IMII & PreScouter

Reducing GHG in Uranium and Potash Mining: 2030-2040

Research Support Service

March 19th, 2021

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PRESCOUTER

Project Goal

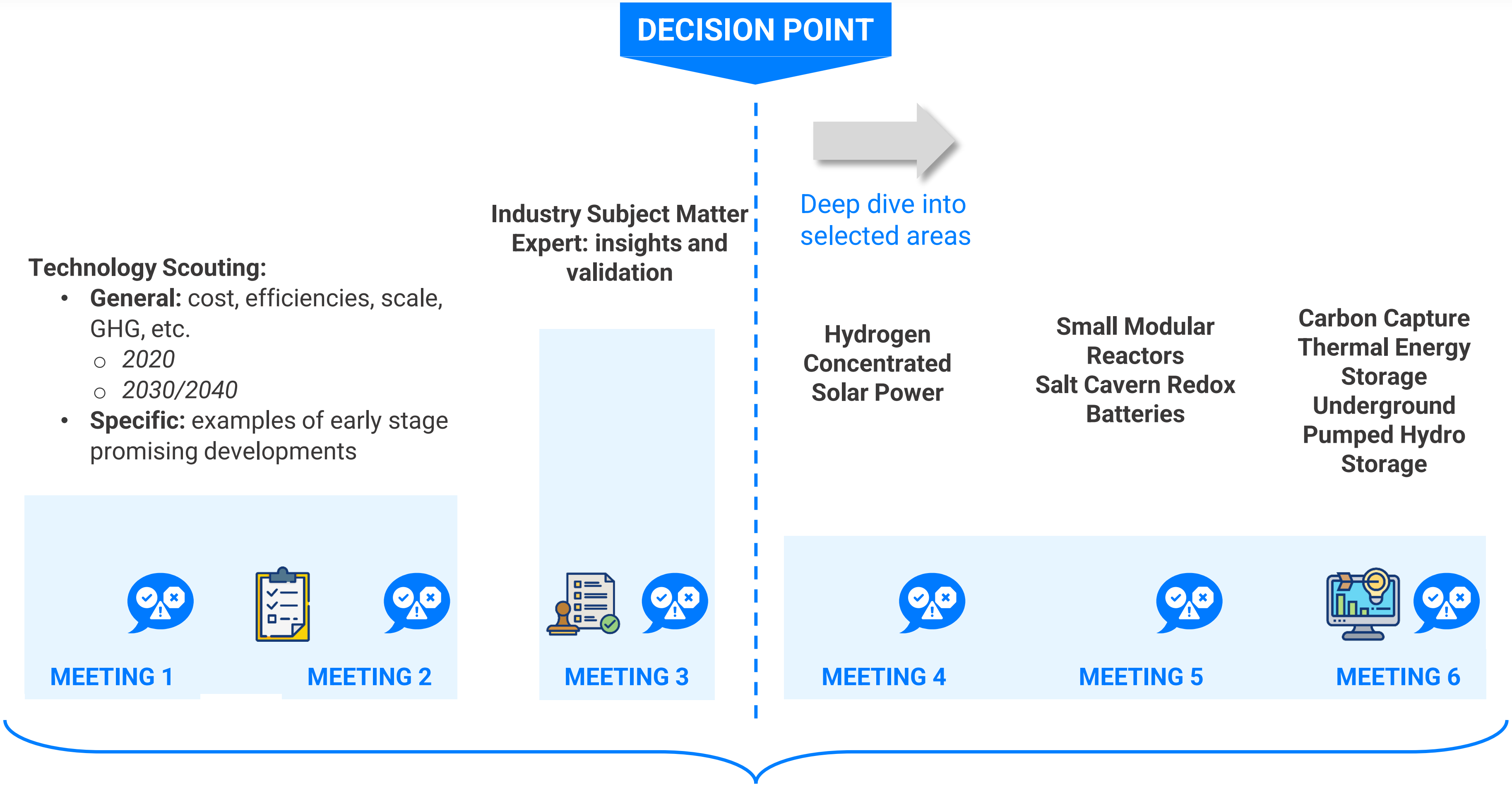
General

One of the objectives of the International Minerals Innovation Institute (IMII) is to help its members to **reduce greenhouse gas emissions**. For that matter, IMII is looking to understand which technologies and strategies might be leveraged in the next **10 or 20 years** to pursue previously mentioned goal, and in particular for **Potash and Uranium Mining**.

PreScouter started with a broad focus identifying the different strategies or technologies for decarbonizing processes related to potash and uranium mining and then, with industry input, did a deeper dive into the most promising technologies/developments.

The overall goal of this engagement was to identify areas where IMII could start projects to develop technologies to reduce emissions for their members' operations within the specified time framework.

Approach



DECISION POINT

Technology Scouting:

- **General:** cost, efficiencies, scale, GHG, etc.
  - *2020*
  - *2030/2040*
- **Specific:** examples of early stage promising developments

Industry Subject Matter Expert: insights and validation

Deep dive into selected areas

Hydrogen
Concentrated Solar Power

Small Modular Reactors
Salt Cavern Redox Batteries

Carbon Capture
Thermal Energy Storage
Underground Pumped Hydro Storage

MEETING 1

MEETING 2

MEETING 3

MEETING 4

MEETING 5

MEETING 6

Areas (and people / institutions) for **projects** for technology **development** identified

Technologies analyzed

Methods

Lowering emissions from fossil fuels

- **Concentrated Solar Power**
- Enhanced Geothermal Systems
- **Small Modular Reactors**
- Solar thermal technology for drying applications
- Biomass Energy
- Bioenergy with CC
- Multirotor Systems Wind Turbines
- Gas-Based Receiver
  - Hydro Harvester Technology
  - High Stable Perovskite Solar Modules

Energy Storage

- **Hydrogen**
  - Ammonia-Fueled Power Generation
  - Concentrated Photovoltaic
  - Thermal System with combined Hydrogen and MgO based storage
- **Thermal Energy Storage**
  - Molten Salt-Based Energy Storage
- Liquid Air Storage
- **Underground Hydro Pumped Storage**
- Potassium Driven Rechargeable Battery
- Air-based encapsulated phase change
- **Salt cavern Redox Batteries**

