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OntarioTech UNIVERSITY

Hybrid nuclear-renewable systems for electricity production and non-electrical applications

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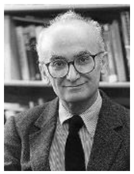
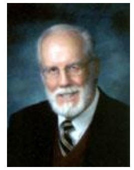
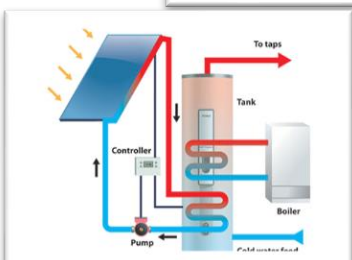
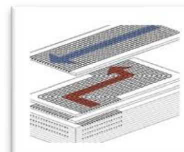
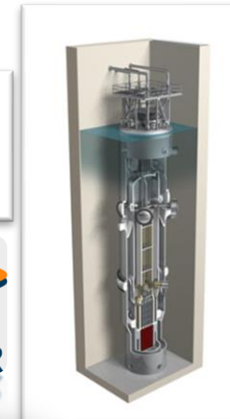
Career summary, Akira Tokuhiro





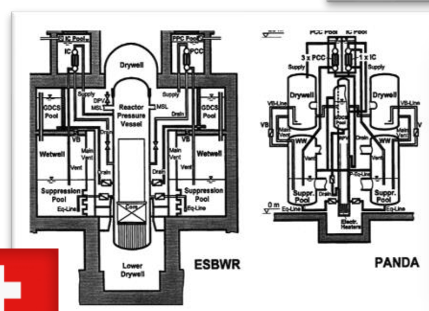


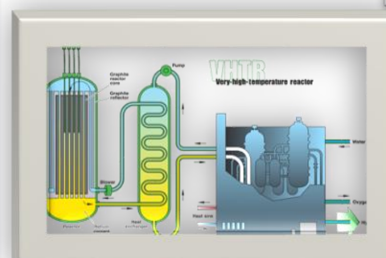


1980 1985 1990 1995 2000 2005 2010 2020 2022

Renewables/Solar thermal, LWRs, LMFR, EFR, GE-SBWR, SCO2_HX, SFR, VHTR, SMR, CANDU

LWRs; BWR, PWR





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confidential

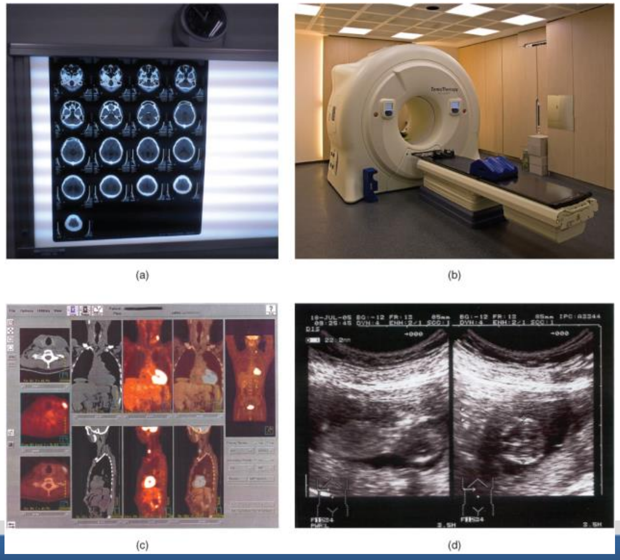
To start…

Non-electric applications.

Application of isotopes, medical isotopes…

Isotopes, medical isotope applications

- Some 730 radionuclides with half-life longer than 60 minute.
- Delivery and application can depend, if produced via reactor, on half-life of isotopes.
- Co-60. Beta decay, then two gammas emitted. Produced as part of reactor operations. Radiotheraypy , sterilization, detection (safeguards)
- Tc-99m. Gamma-emitter Various imaging applications.
- Lu-177. Beta-emitter. Gastroentero-pancreatic tumors.
- Start with Wikipedia. Radionuclide. Link here; https://en.wikipedia.org/wiki/Radionuclide

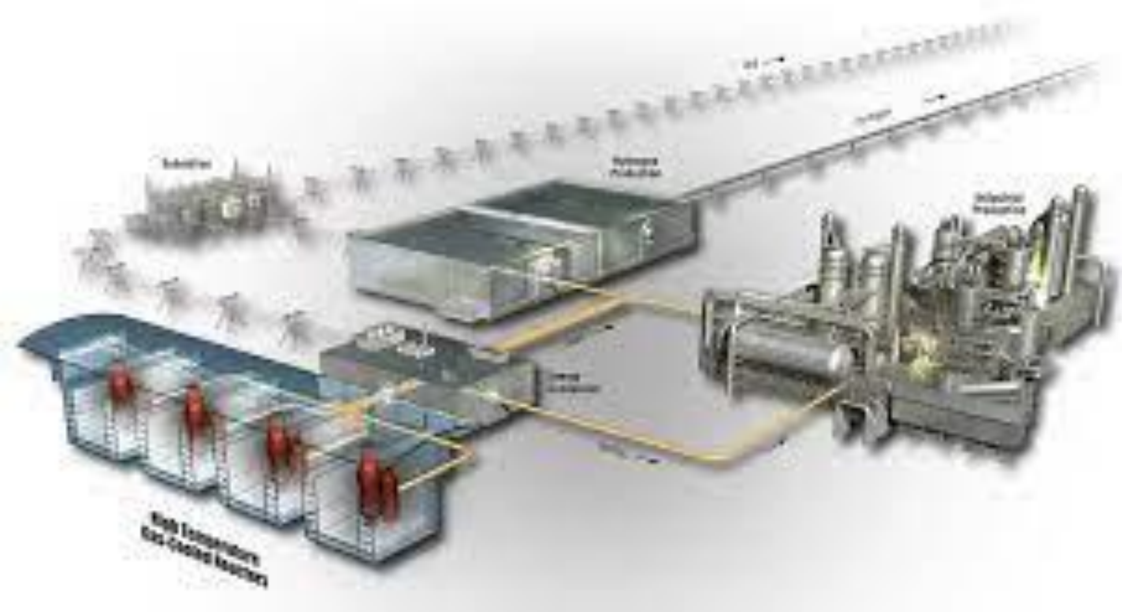


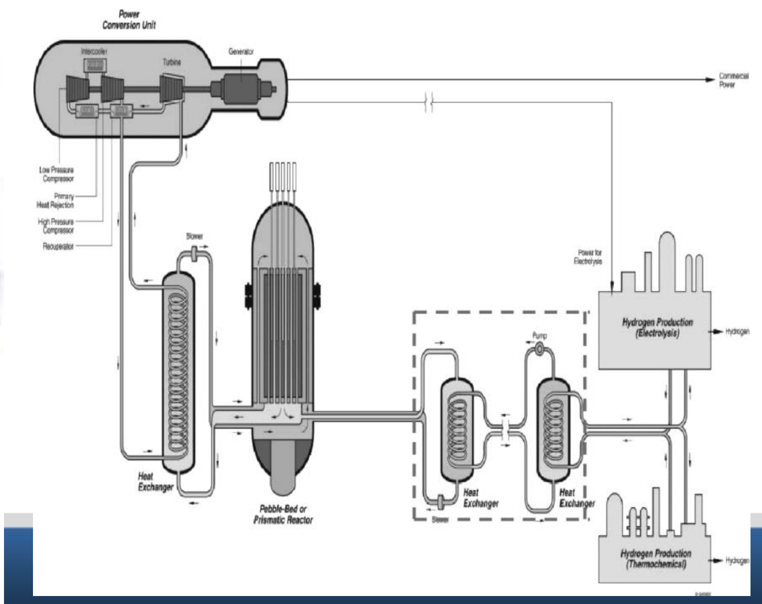
Non-electric applications.

SMR and renewable energy sources…

NGNP/VHTR and hydrogen plant, circa 2005

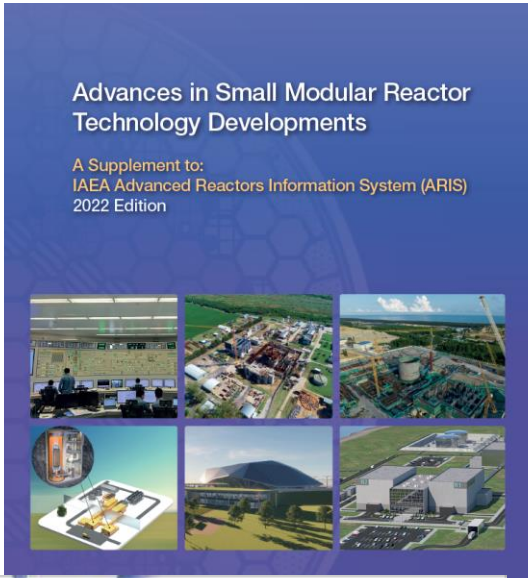
- US DOE interested in developing NGNP/VHTR – next generation nuclear plant/very high temperature (gas-cooled) reactor, and hydrogen production facility, circa 2005-2010; suspended, 2013.
- HTGR concepts – SA-WH's PBMR, Areva's Antares SC-HTGR, GA's Gas-turbine MHeR- modular He-cooled Reactor
- Cf1. C. Sink, USDOE – US Department of Energy; https://www.hydrogen.energy.gov/pdfs/htac_nov14_4_sink.pdf
- Cf2. Wikipedia. Next Generation Nuclear Plant.





