OPPORTUNITIES FOR NUCLEAR CO-GENERATION

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Nuclear Academics Meeting, Zoom Webinar, Sept 9th 2020

Outline

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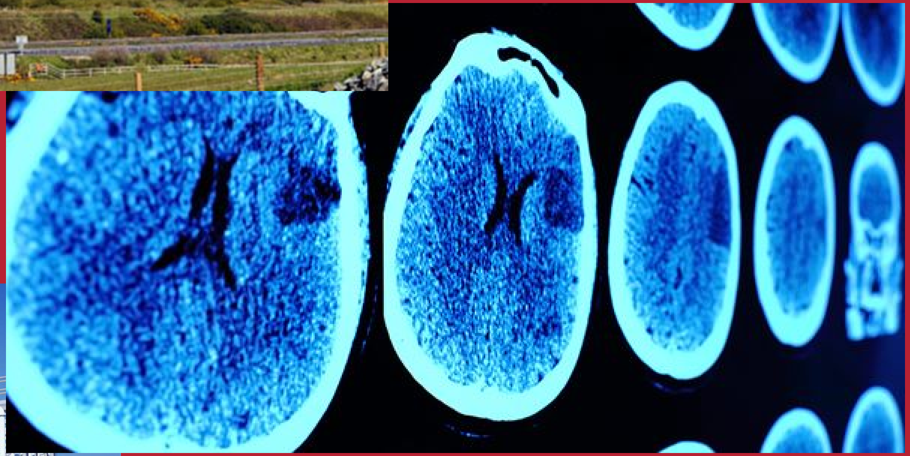
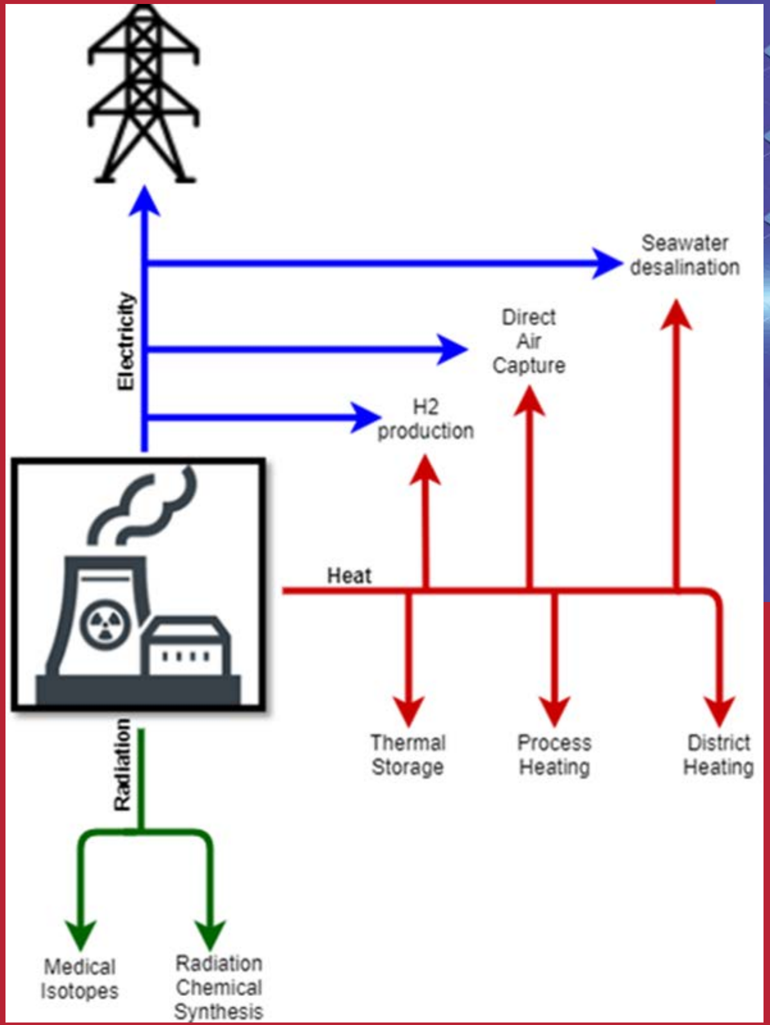
- What is Co-generation?
- Royal Society Policy Briefing Report process
- Historical Co-gen
- Royal Society Policy Briefing Report main findings

