in 2019, DoE’s National Nuclear Security Administration awarded cooperative agreements to 3 companies for ^{99}Mo production not via HEU.
- UK has no indigenous supply of medical isotopes from reactors.

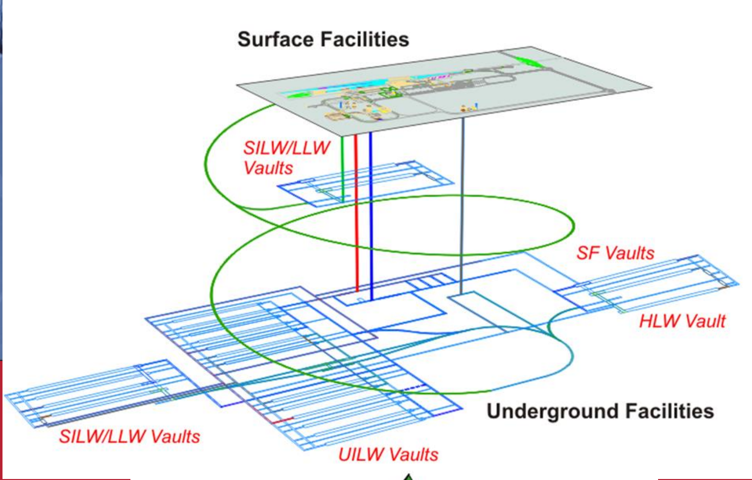


Injecting ^{99m}Tc tracer using shielded syringe

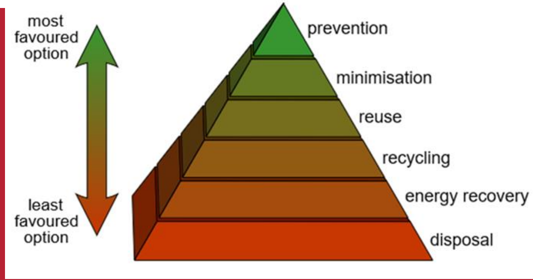


UK's Waste Management Plans.

- All current international waste management programmes plan to either directly dispose of spent fuel or reprocess and dispose of high-level waste in glass.
- In the UK, the current plan is to stop reprocessing in 2020 and directly dispose of any new spent fuel. Sellafield's Magnox Reprocessing Plant is due to close by end 2020.
- Disposal of high-level waste glass and spent fuel is planned to be permanent and aimed at emplacement in deep geological repositories.
- But radio-isotopes are a valuable resource and could be harvested e.g. for medical isotopes or Radioisotope Thermoelectric Generators for space missions.



Waste Hierarchy Pyramid



Isotopes from “Waste”?

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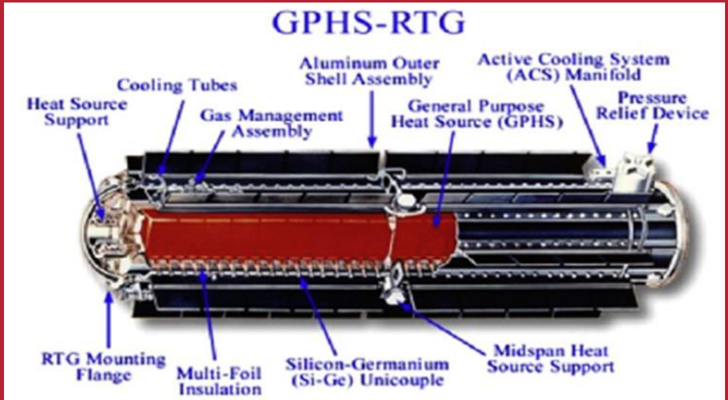
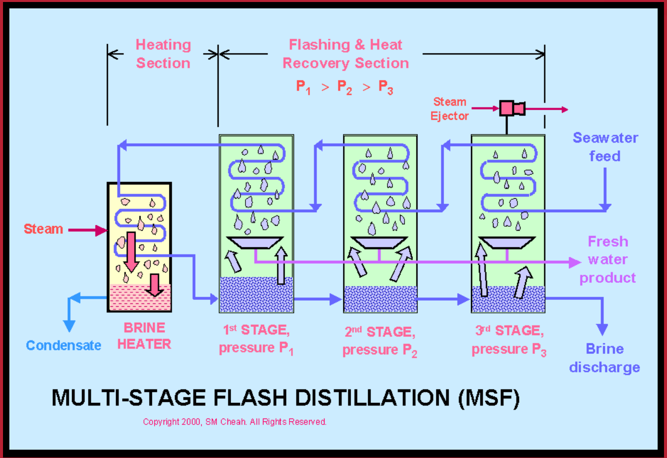
- Co-generation could also be considered as a manner of using nuclear “waste” for commercially astute purposes.
- A number of chemical reactions can be catalysed by the radioactivity emitted from nuclear material and treating SF as a valuable resource may make nuclear energy more acceptable to the public.
- Potential reactions enabled or enhanced by irradiation include:
  - Breakdown C-C, C-H bonds etc. in plastics, producing benign recyclable bi-products.
  - Food sterilisation using gamma rays.
  - Ammonia synthesis for the production of fertiliser
  - Gamma ray assisted methanol production from CO and hydrogen.
  - Nano-technology – radiation can assist in nanoparticle synthesis.
  - Radiolysis of water to produce hydrogen. The use of nuclear waste in this application could allow hydrogen to be produced without the input of significant additional power.
- All of the above would require further research and development.



Seawater Desalination

- Use low temperature steam/heat in thermal processes:
  - Multi-Stage Flash (MSF),
  - Multiple Effect Distillation (MED).
- Use electricity to drive membrane processes:
  - Reverse Osmosis (RO).
- Most current desalination plants use fossil fuels so contribute to global warming.
- NPP desalination first used at Ohi NPP Japan in 1978, 1175 MWe PWR coupled to MSF distillation plant with capacity of 1300m^3/d.
- Currently used by NPP in Japan, Pakistan, India, Kazakhstan and planned in UAE and Saudi Arabia.
- Key driver for Australia to pursue nuclear technologies.



- Small and medium sized nuclear reactors are suitable for desalination, often with cogeneration of electricity.
- US Navy nuclear powered aircraft carriers desalinate 1500 m^3/d for on-board use.
- Main opportunities for NPP identified as the 80-100,000 m^3/d and 200-500,000 m^3/d ranges.
- Not needed in UK.

Conclusions

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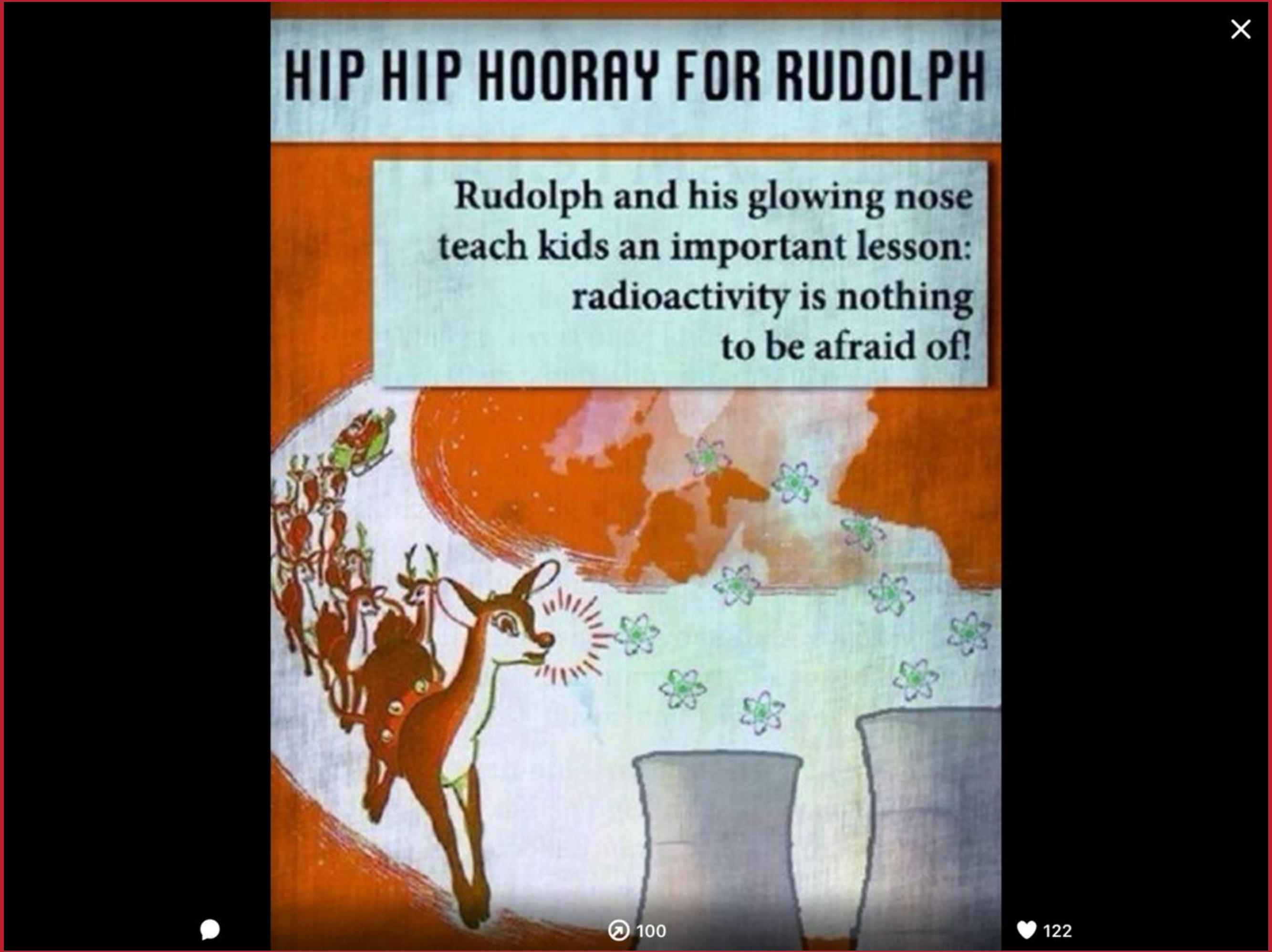
- Co-generation is not new or novel.
- Historically have co-generated medical and other radio-isotopes, site heat and power, power for energy intensive industries (Al).
- Seawater desalination while not needed in the UK is a global cogeneration opportunity.
- Many opportunities to decarbonise industry, improve living conditions and quality of life.


