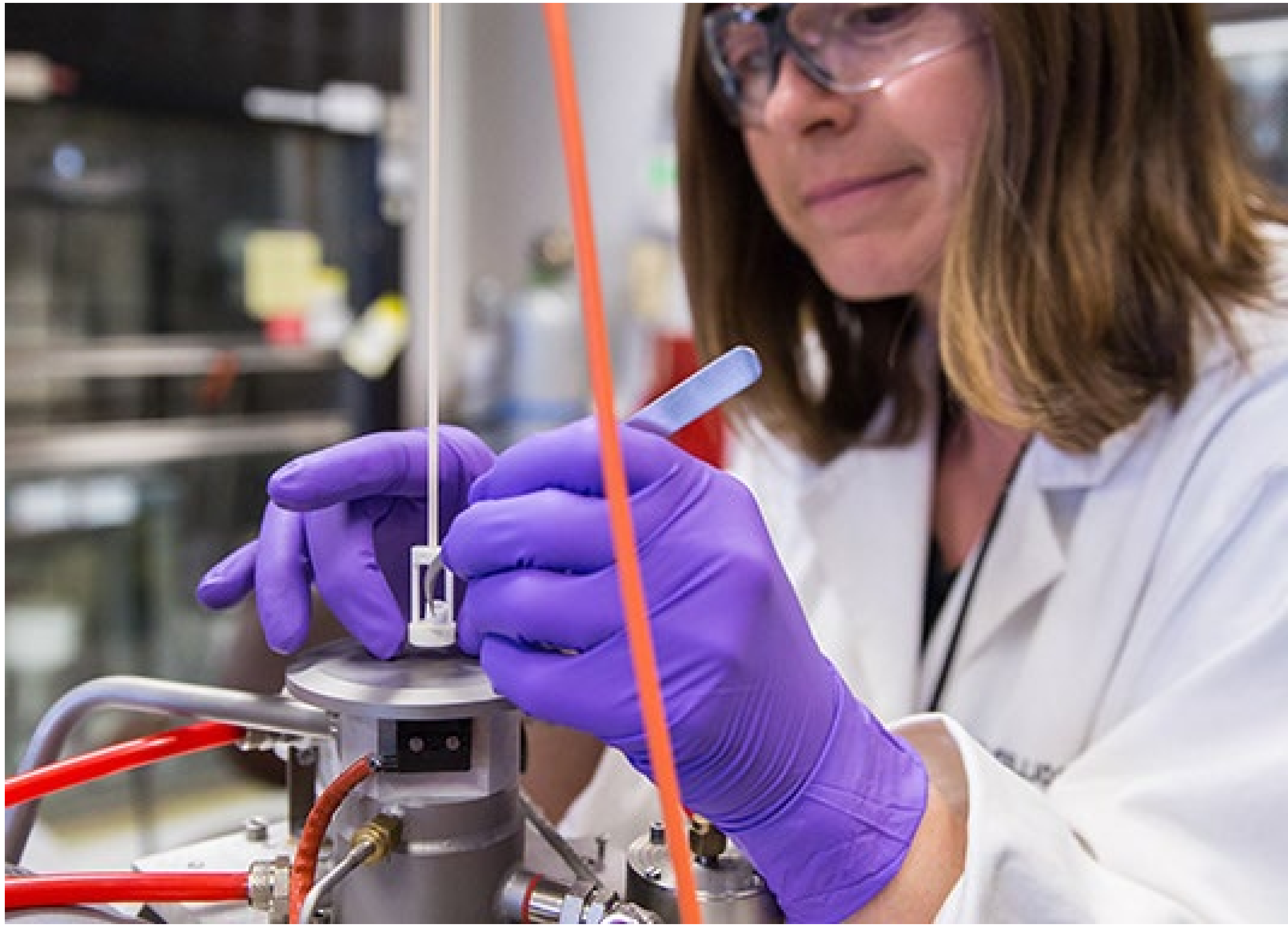
Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Small Modular Reactors for Industrial Applications