Beyond US NGNP/VHTR initiatives…SMRs

- Many of the key challenges considered by OECD-NEA
- Helpful catalogue of many to all, public SMR concepts by the IAEA
- For Ontario, Canada, @gridwatch provides (quasi)live energy portfolio and CO_2 –carbon intensity data
  - Emerging reference is 100gCO_2/kwh; lower than 50gCO_2/kwh is much better
  - Ontario, <10-75gCO_2/kwh; ~60% nuclear, ~30% hydroelectric, 10% NG+renewables; no coal.
- Worldwide, @electricitymap provides (quasi) live energy portfolio and CO_2 – carbon intensity data
- Hydrogen is now "popular" in social media



gridwatch

electricityMap

Cf1. IAEA, Aris site. Link is here; https://aris.iaea.org/sites/Publications.html
Cf2. https://www.oecd-nea.org/jcms/pl_57979/small-modular-reactors-challenges-and-opportunities?details=true

Non-electric applications.

SMRs, issues and challenges…

Challenges, "low, medium and high"

Not in any order

- Initiatives such as "digital twin", though useful in some defined respects, often requires high-performance, computing resources (methods, simulations and $$$) and therefore is unlikely to be substantial use in ongoing engineering and design practices. "Research vs. technology development/deployment"
- As some nuclear reactor concepts (engineering, design) and related thermohydraulic concepts are dated, there is greater global need to maintain knowledge in some of these areas (examples): fast reactors theory, sodium and liquid metal thermohydraulics, fusion reactor concepts, turbulence theory and applications, fundamentals of CFD, analytical methods and simulations, high-performance computational methods, experimental methods, validation and verification. Knowledge preservation.
- There is urgent need to maintain classic books in the above disciplines.
- Increasing focus (scrutiny) on "cost and price" of technology solutions, ROI in investments, coupling of global supply-chain markets, disinformation / misinformation in shared communications. Polarizing "G7/G20" geopolitics.

Technical, non-technical SMR challenges

Not in any priority/order.

- Non-technical. Financial, sustained investments – relative to progress to completion of the SMR design and engineering.
- Non-technical/partially technical. Lack of completed regulatory review and approval. NuScale SMR has USNRC approval; national initiatives - operating or constructing SMR(type) plants of their own design. Export of said designs unclear.
- Non-technical. ~80 current SMR concepts. Is there sufficient workforce? At maximum, how many SMR/new nuclear could be under construction simultaneously? 50? 100? Q: how many, how soon?
- Recognize differences in funded approach – By country differences and similarities; government/commercially funded under investors.
- Technical/partially non-technical. No reference design that is publically accessible. IAEA SMR simulator does exist but PSA/PRA of this design does not.

Hydrogen and social media

- Along with hydrogen, ammonia is being discussed. Ammonia is not a likely energy carrier; toxic gas and its cyclic efficiency is 11-19%.
- To produce…say 10kwh, there will be capital costs for electrolysis, Haber-Bosch plant equipment costs, new standards and manufacturing investments for tankers, loading/off-loading facilities, and fuel cells/gas turbines needs….just to get 1-2 kwh in energy. (Cf. PM)
- Please remember that catalysts (nanomaterials) improve (time-scale) the (chemical) kinetics, but the endothermic reaction and electrical energy will still be needed (thermodynamics).
- Potential depletion and demand price increases of platinum, rhodium, related catalytic materials.
- Cf. Paul Martin (PM). Link here; https://www.linkedin.com/in/paulraymartin/

Non-electric applications.

Non-technical investment/financing challenges

Technology Readiness Level (scale)

European Commission

Technology Readiness Levels

TRL 0: Idea. Unproven concept, no testing has been performed.

TRL 1: Basic research. Principles postulated and observed but no experimental proof available.

TRL 2: Technology formulation. Concept and application have been formulated.

TRL 3: Applied research. First laboratory tests completed; proof of concept.

TRL 4: Small scale prototype built in a laboratory environment ("ugly" prototype).

TRL 5: Large scale prototype tested in intended environment.

TRL 6: Prototype system tested in intended environment close to expected performance.

TRL 7: Demonstration system operating in operational environment at pre-commercial scale.

TRL 8: First of a kind commercial system. Manufacturing issues solved.

TRL 9: Full commercial application, technology available for consumers.

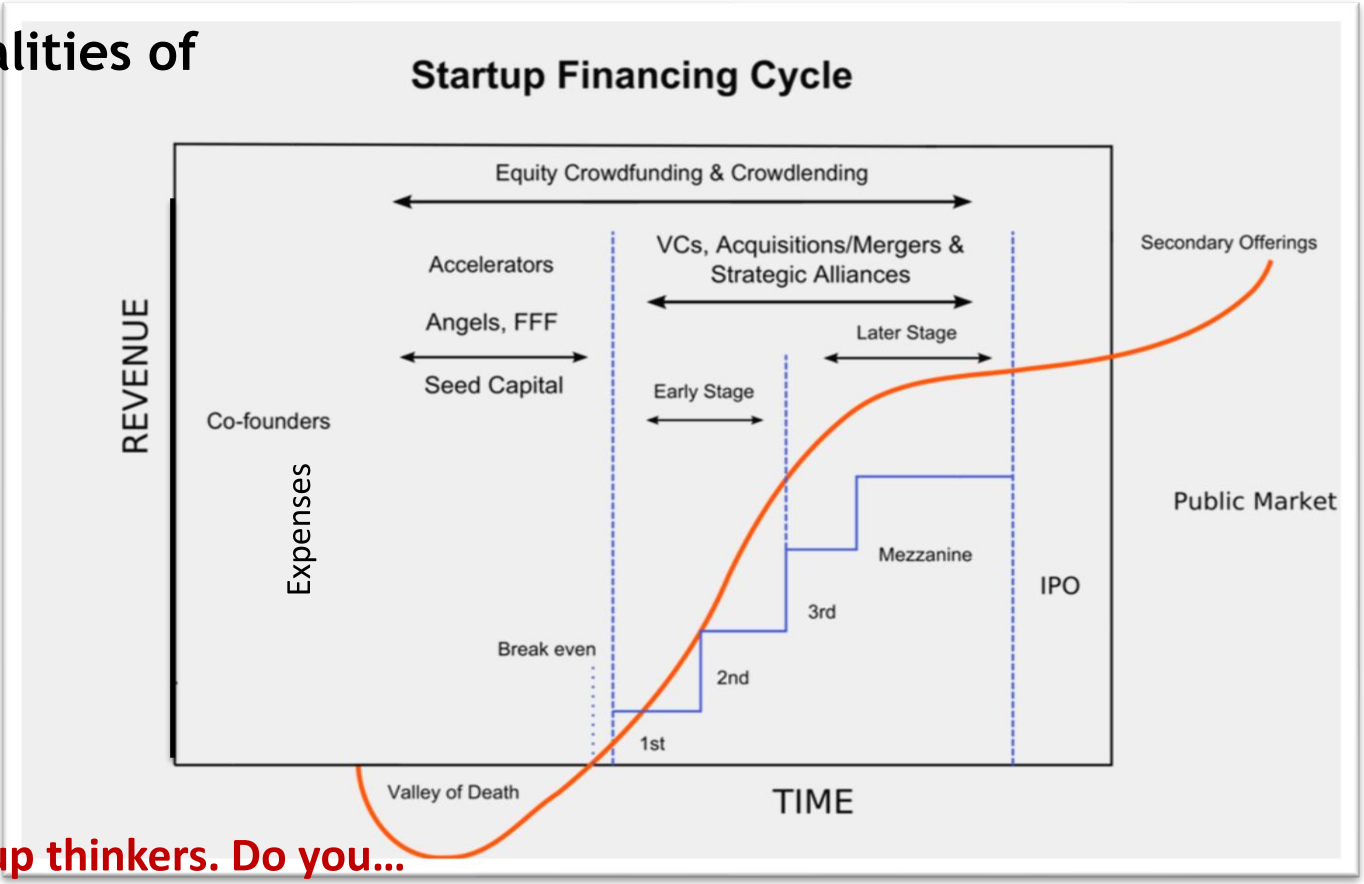
Wikipedia. "TRL"
1) English. https://en.wikipedia.org/wiki/Technology_readiness_level

TRL Definitions

- TRL 1 **basic principles observed**
- TRL 2 **technology concept formulated**
- TRL 3 **experimental proof of concept**
- TRL 4 **technology validated in lab**
- TRL 5 **technology validated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
- TRL 6 **technology demonstrated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
- TRL 7 **system prototype demonstration in operational environment**
- TRL 8 **system complete and qualified**
- TRL 9 **actual system proven in operational environment** (competitive manufacturing in the case of key enabling technologies; or in space)
- Cf. https://serkanbolat.com/2014/11/03/technology-readiness-level-trl-math-for-innovative-smes/

Startup financing cycle.