Conditioning

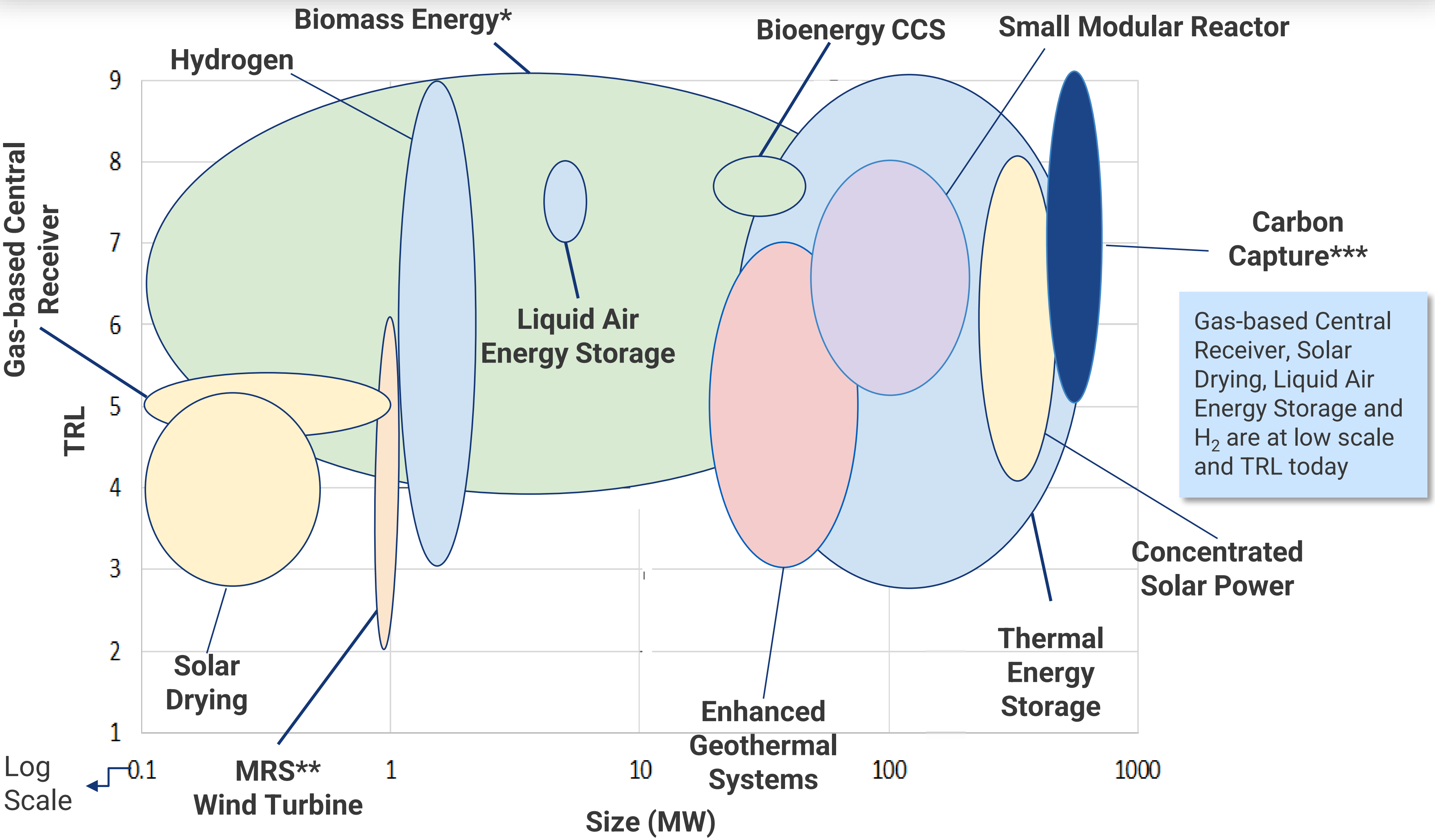
- **Carbon Capture**
  - Faradaic electro-swing reactive adsorption
  - Nanosponges
  - MOF-based Mixed Matrix Membranes
  - Direct CC from Air
  - Magnetohydrodynamic Power Generation