HIP HIP HOORAY FOR RUDOLPH
Rudolph and his glowing nose teach kids an important lesson: radioactivity is nothing to be afraid of!
100
122

Hydrogen Production

Alan Woods
Rolls Royce

THE
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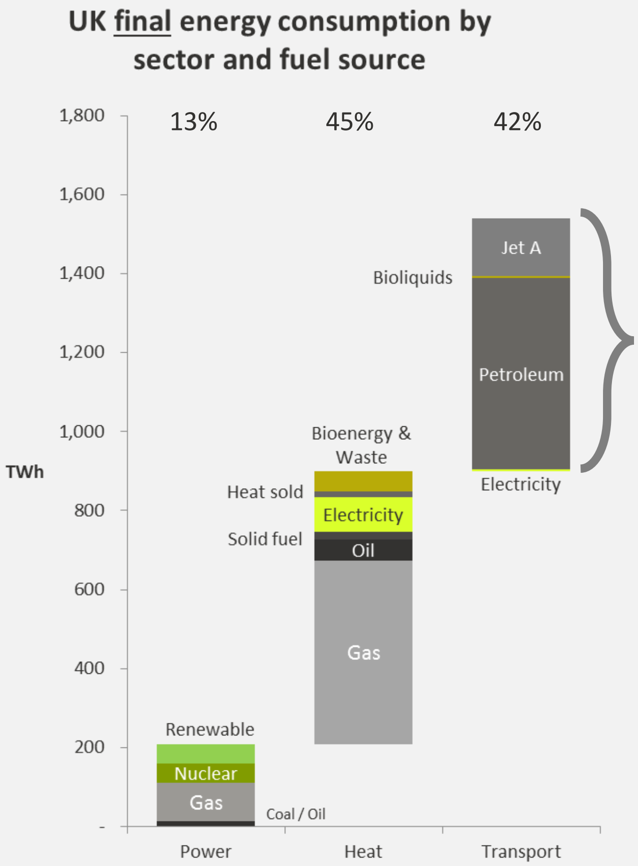
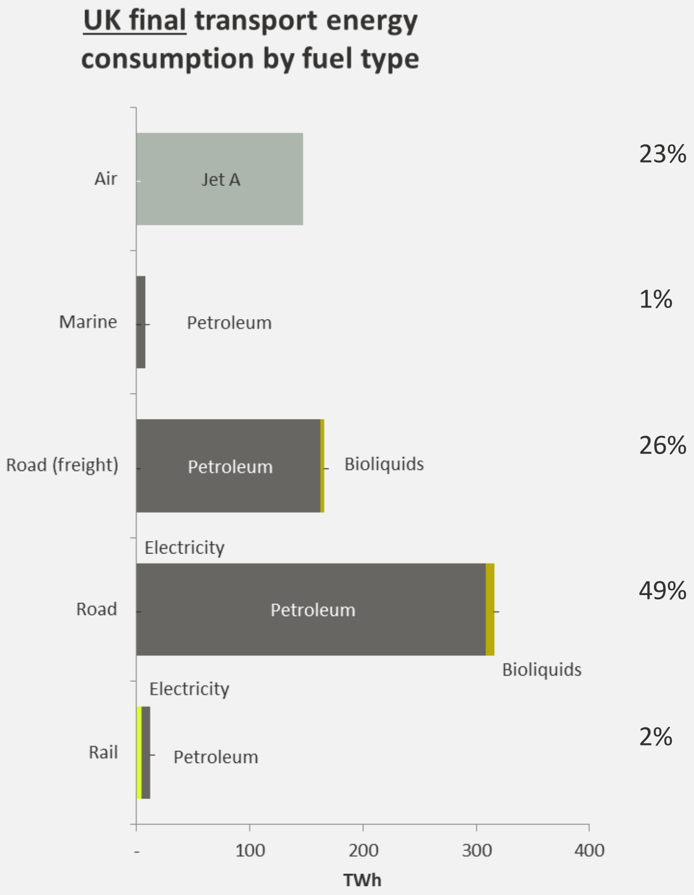
Potential for SMRs with a hydrogen economy

Alan Woods

Only ~12% of energy used in the UK is low carbon by source

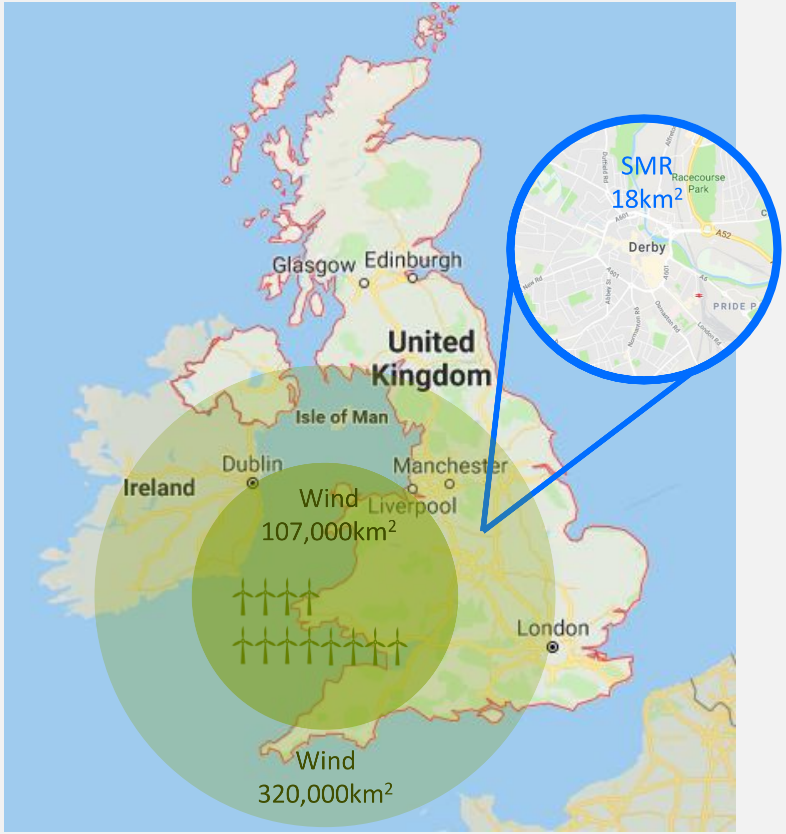
The UK faces a huge challenge to meet emissions targets





Source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695626/Press_Notice_March_2018.pdf

And providing clean energy to support decarbonisation will be a big challenge



Land area of UK 245,339 km²

- The UK currently has ~ 1,344 TWh of energy to decarbonise p.a. across all sectors: Transport, Power, Heat*
- This equates to 153 GW of average power capacity
- 107,000 km² of wind farm or 18 km² of SMR would be needed to serve the average demand assuming unlimited storage capacity
- 320,000 km² wind or 55 km² SMR to accommodate peak **without storage capacity**

*primary energy equivalent is primary source energy required to produce the final energy consumed (recognising generation inefficiencies – varies from fuel type and end use)

But "intermediate fuels" require heat and / or electricity in the generation process

There are a number of mechanisms available to decarbonise today

Hydrogen has versatility across Power, Heat and Transport

				Clean applications
Fossil Fuel source			**Hybridisation** Lower emissions due to efficiency improvements	**Primary fuel based**
Clean generation sources			**Electrification** Carbon free power generation source dependent	• Heat potential • Transport for lower power & energy missions
Clean electricity and / or heat			**Sustainable fuels** Carbon neutral due to generation technology but still emitting	• Transport for higher power & energy missions
			Hydrogen Carbon free depending on generation technology	• Peak power • Heat • Transport for all power & energy missions

SMRs can be key to green hydrogen production where large amounts of baseload power are needed

Single SMR

440MWe
3.5TWh / p.a. electricity

Electrolysis plant

87 m Kg hydrogen p.a.