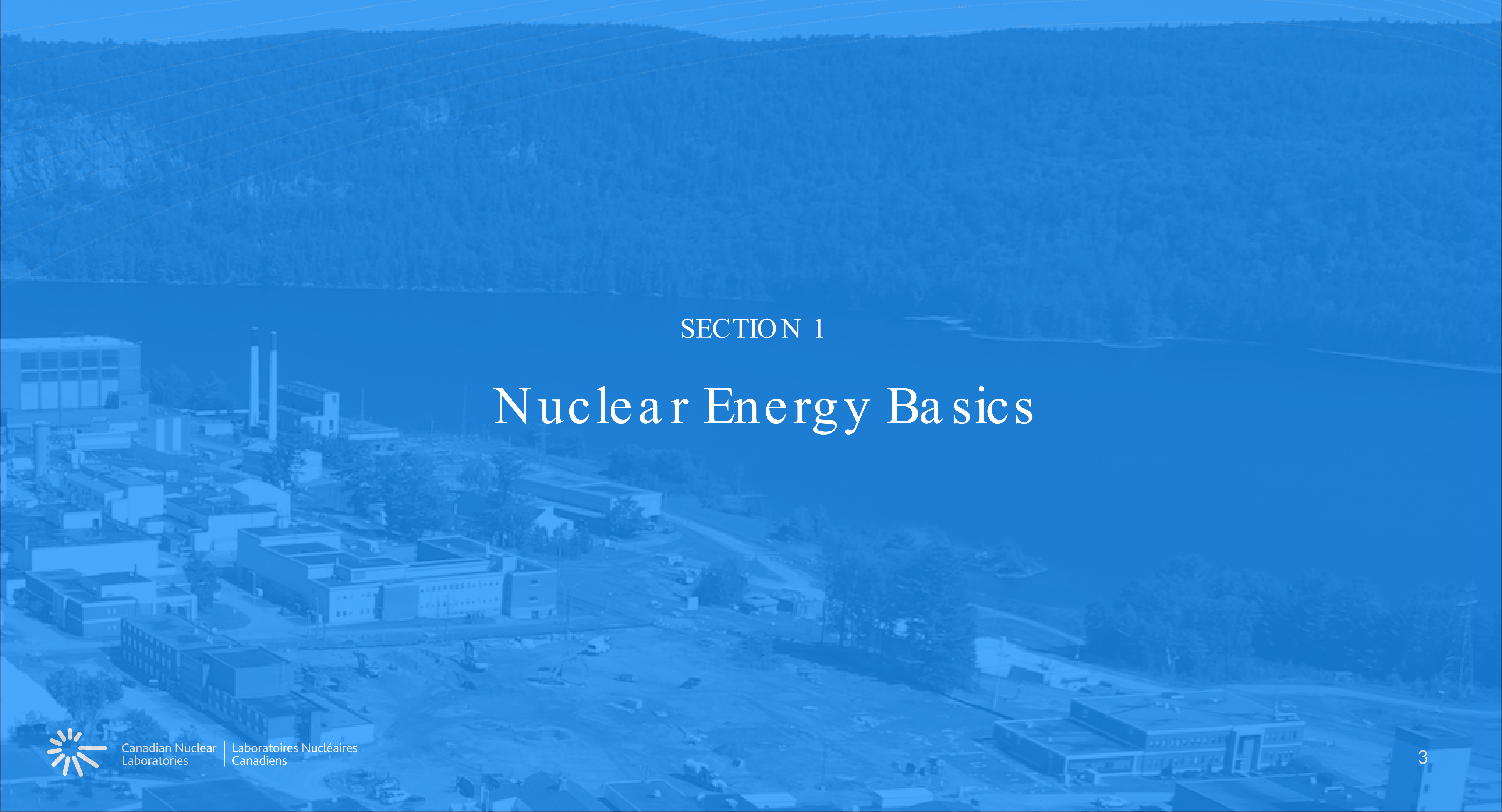


2025 Mining Vehicle Powertrain Conference

Travis Pettigrew
Operations Research Analyst
Advanced Reactors Directorate

Overview

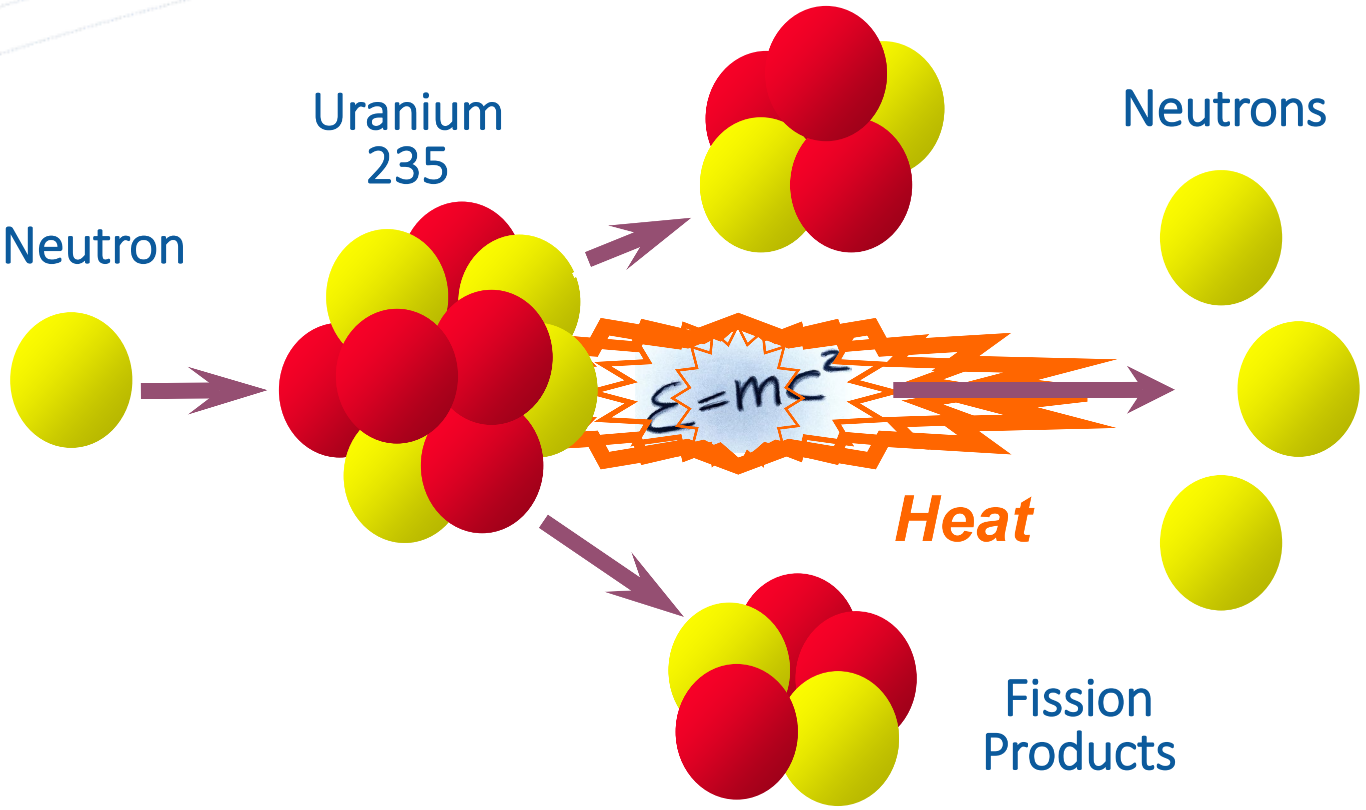
1. Nuclear energy basics
2. Energy landscape in Canada
3. Green Mining Case Study



SECTION 1

Nuclear Energy Basics

Nuclear Fission: A Clean Source of Energy



Neutrons do all the work!!!

Nuclear reactor technology is based on generating neutrons (via splitting atoms) and controlling neutron population.

Recipe for a Nuclear Reactor

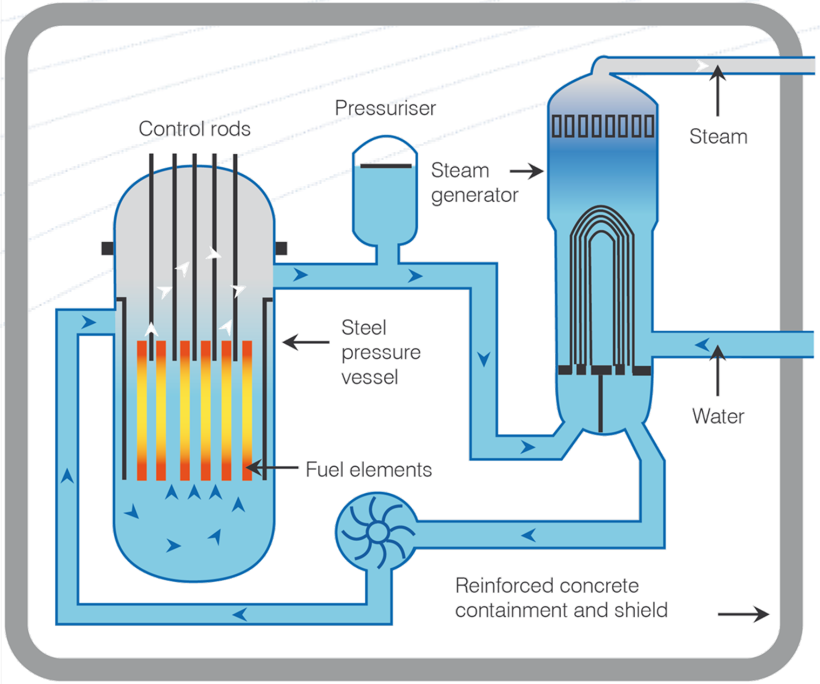
Fuel: Uranium, plutonium, thorium

Moderator: Water, graphite

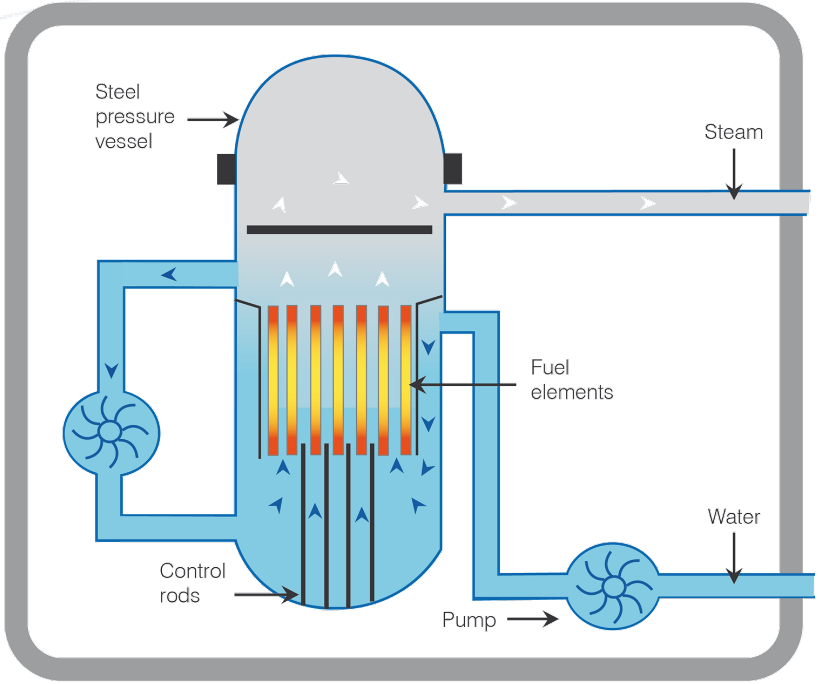
Coolant: Water, helium, molten-salt, liquid metal (Sodium, Lead)

Control Rods: Neutron absorbing materials like Boron or Cadmium

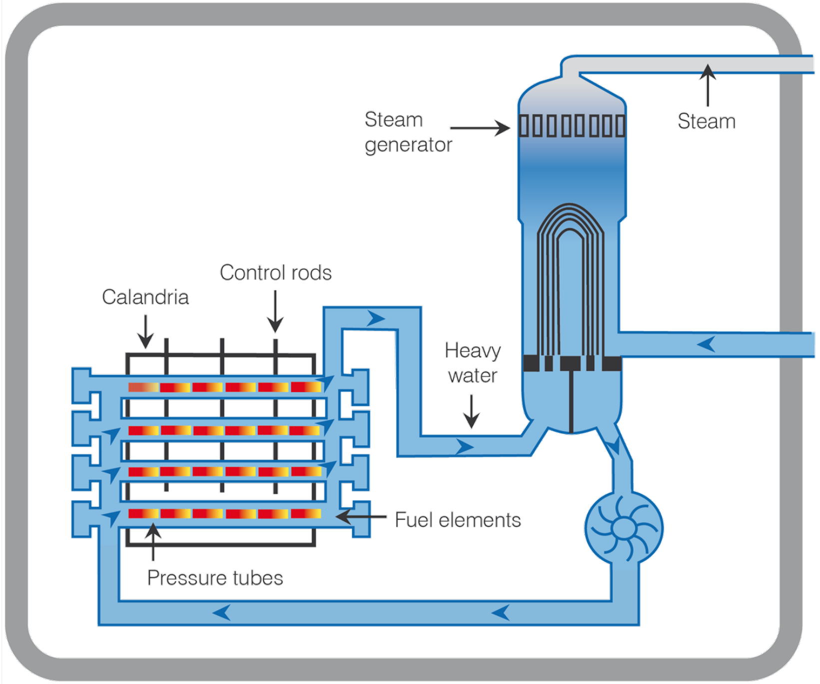
Water Cooled Reactors Most Prevalent Today



- Pressurized Water Reactor (PWR)
- 308 Operating



- Boiling Water Reactor (BWR)
- 61 Operating



- Pressurized Heavy Water Reactor (PHWR/CANDU)
- 47 Operating
- Coolant and moderator heavy water
- Fuel channels vs. reactor vessel
- Fuel is natural uranium

As of 2023 February 06, 95% (416 of the 438) of the global fleet of nuclear reactors is water cooled.