16 General Developments (in **bold** the ones that received further study)

11 Specific Developments

Maturity and Scale - Today

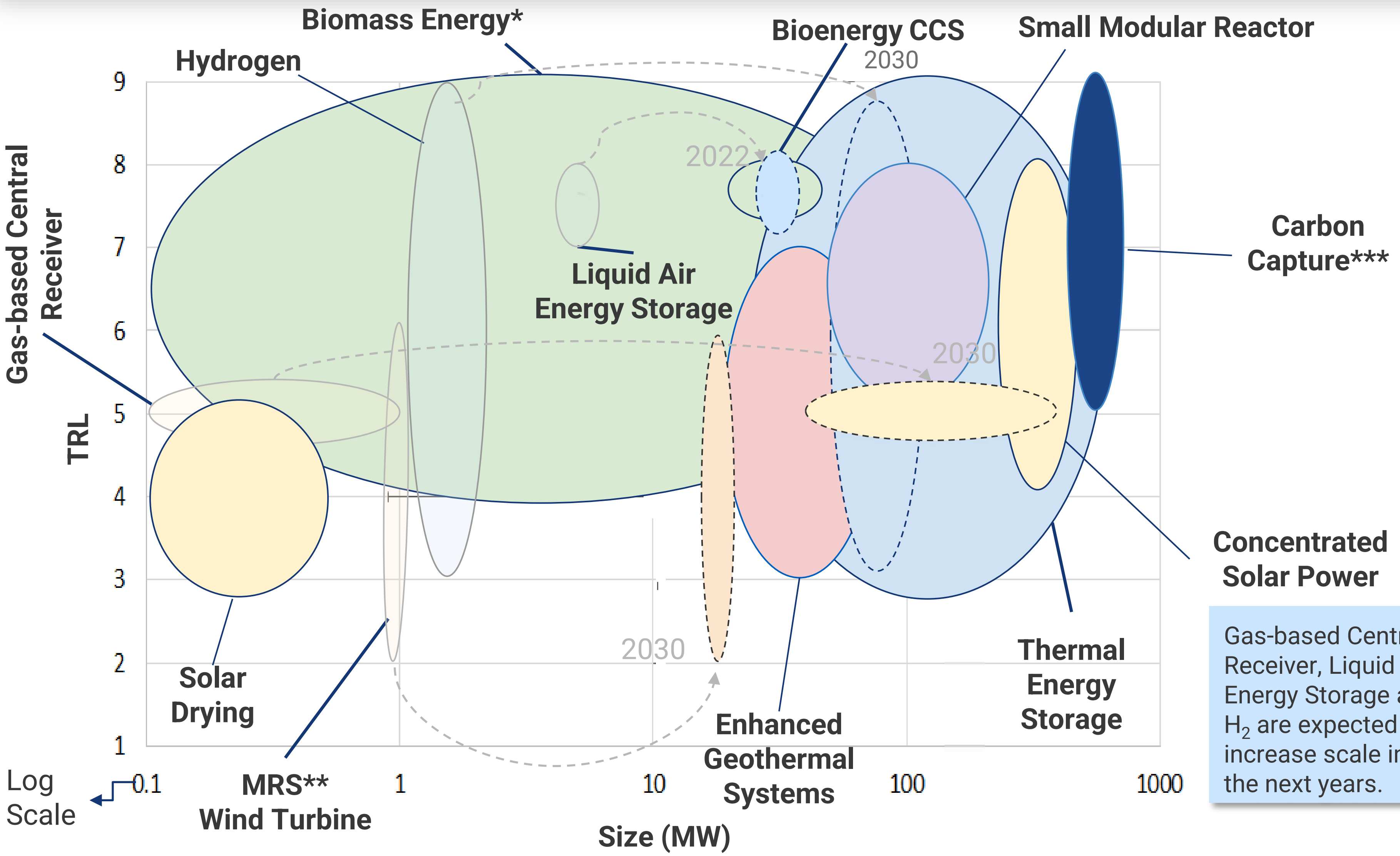
Generation
Storage
Conditioning



Gas-based Central Receiver, Solar Drying, Liquid Air Energy Storage and H_2 are at low scale and TRL today

*plant capacities, higher TRL, are in the range of 49 to 660 MW ** referred to one Turbine. *** Goes to lower sizes too

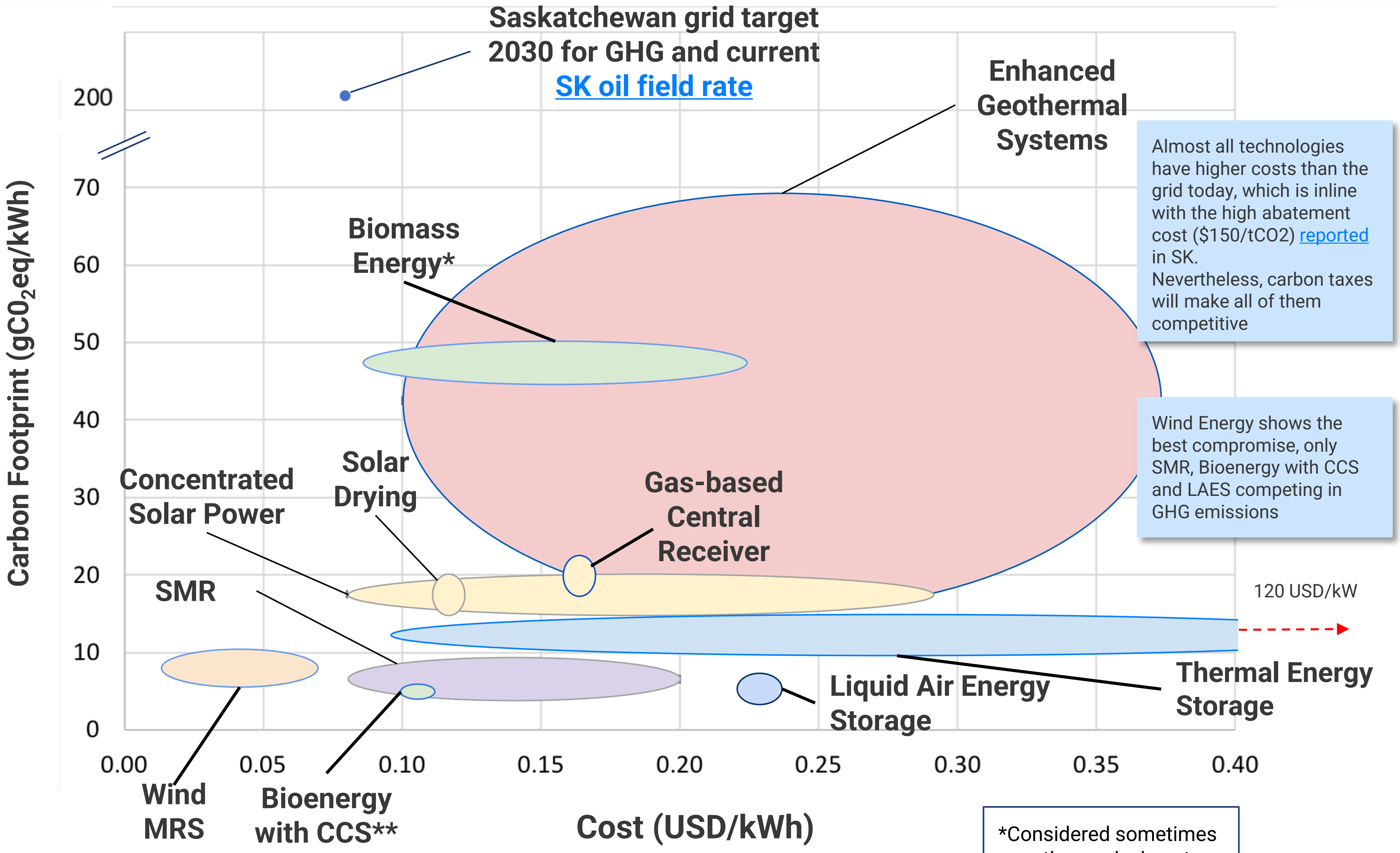
Maturity and Scale - Forecast



Gas-based Central Receiver, Liquid Air Energy Storage and H_2 are expected to increase scale in the next years.