Store for Peak Power	Heat	Transport

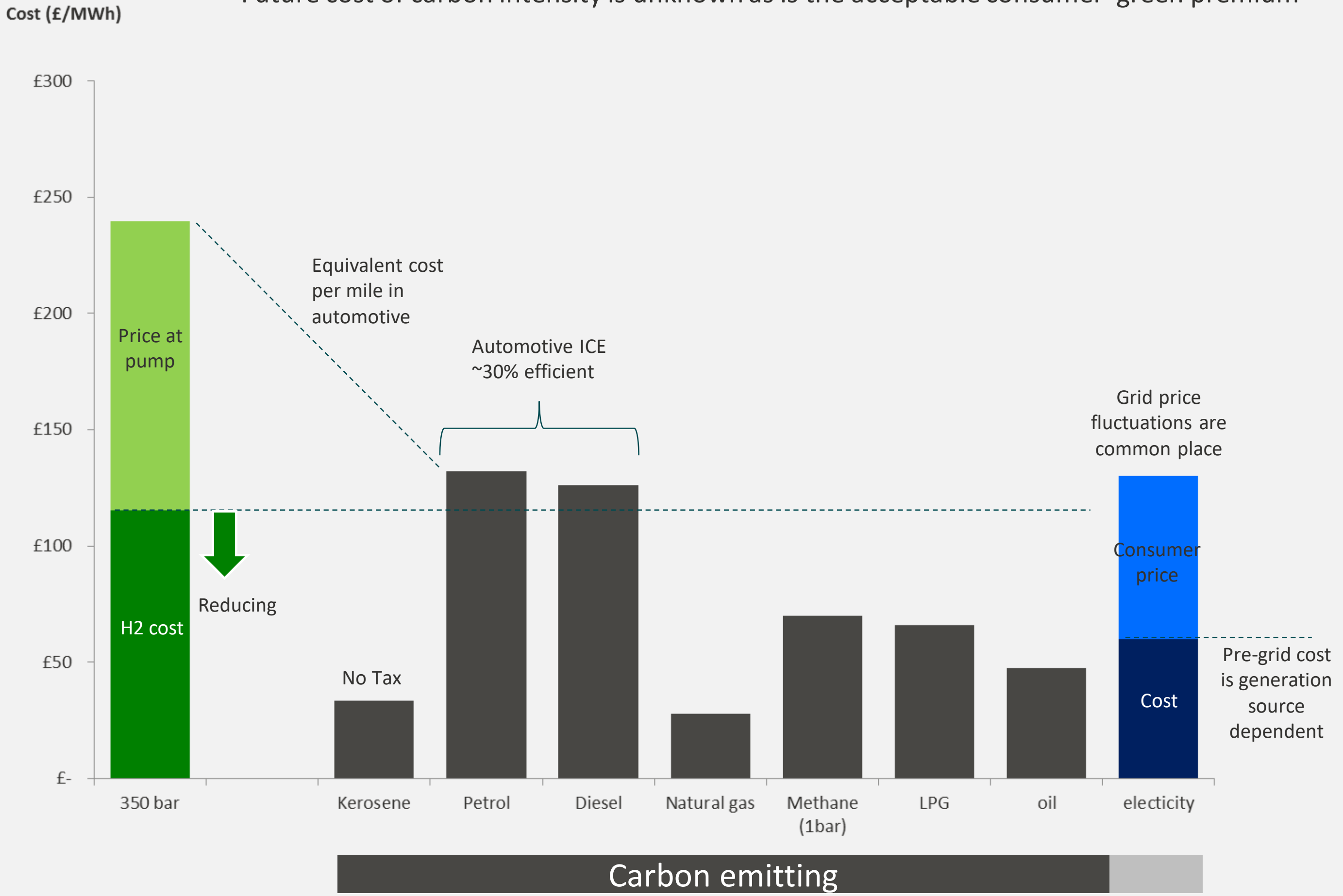
Heat for 240,000 domestic homes

~4% UK HGV market (Based on Fuel cell)

Economics of hydrogen

Cost of hydrogen is directly linked to electricity price for electrolysis method, methane for Steam method

- Cost of hydrogen is dropping as generation technologies mature
- Future cost of carbon intensity is unknown as is the acceptable consumer 'green premium'



Summary

- Decarbonisation across all energy sectors is a huge challenge
- Most methods of decarbonisation require more **clean** electricity – SMRs can play a key role
- Not all applications are appropriate for electrification
- Hydrogen has versatility across Power, Heat and Transport
- Economics of hydrogen is improving and carbon taxation is driving current fuels the other way

Combined Heat & Power: District Heating

Sam Friggens
Mott MacDonald

THE ROYAL SOCIETY

MOTT MACDONALD

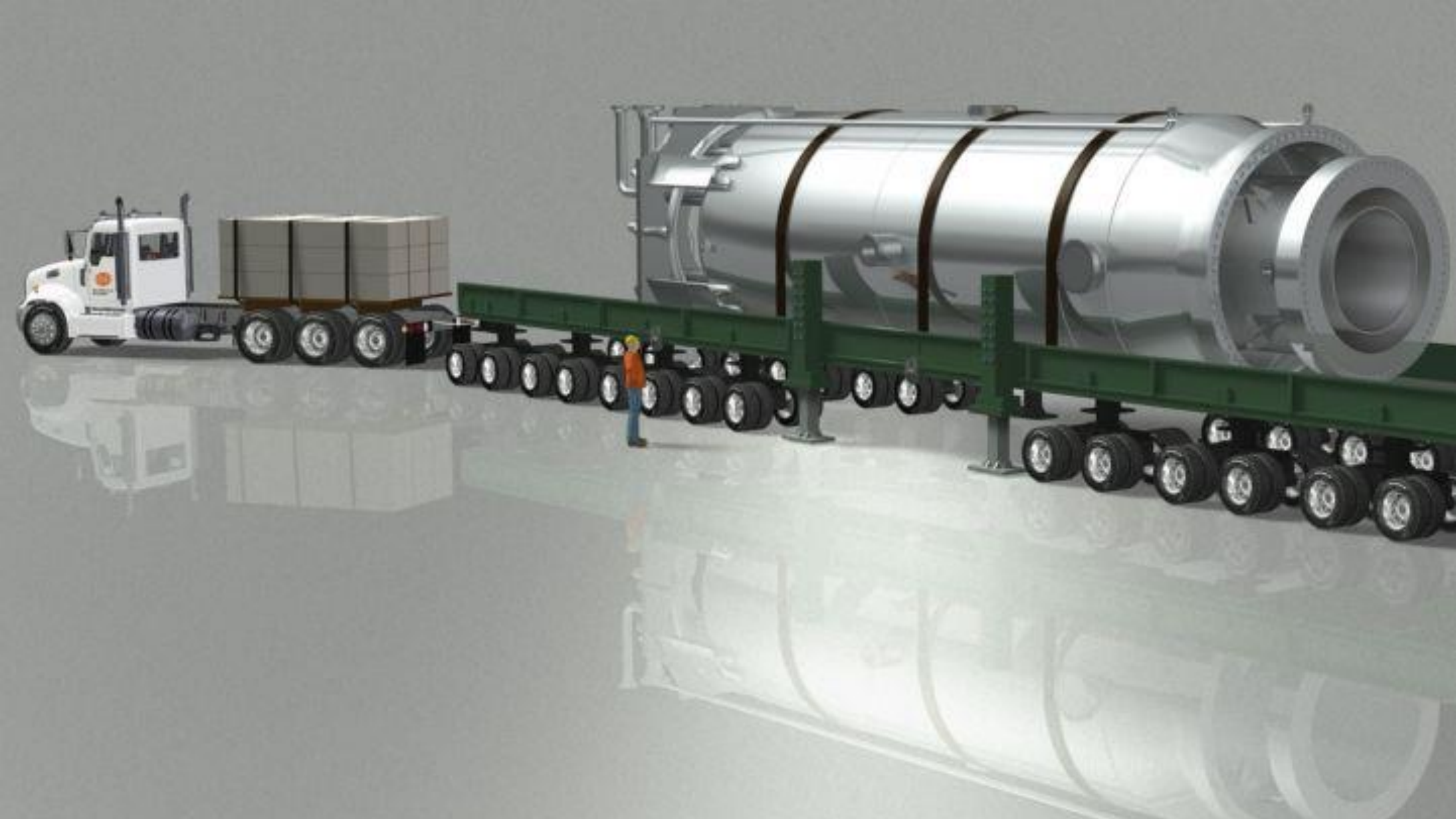
Nuclear Combined Heat & Power (CHP) for district heating networks