About 10% of the world's electricity is produced by 438 nuclear reactors (as of 2023 February)

Reactor Diagrams from World Nuclear Association

Water Cooled Reactors Most Prevalent Today

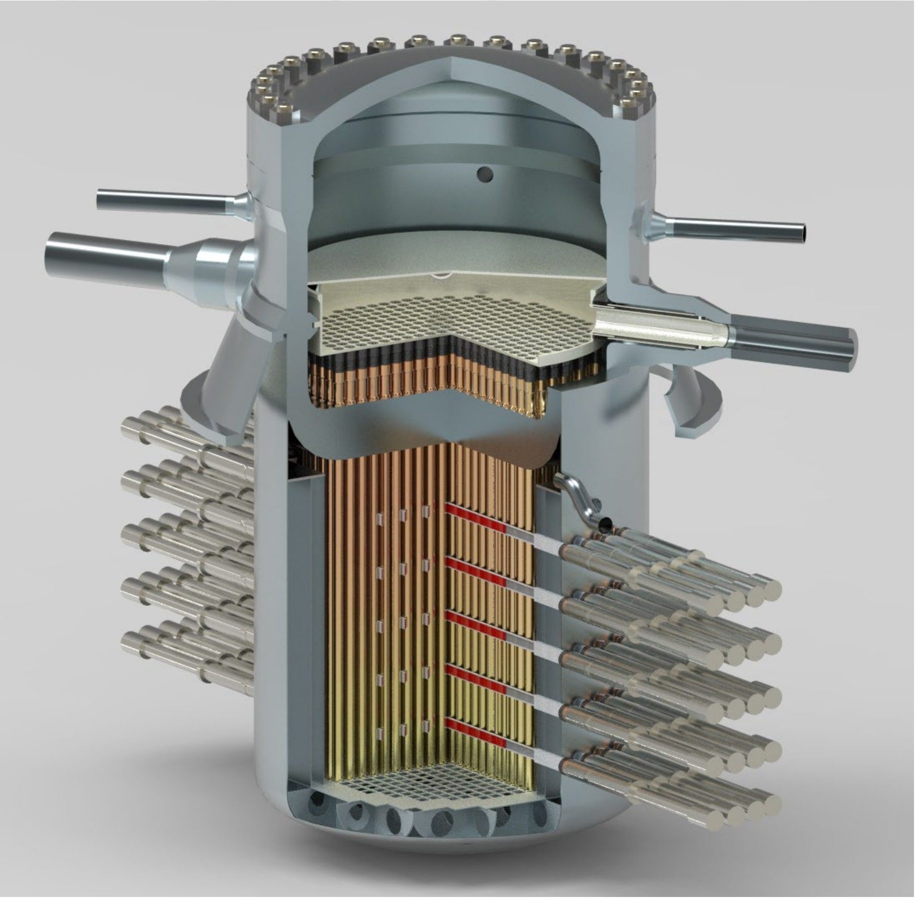


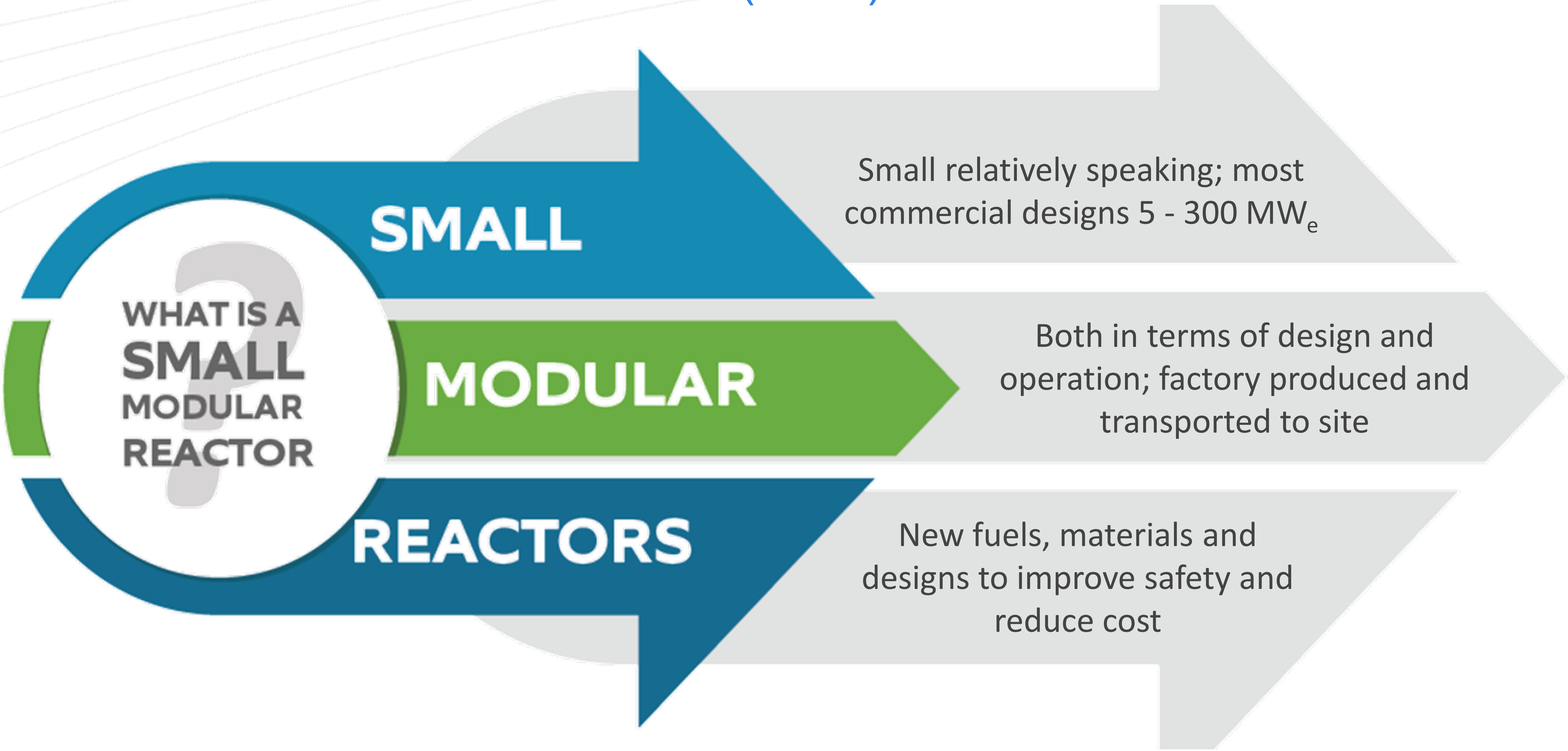
Photo: Canadian supercritical water-cooled reactor core concept

Advanced Reactors incorporate decades of progress in nuclear physics, materials science, system engineering, and computer controls.

Some examples:
- Advanced water-cooled reactors
- Sodium-cooled reactors
- Lead-cooled reactors
- Molten-salt reactors
- High temperature gas-cooled reactors

- Many incorporate innovative fuels, higher temperatures and long core life or other advanced fuel cycles.
- Small and large

What is a Small Modular Reactor (SMR)?



SECTION 2

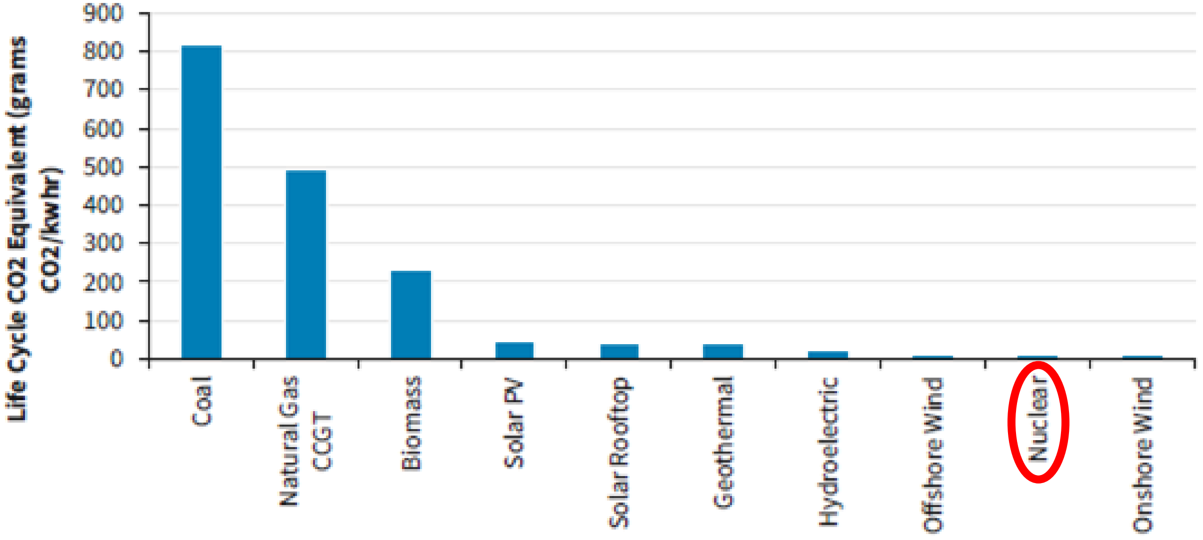
Energy Landscape in Canada

Why Nuclear?