*plant capacities, higher TRL, are in the range of 49 to 660 MW ** referred to one Turbine. *** Goes to lower sizes too

Emissions and Costs

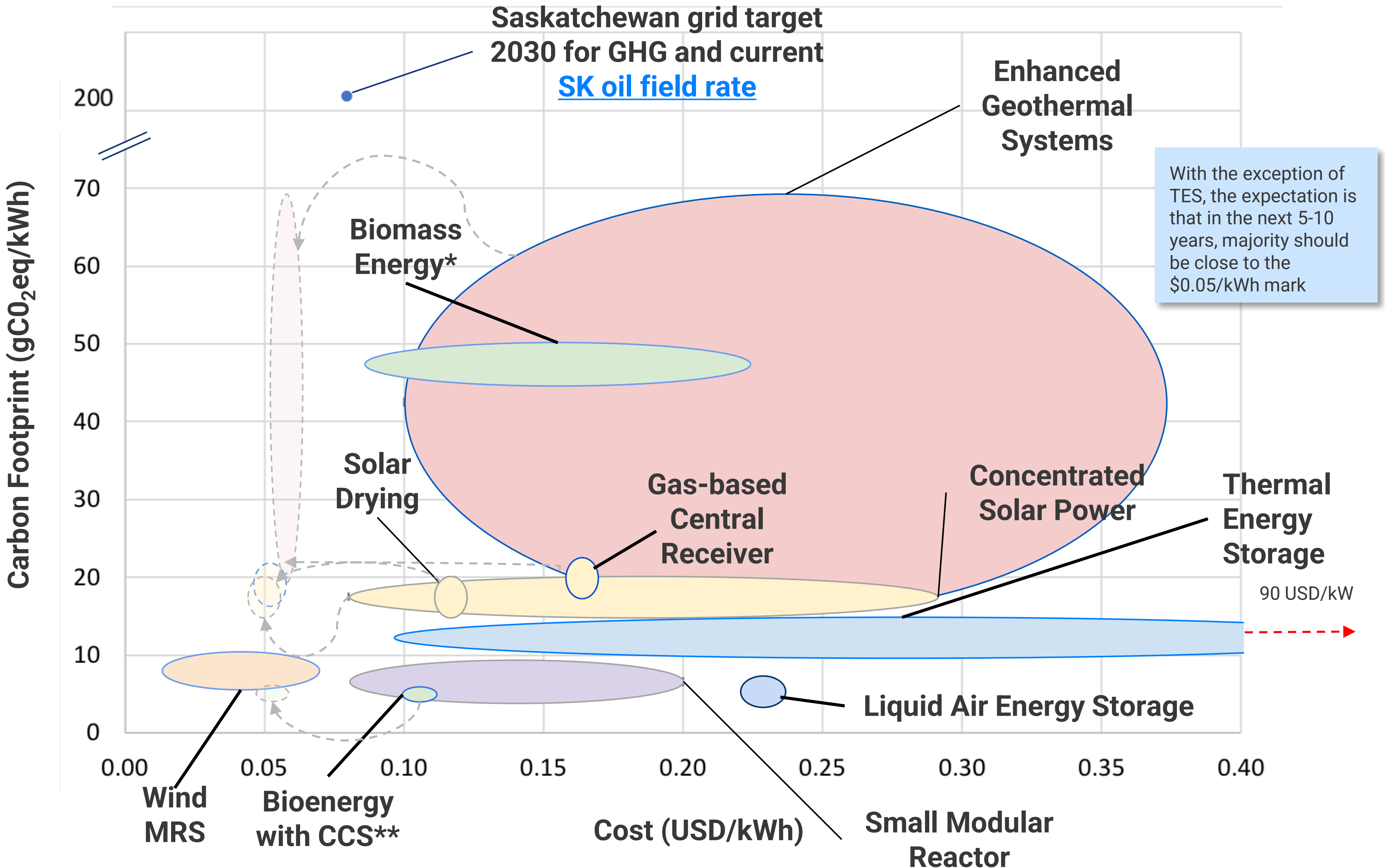


Almost all technologies have higher costs than the grid today, which is inline with the high abatement cost ($150/tCO2) reported in SK.
Nevertheless, carbon taxes will make all of them competitive

Wind Energy shows the best compromise, only SMR, Bioenergy with CCS and LAES competing in GHG emissions

*Considered sometimes negative emissions too

Emissions and Costs - Forecast



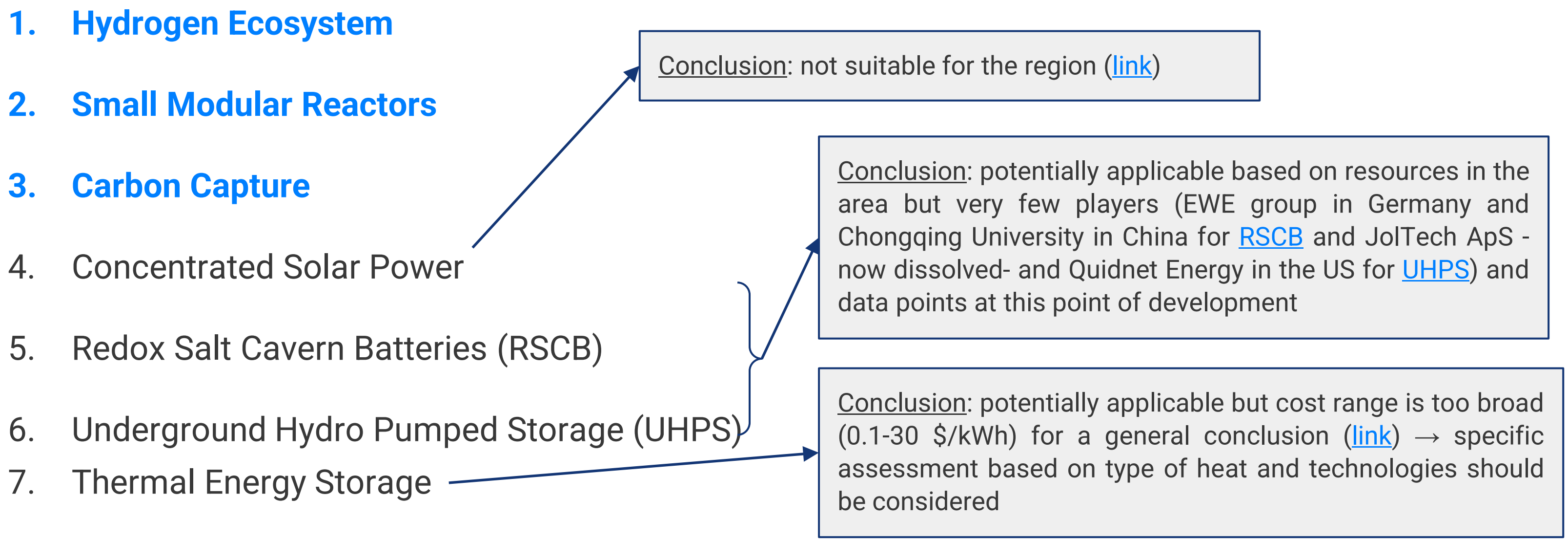
With the exception of TES, the expectation is that in the next 5-10 years, majority should be close to the $0.05/kWh mark

