U-BATTERY®
Local Modular Energy

Netherlands Nuclear Society & KIVI Kerntechniek

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UBATTERY Local Modular Energy

What are the choices? What is the answer?

- Renewables
- Large Light Water Reactors
  - Existing and New Build
  - Robust (Accident Tolerant) Fuels
- Small Modular Reactors (Light Water)
- Advanced Modular Reactors
  - High Temperatures Gas Cooled Reactors
  - Molten Salt Reactors
  - Supercritical-water-cooled Reactors
  - Gas-cooled Fast Reactors
  - Sodium-cooled Fast Reactors
  - Lead-cooled Fast Reactors
- Fusion?

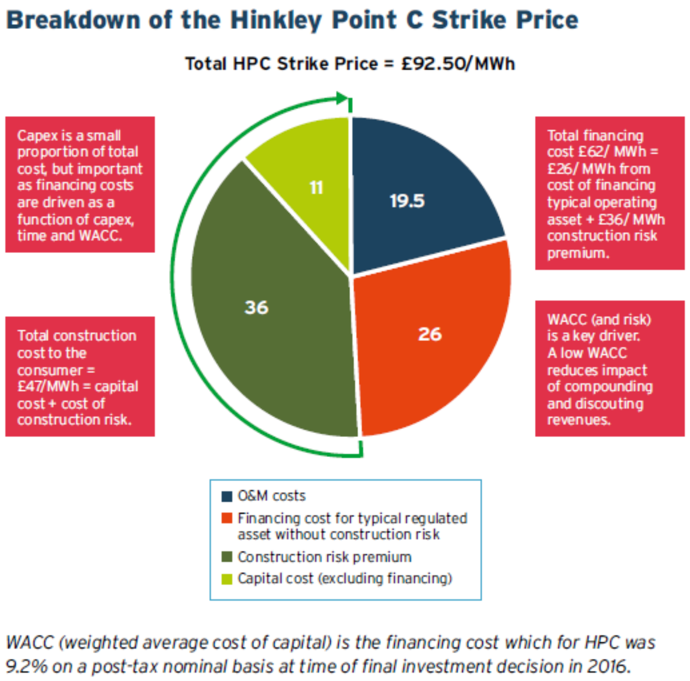
What is the Question?

In 2009, Dr Helmut Engelbrecht (Urenco CEO) set a challenge to the Universities of Delft & Manchester to design a novel small nuclear reactor:

- Small enough to be road-transportable
- Capable of providing process heat and/or electricity
- Safe enough to be built anywhere (hospitals, schools, etc.)
- Capable of autonomous operation for extended periods
- Capable of rapid re-fuelling (“like changing a battery”)
- Economically competitive with other forms of power generation
- Based on well-established technology