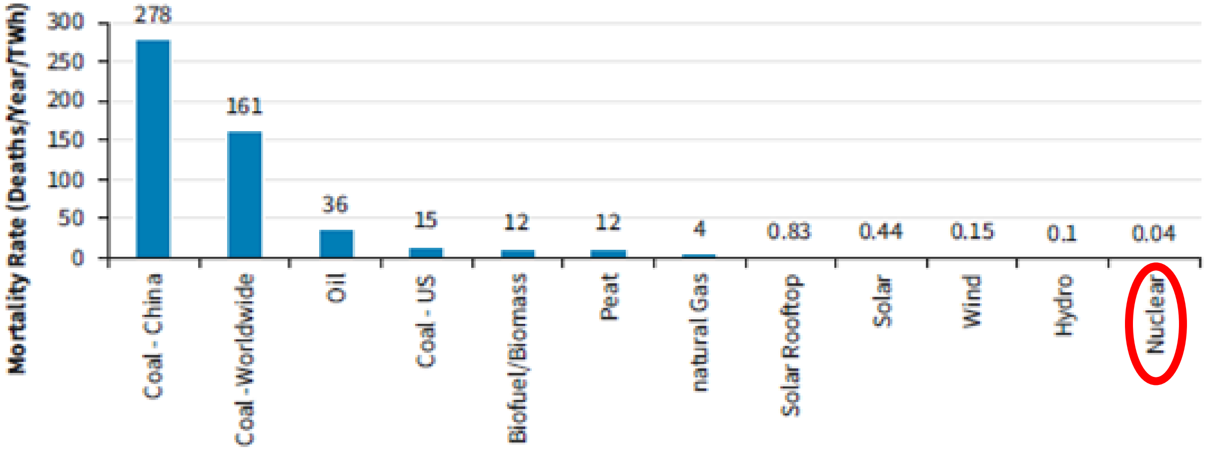
ADVANTAGES

- Actual safety record
- Lifecycle emissions
- Reliable/dispatchable
- Clean heat
- High energy density
- Long operating life
- Cost competitive
- Energy security
- Infrequent refueling (off-grid)

Lifecycle CO2 emissions intensity by generating technology (grams CO_2e/kWh)



Mortality rate by generation type (deaths/year/TWh)



DISADVANTAGES

- High upfront costs
- Long-term waste management
- Fuel availability (advanced reactors)
- Public perception / NIMBY
- Perceived safety risk

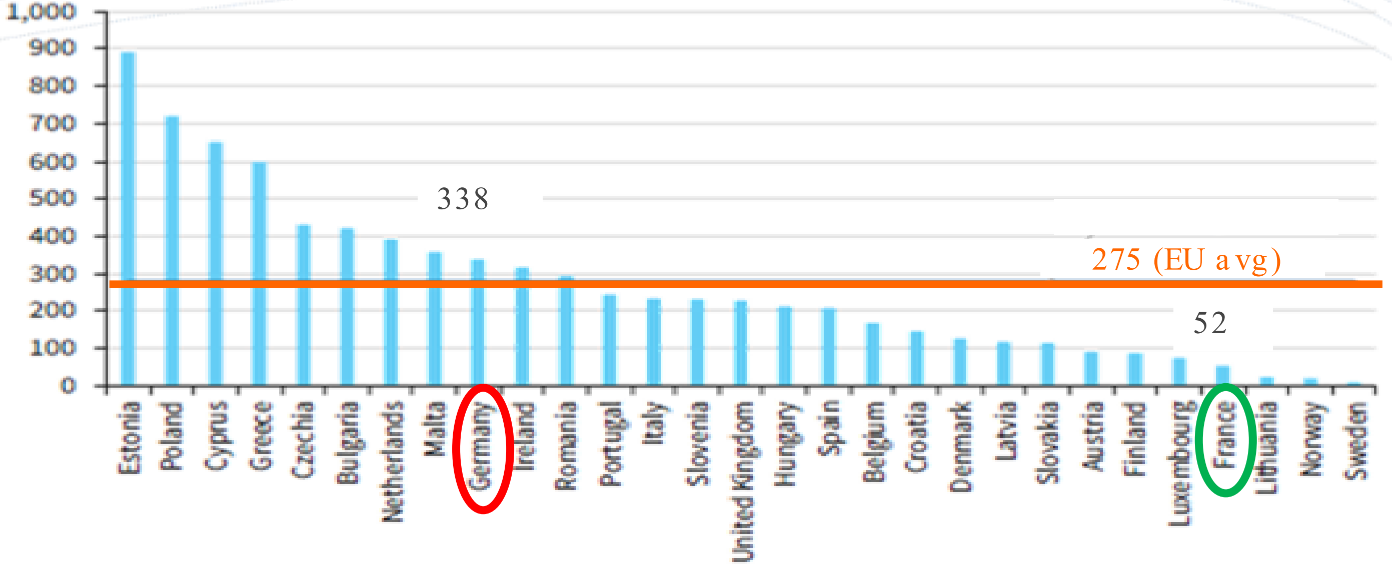
Figure ref:

- Barclays, Global Nuclear – Nuclear for a decarbonized future, Special Report, June 2021.

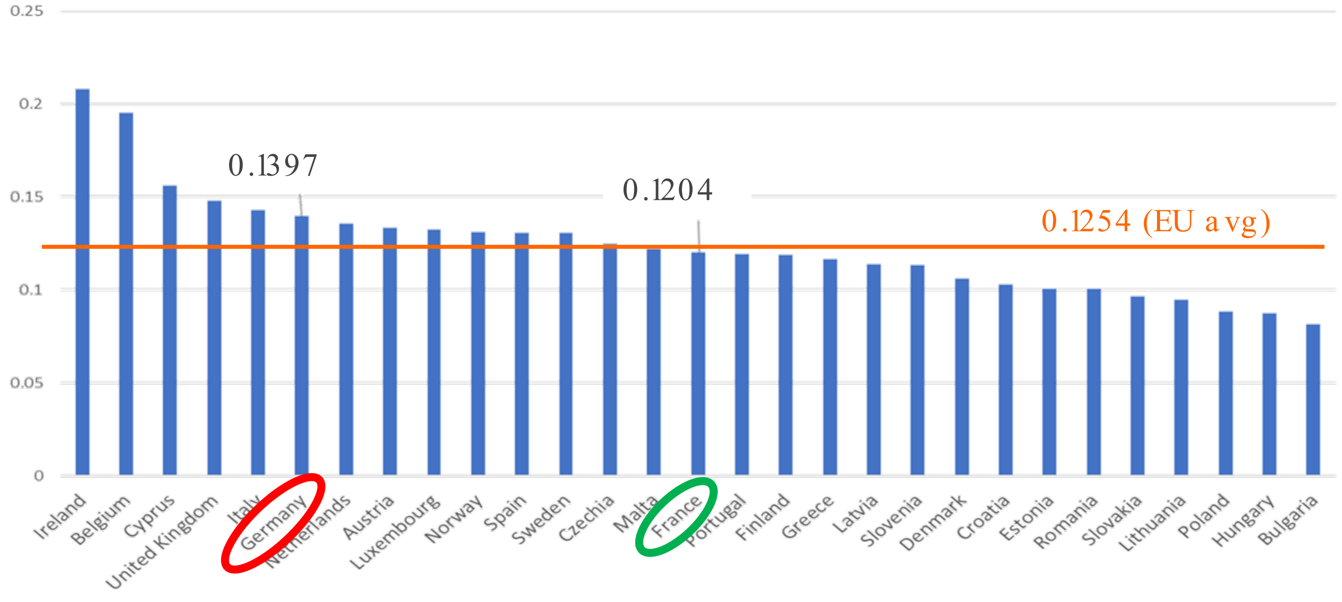
European Perspective

- Renewables are part of the solution, but cannot replace fossil fuels alone
- Clean firm power is a must
- Excluding nuclear can lead to fossil fuel dependence
- Together, nuclear and renewables are a winning strategy

