Nuclear Thermal Energy Applications – Opportunities and Challenges

16th INPRO Dialogue Forum on Opportunities and Issues in Non-Electric Applications of Nuclear Energy

2018 Dec 12-14, Vienna

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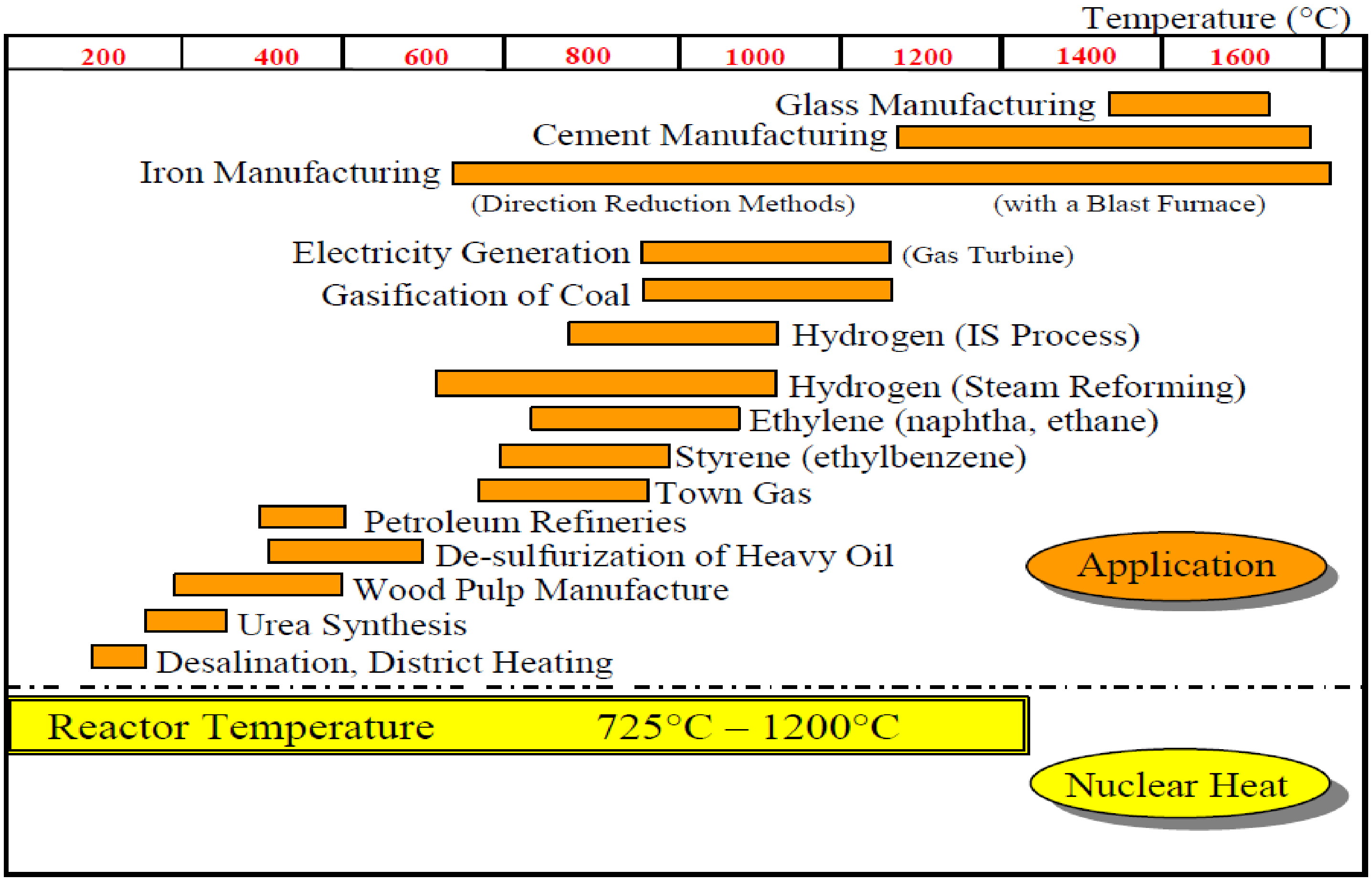
Context

- ➢ Nuclear thermal energy applications – opportunities and challenges related to

1. Replacing fossil fuel in process heat applications
2. Integration with renewables to provide grid reliability

Potential Uses of Nuclear Heat



Generation IV Roadmap – Crosscutting Energy Products R&D Scope Report, GIF-008-00, December 2002

Largest Co-generation Application Operated in Canada - Bruce Bulk Steam System

- Largest bulk nuclear steam system in the world – capacity 5,350 MW medium-pressure steam, 6 km of piping
- Operated until early 2000s, demolished in 2006
- Major users
  - Heavy water Plant – 750 MW thermal
  - Building heating – 15 MWth
  - Bruce Energy Centre (BEC) – 72 MWth

- Bruce Energy Centre supported industries such as greenhouses and plastic manufacturers