Short list of technologies for deeper study

To select the most promising technologies to make a deeper analysis, the following aspects were considered:

- Fulfilment with initial criteria: mature in the next 10-20 years ability to lower current emission levels
- Applicability to Mining activities and Geographical Region (in some cases to be determined)
- Insights from 4 (four) Subject Matter Experts with combined ~100 years of experience in transitioning to low GHG emission technologies
- Discussion and Feedback from industry members after three rounds of research

The selected areas for further research were:



1. **Hydrogen Ecosystem**
2. **Small Modular Reactors**
3. **Carbon Capture**
4. Concentrated Solar Power
5. Redox Salt Cavern Batteries (RSCB)
6. Underground Hydro Pumped Storage (UHPS)
7. Thermal Energy Storage

Conclusion: not suitable for the region (link)

Conclusion: potentially applicable based on resources in the area but very few players (EWE group in Germany and Chongqing University in China for RSCB and JolTech ApS - now dissolved- and Quidnet Energy in the US for UHPS) and data points at this point of development

Conclusion: potentially applicable but cost range is too broad (0.1-30 $/kWh) for a general conclusion (link) → specific assessment based on type of heat and technologies should be considered

Hydrogen Ecosystem

Hydrogen

Overview

Hydrogen has many uses in the mining industry such as generating high-temperature heat, power, feedstock, fuel for transportation and other mining equipment, and energy storage. Nonetheless, Hydrogen production is currently dominated by reforming natural gas, coal and oil (Grey Hydrogen). There is however, an unprecedented political and business momentum to produce ”Green Hydrogen”, which is produced mainly by electrolysis [1].

At a glance

Applicability:	*Heat, steam, power, feedstock, fuel for transportation, and energy storage*	**TRL:**	*6-8*
Cost	*Green hydrogen: \$4-\$6/Kg (2020) - \$1.2-\$1.8/Kg (2030)*	**Carbon Footprint:**	*The most used type of Hydrogen (Grey) has a footprint of > 36.4 gCO_2/MJ. Green Hydrogen has a footprint of < 36.4 gCO_2/MJ*
Scale:	*1-2MW (2020) and 90-100 MW (2030)*	**Hurdles:**	*Require significant efforts to be cost effective. Requires renewable energies for electrolysis to become Green Hydrogen. Carbon footprint could be higher compared to Li-ion batteries.*
Advantages:	*Besides transportation applications, hydrogen can be used for electricity, heat and steam generating, as well as feedstock and even energy storage (potentially bigger scale than Li-ion batteries)*		

Hydrogen

Scale

The current systems support 1-2MW, to achieve a competitive renewable hydrogen from electrolysis production requires about 70 GW of cumulative electrolyser capacity to be deployed over the next decade (figure below), with an implied economic gap to cover of roughly USD 20 billion. [6].

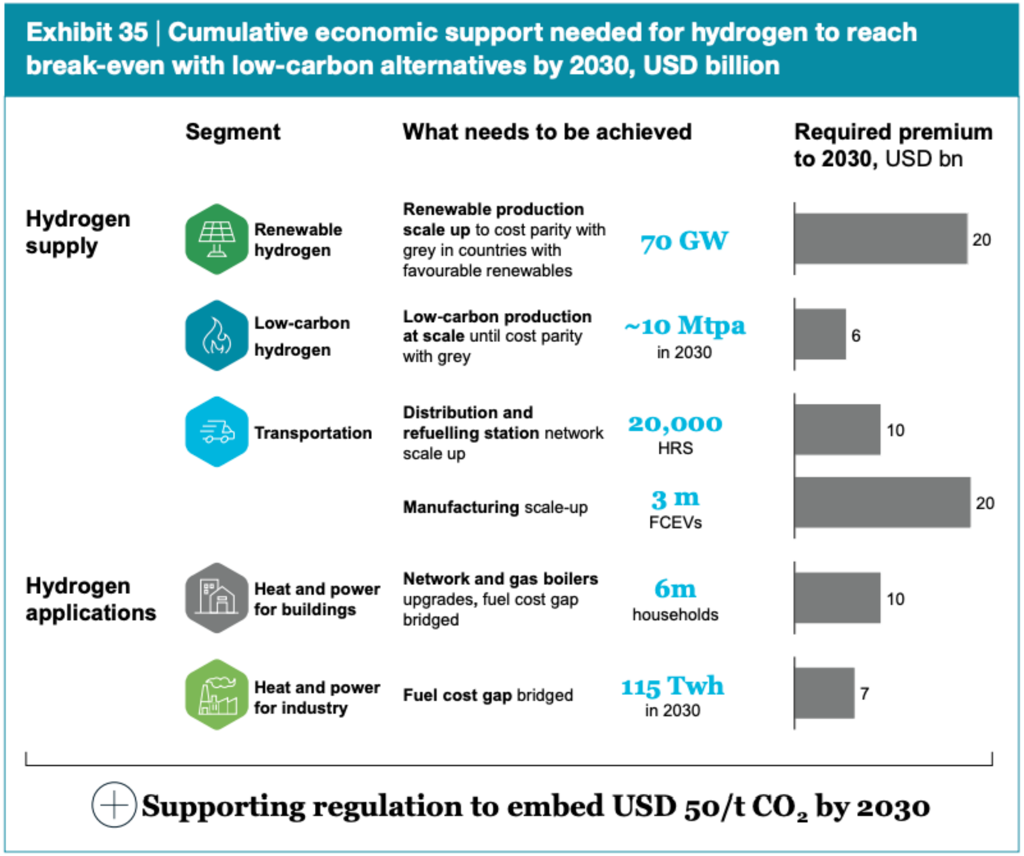


Exhibit 35 | Cumulative economic support needed for hydrogen to reach break-even with low-carbon alternatives by 2030, USD billion