Based on work undertaken for the ETI 2014-16

energy technologies institute

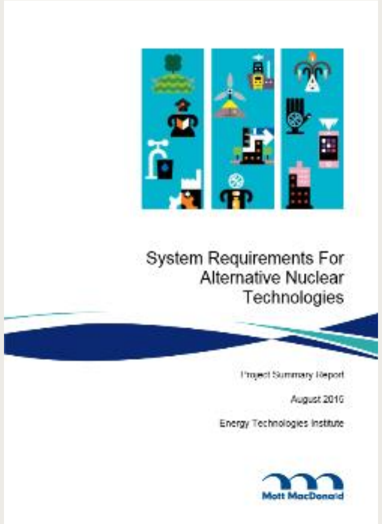
Sam Friggens

Royal Society, 25th September 2019



What is the role for Small Modular Reactors in the UK's future energy system?

- What services and costs?
- Consider power, 'flexibility' and heat
- Focus on light-water reactor technologies
- Assume 2050 decarbonisation
- Assume district heat part of solution
- Excluded public acceptability



https://www.eti.co.uk/library/alternative-nuclear-technologies-summary-report-and-peer-review-letters

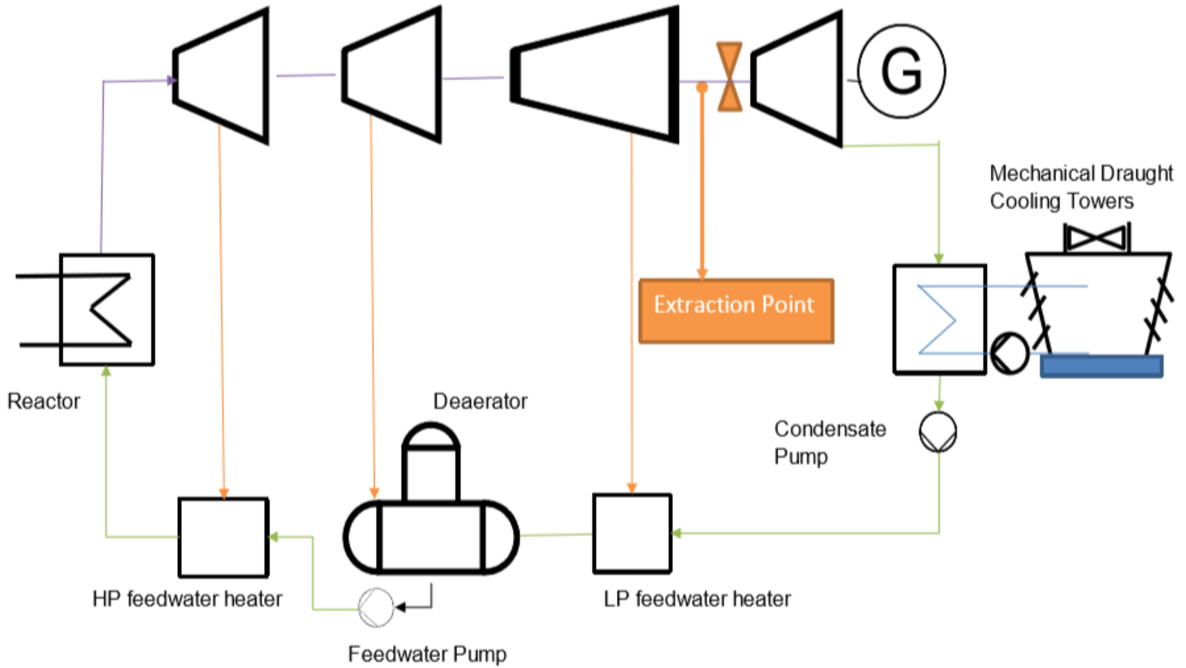
https://www.eti.co.uk/library/system-requirements-for-alternative-nuclear-technologies-phase-3

Key conclusion

SMRs have the potential to operate as CHP plants providing low-carbon heat to city-scale district heat networks as well as low carbon electricity to the grid.

It is technically feasible to extract heat from SMR power plant steam cycles…

Figure 4.8: Indicative steam cycle for Plant A CHP SMR plant



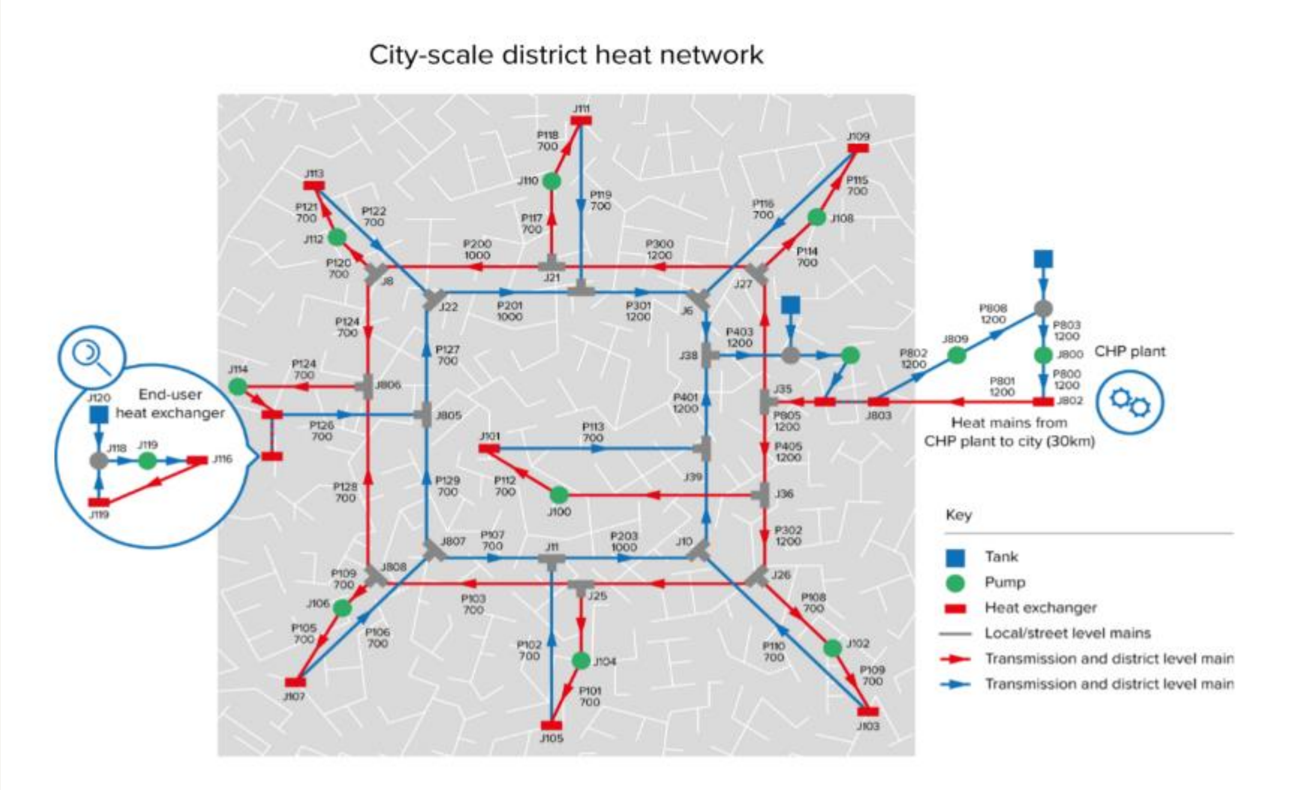
"Extracting heat from the steam cycles of Light Water Reactor type SMR plants is technically feasible and relatively easy to implement"

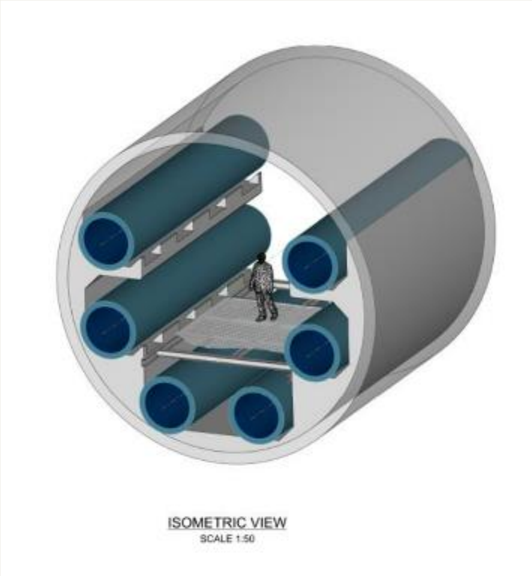
Extract heat from point between IP and LP turbines