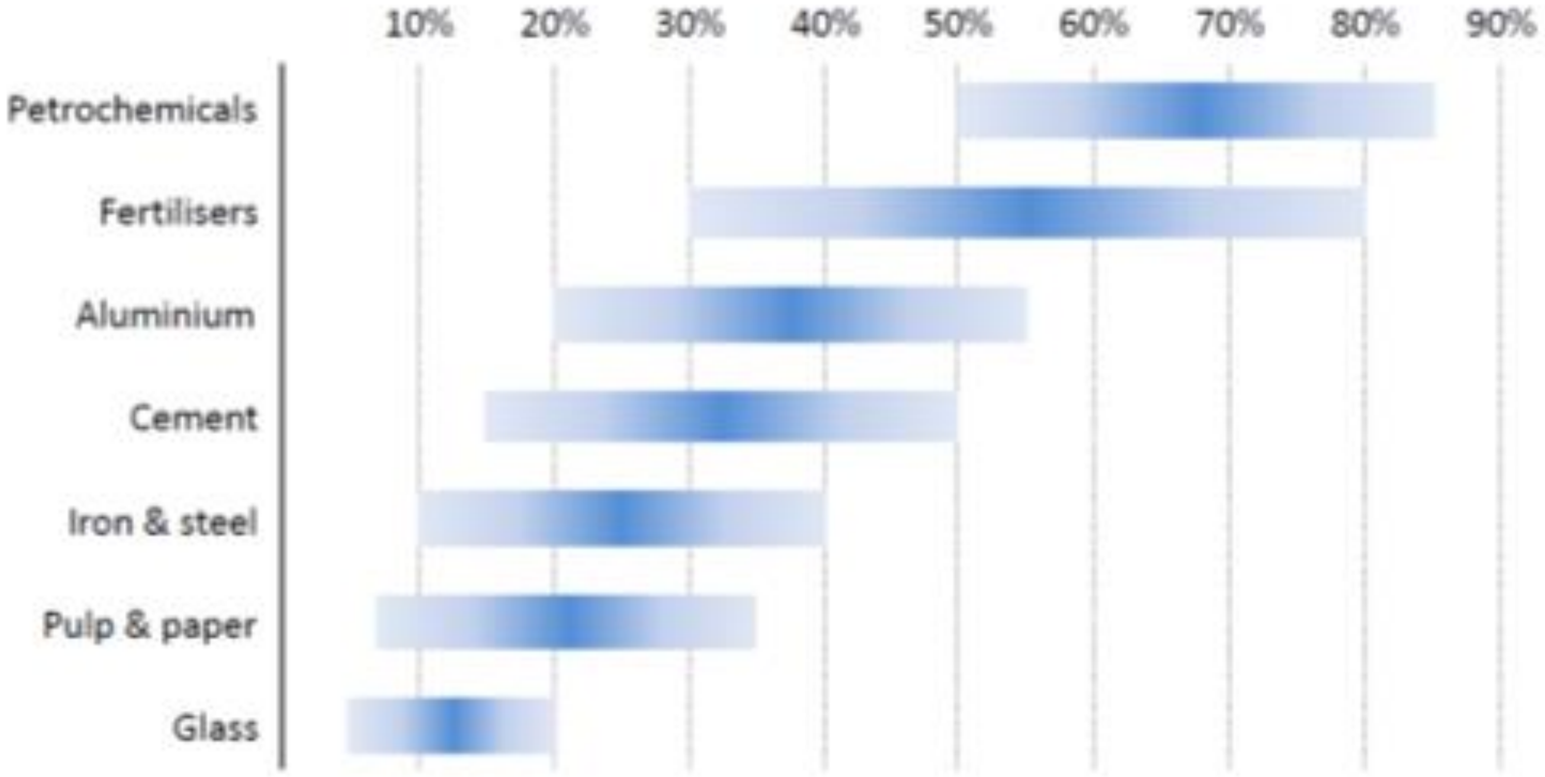
Largest Co-gen - Chemical Plant

- Two heavy water plants (800MT/y/plant) operated at Bruce site from 1973 to 1993
- Steam was (750 MW Th) supplied from Bruce A station ~ 30% of the output of a single unit
- Precedence for collocating chemical plant and NPP

Bruce Heavy Water Plant

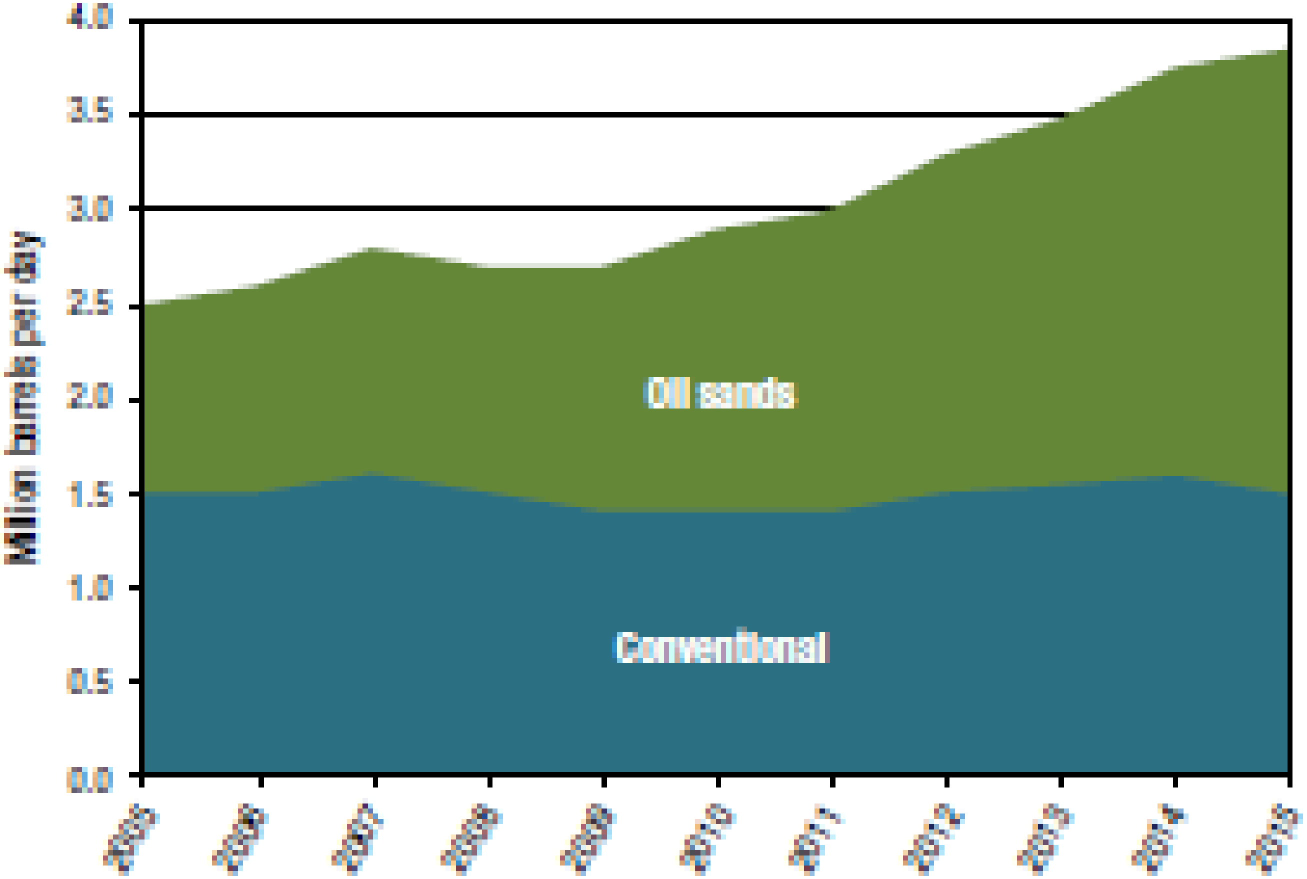
Bruce Nuclear Generating Station

Share of Energy Costs



"World Energy Outlook", OECD-IEA, 2013

Canadian Crude Production

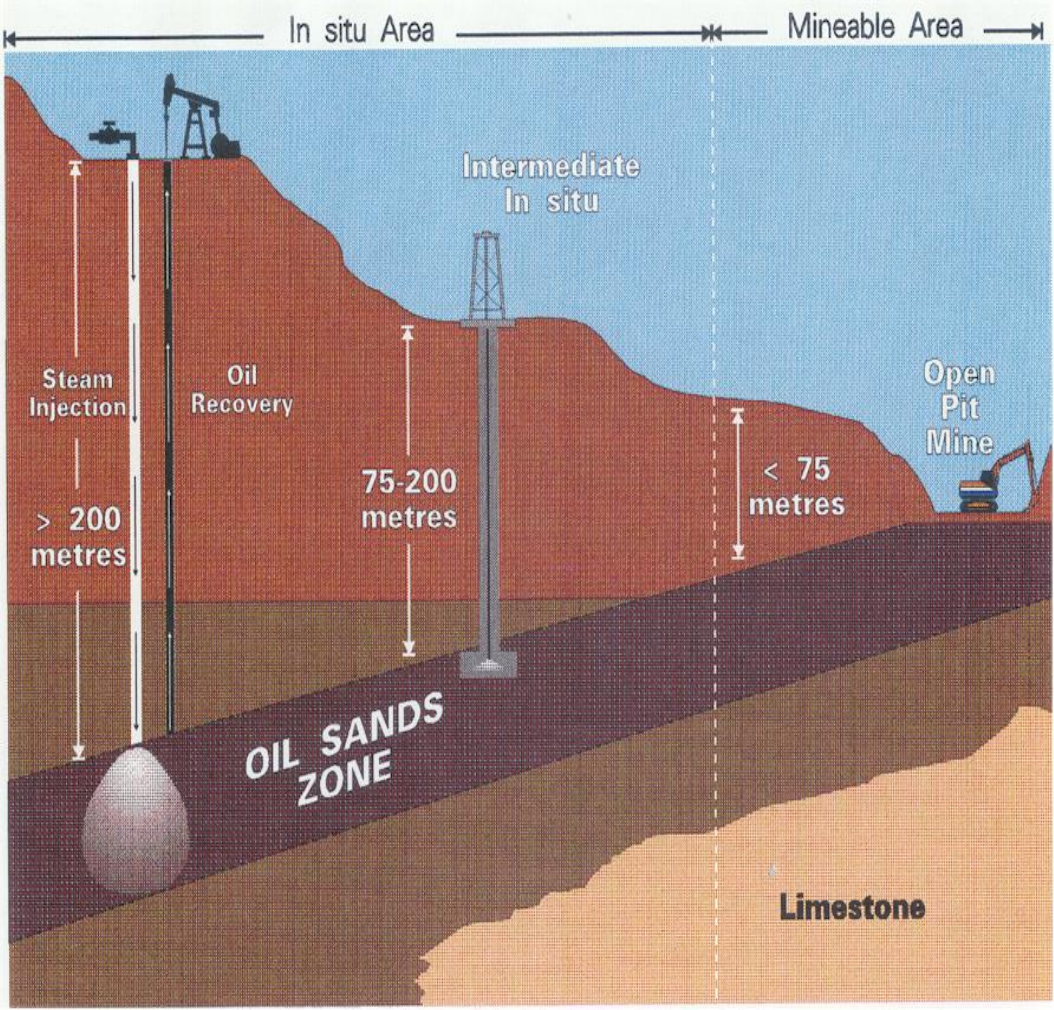


- **Canada 4th largest producer of crude**
- **97% reserve in oil sands**
- **Oil sands account for ~9% of Canada's GHG emissions**