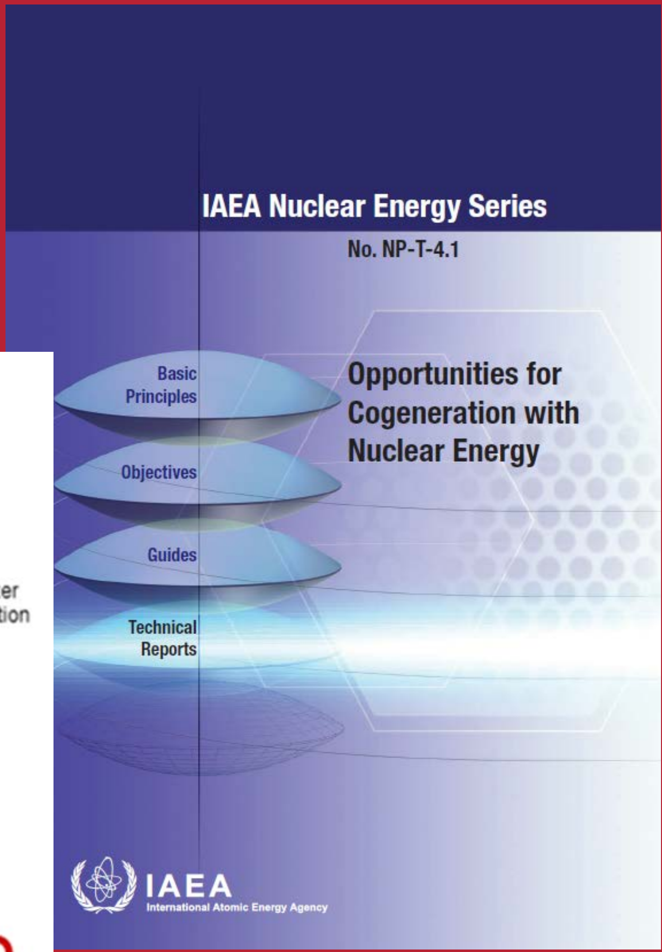


“Atoms for peace”
Atoms for survival

Nuclear Co-generation.

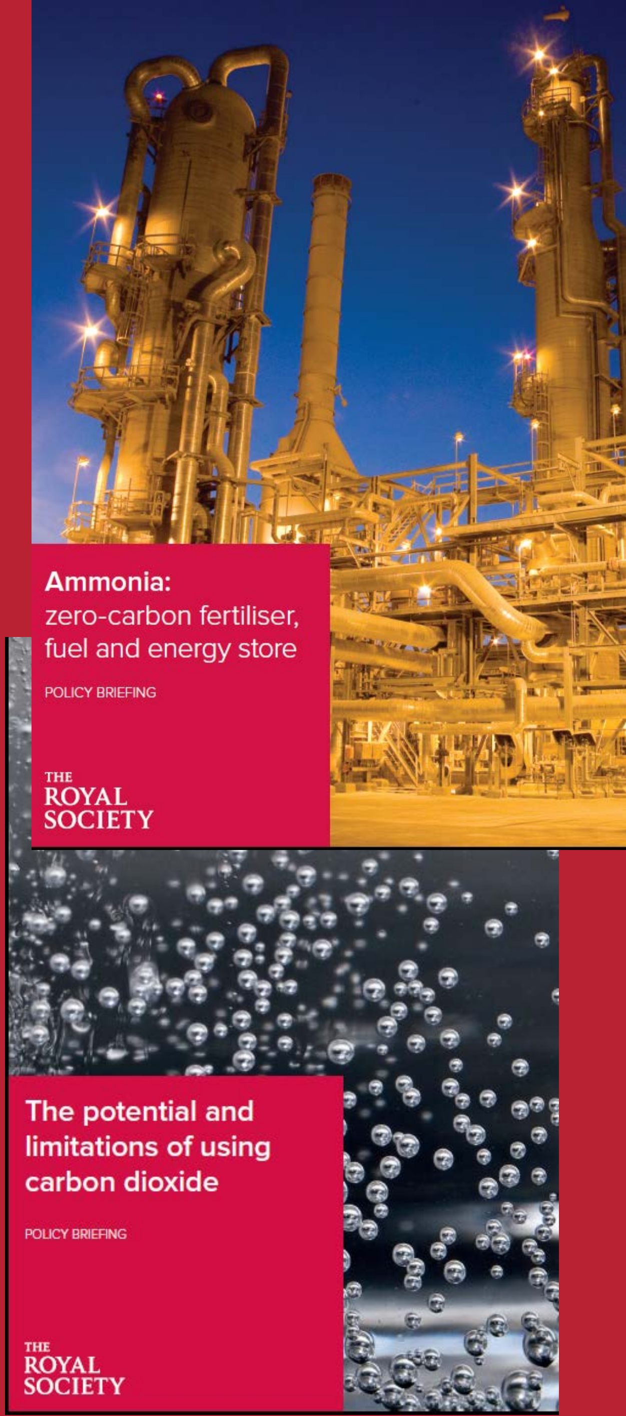
- Defined by IAEA (2017) as "integration of nuclear power plants with other systems and applications. The heat generated by the NPP can be used to produce a range of products such as cooling, heating, process heat, desalination and hydrogen."
- But just using the heat generated ignores using the radiation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