European electricity carbon intensity (gCO2/kWh), 2019



Average consumer electricity price (EUR/kWh), 2019



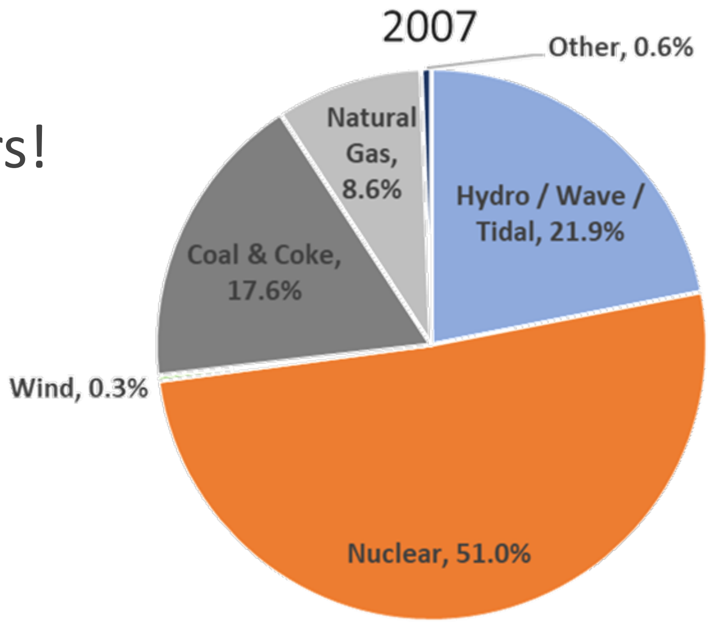
Ref:

- Barclays Special Report, Global Nuclear – Nuclear for a decarbonized future, June 2021.
- Eurostat Data Browser, Electricity prices for household consumers – bi-annual data (from 2007 onwards)

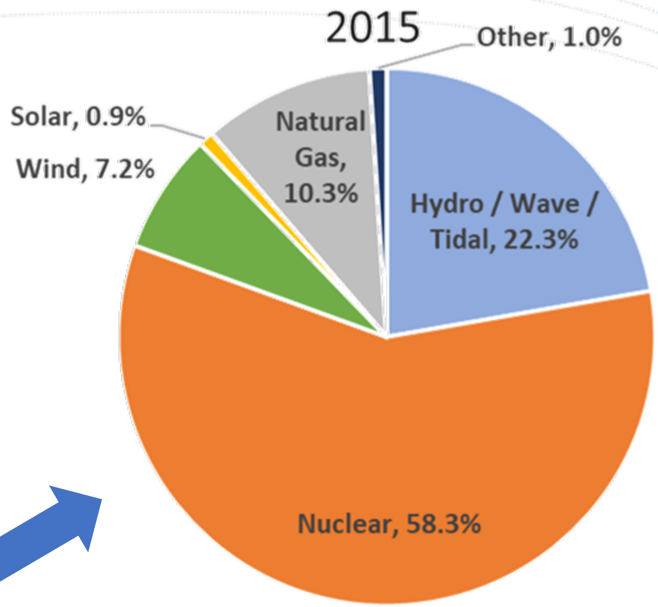
Canadian Historical Perspective

Ontario Grid Decarbonization

34% emissions reduction in 8 years!
Nuclear + renewables



120 Mt-CO_2eq
156.5 GWh



79 Mt-CO_2eq
157.4 GWh

Ref:

- Canada Energy Regulator, Canada's Energy Futures 2023, Electricity Generation.
- Government of Canada, National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada.

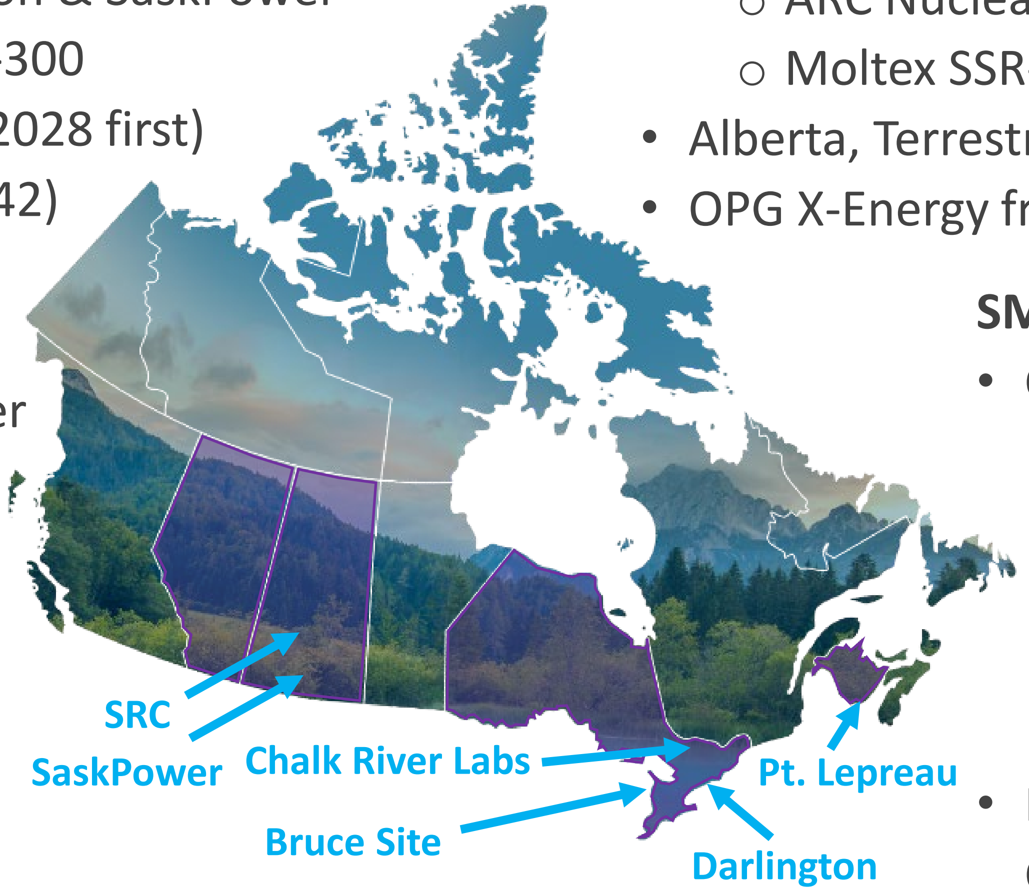
SMR and New Nuclear Deployment Landscape in Canada

SMR Stream 1: On-Grid, ~300 MW_e

- Ontario Power Generation & SaskPower select GE-Hitachi BWRX-300
  - Darlington 4 units (2028 first)
  - SK 4 units (2034-2042)
- Alberta
  - SMART MOU
  - OPG & Capital Power

Large Nuclear

- Refurbs ahead of plan
- Bruce Site 4,800MW_e pre-development
- AtkinsRéalis 1,000 MW_e CANDU® MONARK™



SMR Stream 2: Advanced Reactors

- New Brunswick Power, Point Lepreau
  - ARC Nuclear ARC-100, LTPS submitted
  - Moltex SSR-W
- Alberta, Terrestrial Energy MOU
- OPG X-Energy framework agreement

SMR Stream 3: Off-Grid, <15 MW_e

- Canadian Nuclear Laboratories
  - Stage 3: Global First Power (Nano)
  - Stage 1 (completed):
    - Terrestrial Energy
    - *U-Battery*
    - StarCore Nuclear
- McMaster University – Net Zero Community Project
- Saskatchewan Research Council (SRC) – Westinghouse eVinci MOU

Potential Markets for SMRs in Canada

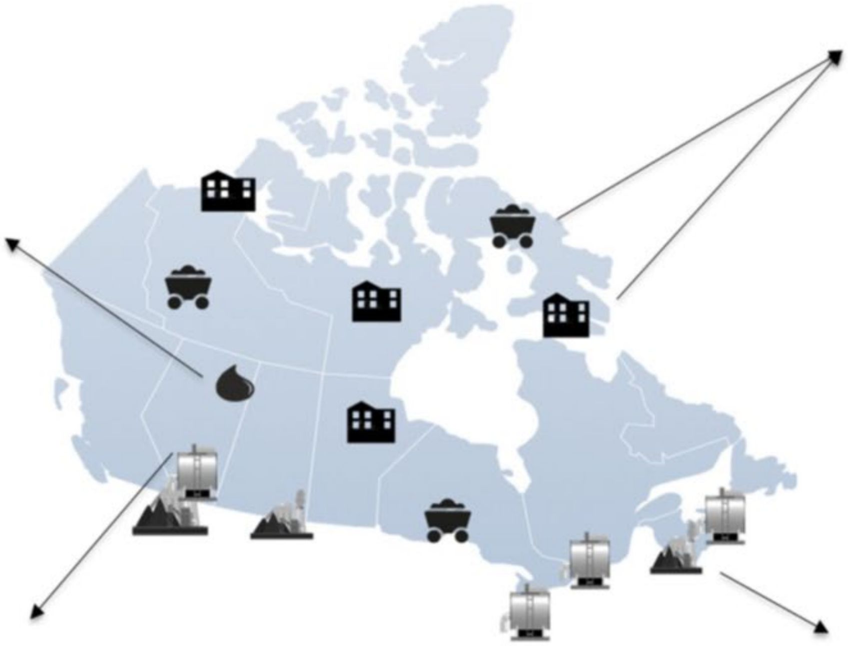
Off-grid energy for resource extraction/ industry
(10-250 MWe)

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**

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**



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

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**

Off-grid for electricity/district heating, in willing remote communities
(<10 MWe)

On-grid power generation
(150-300+ MWe)