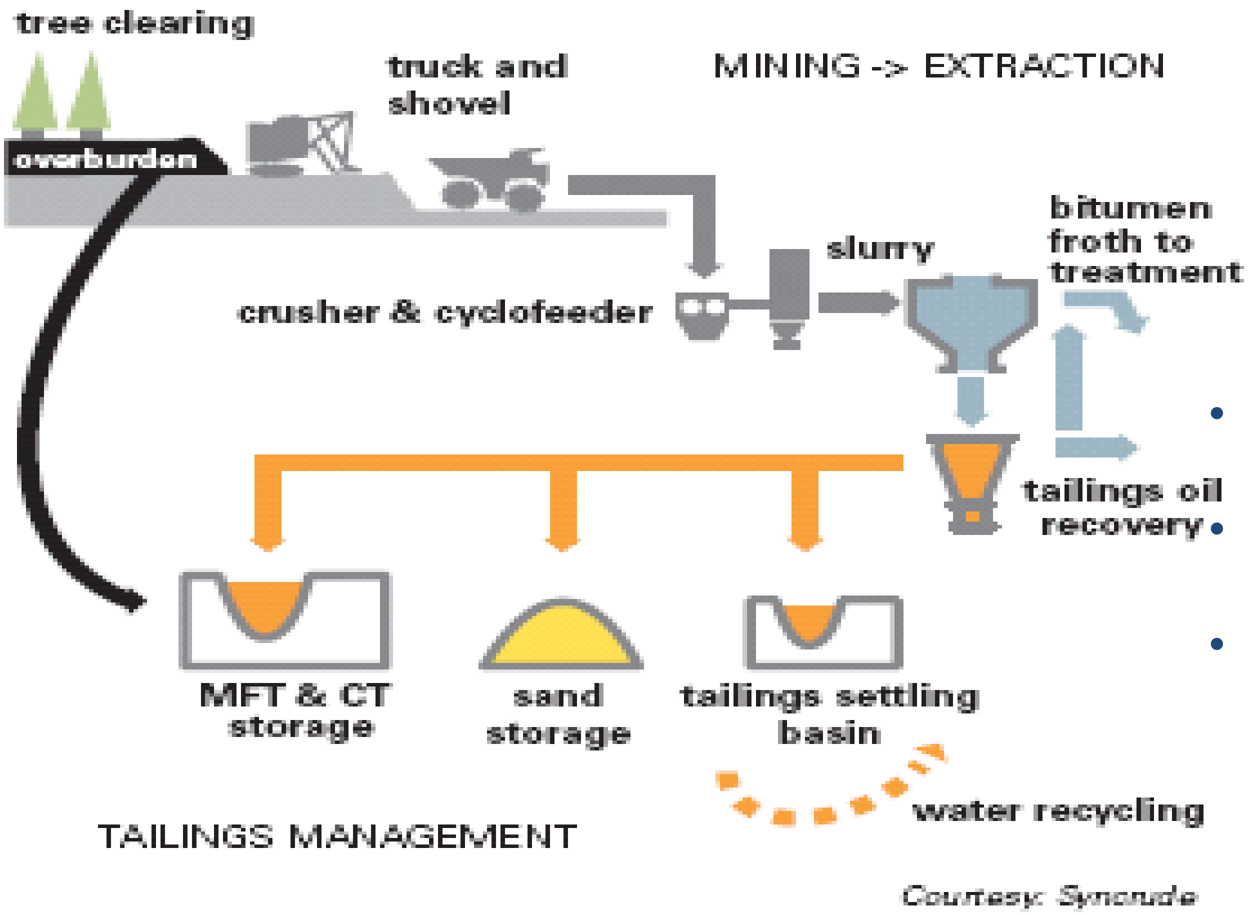
Energy Fact Book 2016-17, Natura Resources Canada

Oil Sands Mining / Bitumen Extraction

- ➢Depending on depth can be extracted in several ways
- ➢Surface mining up to 75 m
- ➢Steam-Assisted Gravity Drainage (SAGD) >200m



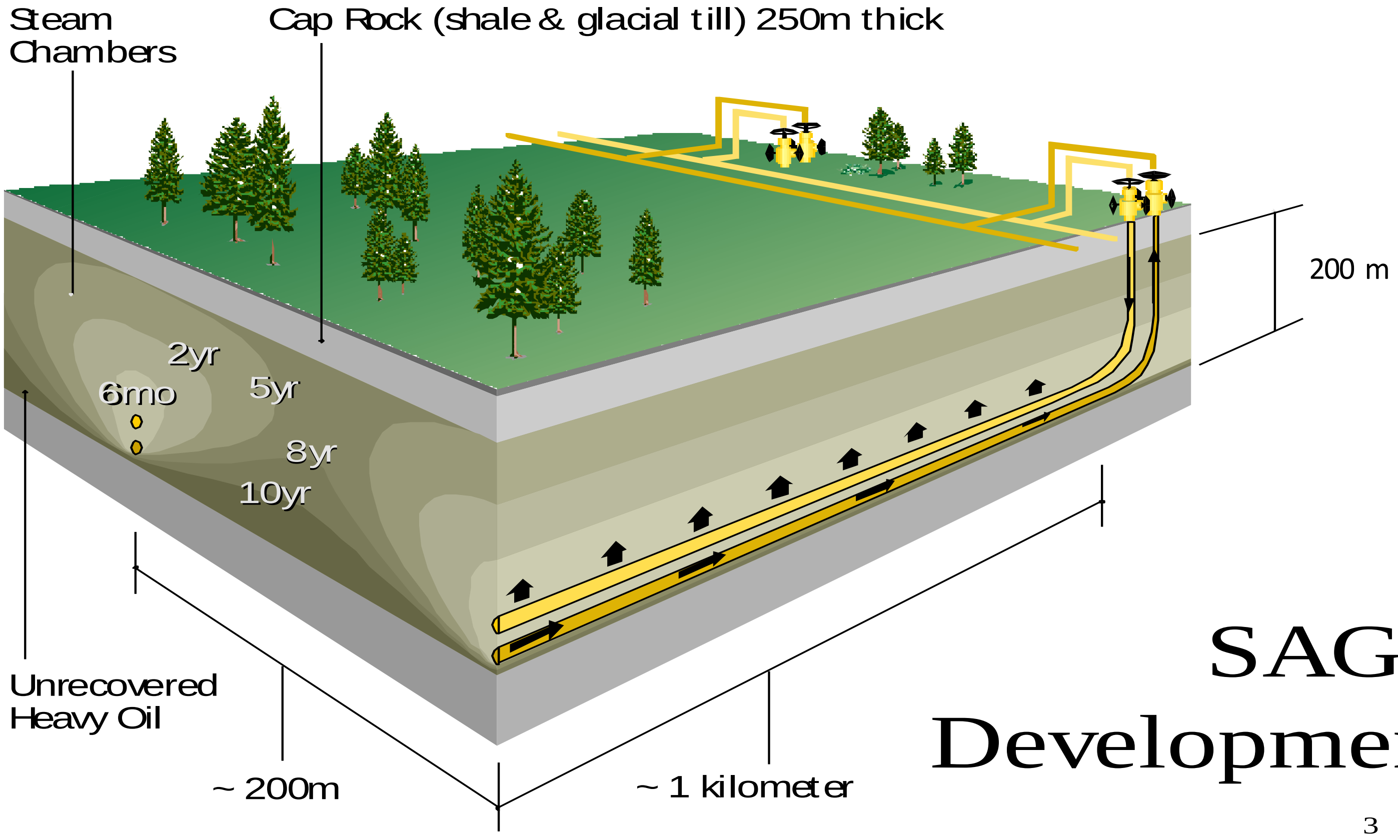
Oil Sands - Surface Mining



Courtesy: Syncrude

- Large scale operation 100,000 bpd
- Extensive surface area disturbance
- Requires large scale tailings management