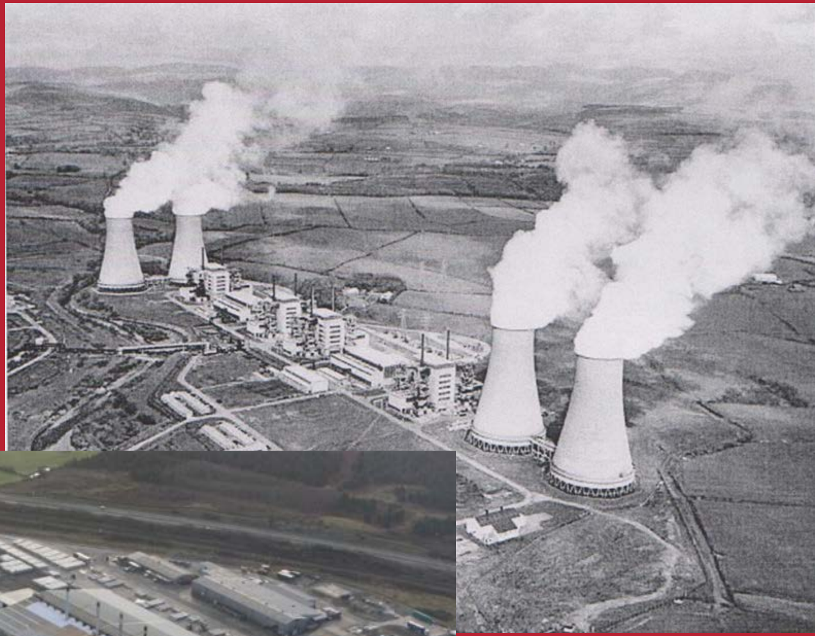


Royal Society Policy Briefing Committee on Nuclear Co-Generation

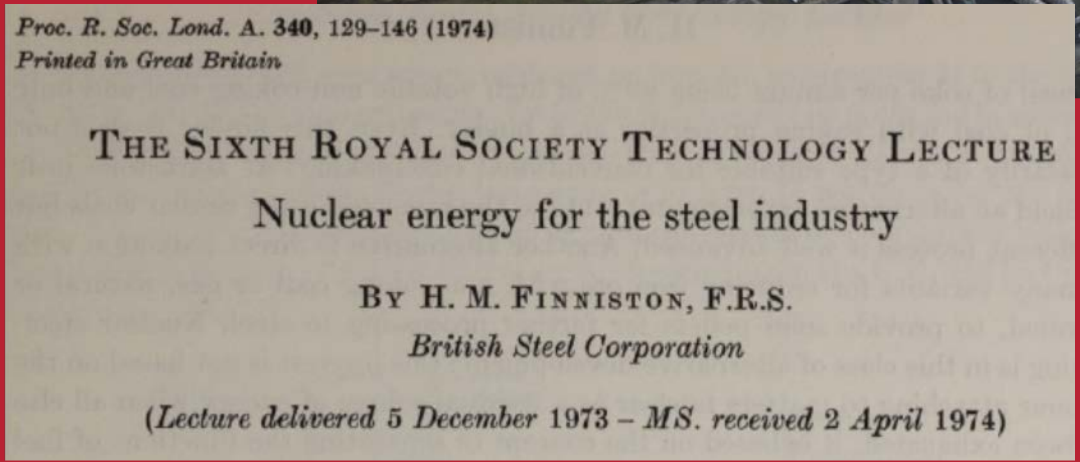
- Part of RS low carbon energy programme producing a number of accessible briefing documents for Government.
- Cogen committee chaired by Robin Grimes, members included David Orr/Alan Woods (Rolls-Royce), Ian Chapman (UKAEA), Gwen Parry-Jones (Magnox), Andy Storer (NAMRC), Roger Cashmore (Oxford), Bob Ainsworth (Manchester), Simon Taylor (Cambridge), Mike Bluck (Imperial), Bill Lee (Bangor).
- Briefing meeting 8th May 2019, workshop 25th Sept and follow-on meetings all at RS.
- Final draft "Nuclear Cogeneration: Civil Nuclear Energy in a Low Carbon Future" August 13th, final publication October 2020.