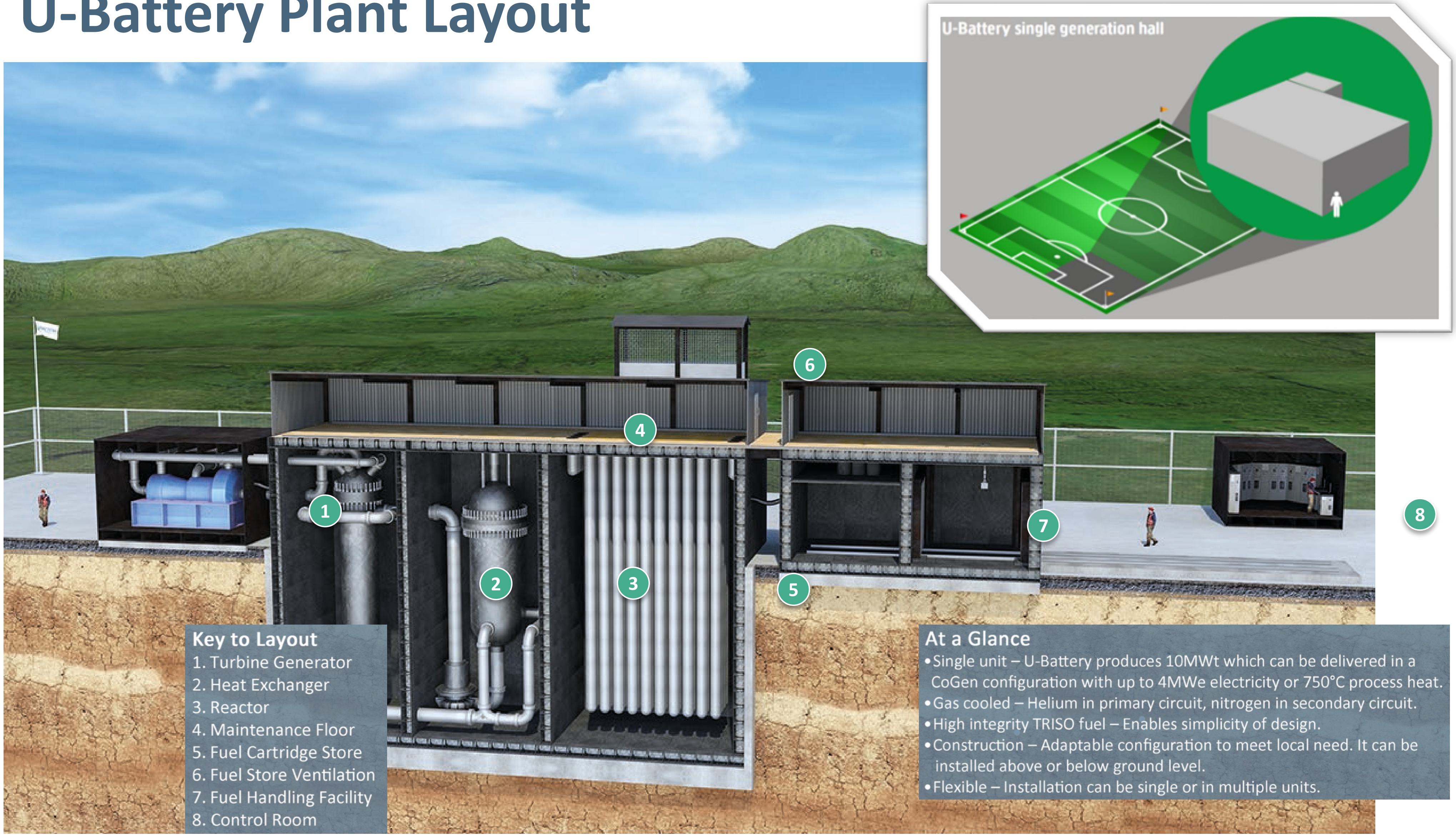
How Can a Small Reactor be Economically Viable?

- Simple design
- Robust TRISO fuel minimises engineered safety systems
- Low licensing cost – simple to demonstrate safety to regulator
- Short construction period
- Low construction risk – modular build, in-factory testing
- Autonomous operation
- On-site demand for power – avoid system cost.
- This justifies low cost of money and enables many sources!



Source - Nuclear Sector Deal: Nuclear New Build Cost Reduction

U-Battery Plant Layout



Key to Layout

1. Turbine Generator
2. Heat Exchanger
3. Reactor
4. Maintenance Floor
5. Fuel Cartridge Store
6. Fuel Store Ventilation
7. Fuel Handling Facility
8. Control Room

At a Glance

- Single unit – U-Battery produces 10MWt which can be delivered in a CoGen configuration with up to 4MWe electricity or 750°C process heat.
- Gas cooled – Helium in primary circuit, nitrogen in secondary circuit.
- High integrity TRISO fuel – Enables simplicity of design.
- Construction – Adaptable configuration to meet local need. It can be installed above or below ground level.
- Flexible – Installation can be single or in multiple units.