In-Situ Steam Assisted Gravity Drainage



- Surface area disturbance <10%
- 90 % of water is recycled
- Energy intensive
- Can be implemented in phases starting with5,000 bpd

SAGD Development

3

Significant interest in Nuclear Energy for oil sands operations

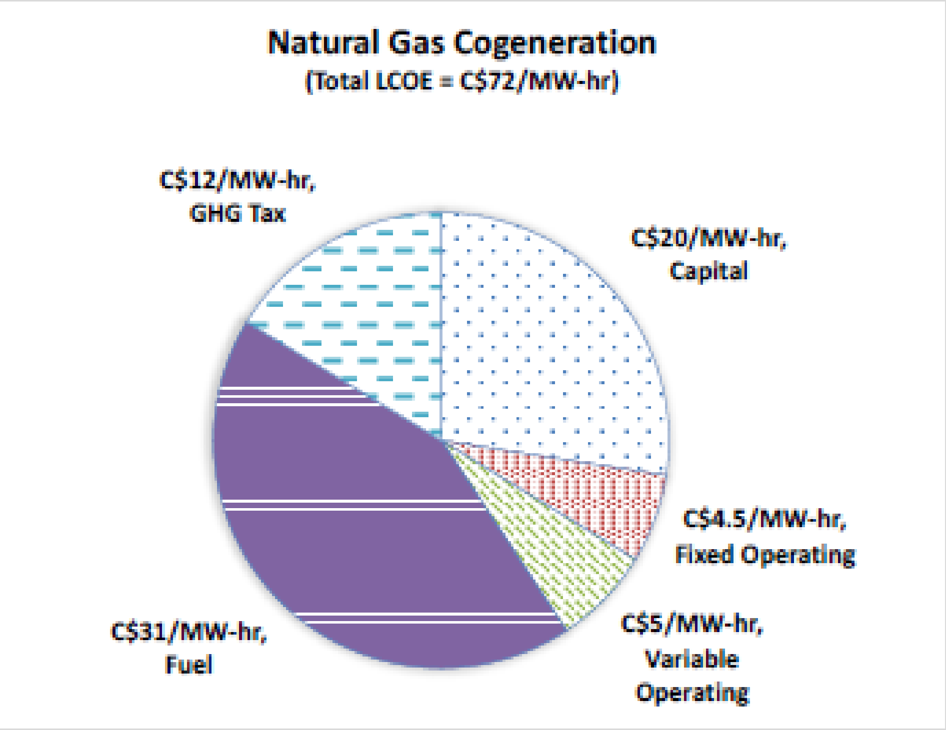
- Reduce GHG emissions – avoid carbon tax
- Currently
  - steam produced by natural gas boilers
  - Hydrogen produced by steam-methane reforming
  - Electricity produced by CCGT

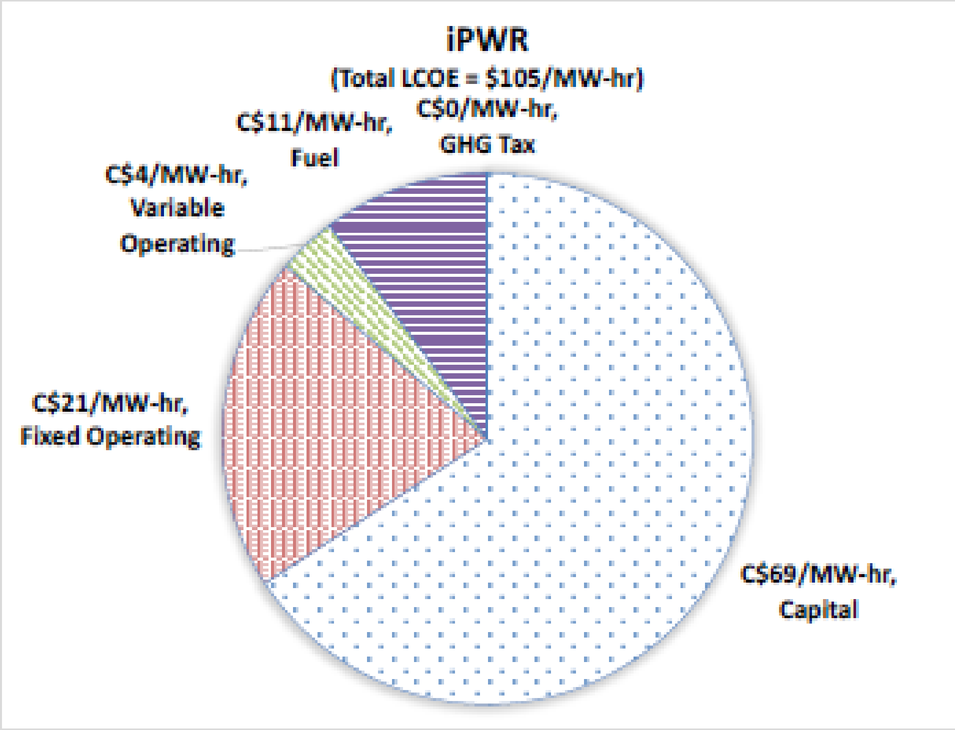
Surface Mining of Oil Sands

- iPWRs considered suitable for this application
- For 200,000 bbl/d operation
  - 150-300 tonnes/h medium pressure steam (2.1 MPa)
  - 450-900 tonnes/h low pressure steam (1.05 MPa), and
  - 127-175 MWe power
- 12 module, 1920 MWth iPWR, Overnight EPC cost C$5,600/kWe (2014)
- Natural gas price C$ 3.25/GJ (would have to increase to C$7.5/GJ for iPWR to be Competitive)
- Carbon tax $30/ton, interest/rate of return 7.5%

Deployability of Small Modular Nuclear Reactors for Alberta Applications – Phase II, PNNL-27270, March 2018