Heat supplied at 97° C

20-30% reduction in electrical output

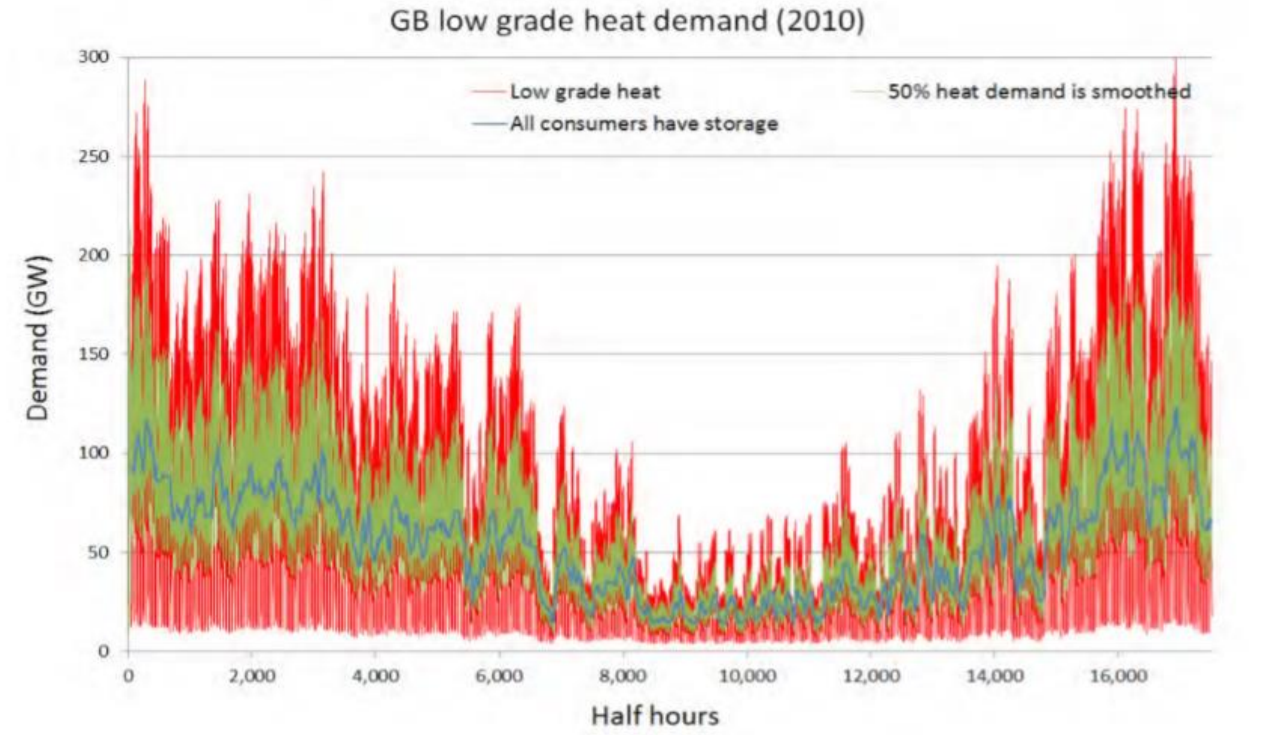
...And distribute around city-scale district heat networks



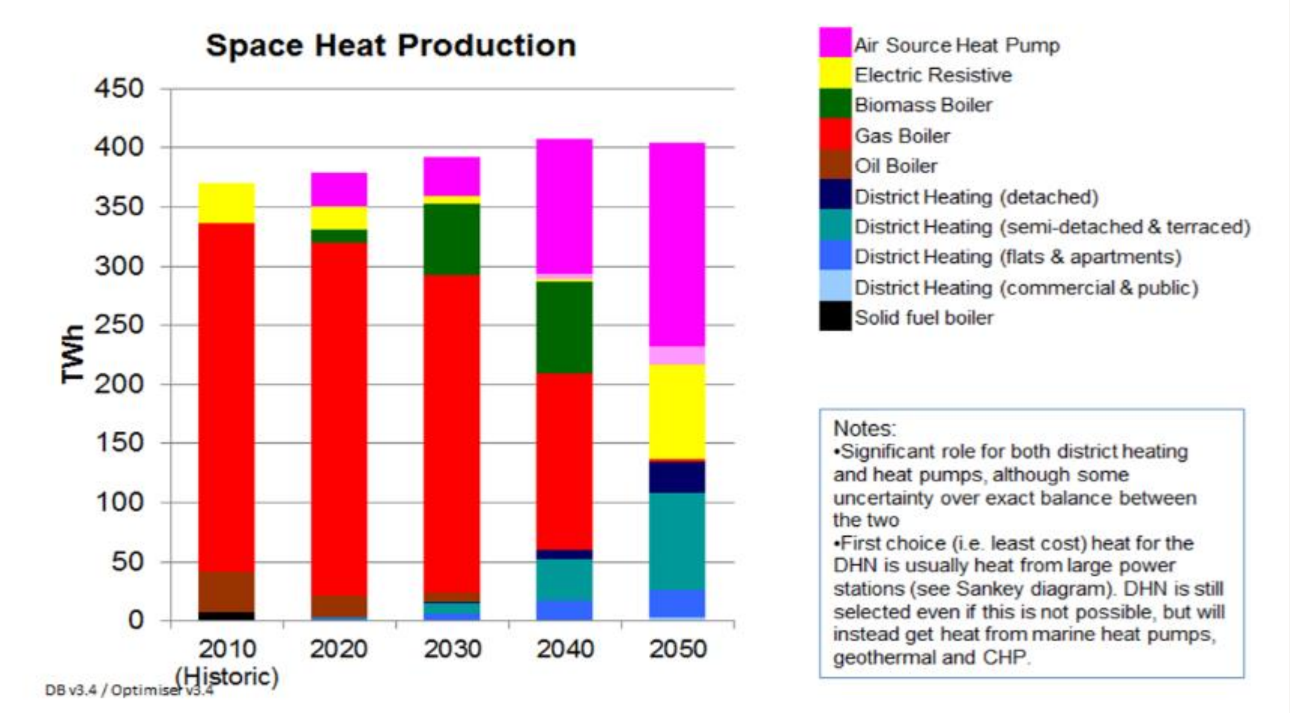


...Operating with other heat supply technologies

Figure 3.7: The impact of diurnal water tank storage on the GB heat load profile



There is a potential market

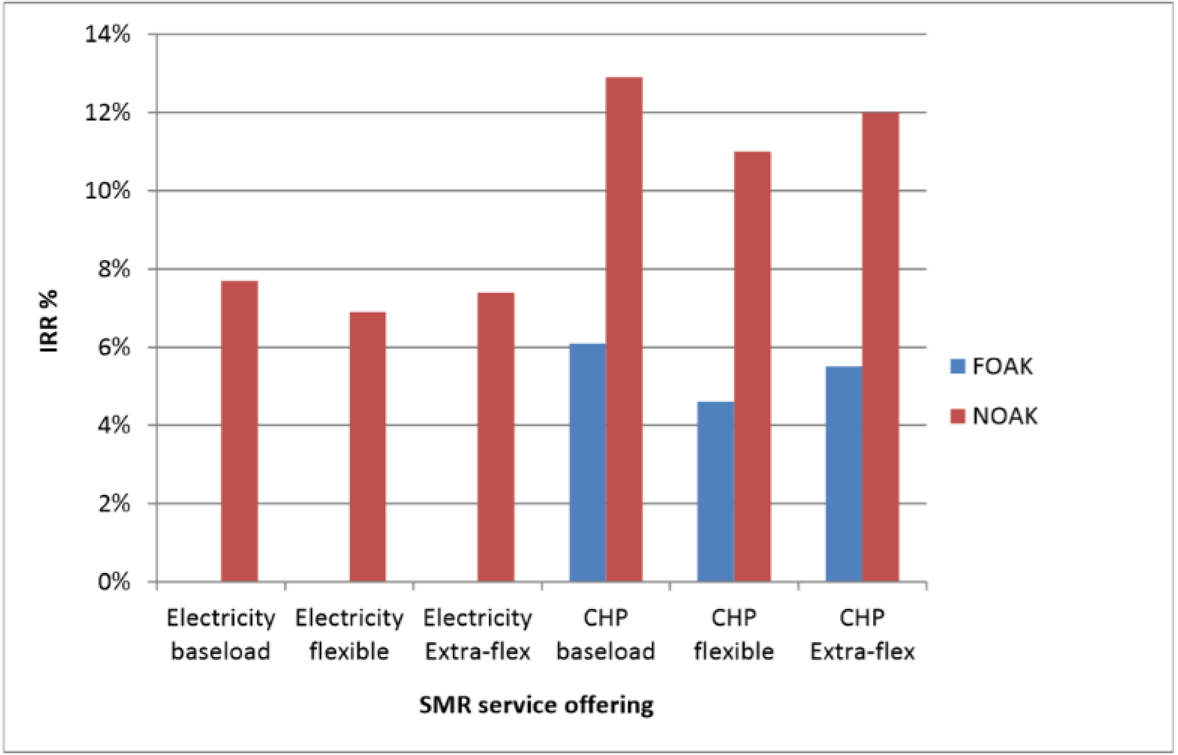


We found there could be around 50 conurbations in GB potentially suitable to host SMR energised DH networks.