Co-Gen is not new (Michael Rushton)



- Historical Co-Gen papers for NI's Nuclear Futures journal to be published Nov/Dec 2020 and Jan/Feb 2021.
- Oct 20th 12.30-2pm Michael Rushton webinar with Nuclear Institute "Multi-role Nuclear Technology: Learning from Historical Co-Generation"
  - Calder Hall and Chapelcross
  - Anglesey Aluminium
  - Nuclear Steelmaking



Proc. R. Soc. Lond. A. **340**, 129–146 (1974)
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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)

Lessons Learned from Al Co-generation 1971-2009.

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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.**

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

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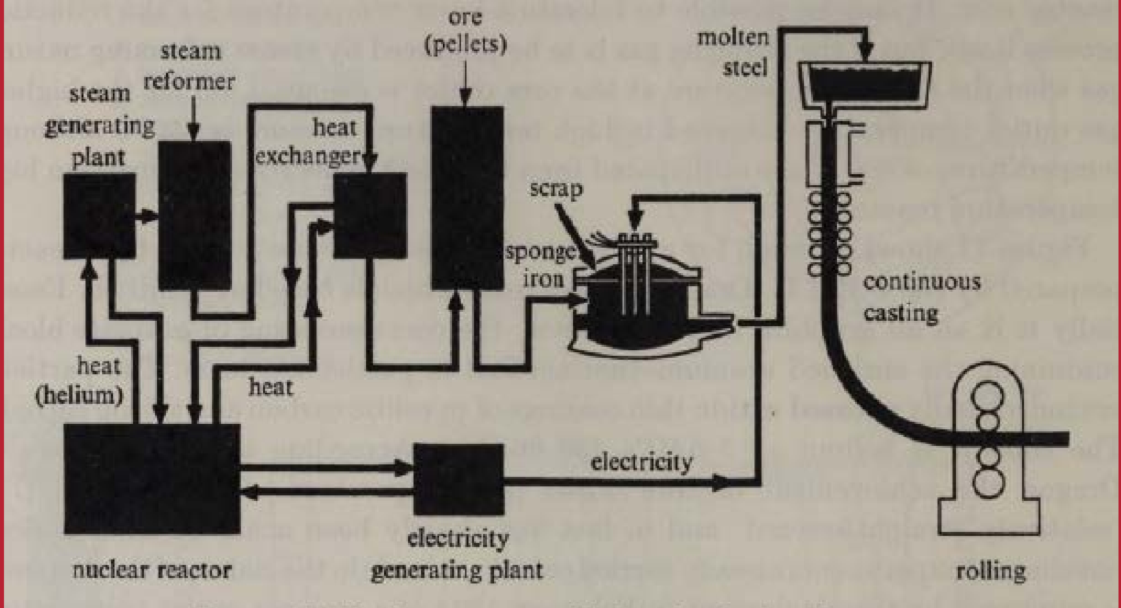
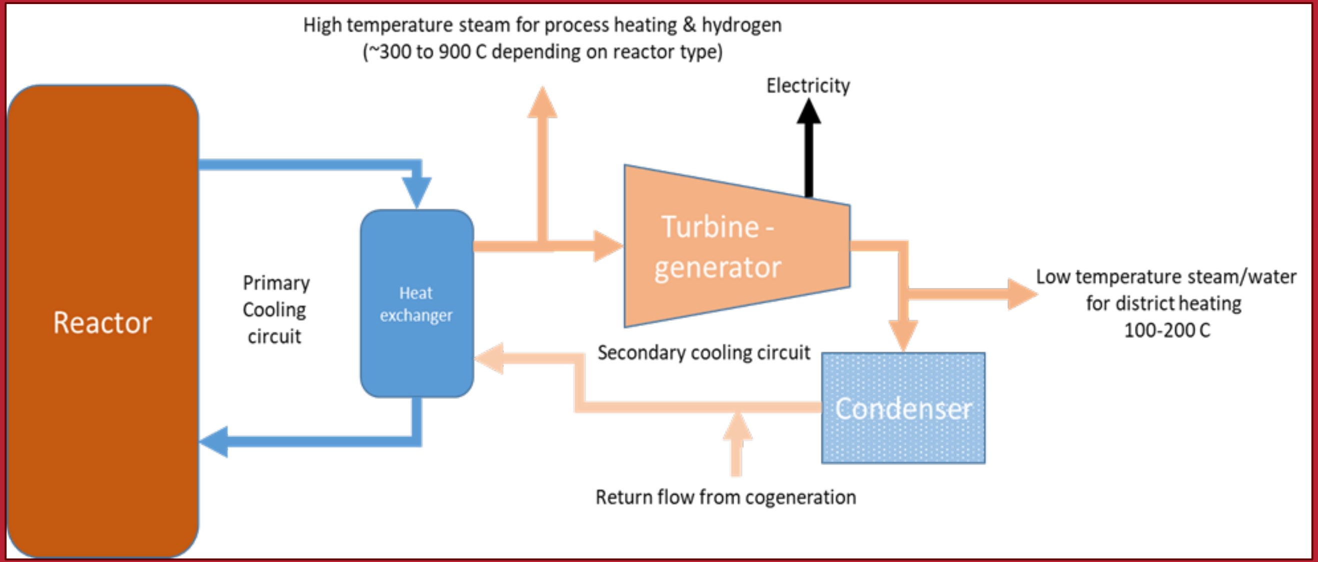
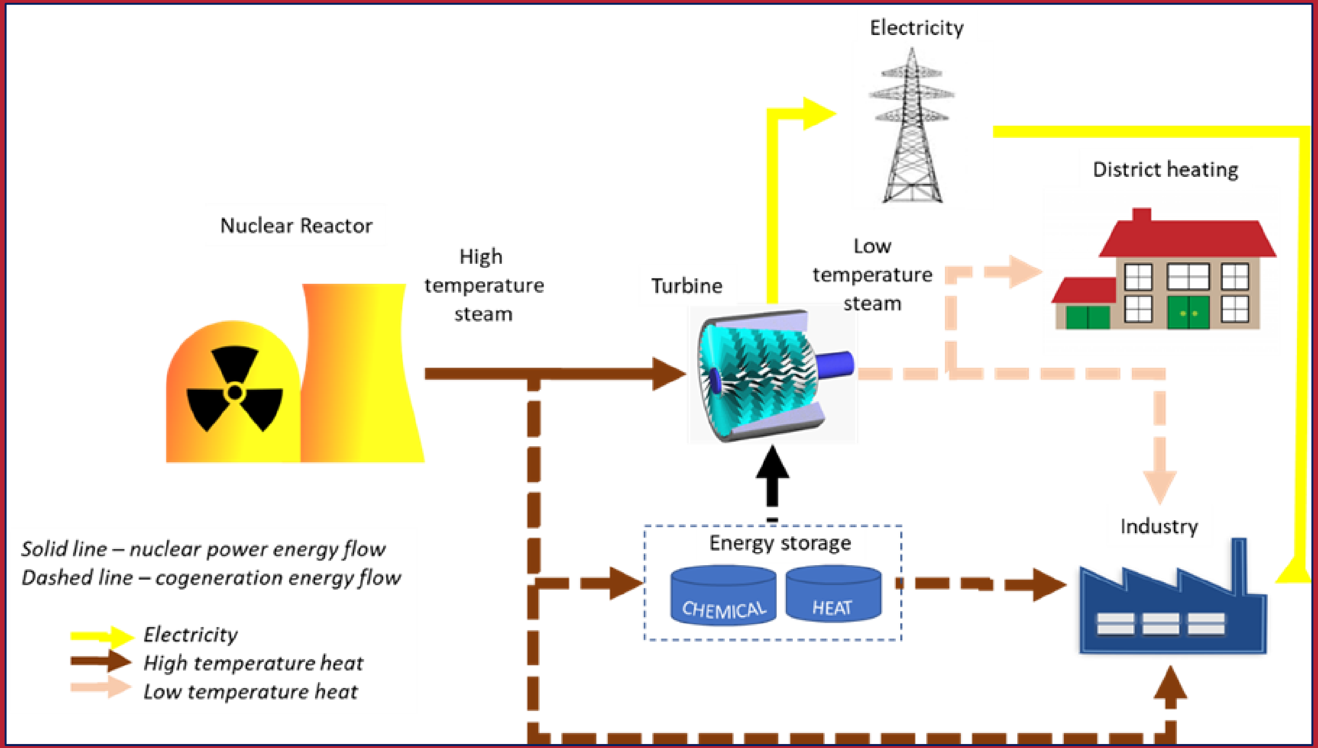


FIGURE 12. Nuclear power applied to the d.r./e.a.f. route.