Cost Comparison – iPWR Vs Natural Gas





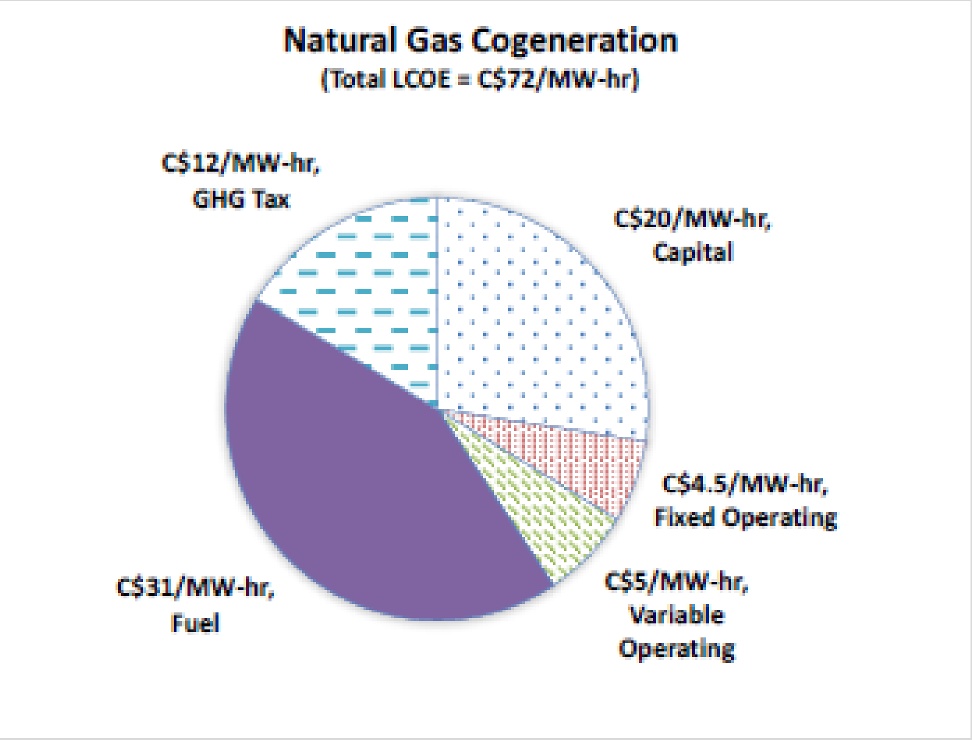
Deployability of Small Modular Nuclear Reactors for Alberta Applications – Phase II, PNNL-27270, March 2018

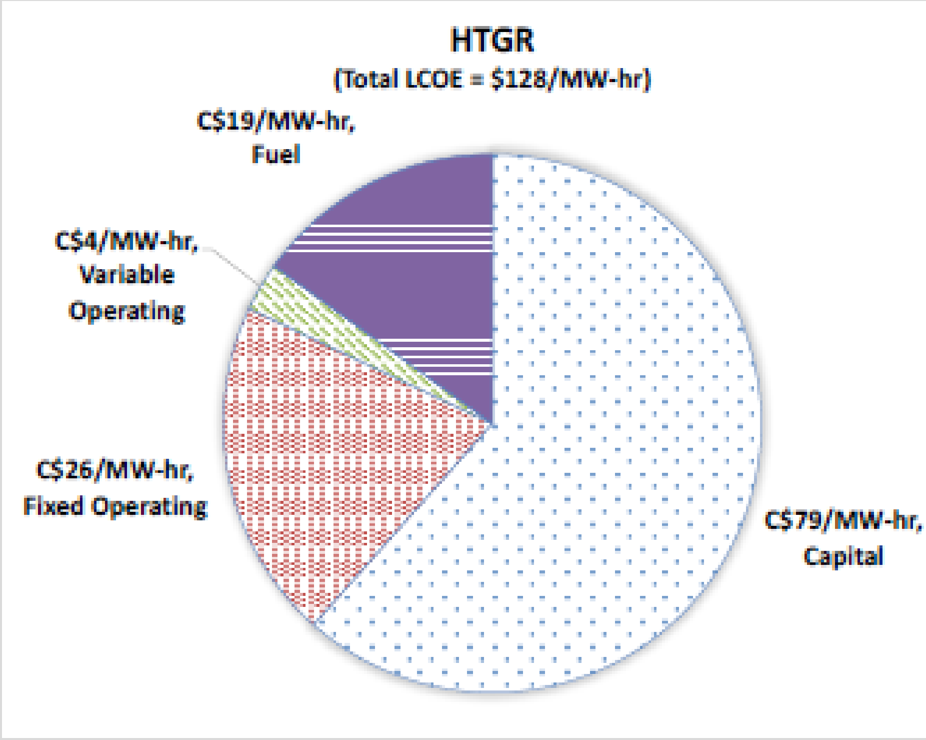
In-situ Recovery of Bitumen

- HTGR considered suitable for in-situ extraction of bitumen
- For 33,000 bbl/d;
  - 655 tonnes/h high pressure steam (10 MPa),
  - 15 tonnes/h low pressure seam (1.05 MPa)
  - 18 MWe power
- 600 MWth single module HTGR, overnight EPC cost C$6,600/kWe (2014)
- Natural gas price C$ 3.25/GJ (would have to increase to C$10.5/GJ for HTGR to be Competitive)
- carbon tax C$30/tonne CO_2 , interest/rate of return 7.5%

Deployability of Small Modular Nuclear Reactors for Alberta Applications – Phase II, PNNL-27270, March 2018

Cost Comparison HTGR Vs Natural Gas



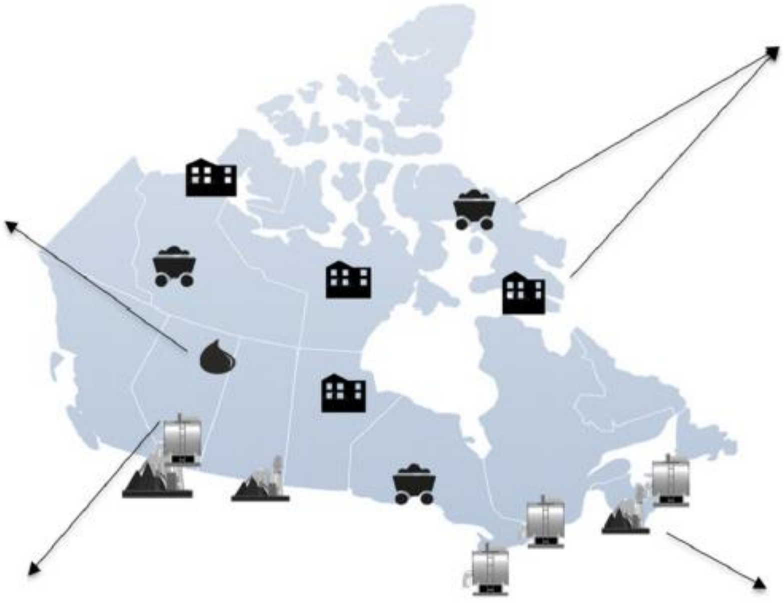


Deployability of Small Modular Nuclear Reactors for Alberta Applications – Phase II, PNNL-27270, March 2018

Oil Sands - Opportunities & Challenges

- Significant energy demand – estimates for current production levels
- 66 iPWRs (45 MWe) for surface mining operations
- 40 HTGRs (600 MWth) for in-situ operations
- 5 to 7.5 GWe for hydrogen production
- Economics unfavourable
  - Low natural gas prices
  - Finance terms for private sector
- Matching lifetime of nuclear with that of oil fields
- Technologies not yet ready
  - Implementation period longer than oil industry expectation
  - Expectation: heat/hydrogen supplied across the fence