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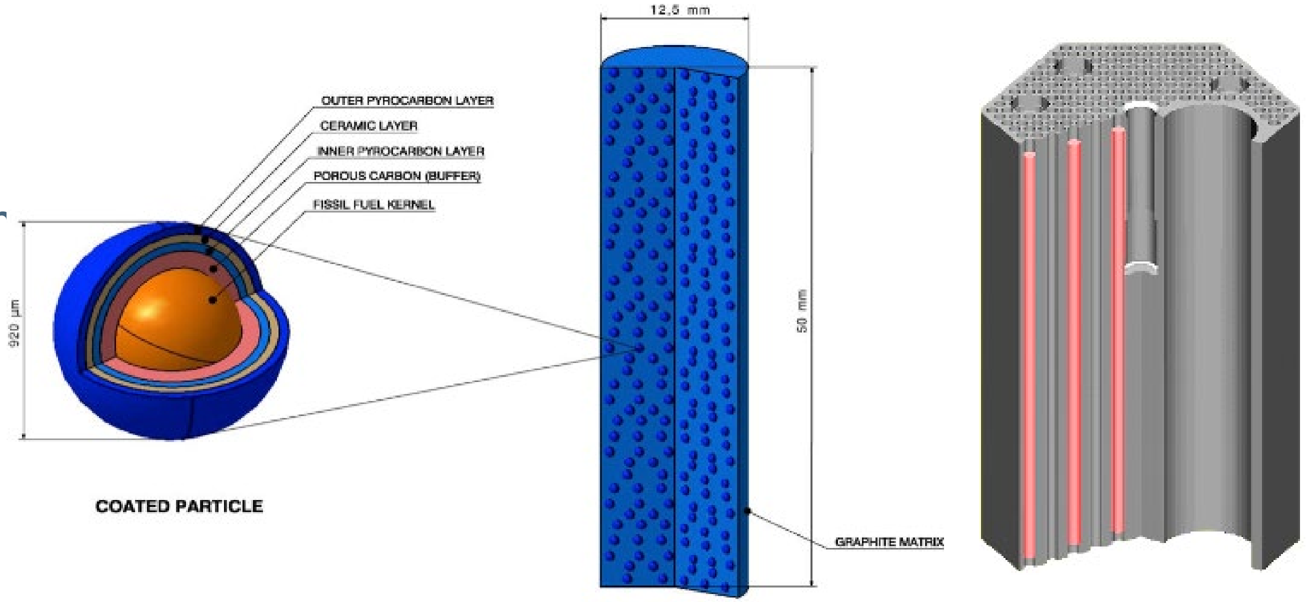
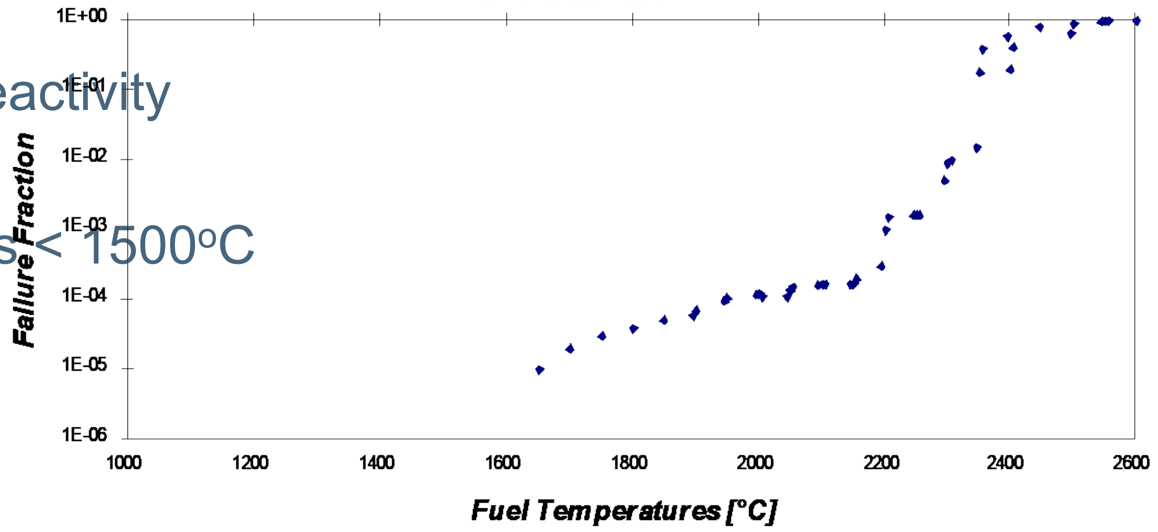
Two pillars of safety