Realities of



1) Solyndra
2) Flywheel energy storage
3) Cellulosics biofuels
4) Solar power tower
5) Small wind turbines
6) Marine energy
7) https://www.worldoil.com/news/2019/8/15/green-energy-has-a-pletho

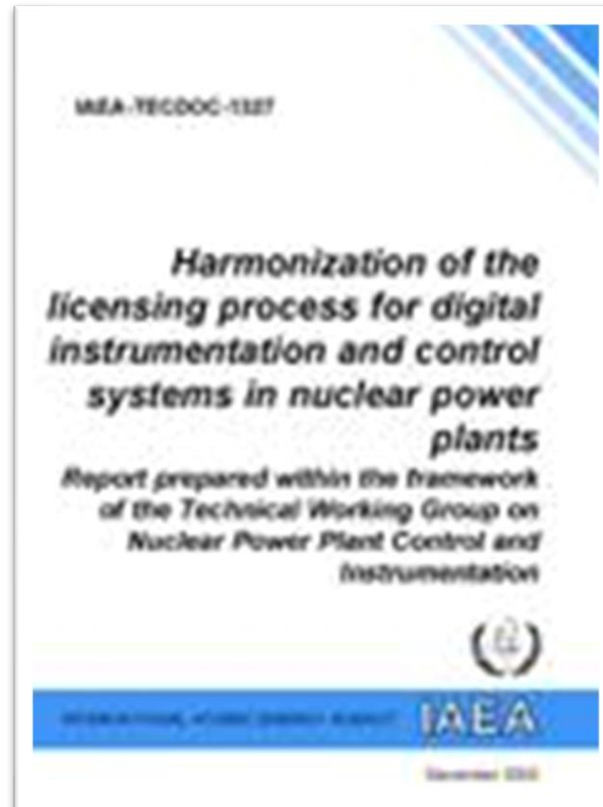
Start-up thinkers. Do you…

- …start a startup full-time or do it part-time, after your full-time job?
- …want a startup to eventually sell and retire young?
- …want a startup to do good for humanity and undergo $ hardship?
- …want a startup to do both good and make it financially sustainable?

National and international nuclear regulation

There are many questions.

- While a needed and good initiative, international agreements are challenging.
- Q1. How much progress can be made, over how many years will it take?
- Q2. Is there willingness and common understanding of the need?
- Cfs (below). OECD-NEA, IAEA



Non-electric applications.

Technical issues and challenges. Coupling SMRs (nuclear) to renewable energy systems

Envisioned co-location of SMR + CSP

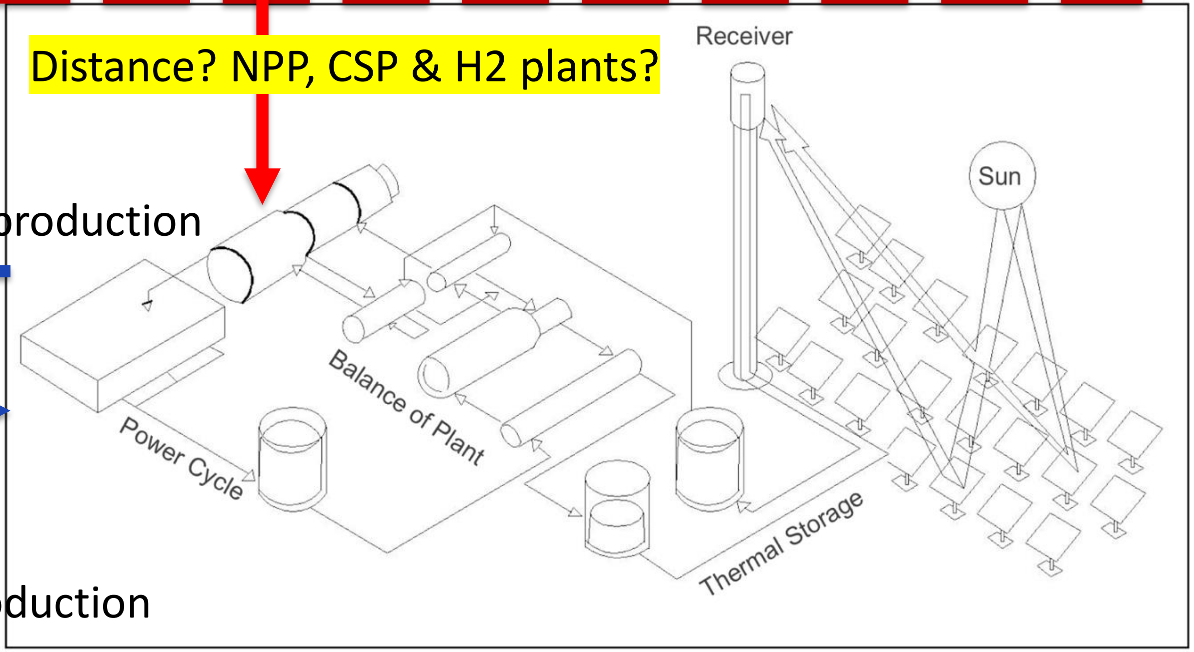
- SMR (left), CSP (below)
- Dotted line is “nuclear plant” boundary, by regulation.
- Q: What is the distance between the NPP & CSP?

Nuclear plant site boundary

Distance? NPP, CSP & H2 plants?

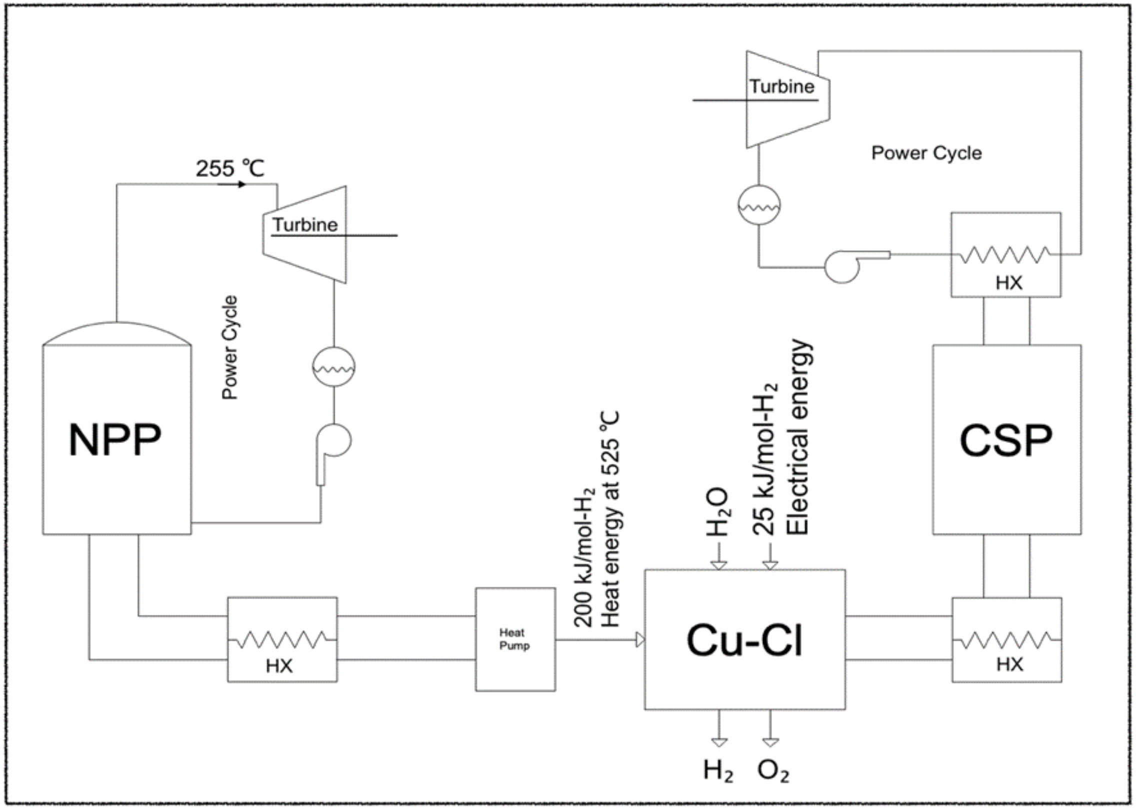
Hydrogen production

Electricity production



Nuclear-renewable hybrid plants

- Operating, output temperature of nuclear plant can determine higher temperature thermo-chemical, hydrogen production processes (I-S [~900C], Cu-Cl ~[500C]).