Other Opportunities for Co-gen in Canada



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

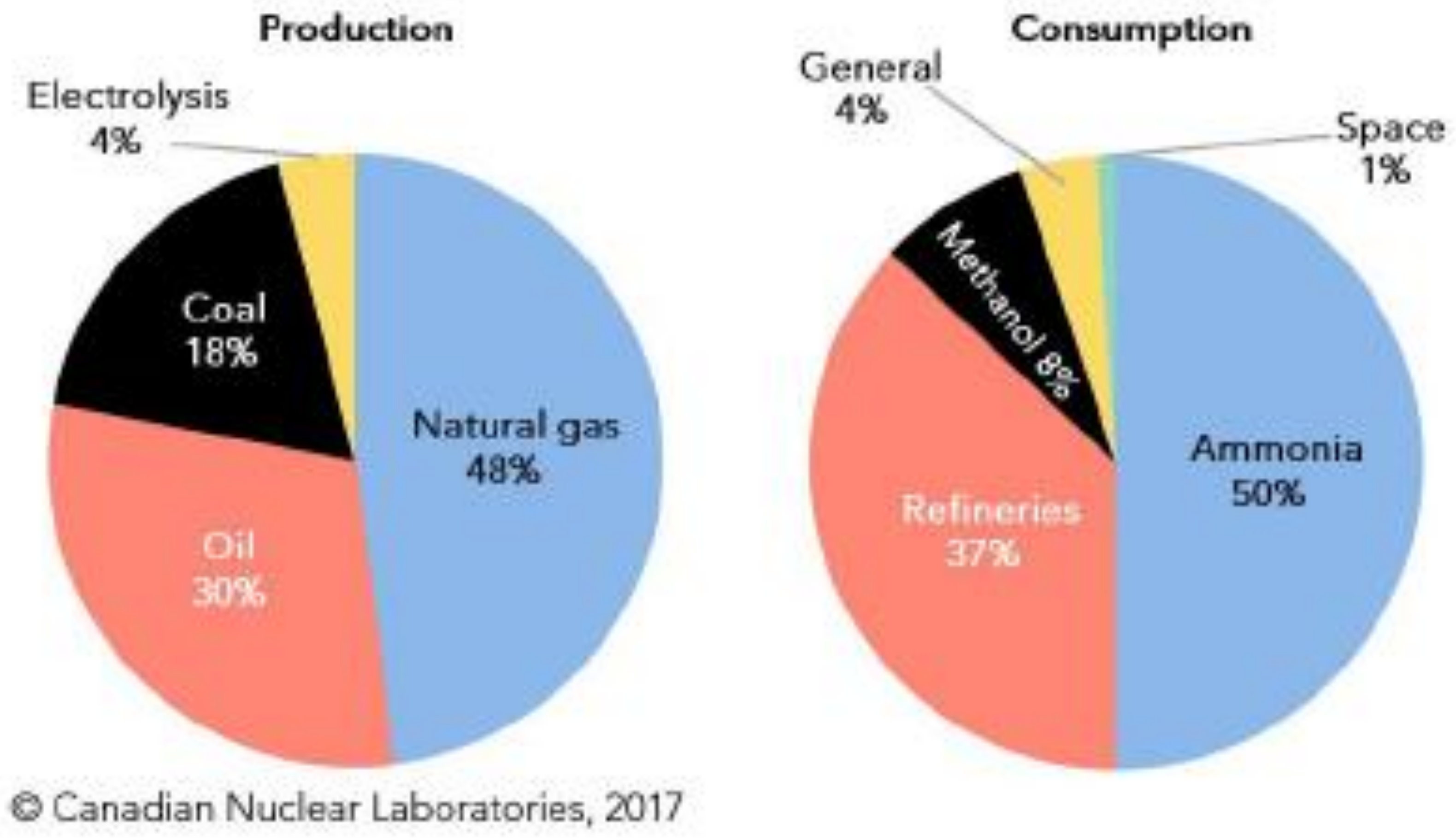
Replacing conventional coal-fired power:

- 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**

(www.smrroadmap.ca)

World Hydrogen Production

137,000 TPD



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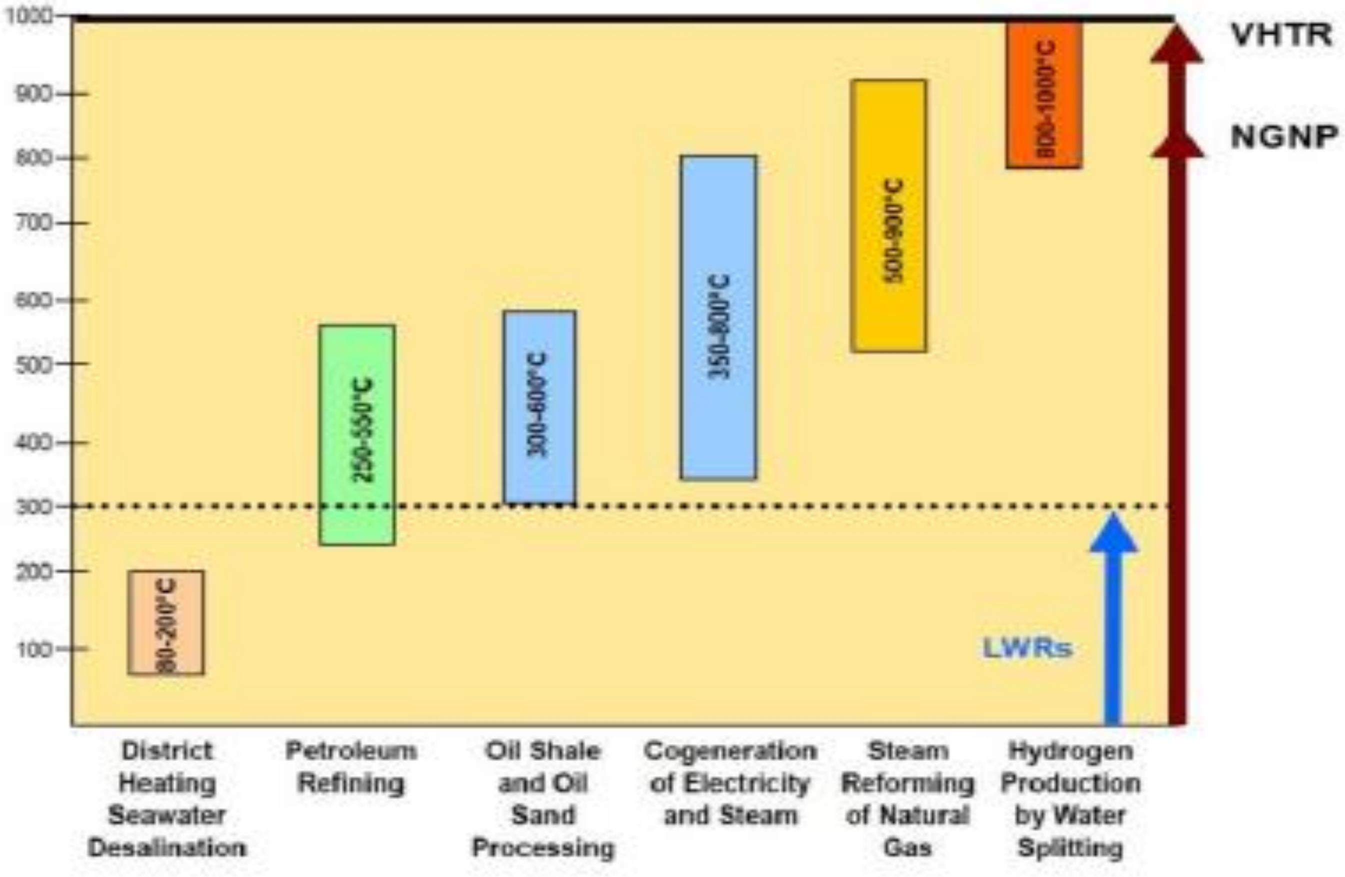
HTR-Potential Applications



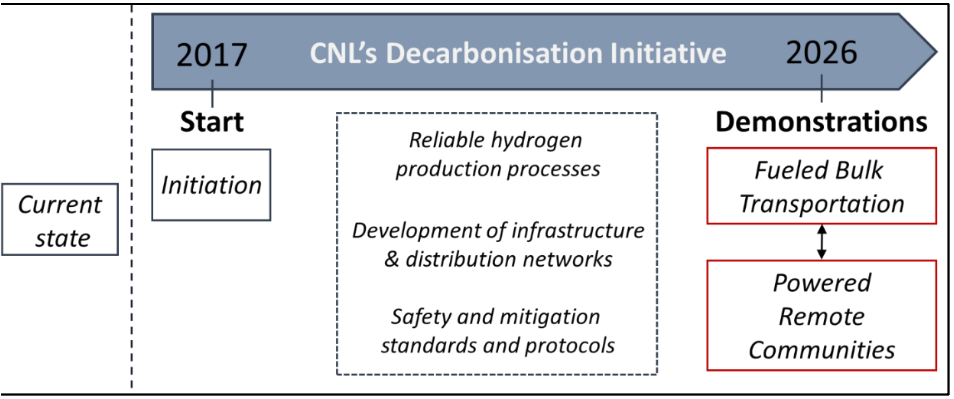
Annual Report 2016, Generation IV International Forum