RS Report Main Findings

- **Applications**
  - Low-temperature co-gen
    - District heating
    - Seawater desalination
  - High-temperature co-gen
    - Decarbonising industry through nuclear process heating
    - Hydrogen production
    - Sustainable synthetic fuel
    - Direct Air Capture of CO_2
    - Thermal energy storage
  - Medical Isotope production
- **Challenges**
- **Conclusions**





Low-temperature Co-Gen: District Heating

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- 18% of UK carbon emissions from home heating
- Nuclear experience mainly in cold climates (Sweden, China etc.)
- Could be considered in UK with SMRs.

District heating used from Haiyang NPP in Shandong province, China eventually will heat all houses in city (population 300,000)

Low-Temperature Co-Gen: Seawater Desalination

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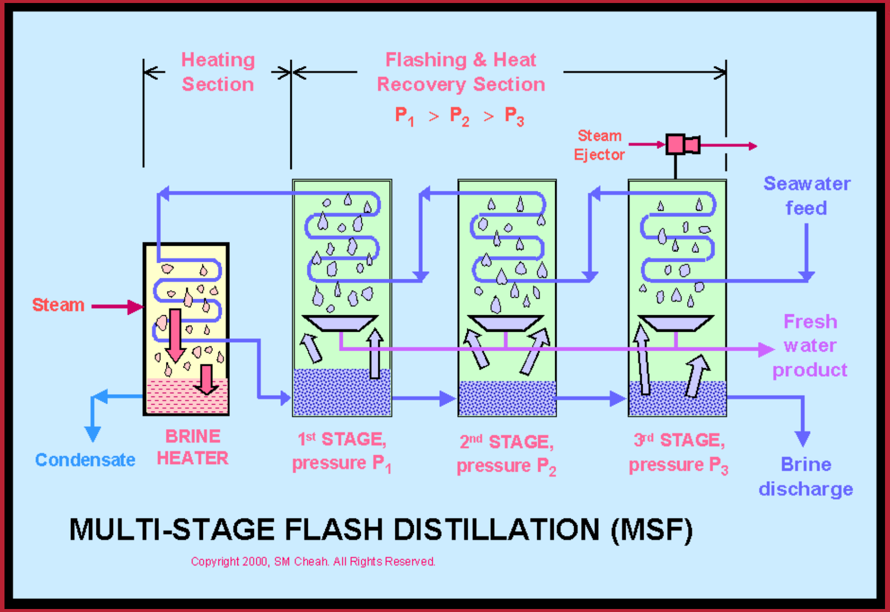
- Use low temperature steam/heat in thermal processes:
  - Multi-Stage Flash (MSF),
  - Multiple Effect Distillation (MED).
- Use electricity to drive membrane processes:
  - Reverse Osmosis (RO).
- Most current desalination plants use fossil fuels so contribute to global warming.
- NPP desalination first used at Ohi NPP Japan in 1978, 1175 MWe PWR coupled to MSF distillation plant with capacity of 1300m³/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 m³/d for on-board use.
- Main opportunities for NPP identified as the 80-100,000 m³/d and 200-500,000 m³/d ranges.
- Not needed in UK.

High-temperature Co-Gen: Industrial Process Heating

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- Contributes 14% UK carbon emissions
- 50% of UK industrial process heat used by energy intensive users (e.g. iron and steel, ceramics, cement, lime etc.).
- Typically need high temperature heat (>400ºC) so favours HT reactors (and UK has good experience with AGRs).
- Could cluster industry around the reactors in areas with energy intensive industries e.g S Wales, Hartlepool.
- Costs competitive but issues with
  - Cross sector regulation of nuclear and energy intensive industries
  - Ideally use proven nuclear technology
  - Need sound, long term investment case.
- Research opportunity e.g. safety and regulation.