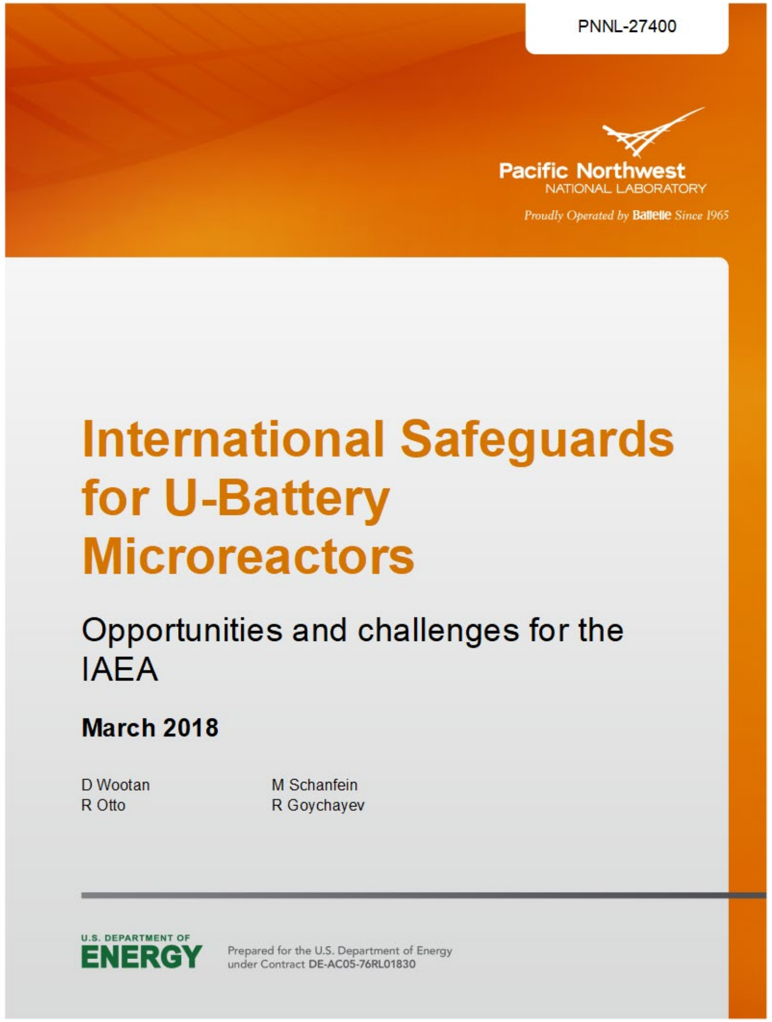
- **Highly accident-tolerant fuel**
  - TRISO fuel: retains fission products to tem
  - Structural integrity retained to > 2000^0C
- **Inherently safe plant design**
  - Small thermal power output (10 MWt)
  - Low core power density
  - High thermal capacity of graphite structures
  - Strongly negative temperature coefficient of reactivity
  - Refractory core materials
  - Maximum temperatures in design basis events < 1500^oC





Security

- No long-term on-site storage of fresh fuel
- Very small quantities of fissile material on site.
  One operating and one spent core together are less than the IAEA definition of a Significant Quantity for U+Pu (c.f. 2 SQs for a single PWR fuel assembly)
- No on-site access to specialised tooling required to remove RPV head and handle fuel elements
- Fuel transport flask (TN 7-2) capacity is limited: three shipments required to transport a single core
- Very difficult to extract fissile material from the fuel
- Independent review by Pacific Northwest National Lab confirms “no serious nuclear proliferation obstacles to deployment of the system in remote locations“


PNNL-27400

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

International Safeguards for U-Battery Microreactors

Opportunities and challenges for the IAEA

March 2018

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Timeline

2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Marketing — Development — Deployment

Activities	Building of consortium Marketing and opportunity assessment	Development of basic design Cost review Pre-Licensing, Safety and Security Commercial viability of fuel cycle*	Development of detailed design Licensing UK GDA plus site or Canada site	Construction of first-of-a-kind (FOAK)	Deployment of business in target geographies
Funding	Urenco Seed funding €5M	Urenco, Govt and Partners €20-25M	Phase 2 €20-30M	Phase 3 €80-100M	Project Financing

Total ~€120-160M (equity, debt, matched funding, grants

** Fuel cycle means HALEU enrichment, working with partners on de-conversion and TRISO fuel fabrication, including transport packages*

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Key UK Government engagement

- UK Government Advanced Modular Reactor (AMR) Competition, part of the Energy Innovation Portfolio
- Second half of 2018, U-Battery one of eight vendors selected to participate in phase 1, developing a feasibility study that made the technical and commercial case for the design
- July 2020 - U-Battery progressed to Phase 2
- £10m awarded for design and development work
- Additional funding from BEIS to design and build mock-ups of the two main vessels for the reactor and the connecting duct