	Segment	What needs to be achieved		Required premium to 2030, USD bn
Hydrogen supply	**Renewable hydrogen**	**Renewable production scale up** to cost parity with grey in countries with favourable renewables	70 GW	20
	Low-carbon hydrogen	**Low-carbon production at scale** until cost parity with grey	~10 Mtpa in 2030	6
	Transportation	**Distribution and refuelling station** network scale up	20,000 HRS	10
		Manufacturing scale-up	3 m FCEVs	20
Hydrogen applications	**Heat and power for buildings**	**Network and gas boilers** upgrades, fuel cost gap bridged	6m households	10
	Heat and power for industry	**Fuel cost gap** bridged	115 Twh in 2030	7

+ Supporting regulation to embed USD 50/t CO_2 by 2030

Hydrogen Technologies Overview

Green H2

AEL
TRL 9
Capacity: 0.05-5 MW
Cost: $3/kg
Emission: 2.2- 2.6 $kgCO_2/kgH$

PEM
TRL 6 - 8,
Capacity: 0.1 - 6MW
Cost: $4.7/kg
Emission: 2.2- 2.6 $kgCO_2/kgH$

SOEC
TRL 6 -7
Capacity: 0.1 - 2.6MW
Cost: ~ as PEM
Emission: 3.2 $kgCO_2/kgH_2$

Chlor Alkali systems
TRL 6 - 7

Anion Exchange Membranes
TRL 6 - 7

Mature technology
Emerging technology
Mature technology
Emerging technology

Blue H2

SMR
TRL 8 - 9

Coal gasification
TRL 5 (w/CC)

Biomass gasification

ATR
TRL 7 - 9

Partial oxidation Gasification

Depleted well gasification (Proton Energy)

Pyrolysis of hydrocarbons
TRL 6)

Microwave technology

Alternative H2 generation

Photobiological water splitting
TRL 5
Emission: 3.2 $kgCO_2/kgH$

Thermochemical water splitting
TRL 3-5
Cost: $2.5/kg
Emission: 0.5 $kgCO_2/kgH$

Emerging technology

Hydrogen Fuel Cells

PEMFC
Capacity: <1 - 100 kW
CAPEX: $2,320/kW
PtP: $0.51/kWh

AFC
Capacity: 1 - 100 kW
CAPEX: $1,200 - 3,000/kW
PtP: $0.42/kWh

PAFC
Capacity: 5 - 400 kW

MCFC
Capacity: 300 kW - 3 MW

SOFC
Capacity: 1 kW - 2 MW
CAPEX: $6,000/kW
PtP: $1.06/kWh

Mature technology

Hydrogen

Other Information

There are significant political and business efforts to bring green hydrogen as an alternative energy supplier.

Key takeaways for IMII

This technology is being improved with the aim of replacing fossil fuels. Besides their popular proposed use in transportation, hydrogen can be seen as much more considering other uses such as for electricity and heat generating as well as feedstock and even energy storage.

The study indicates that the electricity consumption during hydrogen production has the highest environmental impact on the life cycle for PEM and SOEC. The high impact is due to the large quantity of electricity used, together with the energy source (fossil vs RE). So, to reduce the GWP, the focus should be the source of electricity, rather than electrolyzer technology comparisons. In addition, the conclusion from this study indicates that focus for R&D, to achieve a good environmental result, should be to decrease the energy consumption instead of focusing on decreasing the material weights or changing the material types in the electrolyzer design (especially for PEM which is mature already).

References:

1. NREL. 2020.
2. Hydrogen Europe.
3. Standard Chartered. 2020.
4. IEA. 2019.
5. FCH JU CertifHy project.
6. Hydrogen Council. 2020.
7. Wood Mac. 2019.
8. Coventry University. 2012.

Blue Hydrogen - General

Overview

By definition, **blue hydrogen** refers to the hydrogen produced from fossil fuels while coupled to CCS technologies to decrease most of their GHG emissions. Most technologies have been widely developed to produce gray H_2.

At a glance

Mature blue H_2 technology 1	*Steam Methane Reforming*	**Applicability**	*well-known technology, additional CCS infrastructure increase significantly the total cost and decrease efficiency by 5%–14%.*
Mature blue H_2 technology 2	*Coal gasification*	**Applicability**	*Mature technology but due to high carbon content of coal and energy intensity of the process, unlikely to be useful into the future.*
Mature blue H_2 technology 3	*Biomass gasification*	**Applicability**	*Wood, straw or waste can be used in gasification, process similar as using coal but the need for pre-treatment adds complexity and cost.*
Mature blue H_2 technology 4	*Autothermal reforming*	**Advantage**	*A standard production processes for syngas (H_2+CO), can be combined with SMR as a Combined Reforming.*
Mature blue H_2 technology 5	*Partial oxidation Gasification*	**Advantage**	*also produce syngas, operates at smaller scales, and has similar efficiencies as SMR and ATR*

Blue Hydrogen - General

Overview contd.

By definition, **blue hydrogen** refers to the hydrogen produced from fossil fuels while coupled to CCS technologies to decrease most of their GHG emissions. Most technologies have been widely developed to produce gray H_2.

At a glance

Emerging blue H_2 technology 1	*Pyrolysis of hydrocarbons*	**Advantage**	*Process heats the hydrocarbon to a high temperature without oxygen. The solid carbon could, once isolated and collected, be sequestered.*
		Hurdles	*Still under development, efficiency 35 - 50%*
Emerging blue H_2 technology 2	*Underground coal gasification*	**Advantage**	*To be used in conventional fossil fuel reservoirs. shale gas reservoirs offer the potential for hydrogen generation and release, coupled with CO_2 adsorption.*
		Hurdles	*Unknown reaction engineering and process under downhole conditions and detailed environmental considerations*
Emerging blue H_2 technology 3	*Microwave technology*	**Advantage**	*New, used with bespoke catalysts releases hydrogen from diesel and wax with purity >98%*
		Hurdles	*A source of low carbon electricity will be required.*
Relevance to mining	*Alberta in particular, and Canada in general are incentivizing the production of “blue H_2” aiming to serve city and industrial sectors. CO_2 emissions are about 23 - 180 gCO_2/kWh of H_2).*		

Blue Hydrogen - General

Other Information

The Alberta Industrial Heartland is a potential hydrogen node. It is already a center for low cost grey (GHG emissions of about 9 kg CO_2/kg H_2) and blue (GHG emissions of about 1 kg CO_2/kg H_2) hydrogen production in Alberta. The hydrogen is primarily used as an industrial feedstock for making nitrogen fertilizer, cracking bitumen to synthetic crude oil and making refined petroleum products. There is capacity and interest among industry and all levels of government to make more blue hydrogen and use it as both an industrial feedstock and as a fuel to support heavy transport, space heating and other applications.