A parallel study by Atkins for the ETI found there are potential sites within 20km of these towns and cities

Operating as CHP plants improves SMR economics

Figure 4.4: Projected IRRs for SMR power plants under different service offerings



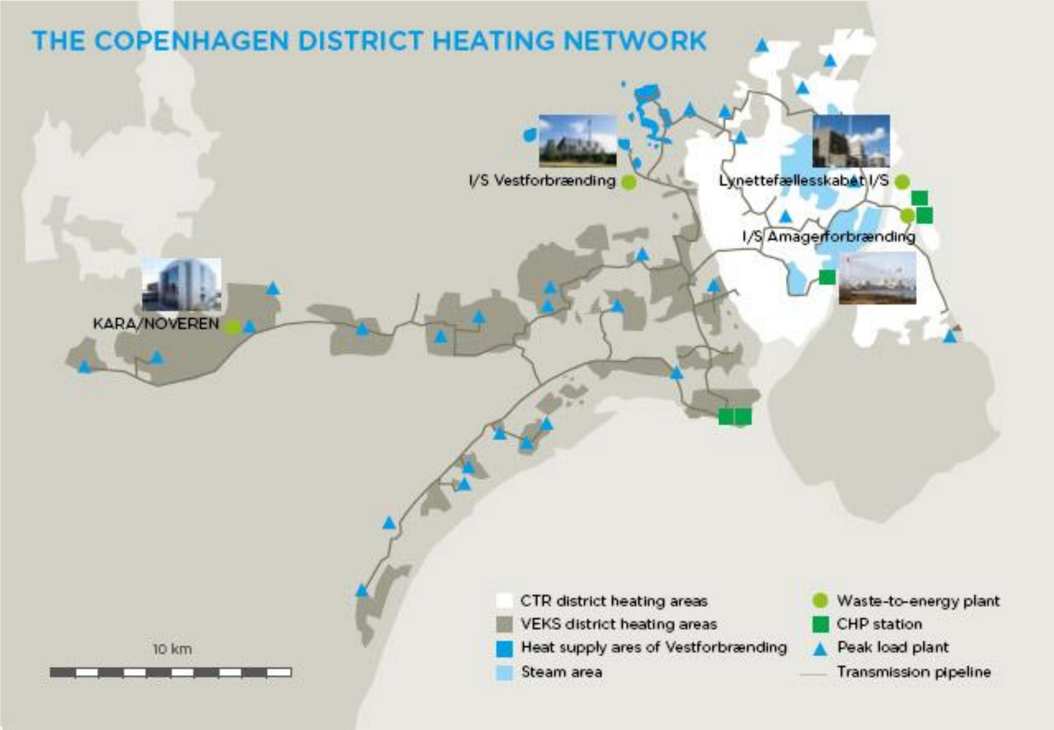
Additional costs of heat extraction are low

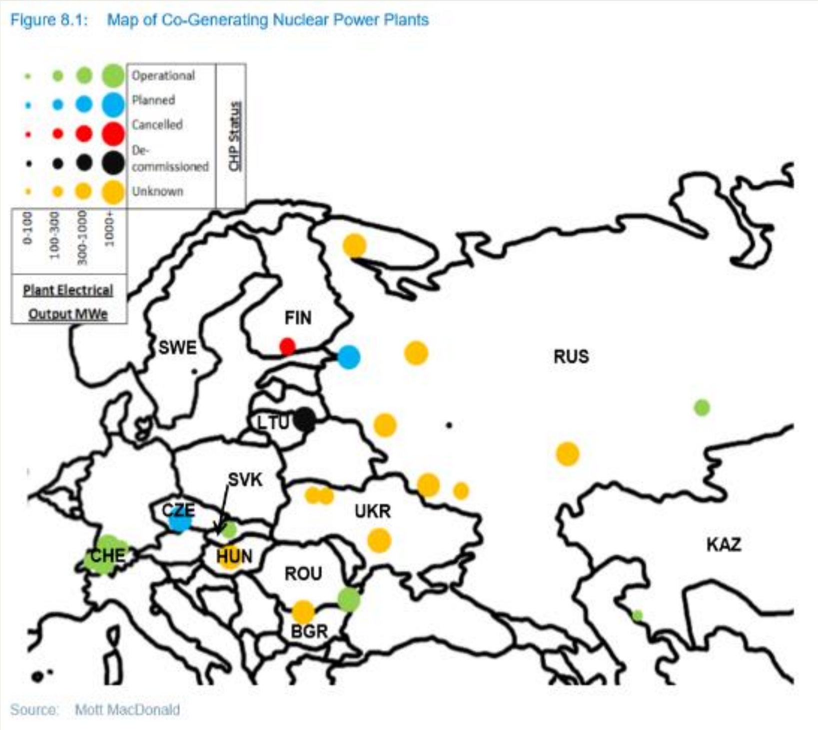
Value of low carbon heat is high

Caveats:

- Doesn't include DH network costs
- Future prices power and heat uncertain

There are international precedents





Thank you

Thermal Energy Storage

Professor Phil Eames
Loughborough University

THE ROYAL SOCIETY

THERMAL ENERGY STORAGE

P C Eames

Centre for Renewable Energy Systems Technology,

Wolfson School of Mechanical, Electrical and Manufacturing Engineering

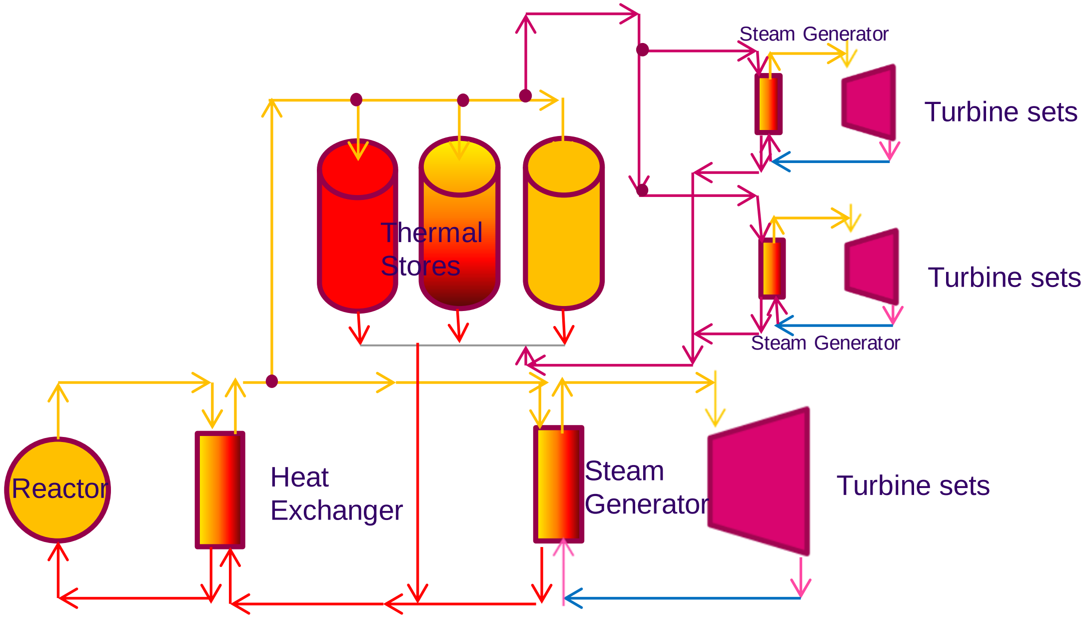
Loughborough University,

LE11 3TU, UK

E-mail p.c.eames@lboro.ac.uk

High Temperature Thermal Energy Storage for Flexible Nuclear: The Proposed Approach

Heat generated by a nuclear reactor can either be used to directly generate steam for power generation or be used to charge a store /stores for generation of steam at a later time giving great flexibility in terms of generation capacity.



The thermal store is charged at times of low electrical load or when electricity from renewables is in excess and would be shed.