The markets

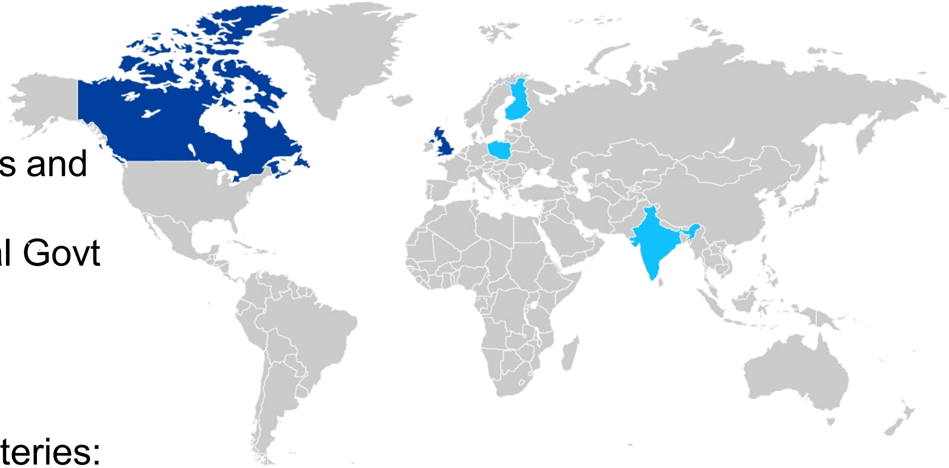
Sizeable early markets for deployment

Canada

- Replacement of 600 very high cost diesels used in remote communities and mining.
- Strong interest by Federal and local Govt
- Registered for pre-licensing (VDR)
- Favorable regulatory environment

UK

- Potential for industrial use of U-Batteries: **glass, ceramics, chemicals, paper, etc to total 50-200.**
- Generic Design Assessment process being streamlined.
- Experience in gas-cooled reactors
- Government funding for design and support for manufacture.



Potential markets for expansion

Poland

- Seeking reduction of carbon emission and long-term energy independence
- U-Battery identified by Polish authorities as potential solution

India

- U-Batteries identified as potential solution for self-contained communities

Finland

- Interest expressed by Govt.

Later large markets

- Many mines, developing nations in Africa/Asia and island nations.

Canada and UK market potential confirmed by market studies and Canadian Roadmap

Canadian and UK early markets

Remote communities and mines

Oil sands

- Steam for SAGD and electricity for upgrading **at 96 facilities**
- 210 MWe average size for both heat and power demands
- 5% replacement by SMRs between 2030 and 2040 could provide **$350-450M in value annually**

Remote communities and mines

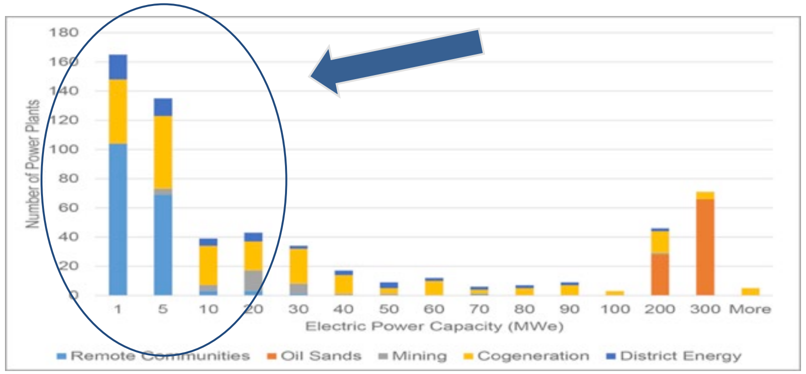
- 79 remote communities in Canada with energy needs > 1 MWe
- SMRs replacing costly diesel and heating oil could **reduce energy costs to the territorial government**
- **The high cost of energy from diesel is a barrier. SMRs could facilitate and enable new mining developments**
- 24 current and potential off-grid mines

High-temperature steam for heavy industry

- 85 heavy industry locations (e.g. chemicals, petroleum Refining)
- 25-50 MWe average size
- 5% replacement by SMRS between 2030 and 2040 **could provide $46M in value annually**

Replacing conventional coal-fired power:

- 29 units in Canada at 17 facilities
- 343 MWe average size
- 10% replacement by SMRs between 2030 and 2040 could **provide $469M in value annually**