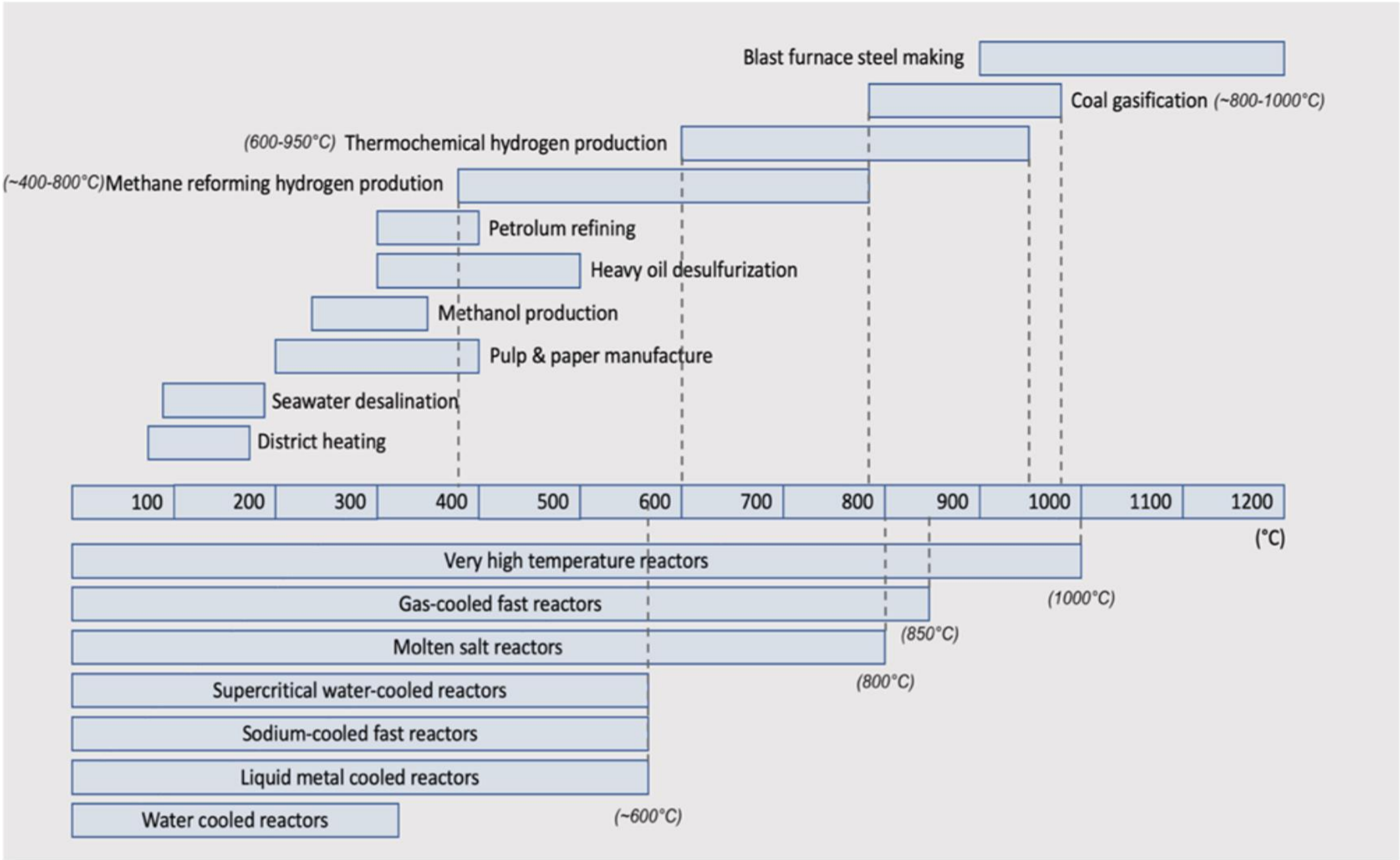
- Hybrid systems can produce electricity, hydrogen, low-grade thermal applications such as district heating.
- Energy conversion system for NPP, CSP likely to be separate.
- Main technical challenge may be “intelligent control” system; quasi-steady output (NPP), coupled to fluctuating output (CSP, renewable).
- Partial operational energy storage may be practical.

Sample specification of Gen' IV reactor concepts

	SWCR	GFR	LFR	MSR	SFR	VHTR
Coolant	Water	Helium	Lead/Lead-Bismuth	Fluoride Salts	Sodium	Helium
Neutron Spectrum	Thermal/Fast	Fast	Fast	Thermal/Fast	Fast	Thermal
Capacity (MWe)	300-1500	1-200	20-1000	800-700	50-1600	250-300
Fuel Cycle	Open/Closed	Closed	Closed	Closed	Closed	Open
Outlet temperature (°C)	510-625	850	480-570	700-800	500-550	900-100
Reference	[61, 62]	[62-64]	[62, 65]	[62, 65]	[62, 65]	[66, 67]

- NPP outlet temperature determines the thermochemical H_2 production
- Cf. M. Ciftcioglu. Optimized Clean Hydrogen Production using Nuclear Small Modular Reactor and Concentrated Solar Power as a Renewable, MASc. thesis, Ontario Tech University. December 2022. References noted.

Reactor concepts, operating tempertures and thermal energy applications



- Cf. M. Ciftcioglu, Optimized Clean Hydrogen Production using Nuclear Small Modular Reactor and Concentrated Solar Power as a Renewable, MASc. thesis, Ontario Tech University, Dec. 2022.

Hydrogen production, targeted market values

Table. An overview of the prices for generating hydrogen utilizing various technologies that have been published in the literature. Note that CCUS is carbon capture use and storage. M. Ciftcioglu's MASc thesis, Ontario Tech U., Canada.

	Methods								
	Black Hydrogen without CCUS	Grey Hydrogen without CCUS		Blue Hydrogen with CCUS		Green Hydrogen			
Energy Source	Coal	Natural Gas		Coal	Natural Gas	Renewable Electricity			
Location	Canada	Canada		Canada		Canada			Europe
Hydrogen Cost (US$/kg-$H_2$)	1.35	1.31	0.67-1.05	1.60-2.05	1.61-1.83	7.39	2.56-6.84	2.28-3.69	2.36-8.26
Reference	[57, 117]	[57, 117]	[57, 118]	[57, 117]		[57, 119]	[57, 120]	[57, 118]	[57, 121]

Note: Hydrogen prices in €/kg are converted into US$/kg-$H_2$.

- Cf1. M. Ciftcioglu, Optimized Clean Hydrogen Production using Nuclear Small Modular Reactor and Concentrated Solar Power as a Renewable, MASc. thesis, Ontario Tech University, Dec. 2022.
- Cf2. Pinsky, R., Sabharwall, P., Hartvigsen, J., & O'Brien, J. (2020). Comparative review of hydrogen production technologies for nuclear hybrid energy systems. Progress in Nuclear Energy (New Series), 123(C), 103317-. https://doi.org/10.1016/j.pnucene.2020.103317

Nuclear – hydrogen demonstrations, US

There are 4 ongoing USDOE demonstration projects. In summary:

1) Nine Mile Point (Oswego, New York). Low-temperature electrolysis from this Constellation (utility) plant; by end of 2022 or early 2023.

2) Davis-Besse (Oak Harbor, Ohio). Energy Harbor, utility. Low-temperature electrolysis; demonstrate techno-economic feasibility to support local manufacturing, transportation. Hydrogen production in 2023.

3) Prairie Island (Red Wing, Minnesota). Bloom and Xcel Energy, utilities. High-temperature electrolysis to support scaled modeling. Production expected in 2024.

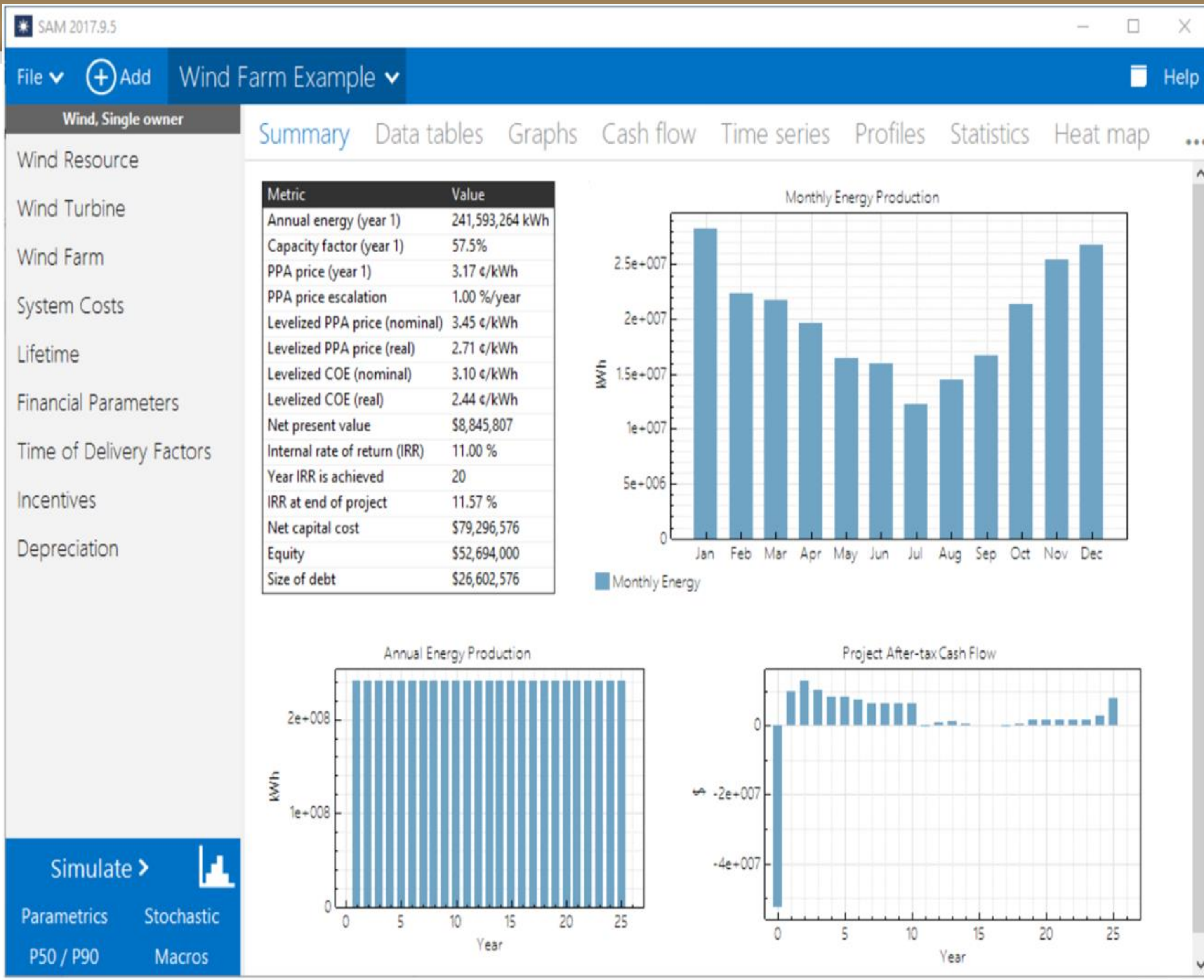
4) Palo Verde (Tonopah, Arizona). Arizona Public Service, and PNW Hydrogen, demonstrate low-temperature electrolysis. Use H2-based electricity during high demand, produce other chemicals and fuels. Hydrogen expected in 2024.