Generation IV International Forum - Hydrogen Production Project

- Thermochemical Processes
  - Japan: S-I demonstrated at 20L/h
  - China: S-I demonstration 60L/h
  - South Korea: S-I demonstration 50L/h
  - Canada: Cu-Cl (<530° C) demonstration planned for 50 L/h
- High-Temperature Electrolysis
  - US: INL building 26 kW facility as part of the Dynamic Energy Transport and Integration Laboratory (DETAIL)
  - Development activities in Canada, China and France

Annual Reports 2016 7 2017, Generation IV International Forum

Current Thrust at CNL



Current state

2017 CNL's Decarbonisation Initiative 2026

Start

Initiation

Reliable hydrogen production processes

Development of infrastructure & distribution networks

Safety and mitigation standards and protocols

Demonstrations

Fueled Bulk Transportation

Powered Remote Communities

1) *Lab-scale demonstration of individual steps in the Cu-Cl cycle for a H_2 production rate of 50 L/h (over next 2 years)*
2) *Pilot plant design for 1 ton/d H_2 production (over next 3 to 5 years)*
3) *Large-scale production (over next 8 years)*

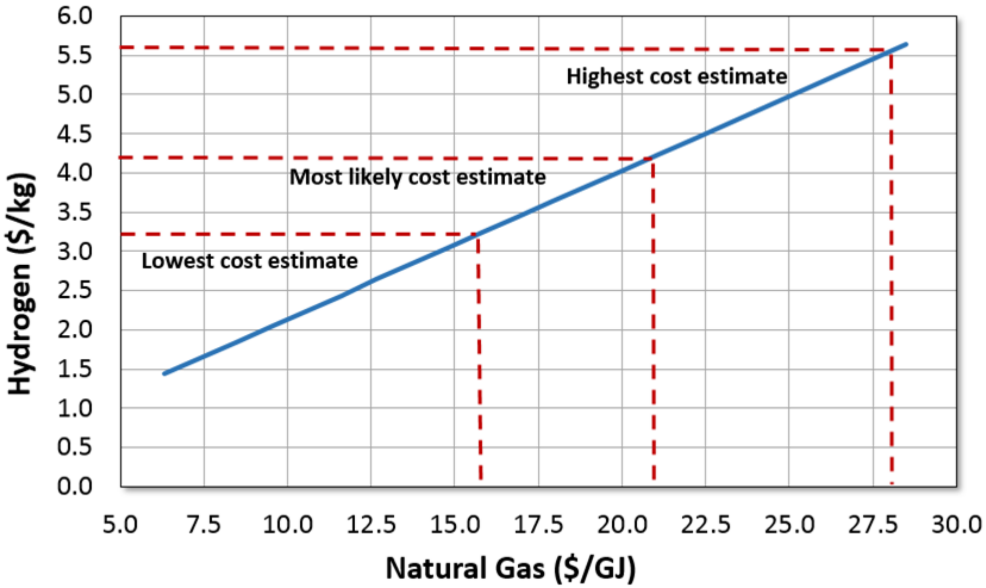
Four-Step Hybrid CuCl Thermochemical Cycle for Bulk Hydrogen

Reaction Step Name	Reaction	Temperature (°C)
1. Electrolysis	$2CuCl(s) + 2HCl(aq) \rightarrow 2CuCl_2(s) + H_2(g)$	~80
2. Drying/Separation	$CuCl_2(aq) \rightarrow CuCl_2(s)$	>110
3. Hydrolysis	$2CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g)$	350 to 400
4. Decomposition	$Cu_2OCl_2(s) \rightarrow 2CuCl(l) + \frac{1}{2}O_2(g)$	500 to 550

Estimated Cost of H2 Production

Assumptions:

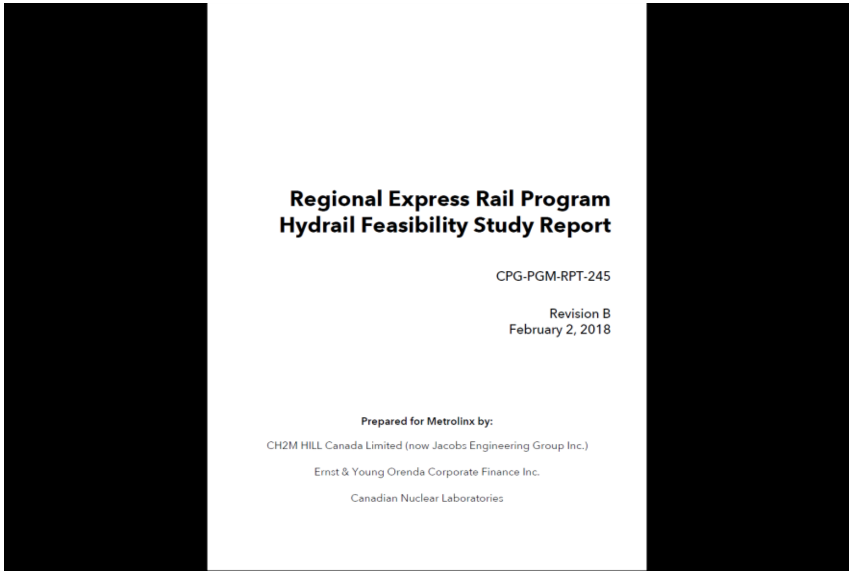
- 1200 MWe SCWR
    - 625° C outlet temp.
- 470 tons/day H_2 plant (HTSE)
- Capital costs
    - NPP - $4,000/kWe
    - High-temp electrolysis, $700M
    - Steam-methane reformer$ 350M
- No carbon tax, no steam credit
    - Nuclear hydrogen competitive over natural gas price range of $16 - $21/MMBTU



Benchmarking of Economic Models for Nuclear Hydrogen Production
R. Sadhankar et al, Pacific Basin Nuclear Conference
San Francisco, October 2018

Hydrogen Powered Trains - 'Hydrail'

CNL jointly developed hydrail feasibility study for Government of Ontario Trains in 2017-18



Regional Express Rail Program
Hydrail Feasibility Study Report

CPG-PGM-RPT-245

Revision B
February 2, 2018

Prepared for Metrolinx by:

CH2M HILL Canada Limited (now Jacobs Engineering Group Inc.)

Ernst & Young Orenda Corporate Finance Inc.