Key takeaways for IMII

Blue Hydrogen has risen to dizzy heights in recent years as a promising low-carbon fuel across the world, and although many hydrogen energy systems are in the demonstration phase, the mining sector is set to be an early adopter. There's a strong drive to decarbonize mining operations. Hydrogen can be used to store renewable energy to generate electricity, it can power equipment and trucks and cars, and it can even be used in certain mining processes as a reductant.

References:

1. The Royal Society (Link)
2. IEA (Link)
3. CESAR & University of Calgary (Link)
4. UCSI University (Link)
5. Fondazione Eni Enrico Mattei (Link)
6. Murdoch University (Link)

Blue Hydrogen - Life Cycle Assessment

Conclusion

According to the analysis, TDM could be a cost efficient technology in small or medium industrial scale on-site H_2 production. Even though the centralized H_2 production by SMR is a relatively inexpensive method, the need for transportation would raise the H_2 production cost by 25.96–59 USD/MWh H_2.

A break-even value for the TDM product carbon was found as 310 EUR/tC in the current market situation and 280 EUR/tC in a potential market situation in 2030 above which TDM would be economically competitive with SMR.

The break-even value for the TDM product carbon is less than the current market price of carbon black that vary between 590 USD/t and 2360 USD/t.

The H_2 produced by TDM has the lowest specific CO_2 emissions in this study (40 kg CO_2/MWh H_2). The CCS coupling reduces the CO_2 emissions from the H_2 production by SMR, but lower emissions than in TDM cannot be achieved if CO_2 is captured exclusively from the syngas.

Additional CO_2 capture from the furnace flue gas would reduce the emissions in SMR but would cause additional costs that were not taken into account in this study.

The specific CO_2 emissions from electrolysis are highly dependent on the electricity generation technology, and thus, using any other power source except renewable electricity for electrolysis causes unacceptably high specific CO_2 emissions.

The advantages of TDM are the ability to utilize the current natural gas network for the feedstock supply and a good feedstock availability that enables demand-driven H_2 production.

Blue Hydrogen - Life Cycle Assessment

Other Information

The current state-of-the-art technology for capturing CO_2 from an SMR Based H_2 plant where CO_2 is captured from the shifted syngas using MDEA solvent consumes about 14.67 MJ/Nm3 H_2 and captures around 56% of the total CO_2 emitted (avoiding around 54% CO_2 as compared to without CCS).

The LCOH would $16 cents/Nm3 which is about $ 2.5 c€/Nm3 higher compared to SMR without CCS. The increase in the LCOH is predominantly contributed by the increase in CAPEX and cost of NG consumption; and the loss of revenues from sale of electricity.

Key takeaways for IMII

Steam reforming is a well-established thermochemical process used for converting natural gas to hydrogen and syngas. The steam reforming process is however constraint with challenges such as catalyst deactivation, the high thermal energy required for steam generation and to initiate the reaction and the emissions of CO_2. Research attention has focused on other emerging thermochemical processes such as the CO_2 reforming of methane, partial oxidation reforming, autothermal reforming, and photocatalytic reforming to overcome the challenges associated with the steam reforming. The values presented in this study fit with those considered by other key studies in Europe done by the Royal Society for the UK.

References:

1. https://doi.org/10.1016/j.enconman.2017.12.063
2. https://doi.org/10.1016/j.egypro.2017.03.1533
3. https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf

Alternative Hydrogen Generation methods - General

Overview

Three alternative technologies for hydrogen production have been summarized in this section. While the **Proton Process** (developed by Canadian company Proton Technologies), is on its way to commercialization, the **photobiological** and **thermochemical** water splitting technologies are still under lab-scale/prototype testing stages and require some more research before commercialization is possible.

At a glance

Alternative H_2 technology 1	*Underground Coal Gasification*	**Advantage**	Suitable for Canada as it has many abandoned oil and gas fields which can be tapped for H_2 generation, once constructed and running, there are no emissions
		Hurdles	Existing hydrogen transport infrastructure will have to be figured out if oil field is not close to mining site (for energy use)
Alternative H_2 technology 2	*Photobiological water splitting (TRL 5)*	**Advantage**	Simple bioreactor that uses algal waste and lignocellulostic as feedstocks, sunlight, microorganisms are abundant, new strains of microbes which will increase efficiency and hydrogen production are being studied
		Hurdles	Hydrogen production rates and efficiencies need to be improved for large-scale deployment
Alternative H_2 technology 3	*Thermochemical water splitting (TRL 5-6)*	**Advantage**	uses only high temperatures (could be from CSP or SMR) and chemical reactions to produce hydrogen from water. potential for large-scale, with low or no GHG emissions
		Hurdles	Durability of reactant materials for thermochemical cycling need to be improved
Relevance to mining	These emerging methods can all be applied to mining industry for electricity production (through hydrogen used in fuel cells)		

Alternative Hydrogen Generation methods - General

Other Information

Another method is the **photoelectrochemical splitting of water** (using sunlight and specialized semiconductor materials to split water), although, it appears that continued improvements in efficiency, durability, and cost are still needed for market viability. Additionally, **RE liquid reforming** (using biofuels like ethanol with steam reforming) could also be employed which is similar to the natural gas reforming process. Research is being done to identify better catalysts to improve yields and selectivity together with ways to reduce CAPEX and OPEX costs [7,8].