High-temperature Co-Gen: Hydrogen Production

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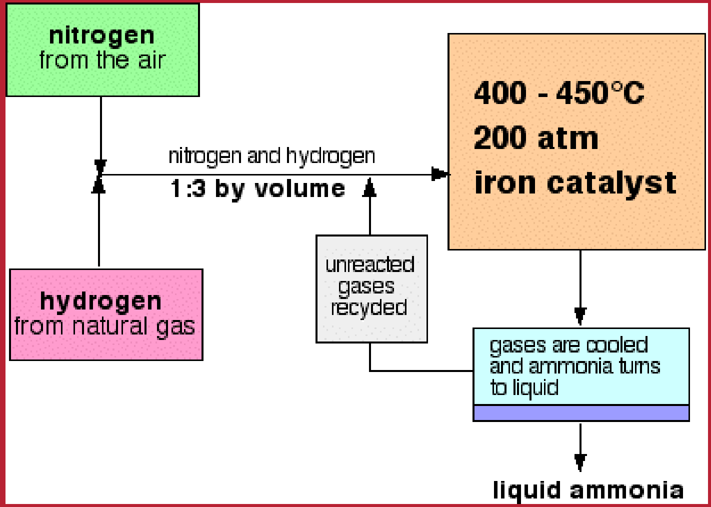
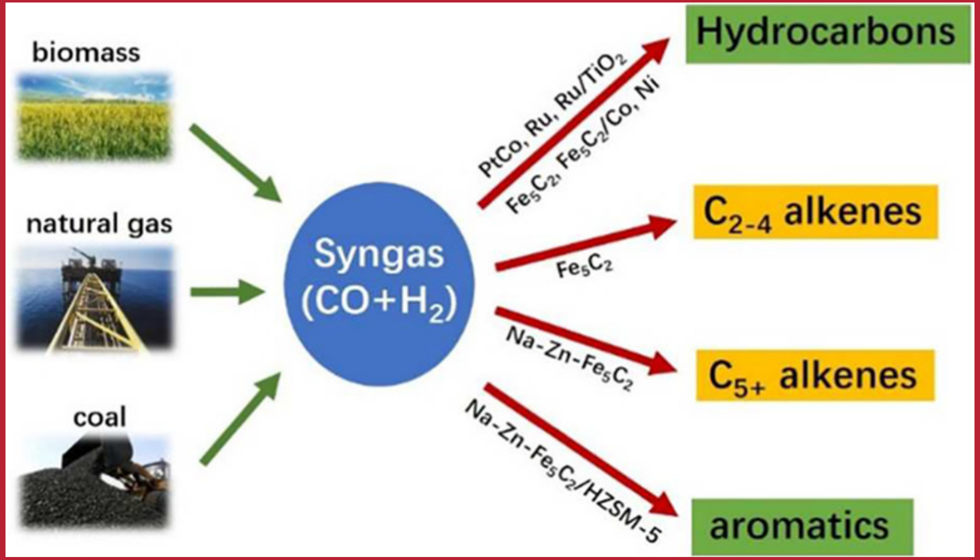
- Moving towards hydrogen economy
- Hydrogen from nuclear via
  - Water electrolysis
  - Steam (600-1000ºC) electrolysis more efficient than water
  - Thermochemical (e.g. S-I, Cu-Cl and hybrid S cycles) using nuclear heat and small amount nuclear electrolysis
  - Steam reform fossil fuels using nuclear heat – hydrogen from methane and need CCS
- Research opportunity e.g. materials for high temperature and corrosive environments

High-temperature Co-Gen: Synthetic Fuel Production

- **High-temp heat to produce feedstocks:**
  - Single molecule e.g. ammonia via Haber-Bosch process which uses N from the air and H from natural gas at 400-450ºC with iron catalyst at 200 atm

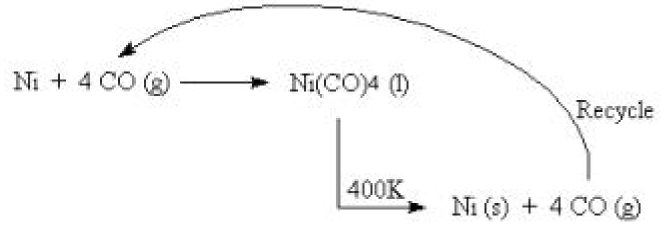


  - Complex molecules e.g. synthetic fuels for transportation (shipping, aircraft) via Fischer-Tropsch process which converts CO + H_2 to liquid hydrocarbons at 150-300ºC in presence of metal catalyst at ~20 atm.



High-temperature Co-Gen: Direct Air Capture of CO_2

- **Both liquid solvent (LS) and solid sorbent (SS) technologies are energy intensive requiring 80% thermal 20% electricity energy split.**
- **LS needs T up to 900ºC, SS < 150ºC.**
- **Sequester or reuse captured CO_2 e.g. as feedstock for polymers or convert to CO and use in Mond process to extract and purify Ni.**



Ni reacts with CO (leaving the impurities behind), to form $Ni(CO)_4$.