At times of peak load or reduction in renewable generation the thermal store is used to provide additional electricity generation capacity by the addition of an additional turbine set or sets.

Due to the direct storage of thermal energy, storage efficiency can be very high and electricity produced using stored heat will be produced with a similar efficiency to that of a standard nuclear plant.

Thermal energy storage is currently implemented on most CSTP plants and could form the basis for nuclear plant thermal stores.

- **Andasol 1 Heat Storage: Molten salt**
- NaNO3/KNO3 (60:40)
- Capacity around 1010 MWh thermal
- Operational store temperatures :-

  hot store 390ºC

  cold store 290ºC

Provides 7.5 hours output at 50MWe.

CSP plants are currently being built with a few hours of storage to generate electricity during the night period.

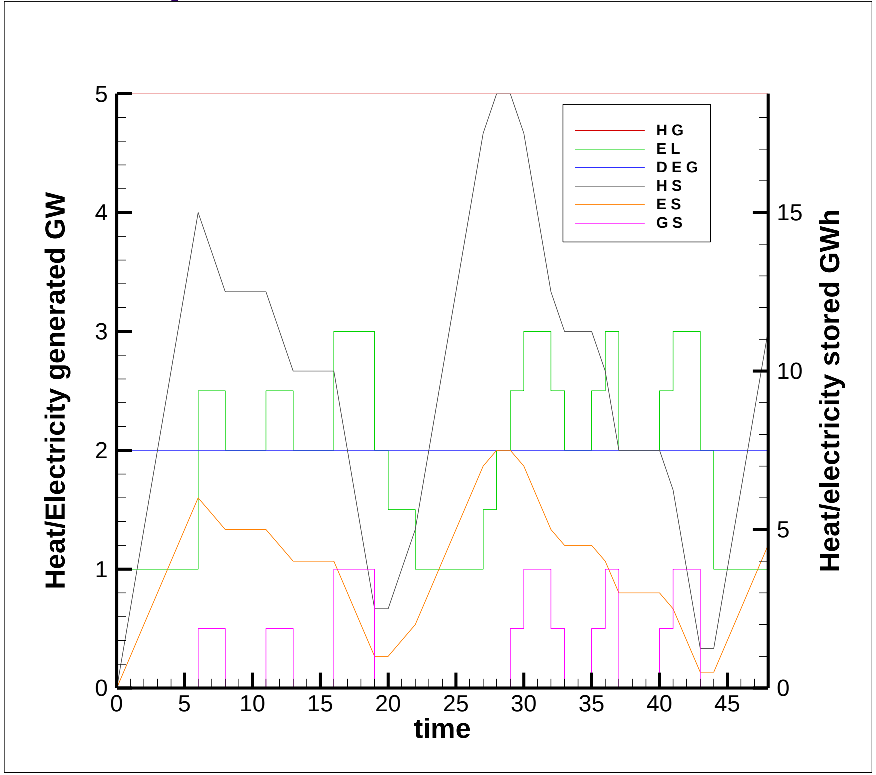
How large do stores need to be for large scale power generation?

- The Andasol storage systems are around 14,000 m^3 in volume and store approximately 1 GWh_t or 375MWhe working between 390 and 290˚C.
- If such a store was working between 490 and 290˚C the stored energy available would be approximately twice this thus a store of 18,667 m^3 could provide a GWh_e storage, that is a cube of side 26.5m would store around 1/9 of the energy available from Dinorwic, the UK's largest pumped storage facility.
- To store 20 GWh_t, 8 GWh_e, the volume required is 149,334 m^3 Although sounding large this volume is provided by stores 21m high over an area equivalent to 1 football pitch (7140 m^2).

The potential flexibility afforded by adding 20GWh of heat storage to a 2GWe Nuclear plant

H G = Heat Generated
E L = Electrical Load Provided
D E G = Direct Electrical Generation
H S = Heat Stored
E S = Equivalent Electricity Stored
G S = Electricity Generated from Storage
Turbine Sets 500MWe

In a future with Nuclear and Renewables, heat storage linked to Nuclear could provide large scale low cost energy storage helping balance variable renewable generation to meet variable demand profiles.

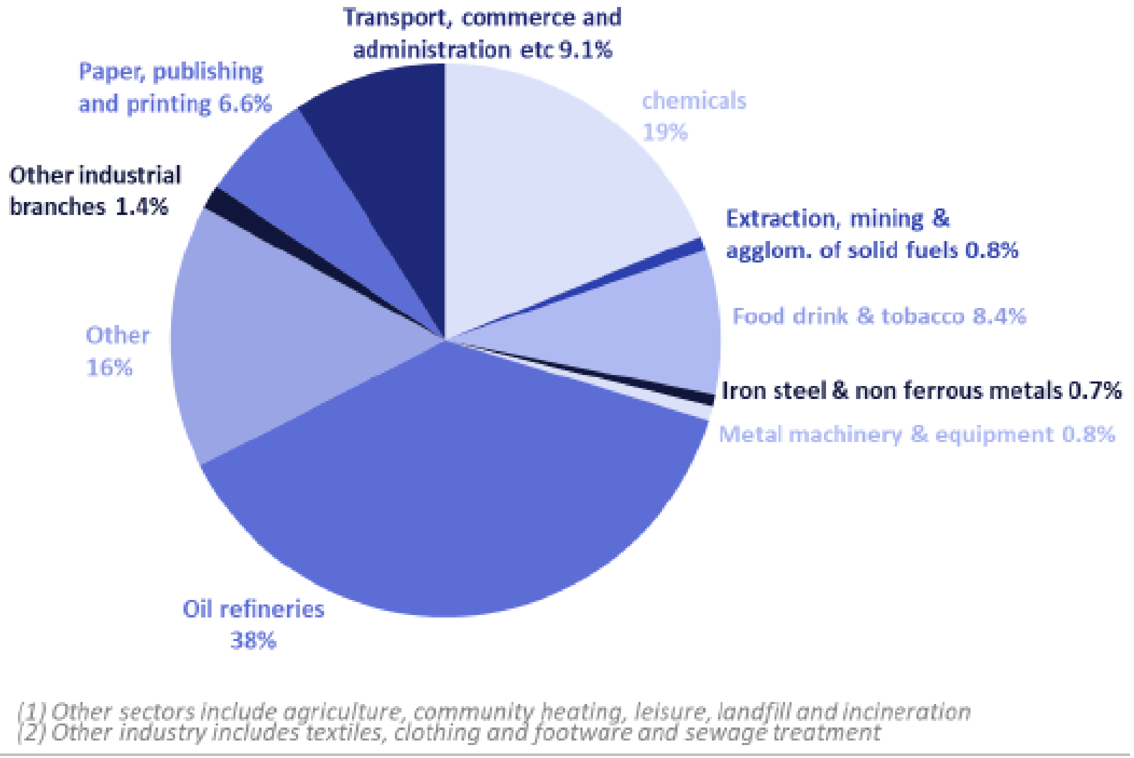


Thermal process heating

Mark Brennan
Former Cavendish Nuclear

THE ROYAL SOCIETY

CHP Capacity by Sector (2017)



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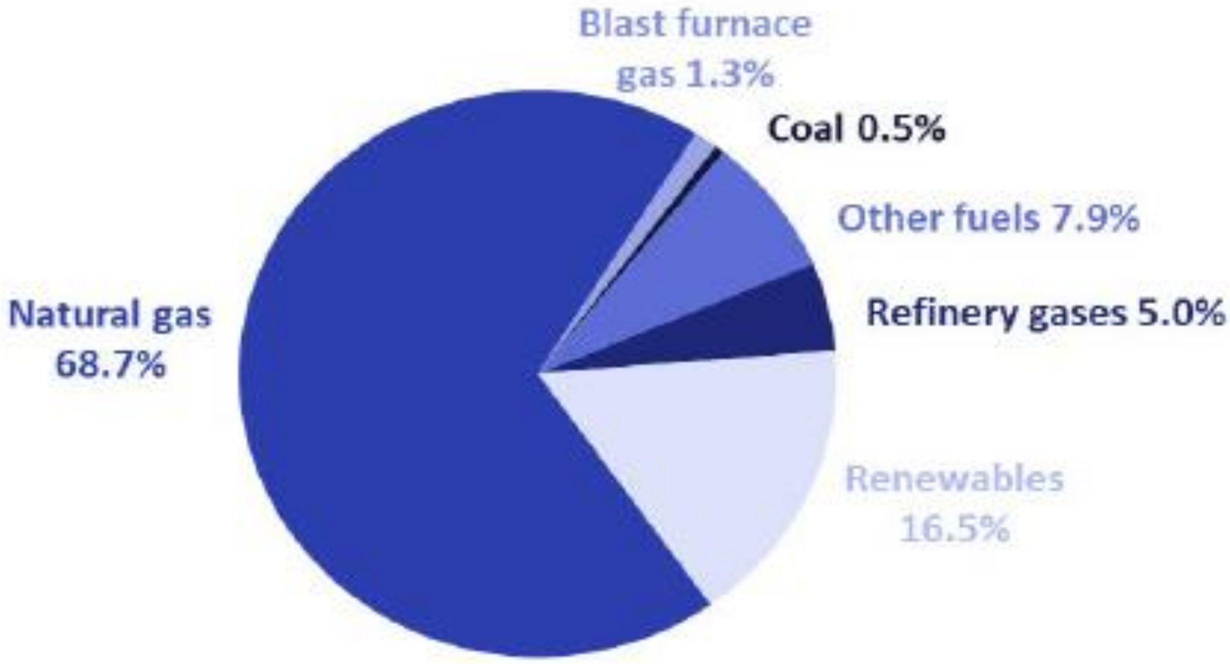
CHP Fuel Types (2017)