Cf. USDOE 4 nuclear power plants gearing up for clean hydrogen production; https://www.energy.gov/ne/articles/4-nuclear-power-plants-gearing-clean-hydrogen-production

Challenges in operational methods

- Can be viewed, largely as an semi- to fully-automated applied controls problem. Nuclear source (SMR), can at most vary in thermal output, seasonally in time (multi-unit). Other than hydroelectric, renewables such as wind/solar fluctuate (hourly) in thermal/electrical output.
- Thus for fluctuating sources, ~8760 hours (year) solar or wind data is needed, in order to characterize hybrid operational behavior.
- Multiple renewable sources, and energy storage – electrical or thermal, can add complications, but also “time-lag” capability.
- Remember, NPP may need off-site electrical power or be designed to operate in “island mode” (without need for off-site electrical power).
- Applications of neuro-fuzzy, machine learning methods for steady-state operational data analytics, will add details and maintain safety margins.
- Remember, NPP is by far the most regulated.

SAM – System Advisor Model (Cf. US NREL)



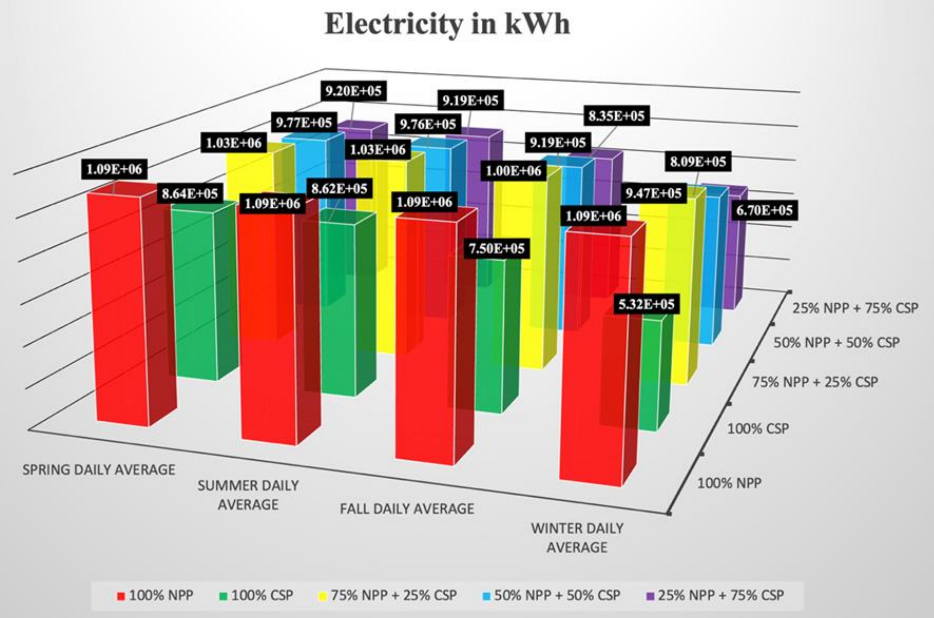
- SAM maintained by US NREL.
- SAM provides techno-economic SW model for:
- renewables (not nuclear)
- Solar PV
- Battery storage
- CSP; solar thermal
- Wind
- Geothermal
- Biomass
- Fuel cell etc.

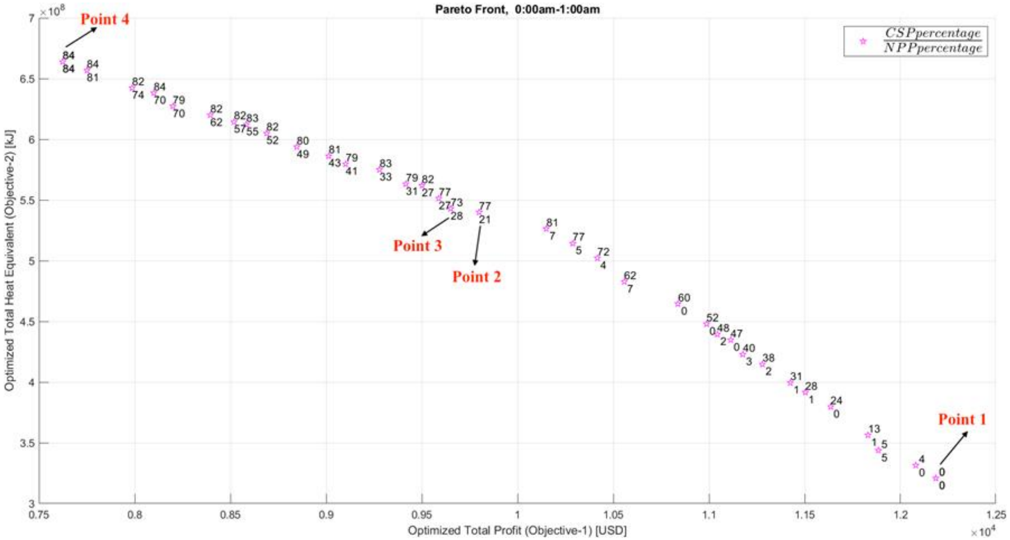
Ongoing study by M. Ciftcioglu

- Modeling, simulation and optimization study of…
  - Prototypic iPWR-type SMR with safety-in-design, passive safety systems
  - Coupled to a molten-salt loop CSP; Daggett, California, USA (1 year data, 8760 hours); high desert location, solar data.
  - Plant must generate electricity and hydrogen
  - Current regulatory framework
  - Using a Cu-Cl cycle for hydrogen generation.
  - No energy storage, nor other renewable sources. No low temperature electrolysis.
- Constraint. Both NPP, CSP cannot produce electricity nor hydrogen only.

Early results; maximizing e-generated, H2 produced

- Early results as shown. First total kWh electricity (right) generated, during seasons (Spring, Summer, Fall, Winter) with varying percentages dedicated to electricity and H2 production.
- Early results as shown. Next when (lower, right) maximum electricity generated is plotted versus the maximum ROI/profit at anticipated H2 price.
- Also, consideration of unanticipated transients at NPP with 4 hours (beyond event initiation) being shutdown (phase); actually, 2, 4, 8, 16, 24, 48 hours being representative time beyond event initiation.