Source: NRCan Roadmap Nov 2018

Energy Intensive Industries needing process heat

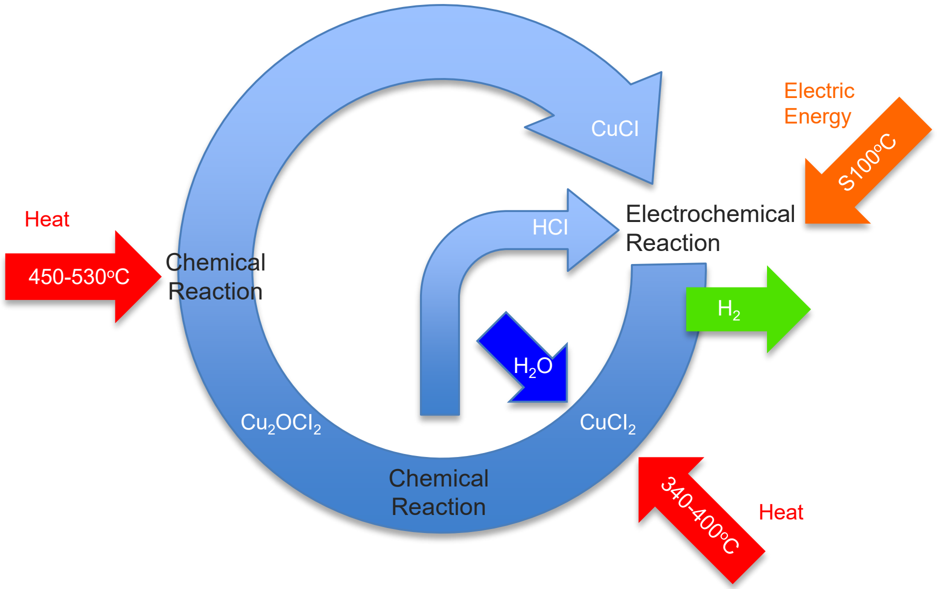
Alongside renewables, U-Battery can play a vital role in UK's transition to a clean energy future by providing process heat and electricity to Energy Intensive Industries.

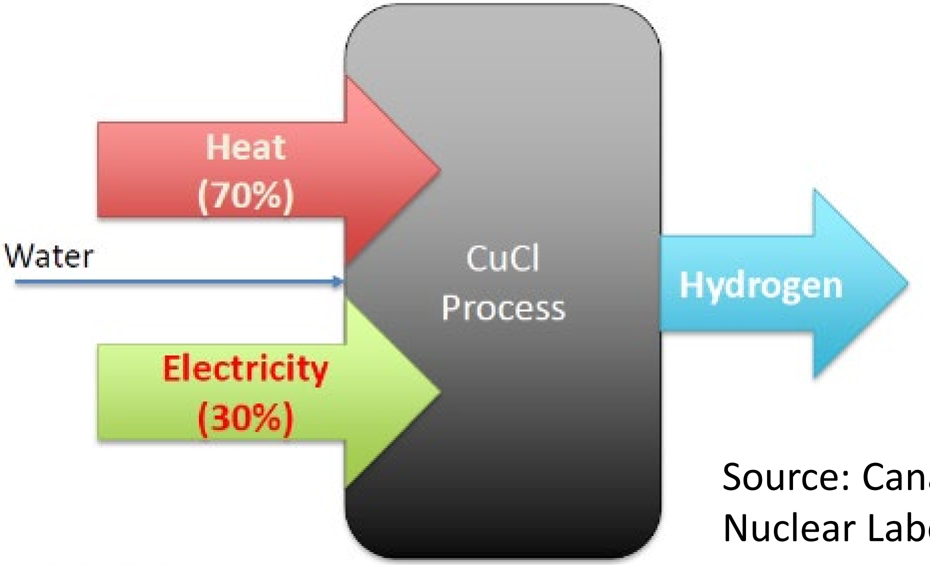
Sector	No. of U-Batteries	Use
Glass	14	Heating raw materials and annealing
Paper	20	Drying paper
Steel	20	Less likely – very sensitive to price
Ceramics	50	Process heat need 220-650^{O}C for drying and spray drying.
Minerals	10	Cement production
Chemical	Large and varied	Heating fluids at 450^{O}C

Source: University of Manchester Report – October 2018

Hydrogen - Copper chloride process

- The U-Battery heat and power CHP output is very well suited to hydrogen production, most likely when co-located and process matched to the copper chloride production cycle.
- Provides an alternative production to electrolysis or carbon based methane reformation
- Avoid the need for the expense and operational constraint of backend carbon capture and storage