From the 2018 SMR Roadmap: www.smrroadmap.ca

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SECTION 3

Green Mining Case Study

Case Study Site Description

Mine	Victor mine, ON	Prairie Creek mine, NT
Excavation type	Open-pit	Underground
Life of mine	14 years	15 years
Product	Rough diamonds	Base metal concentrates
Production rate	7,400 t/day	1,600 t/day
Primary generation	26.4 MW_e diesel 4.6 MW_e wind	8MW_e diesel
Backup generation	5.2 MW_e diesel	4MW_e diesel
Installation type	Retrofit	Greenfield
Carbon price	170 $/t$CO_2$e	

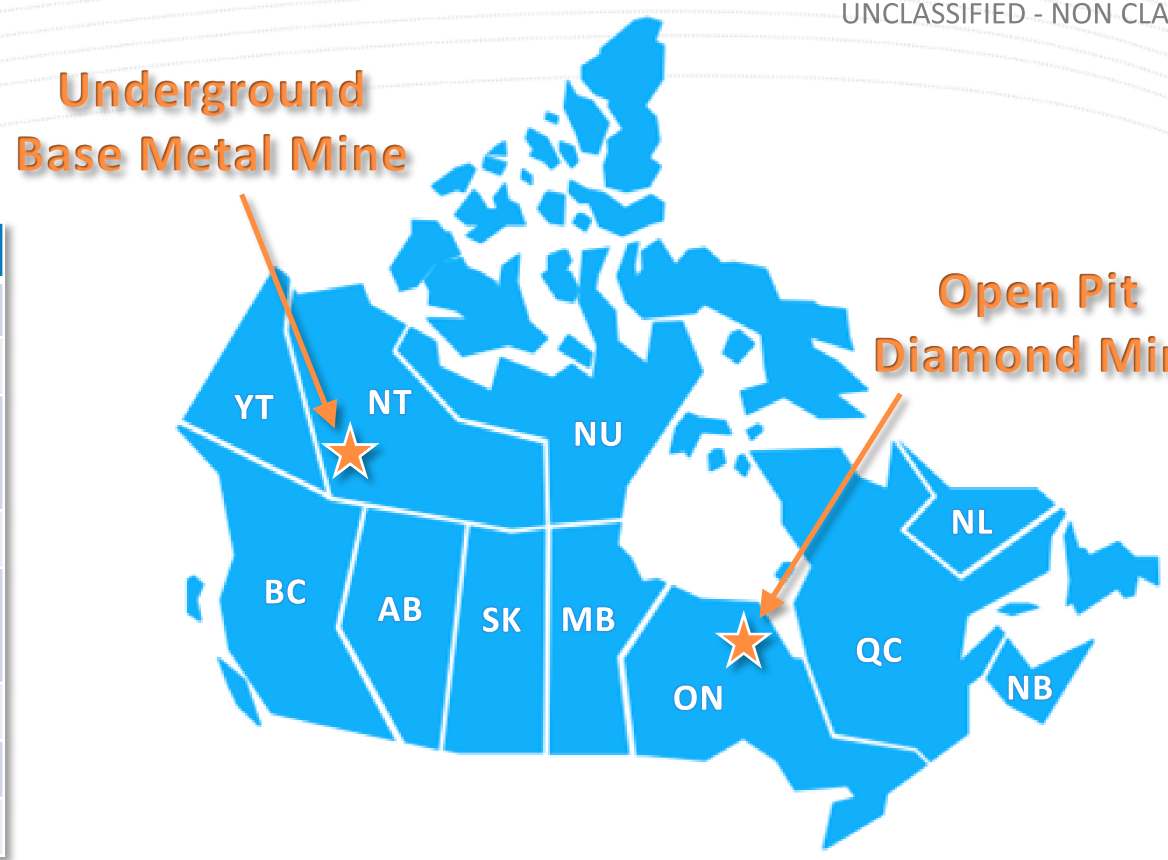


Photo by Newmont Corporation via https://www.newmont.com/operations-and-projects/global-presence/north-america/cripple-creek-victor-us/default.aspx

Electricity and Head Demand

- Publicly available data
- Hourly demand extrapolated from monthly average
- Steady electricity demand
- Variable heat demand
- Steady vehicle fuel demand

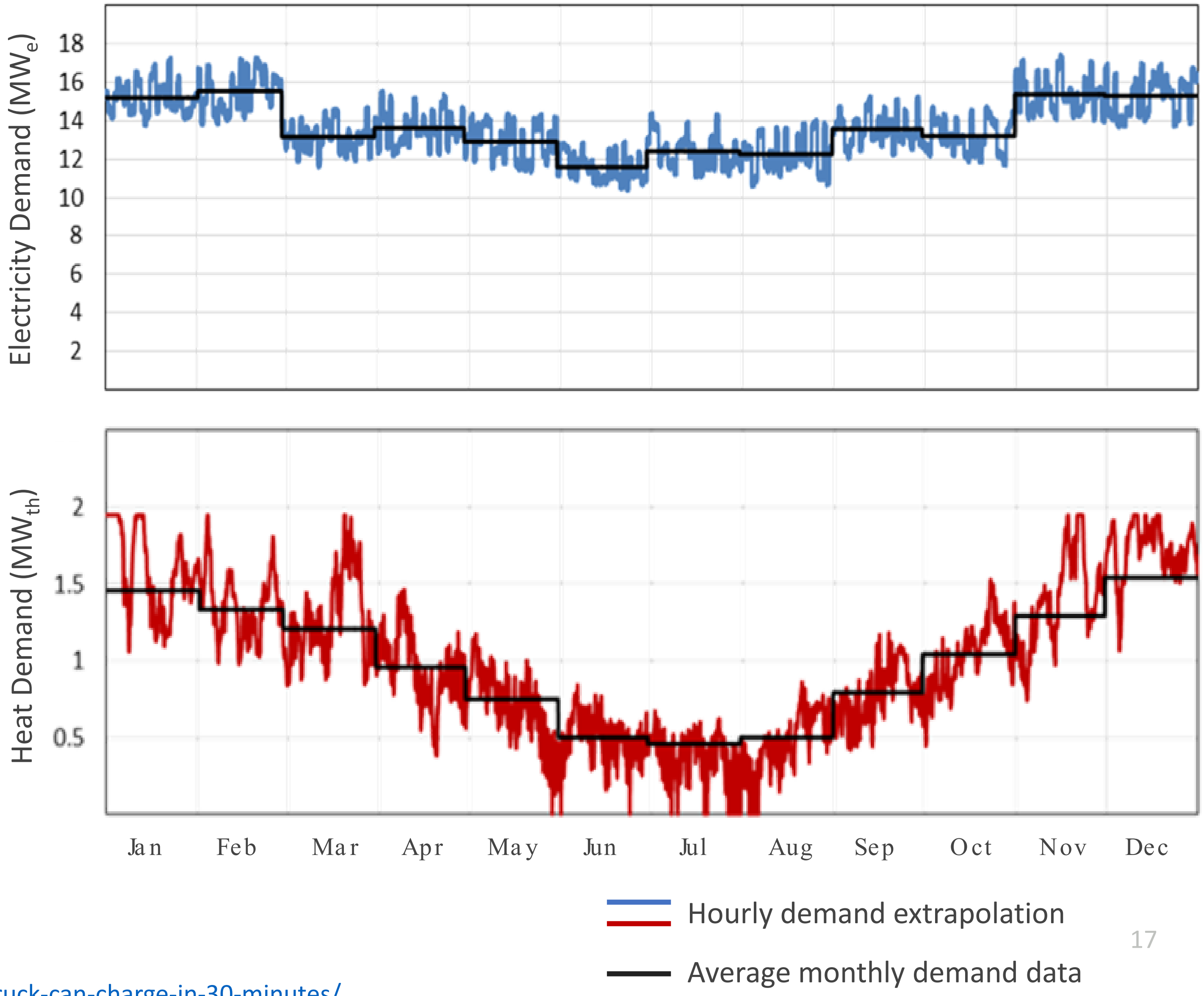
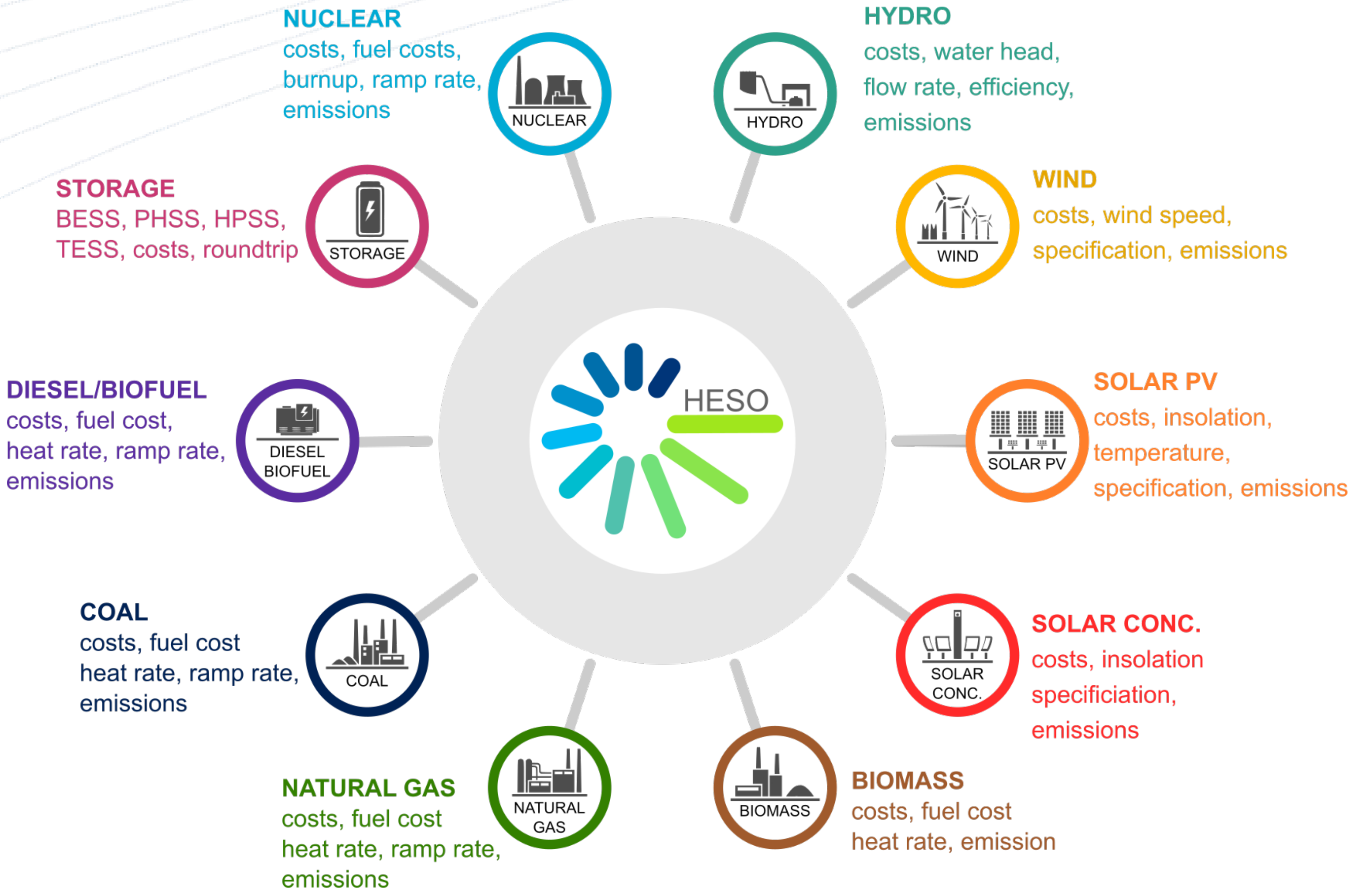