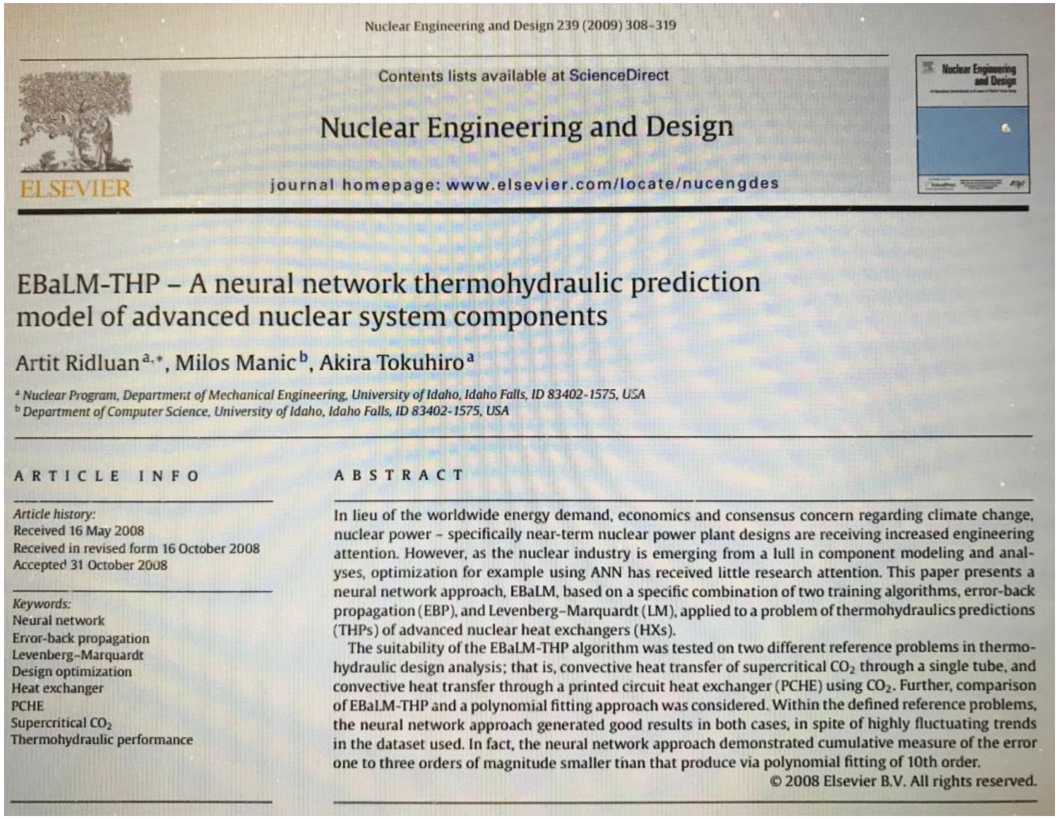




On data analytic methods; AI/ML…

Data analytics, optimization and approaches

- For thermal systems, higher level optimization problems, please try a backward propagation, Levenberg-Marquardt algorithm; it may be suitable
- There is small but promising evidence that it may be well-suited for thermal systems engineering and design.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EBaLM-THP – A neural network thermohydraulic prediction model of advanced nuclear system components

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ABSTRACT

In lieu of the worldwide energy demand, economics and consensus concern regarding climate change, nuclear power – specifically near-term nuclear power plant designs are receiving increased engineering attention. However, as the nuclear industry is emerging from a lull in component modeling and analyses, optimization for example using ANN has received little research attention. This paper presents a neural network approach, EBaLM, based on a specific combination of two training algorithms, error-back propagation (EBP), and Levenberg–Marquardt (LM), applied to a problem of thermohydraulics predictions (THPs) of advanced nuclear heat exchangers (HXs).

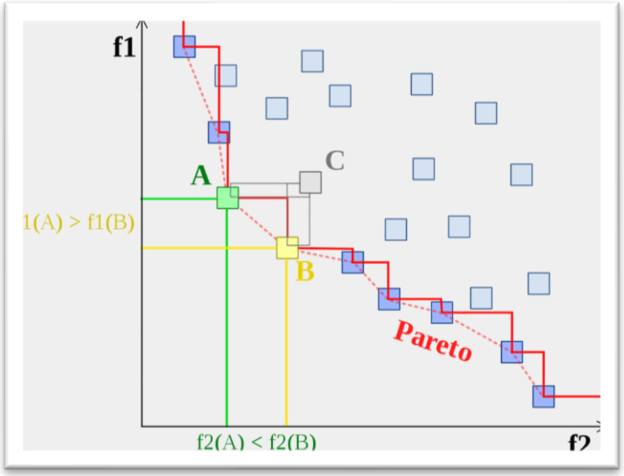
The suitability of the EBaLM-THP algorithm was tested on two different reference problems in thermohydraulic design analysis; that is, convective heat transfer of supercritical CO_2 through a single tube, and convective heat transfer through a printed circuit heat exchanger (PCHE) using CO_2. Further, comparison of EBaLM-THP and a polynomial fitting approach was considered. Within the defined reference problems, the neural network approach generated good results in both cases, in spite of highly fluctuating trends in the dataset used. In fact, the neural network approach demonstrated cumulative measure of the error one to three orders of magnitude smaller than that produce via polynomial fitting of 10th order.

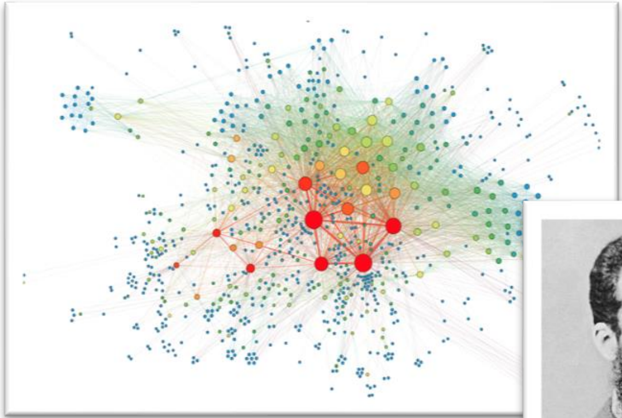
Cf. Ridluan, A., Manic, M., & Tokuhiro, A. (2009). EBaLM-THP – A neural network thermohydraulic prediction model of advanced nuclear system components. *Nuclear Engineering and Design*, *239*(2), 308–319. https://doi.org/10.1016/j.nucengdes.2008.10.027

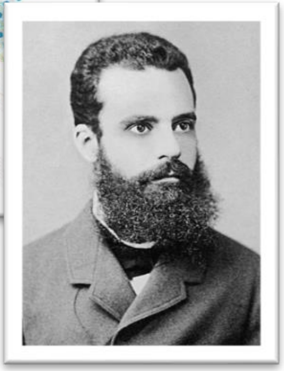
Cf. Wikipedia. https://en.wikipedia.org/wiki/Levenberg%E2%80%93Marquardt_algorithm

Complex systems, design; complexity & optimization

- Heuristic or heuristic technique is an approach to problem solving ; employs a practical method that does not guarantee an optimal or “near perfect” approach but nevertheless reaches a short-term goal or approximation. Use of heuristics can speed up the process of finding a satisfactory solution. (Cf. Wikipedia, Heuristic)
- On optimization, using Pareto “efficiency” or optimality is a engineering design situation where no objective or preference criterion can be “improved” without making at least one individual or preference criterion “worse “. (Cf. Wikipedia, Pareto efficiency)
- Keywords. Complexity, complex systems dynamics, multi-objective, multi-parameter.

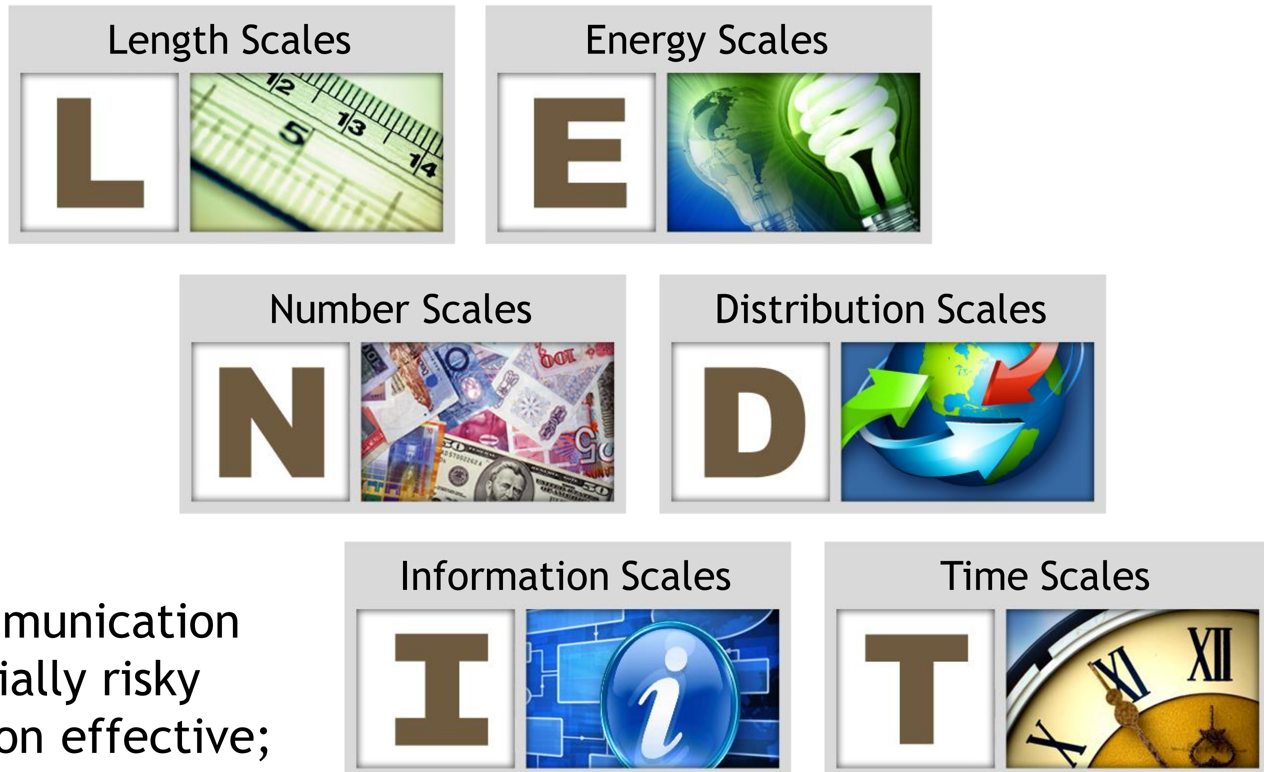






Vilfredo Pareto, 1848-1923, Cf. https://en.wikipedia.org/wiki/Vilfredo_Pareto

Complex Issues; ‘Metrics’ LENDIT



Purpose:
common communication basis; potentially risky communication effective; applicable across soft and hard domains; linked to analytical approaches

PTGVL - Pressure, Temperature, Mass flowrate, Valve position, Liquid level

Pressure

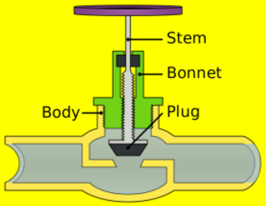
P

Temperature

T

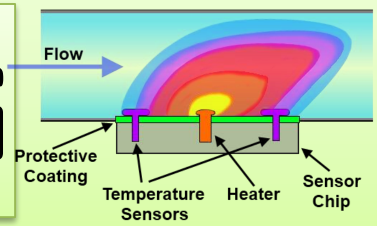
Valve position

V



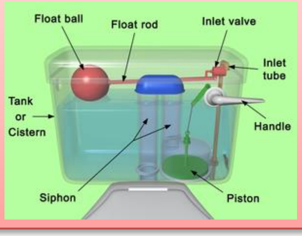
Mass flowrate

G



Liquid level

P



S2R2 - System, State, Resource, Response

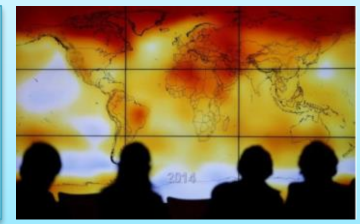
During consideration of unanticipated events, the following....