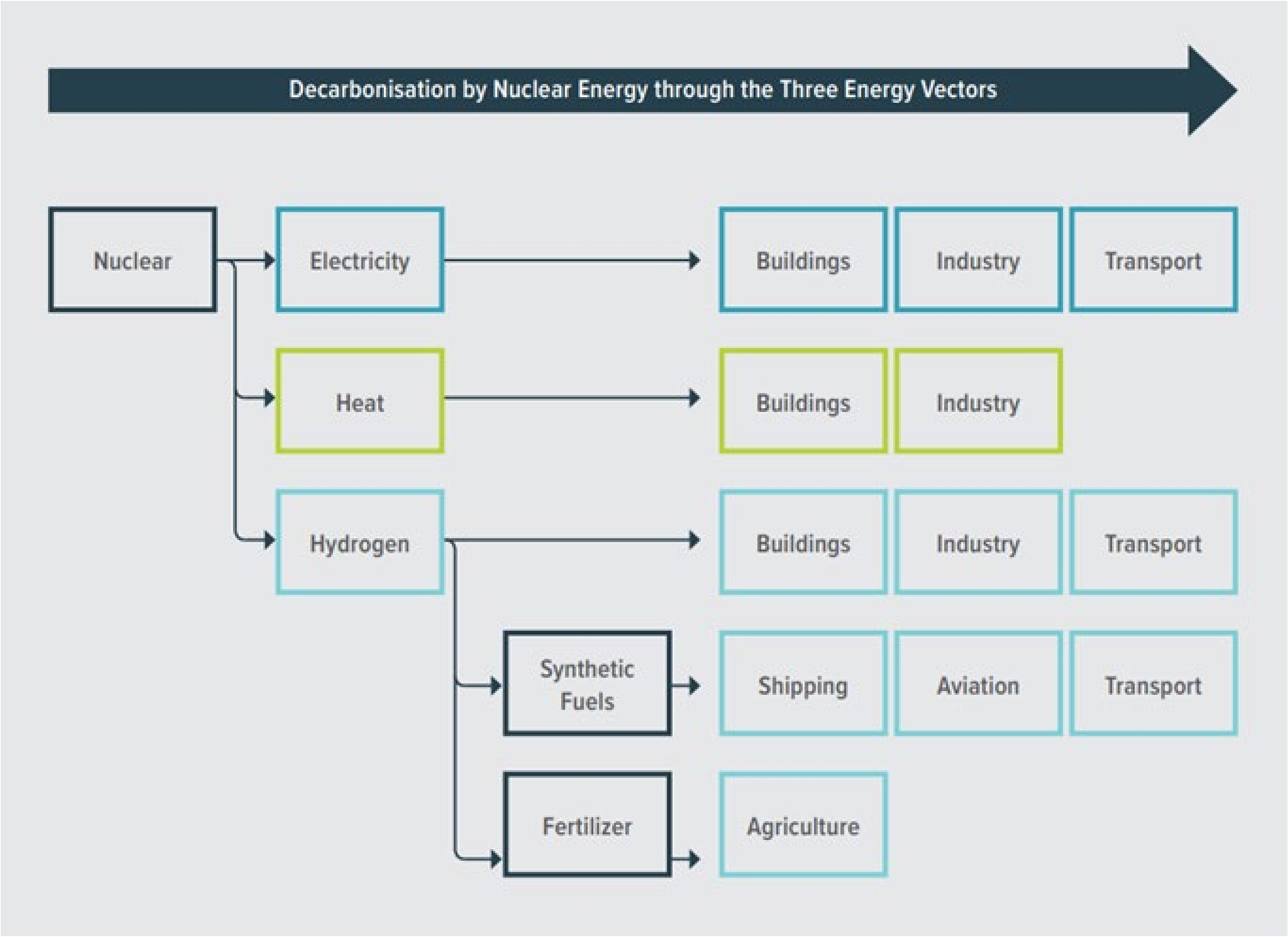




Source: Canadian Nuclear Laboratories

Final thoughts on the future of nuclear

- Very difficult to decarbonise some sectors without nuclear.
- Nuclear perfectly complements renewables and hydrogen in a net zero world.



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Questions

Thank you for your time today.

Please visit www.u-battery.com