Photo via https://electrek.co/2023/01/13/this-240t-electric-mining-haul-truck-can-charge-in-30-minutes/

Hybrid Energy System Optimization (HESO) Model



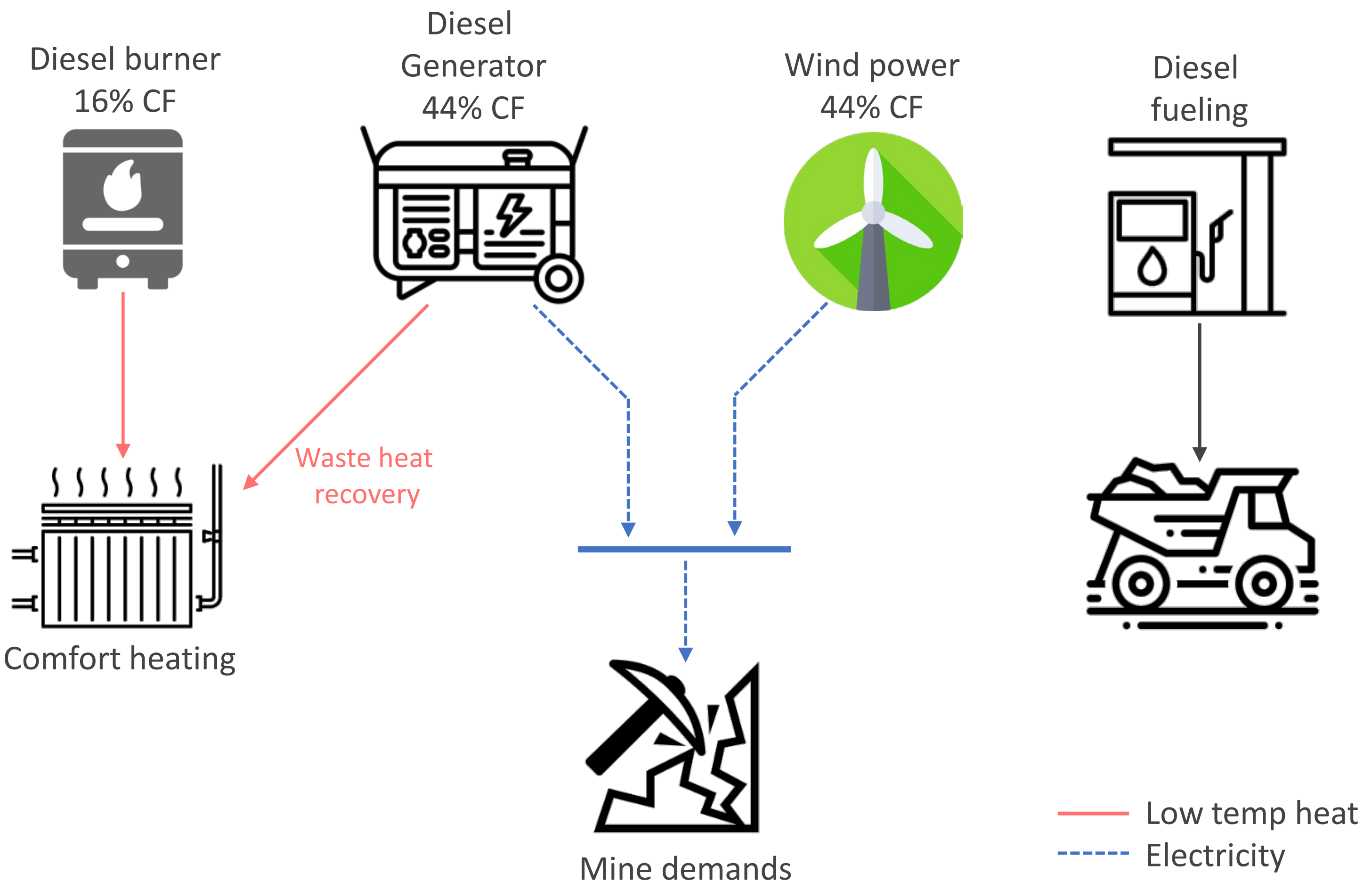
Key Features

- ✓ Multiple energy generating and storage technologies
- ✓ Ramp rate
- ✓ Nuclear technical constraints
- ✓ Maintenance schedule
- ✓ Three types of demands
  - Electricity
  - Heat
  - Hydrogen
- ✓ Hourly time step
- ✓ Life cycle GHG emissions
- ✓ Carbon tax (fossil fuels)
- ✓ Cogeneration
- ✓ Carbon capture and storage
- ✓ On-grid and off-grid
- ✓ No installed capacity information required