System

S

State

S



Resource

R

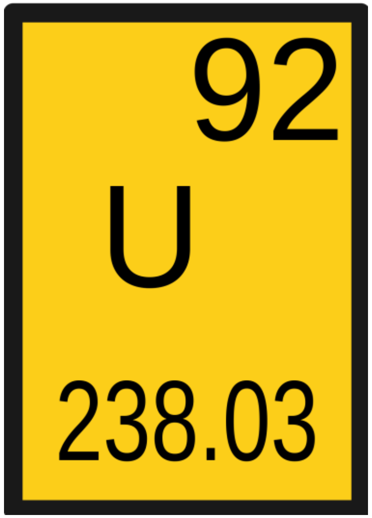
Response

R

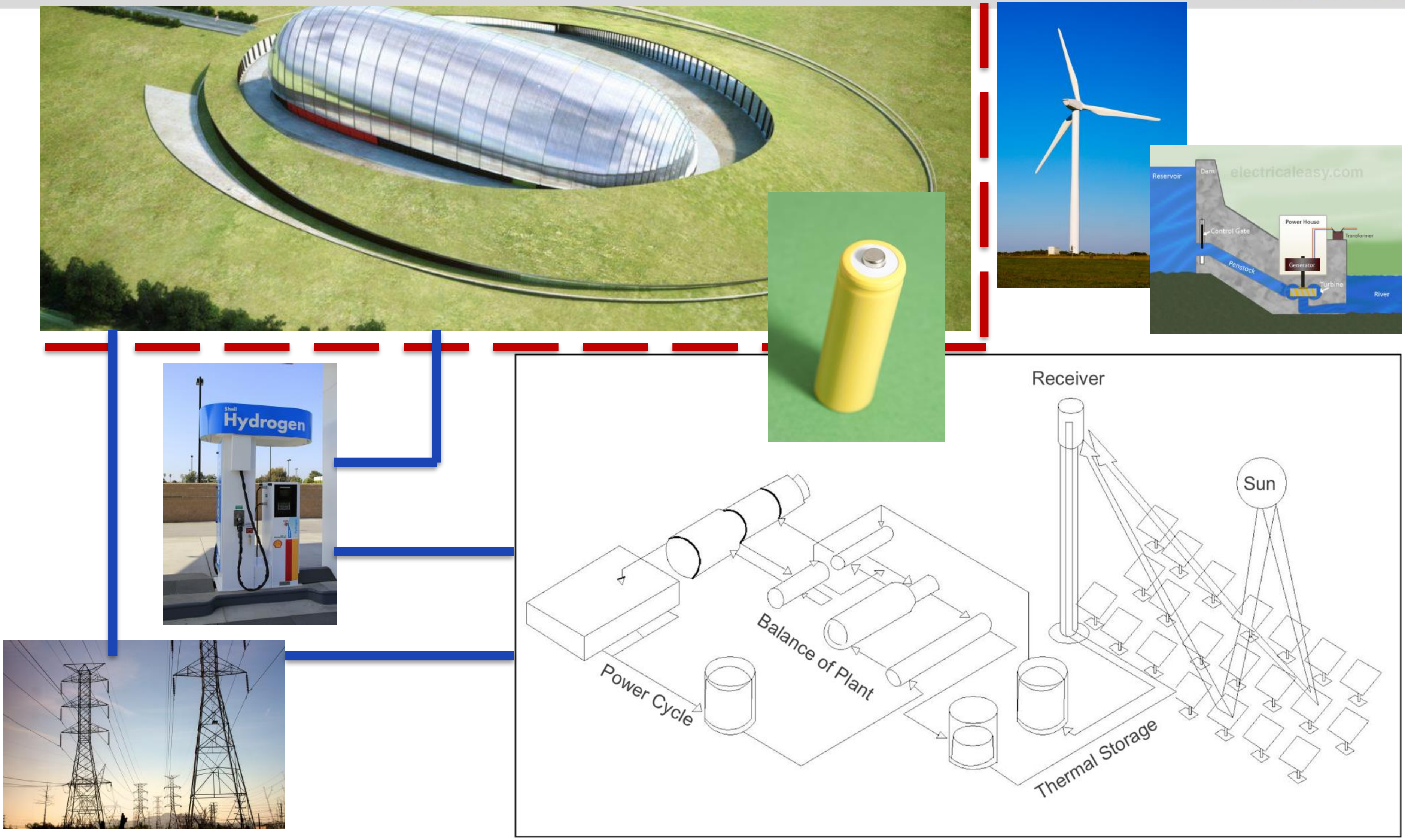
Partial conclusions…

Conclusions to date

- (Opinion) Integration and diversity, are key. There is tendency to look at stand-alone energy solutions – nuclear energy separated from other sources.
- Still to consider. Multiple unit nuclear sites coupled to one or more renewable energy sources, with energy storage, generating electricity, hydrogen, localized (district) heating/cooling. How much "energy" can be extracted?
- (Opinion) Nuclear, renewable and fossil-fuel SMEs and stakeholders need to collaborate….urgently.
- (Opinion) Be cognizant of social media; public acceptance
- Applied optimization methods, Pareto-like approaches, heuristic approaches in energy technologies needed. Renewed and/or more training/education in such methods needed.

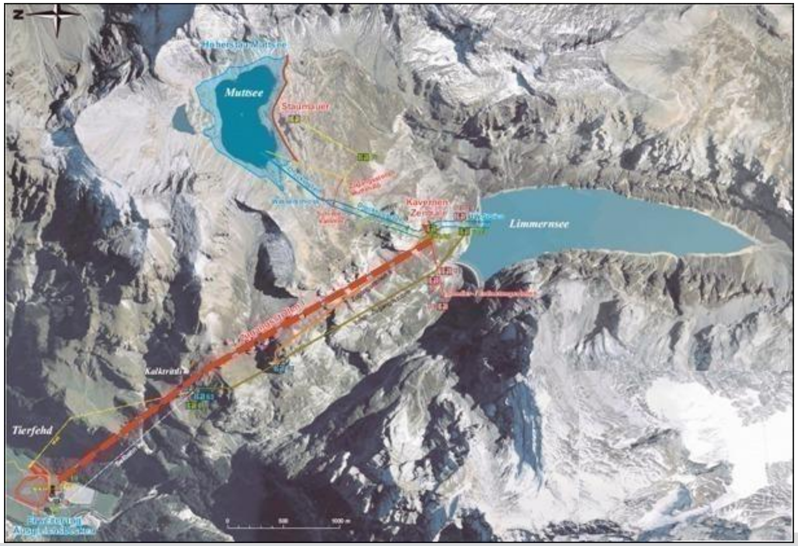


Envisioned co-location of SMR + CSP



Electrical energy storage

- Battery electrical energy storage. About ~200kwh; 10 minutes of 1300 MWe plant
- https://www.bbc.com/news/uk-england-humber-63707463?s=09
- Water storage. Kraftwerke Linth-Limmern (Switzerland) shown below. 1480 MW installed capacity.
- Cf. https://en.wikipedia.org/wiki/Linth%E2%80%93Limmern_Power_Stations
- Q1-3. With any infrastructure project…..How many? How much? How soon?



Starting references

Starting references

- Mustafa Ciftcioglu. Optimized Clean Hydrogen Production using Nuclear Small Modular Reactor and Concentrated Solar Power as a Renewable, MASc. thesis, Ontario Tech University. December 2022.
  - Some 180 references
- M. Ciftcioglu, F. Genco, A. Tokuhiro, Optimized Clean Hydrogen Production using Nuclear Small Modular Reactors and Renewable energy sources: a review. ATW – International Journal for Nuclear Power. March, 2022.
- A. Borissova and D. Popov, "An option for the integration of solar photovoltaics into small nuclear power plant with thermal energy storage," Sustain. Energy Technol. Assess., vol. 18, pp. 119–126, 2016, doi: 10.1016/j.seta.2016.10.002. (also Popov and Borissova)
- R. Pinsky, P. Sabharwall, J. Hartvigsen, and J. O'Brien, "Comparative review of hydrogen production technologies for nuclear hybrid energy systems," Prog. Nucl. Energy, vol. 123, p. 103317, 2020, doi: 10.1016/j.pnucene.2020.103317.
- A number of IAEA, OECD-NEA publications for nuclear-hybrid systems and system level techno-economic studies.