The $Ni(CO)_4$ is passed through a tower filled with nickel pellets at a high velocity and 400 K. Pure Ni plates out on the pellets.

High-temperature Co-Gen: Thermal Energy Storage

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- Store thermal energy from NPP for later use or as buffer in Co-Gen applications.
- Already deployed alongside concentrated solar power stations but limited to sunny locations.
- Various storage media being examined e.g. clay-based refractory brick chequer work, molten salts, phase change materials etc.
- Research opportunity e.g. to assess potential and safety of operation.

FIRES – FIrebrick Resistance heated Energy Storage – Forsberg MIT

Medical Isotopes

- **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

Medical Isotopes

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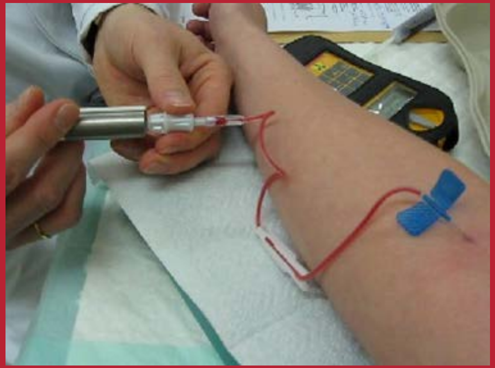
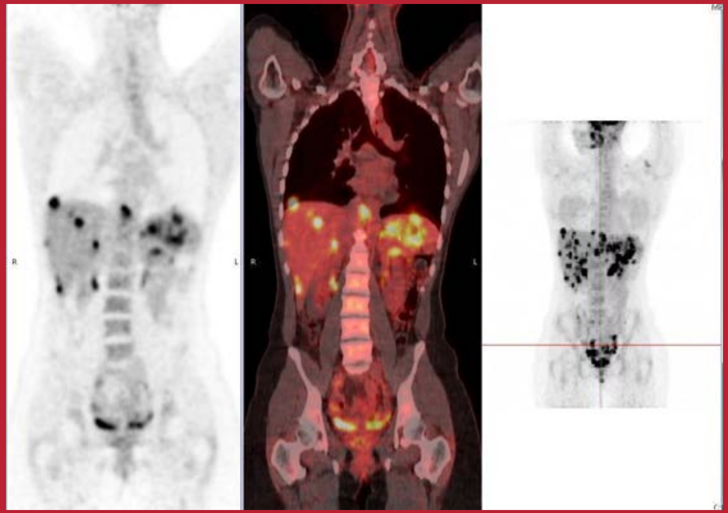
- Radio-isotope market supplied by research reactors which use neutrons to generate isotopes in Mo metal targets.
- UK (Harwell) supplied most of Europe in 1950's while Amersham became important in 1960's and due to its profitability was privatised by Thatcher Government in 1981.
- ^{99}Mo and ^{99}Tc 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 EU.
- 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 EU).
- 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 so opportunity to create UK facility (BEIS process).



Injecting ^{99m}Tc tracer using shielded syringe



Challenges

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- Safety and Security
- Regulation
- Waste reuse, recycle and disposal
- Economics
- Public attitudes and behavioural science opportunity
- Need to coordinate UK Co-Gen R&D perhaps via a Centre of Excellence

Conclusions

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- Nuclear is needed to meet Net Zero by 2050 target
- 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.
- New reactors can be designed and built with Co-Gen included.
- Many opportunities to decarbonise industry, improve living conditions and quality of life.

Bangor University Sêr-Cymru Positions Available 2020

UNDEB EWROPEAIDD
EUROPEAN UNION
Llywodraeth Cymru
Welsh Government
Cronfa Datblygu Rhanbarthol Ewrop
European Regional Development Fund

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- Academics:
  1. Reactor Physics/Thermal Hydraulics
  2. Medical Isotopes and Nuclear Medicine
  3. Structural Integrity and Materials Processing
  4. Control and Instrumentation.

- PDRAs:
  1. Thermal hydraulics and reactor design
  2. Policy, Regulation and Safety, Safeguards and Security (SSS)
  3. Functional Materials for Sensors
  4. Nuclear Co-generation
  5. Structural Integrity (finite element modelling)
  6. Nuclear Glasses
  7. Nuclear Medicine
  8. Control and instrumentation

- Technical Support:
  1. Lab based
  2. Computer based
  3. Senior experimental officer

For more information see https://nubu.nu and contact Prof Bill Lee, b.lee@bangor.ac.uk