Baseline Energy System

Features

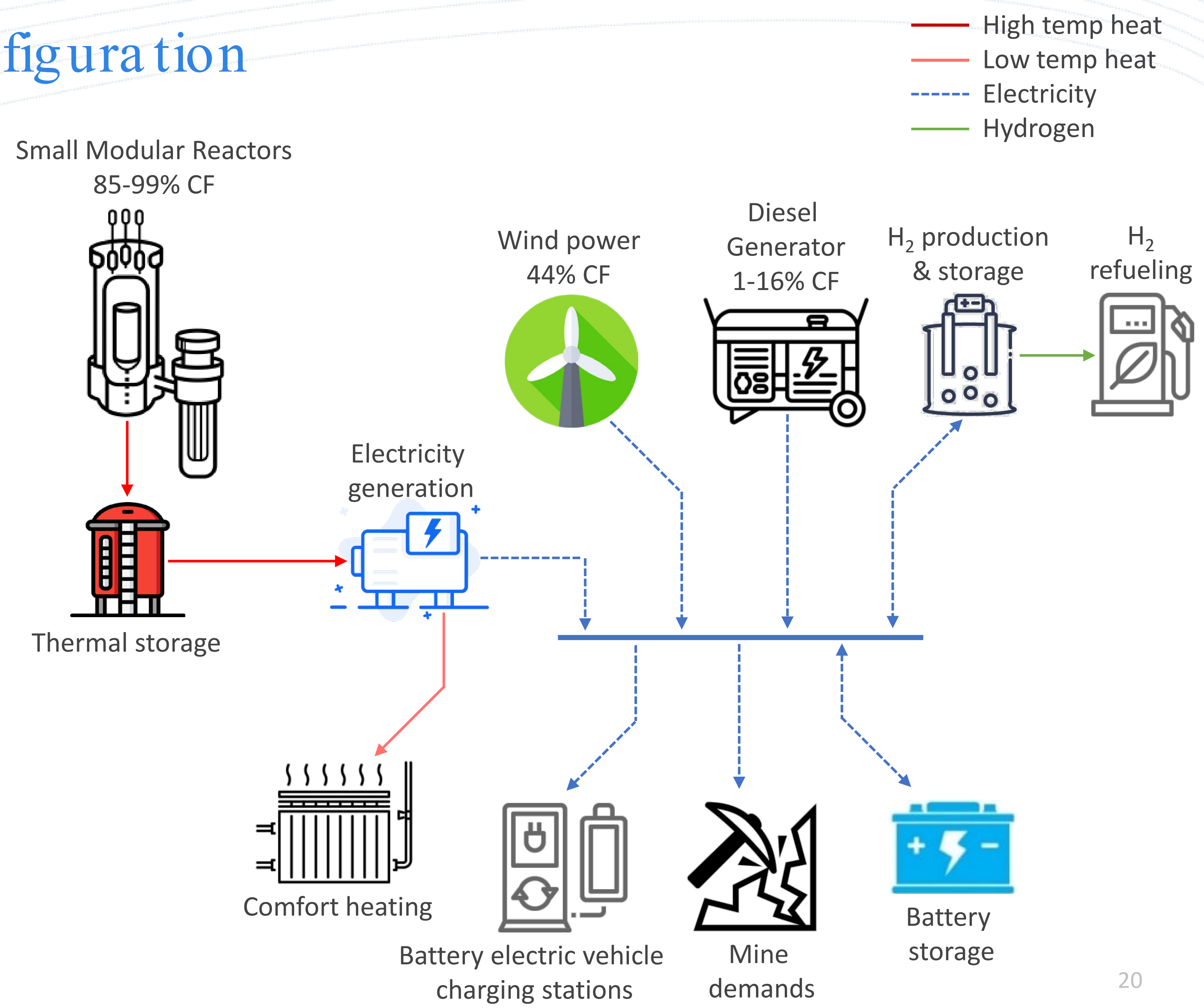
- Energy systems segregated
- Reliance on diesel
- High energy costs
- Electricity demand: 120 GWh/y
- High emissions (93.1 kt-CO_2/yr)



Near-Zero Emissions Configuration

Features

- Increased integration
- Diesel peaking and backup
- Competitive energy costs
- 2-3x electricity demand
- Deep decarbonization (90-97% GHG reduction)



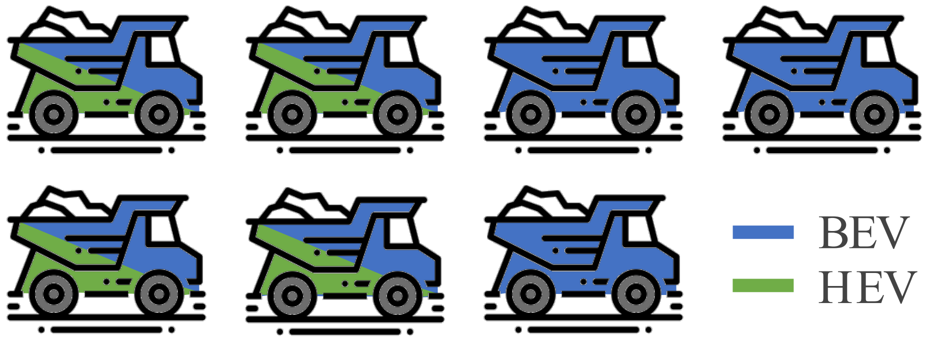
Haul Truck Fleet Analysis

Desirable features of clean fleet

BEV {
- Energy efficiency

HEV {
- Short refuel/recharge cycle
- Minimal fleet size impact
- Minimal infrastructure impact

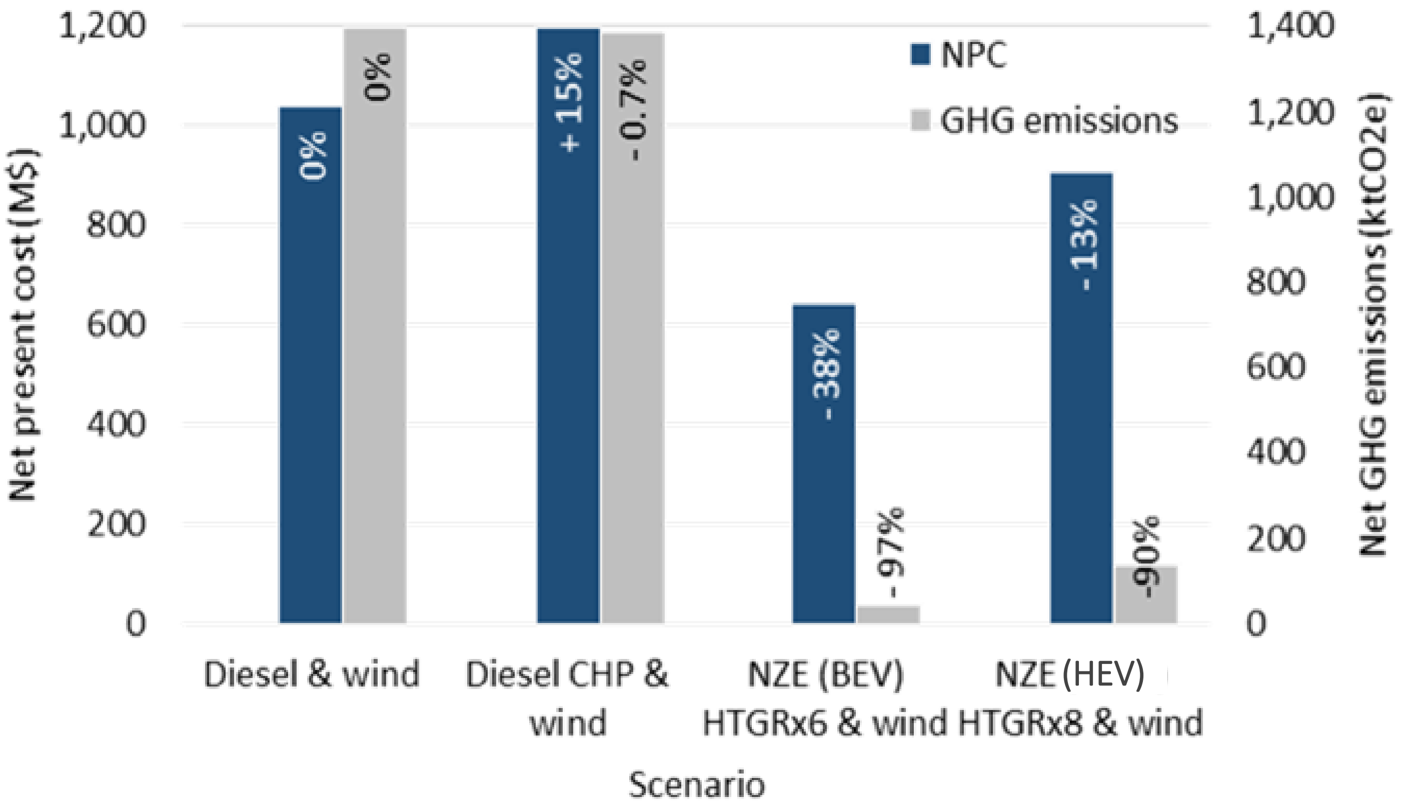
	Baseline	BEV	HEV
Trucks	4	7	4
Daily trips (trips/day/truck)	19	12	20
Total haulage (t-ore/day)	1,672	1,787	1,760



Results and Discussion

Key Findings

- 90% emissions reduction achievable
- Electricity increases 2-3x
- Vehicle fleet size likely to increase
- Diesel generation has a role
- SMR unit size matters
- Life of mine is a critical parameter
- Decision between BEVs and HEVs is complex and may vary site to site



Acronyms

BEV – Battery Electric Vehicle
CHP – Combined Heat and Power
GHG – Greenhouse Gas
HEV – Hydrogen Electric Vehicle
HTGR – High Temperature Gas Cooled Reactor
NPC – Net Present Cost
NZE – Near-Zero Emissions configuration

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Other Studies

Other Case Studies

- **Remote mining (OPG, MIRARCO)**
- **Oil sands & hydrogen production for bitumen upgrading**
- **Remote community**
- **Garrison Petawawa (DND)**
- Research park
- Electric vehicles
- Low emission steel
- Electrification of residential heating in Ontario
- Impact of high penetration of renewable energy, Ontario
- Influence of the increasing carbon tax
- NR-HES and thermal storage

Future Interests

- **Case studies with industry partners**
  - Meaningful case studies require real-world data
  - Vehicle fleet size impacts require input from site designers
- **University partnership**
  - Collaborative work
  - Establishing a network of clean energy labs across Canada
- **Indigenous and public engagement**
  - Fostered as part of CEDIR Initiative
  - Looking for meaningful input early and often

Thank you. Merci.

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