Spent fuel, nuclear waste

Spent fuel….called nuclear waste

- Because we predominantly use a once-through fuel cycle approach, we have spent fuel – only partially burned with energy content still within.
- Several deep geological repositories (DGR) are ready or will be ready.
- Public acceptance/social license; political backing difficult.
- People, society focus on one type of waste, when for example plastic waste is also globally problematic.

QUESTIONS?

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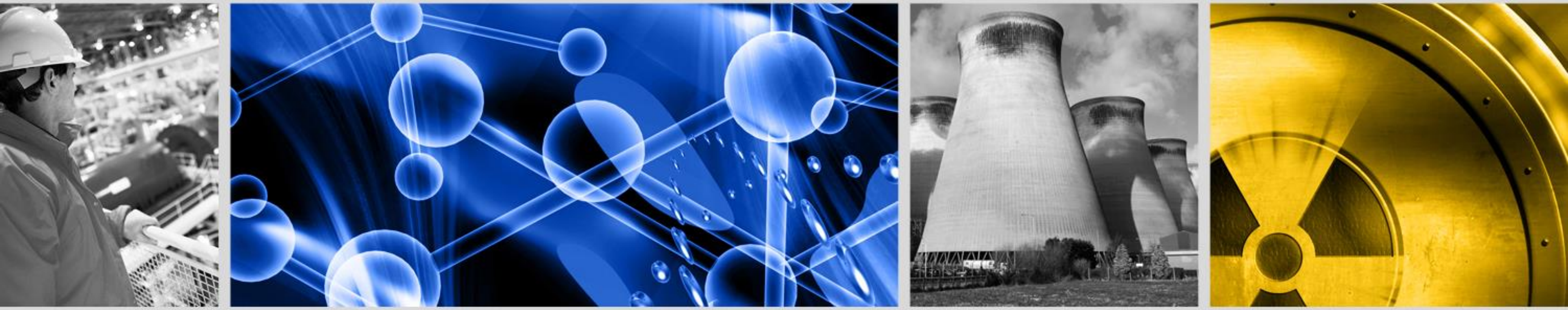


Ontario Canada
Land acknowledgement
to Indigenous peoples

Land acknowledgement

(Ontario indigenous below)

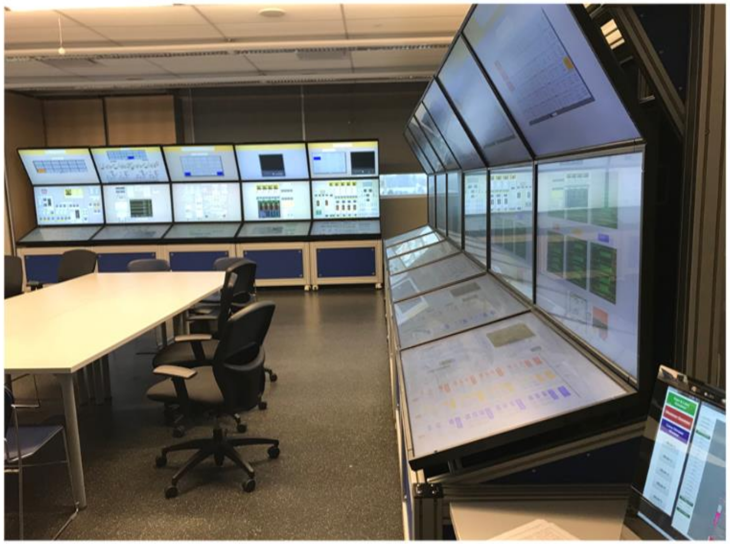
Ontario Tech University is proud to acknowledge the lands and people of the Mississaugas of Scugog Island First Nation. We are situated on the Traditional Territory of the Mississaugas, a branch of the greater Anishinaabeg Nation which includes Ojibway, Odawa and Pottawatomi.

Cf. Truth and reconciliation

Ontario Tech University

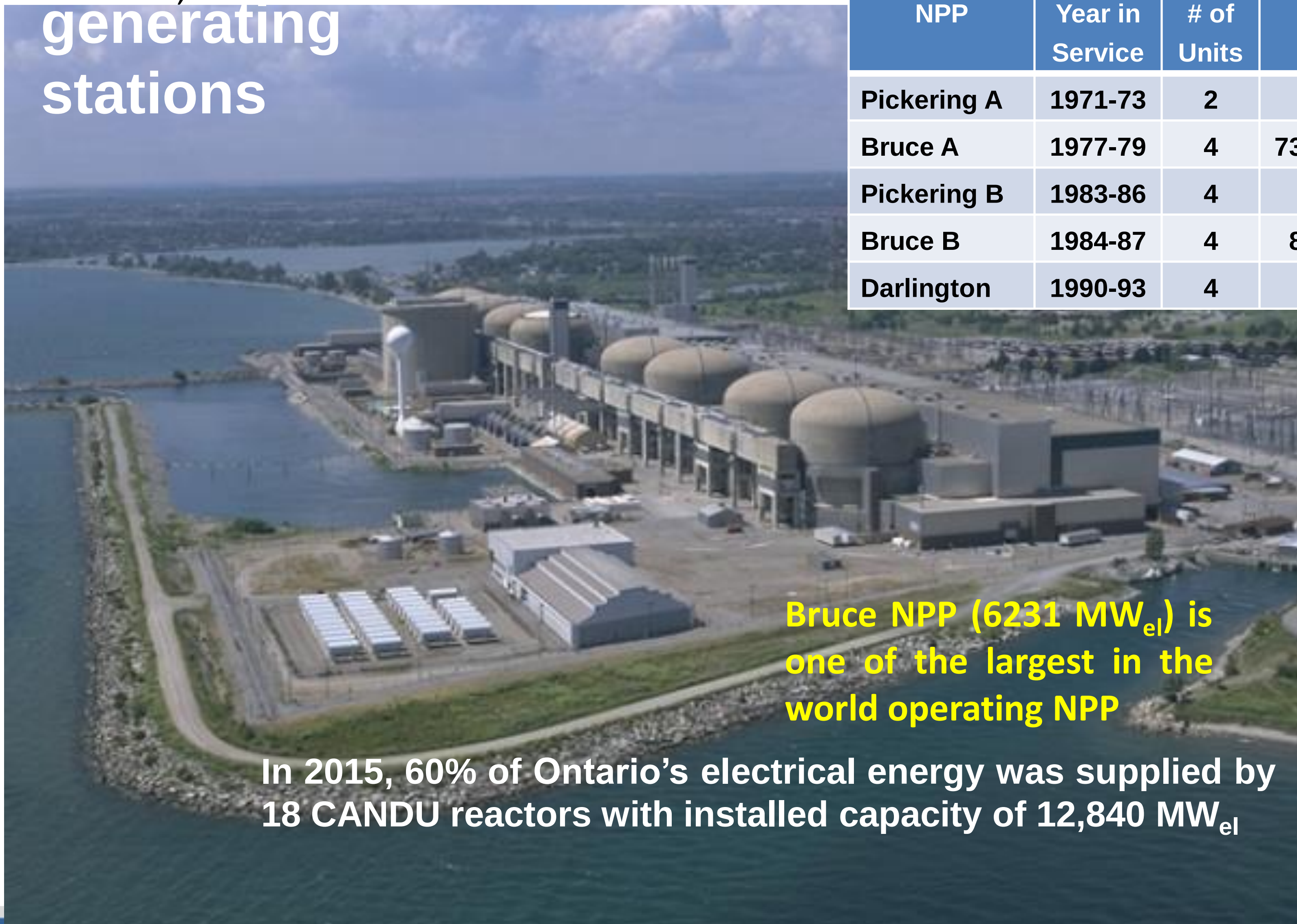
Oshawa, Ontario Canada

Ontario Tech University



- *Faculty of Energy Systems and Nuclear Science; one of 7 Faculties*
- *Ontario Tech U. (UOIT); started 2002, 1st students in 2003; 1st graduates in 2007; ~10,000 students ("millenials")*
- *BEng, MS, PhD, MEng, GDip in NE, HP&RS*
- *1000+ FESNS graduates since 2007*
- *#3 in North America, BEng graduates*
- *15 faculty members*
- *Brilliant Energy Institute, IAEA Collaborating Centre; CfSMRs, CERL*

Ontario's nuclear generating stations



NPP	Year in Service	# of Units	Units' Installed Capacity, MW_{el}
Pickering A	1971-73	2	515×2=1030
Bruce A	1977-79	4	730×2+770×2=3000
Pickering B	1983-86	4	515×4=2060
Bruce B	1984-87	4	817×3+782=3233
Darlington	1990-93	4	878×4=3512

Cf. G. Harvel

Bruce NPP (6231 MW_{el}) is one of the largest in the world operating NPP

In 2015, 60% of Ontario's electrical energy was supplied by 18 CANDU reactors with installed capacity of 12,840 MW_{el}