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UK CHP Plants by Capacity (2017)

Electrical capacity size range	Number of schemes	Share of total (per cent)	Total electricity capacity (MWe)	Share of total (per cent)
Less then100 kWe	605	25	36	0.6
100 kWe - 1 MWe	1,291	54	331	5.7
1 MWe - 2 MWe	183	7.7	259	4.4
2 MWe - 10 MWe	240	10	1,027	18
> 10 MWe +	67	2.8	4,181	72
Total	2,386	100	5,835	100

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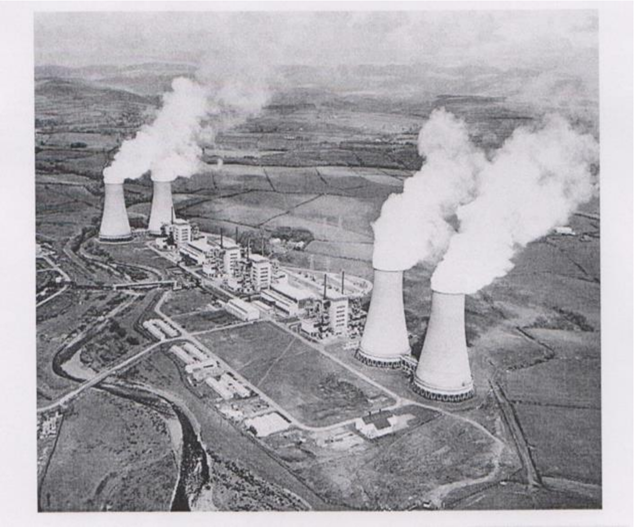
International Experience of Nuclear CHP

- In the UK, the Magnox reactors at Calder Hall provided:
  - ~ 200 MWe of electricity
  - low and high pressure steam for reprocessing and other industrial plants
  - building heating on Sellafield site
- Have been replaced by a 168 MWe gas fired CHP plant adjacent to Sellafield



Other international experience includes:

- A CANDU reactor at Bruce in Canada that provided process heat for heavy water production
- Low temperature process heat from water cooled reactors at Halden in Norway and Gösgen in Switzerland used in paper and cardboard production
- Low temperature process heat from a PWR at Stade in Germany used in a salt refinery

Barriers to Adoption

- Industry requirement is for **cost competitive** and **reliable** process heat for core business activities
  - ➢ Nuclear plant costs/economics
  - ➢ Uncertain long term costs/liabilities of decommissioning and waste management
  - ➢ SMR technologies unproven – require significant investment in design and development
  - ➢ Higher processes temperatures require hybrid systems or next generation reactors
  - ➢ Most economically advantageous sites already served by gas fired CHP
- Safety
  - ➢ Reactors normally sited away from centres of population and industry
    - ▪ Hazard posed by reactor to industrial plant and vice versa
  - ➢ Need to address other potential interactions in a coupled system
  - ➢ Cost and timescale for reactor licensing
  - ➢ Know-how and expertise needed to become a UK Nuclear Site Licensee
    - ▪ Can this be sub-contracted to a 3rd party?
  - ➢ Liabilities for and insurance against nuclear accidents
- PR implications for companies with a significant public profile

Breakout session 1

Group 1

Chair: Professor Roger Cashmore
Room: Wolfson 1
Note-taker: Shema Bhujel

Sir Steve Cowley
Professor Laurence Williams
Dr Paul Norman
Dr Martin Leurent
Andrew Bailey
Dr Yoichi Wada
Dr Rebecca Weston
Norman Harrison
Simon Dilks
King Lee

Group 2

Chair: Professor Andy Storer
Room: Wolfson 1
Note-taker: Frances Bird

Professor Chris Llewellyn Smith
Mike Roberts
Dr Simon Middleburgh
Professor Bill Nuttall
Dr John Lillington
Alan Woods
Neil Thomson
Dan Wolff
Dr Jenifer Baxter
Richard Deakin

Group 3

Chair: Professor Ian Chapman
Room: Wolfson 1
Note-taker: Paul Davies

Gwen Parry-Jones
Professor Andrew Sherry
Dr Eugene Shwageraus
Professor Philip Eames
Andrew Carlick
Dr Frank Tutu
Dr David Kingham
Gianluca Pisanello
Baroness Brown of Cambridge
Dan Mathers
Professor Bill Lee

Group 4

Chair: Professor Simon Taylor
Room: Wolfson 2
Note-taker: Benjamin Konnert

Neil Hirst
Tony Roulstone
Professor Giorgio Locatelli
Professor Grzegorz Wrochna
Tom Greatrex
Robert Davies
Ross McGhin
Dr Robert Hoyle
Dr Daisy Ray
Marie Carlick

Group 5

Chair: Dr Mike Bluck
Room: Wolfson 3
Note-taker: James Musisi

Dr Neil Smart
Professor Myles Allen
Professor Ian Farnan
Tim Tinsley
Mark Brennan
Candida Whitmill
Sam Friggens
Dr Jo Nettleton
Chris Harrington
Alasdair Harper

Group 6

Chair: Dame Sue Ion
Room: Wolfson 3
Note-taker: Yayoi Teramoto

Professor Juan Matthews
Dr Michael Rushton
Professor Neil Hyatt
Dr Robert Holmes
Professor Steve Garwood
Dr Tim Stone
Michael Jones
Craig Lester
Professor John McCloy

Breakout session 1

- Have we missed any technologies?
- Which technologies are most relevant to the nuclear power in the UK now and which in the future?
- Where is nuclear cogeneration in operation around the world?
- Where the expertise in the world is and what expertise does the UK possess?

Breakout session 2

Group 1

Chair: Professor Roger Cashmore
Room: Wolfson 1
Note-taker: Shema Bhujel

Sir Steve Cowley
Professor Laurence Williams
Dr Paul Norman
Dr Martin Leurent
Andrew Bailey
Dr Yoichi Wada
Dr Rebecca Weston
Norman Harrison
Simon Dilks
King Lee

Group 2

Chair: Professor Andy Storer
Room: Wolfson 1
Note-taker: Frances Bird

Professor Chris Llewellyn Smith
Mike Roberts
Dr Simon Middleburgh
Professor Bill Nuttall
Dr John Lillington
Alan Woods
Neil Thomson
Dan Wolff
Dr Jenifer Baxter
Richard Deakin

Group 3

Chair: Professor Ian Chapman
Room: Wolfson 1
Note-taker: Paul Davies

Gwen Parry-Jones
Professor Andrew Sherry
Dr Eugene Shwageraus
Professor Philip Eames
Andrew Carlick
Dr Frank Tutu
Dr David Kingham
Gianluca Pisanello
Baroness Brown of Cambridge
Dan Mathers
Professor Bill Lee

Group 4

Chair: Professor Simon Taylor
Room: Wolfson 2
Note-taker: Benjamin Konnert

Neil Hirst
Tony Roulstone
Professor Giorgio Locatelli
Professor Grzegorz Wrochna
Tom Greatrex
Robert Davies
Ross McGhin
Dr Robert Hoyle
Dr Daisy Ray
Marie Carlick

Group 5

Chair: Dr Mike Bluck
Room: Wolfson 3
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Dr Jo Nettleton
Chris Harrington
Alasdair Harper

Group 6

Chair: Dame Sue Ion
Room: Wolfson 3
Note-taker: Yayoi Teramoto

Professor Juan Matthews
Dr Michael Rushton
Professor Neil Hyatt
Dr Robert Holmes
Professor Steve Garwood
Dr Tim Stone
Kirsty Gogan
Michael Jones
Professor John McCloy

Breakout session 2

- What are the main technical and regulatory barriers to cogeneration systems?
- What are the economic and socioeconomic considerations?
- What are the main research needs?
- What does the UK need to do to develop the skills necessary to implement nuclear cogeneration?
- What are the practical timescales for implementing nuclear cogeneration?

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Closing Remarks

Dame Sue Ion FREng FRS

Professor Robin Grimes FREng FRS

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