Canadian Nuclear Laboratories

Regional Express Rail Program – Hydrail Feasibility Study Report, available at the Metrolinx website – Published 2018 Feb

- Partnered with Jacobs, Ernst & Young
- Systems assessment, safety review, operational simulation model, feasibility and industry engagement

Metrolinx Hydrail Feasibility Study

Highlights from the study

- **Two Technology Options**: (i) Overhead catenary system(OCS); (ii) hydrogen powered trains
- **Ontario grid assessment**: the ability to make all of the hydrogen for GO trains at low electricity price periods gave an advantage to hydrail vs OCS
    - Better utilization of nuclear assets
- **Hydrogen requirement**: up to 50 tonnes/day
- **Electricity consumption**: 2.2 GWh/day
- **Operating cost**: almost half of OCS technology

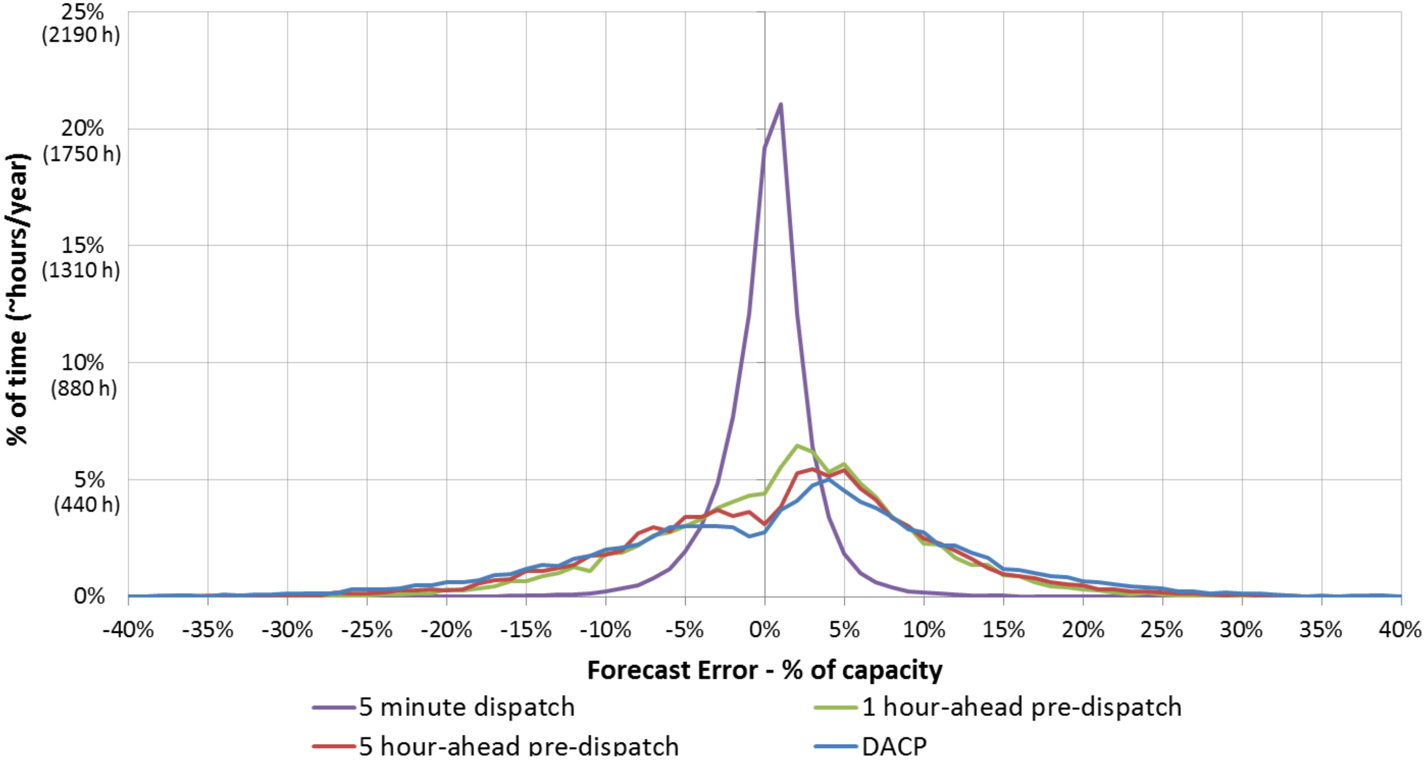
Issues for Nuclear Heat Applications

- Technology development and demonstration – high temperature reactors, water-splitting hydrogen processes, SMRs
- Intermediate heat transfer; eliminate contamination
- Integrated safety – NPP coupled to high temperature processes, coupled system dynamics, licensing
- Public perception about the quality of final product
- Economics – private sector financing, low natural gas prices

Nuclear Co-generation's Role in Grid Reliability

- Reliable grid
  - Flexible to meet variable demand
  - Meets peak demand
  - Maintains steady frequency
  - Maintains voltage in acceptable range (reactive power)
- Increasing renewable sources create challenges for grid reliability
  - Variable generation
  - Inability to provide frequency control
- Co-generation and/or thermal energy storage help integration with variable renewable resources and provides grid reliability

Variable Renewable Sources Generation Uncertainty



Uncertainty in wind forecast requires even more flexible grid

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

2016 IESO Operability Assessment – Summary. Review of the Operability of the IESO-Controlled Grid to 2020, Independent Electricity System Operator, June 2016

Hybrid Energy Systems

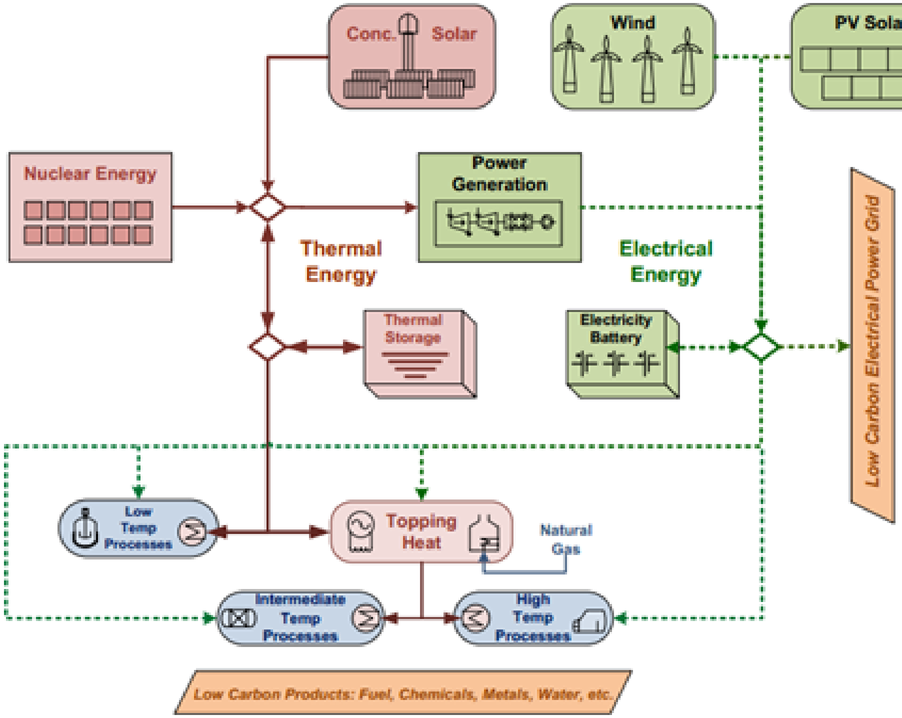


Figure ES-1. General architecture of a tightly coupled nuclear-renewable hybrid energy system, where the generation sources are integrated behind a single connection point to the grid and are managed by a single financial entity.

ix

"Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan" Idaho National Laboratory, INL/EXT-16-38165, March 2016,

Hybrid Systems Benefits/Challenges

- Provides dispatchable, flexible electricity generation to match grid demand
- Minimizes cycling of baseload nuclear
- Provides synchronous electromechanical inertia to grid
- Reduces carbon footprint of industrial sector (co-generation of chemicals, hydrogen)
- Reduces levelized energy cost
- Supports stabilization of energy cost
- Requires flexibility of dynamic balancing of nuclear heat/electricity production
- Requires large scale energy storage
- Requires flexible co-generation application
- System configuration varies with geographical area/regional industrial applications
- Large capital investment, business model and financing would determine viability

Concluding Remarks

- Huge opportunity for advanced reactors to penetrate process heat applications; particularly in energy-intensive industries; supported by evolving decarbonisation policies
- Advanced flexible nuclear reactors and co-gen applications enable integration with variable renewable resources while maintaining grid reliability
- Challenges
  - Technology development/demonstrations
  - Economics; need to reduce costs of new technologies
  - Policies required to drive deep decarbonisation
  - Public perception

Thank you. Merci.

Questions?

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