Key takeaways for IMII

Apart from green hydrogen (which is currently booming) and conventional production methods, alternative hydrogen generation methods such as the proton energy process, photobiological water splitting and thermochemical water splitting are also being considered by the scientific and corporate community. Although not yet commercialized at industrial scale, researchers indicate that these will be potentially cost-effective as well as non-polluting. These methods depend highly on successful research progress and need to be monitored closely for future use.

References:

1. Proton Energy, 2020
2. Avenue Magazine, 2020
3. Russian Science Foundation and others, 2015
4. US DoE [Link1]
5. University of Ontario Institute of Technology, 2020
6. US DoE [Link2]
7. US DoE [Link3]
8. US DoE [Link4]

Policy Framework in Canada

Overview

The Government of Canada has released a National Hydrogen Strategy in Dec 2020 [1]. This was done in consultation with Canadian Hydrogen and Fuel Cell Association (CHFCA) and other stakeholders such as industry partners, educational institutes, NGOs and funding organizations. CHFCA represents the majority of stakeholders in Canada's hydrogen and fuel cell sector. Another stakeholder is the Hydrogen Canada Strategic Research Network (H_2CAN) which is pan-Canadian research network of 29 leading researchers including NSERC (Natural Sciences and Engineering Research Council of Canada) chair holders and scientists and engineers from leading research centers and labs like NRC (National Research Council) and CanMet lab (Canadian Centre for Mineral and Energy Technology) [2].

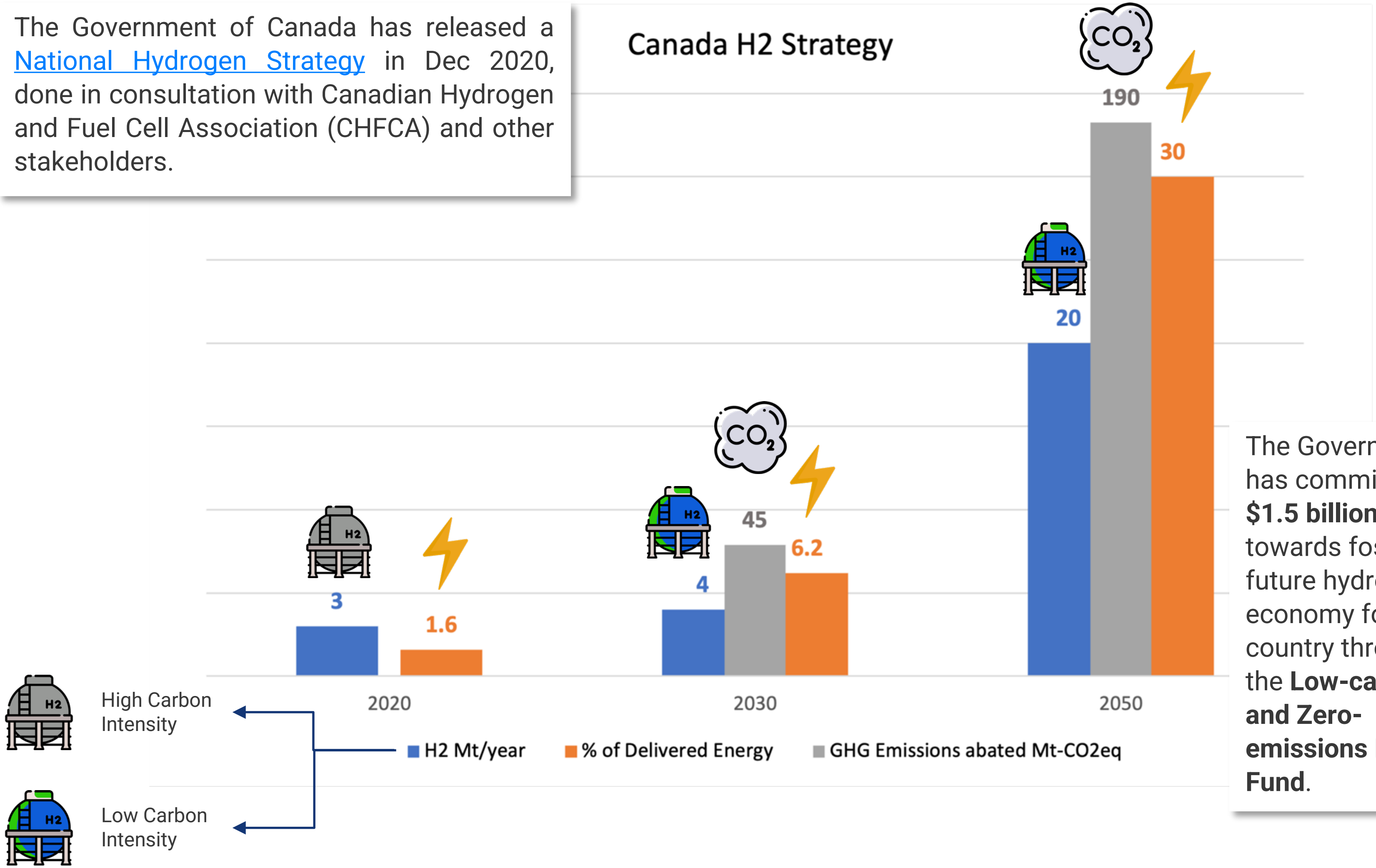
The Canadian government has committed $1.5 billion towards fostering a future hydrogen economy for the country. The Strategy intends to help the mining industry through the adoption of hydrogen-powered heavy vehicles and microgrid power systems for stationary operations.

At a glance

Target (GW):	*20 Mt of H_2/y @ cost of $ 1.5-3.5/kg H_2*	**Target (year):**	*2050*
Financial support:	*$1.5 billion - Tax exemptions, Government incentives, grants, and clean vehicle rebates*	**Applicability of support:**	*All sectors (value chain, equipment manufacturers, transportation) can apply. Mining sector is encouraged.*
Hurdles:	*Lack of transport and distribution infrastructure, robust regulations and industry standards, high generating costs*	**Incentivization compared to Europe:**	*Comparable to EU (after release of strategy)*

Canada H_2 Policy Framework

The Government of Canada has released a National Hydrogen Strategy in Dec 2020, done in consultation with Canadian Hydrogen and Fuel Cell Association (CHFCA) and other stakeholders.



The Government has committed **$1.5 billion** towards fostering a future hydrogen economy for the country through the **Low-carbon and Zero-emissions Fuels Fund**.

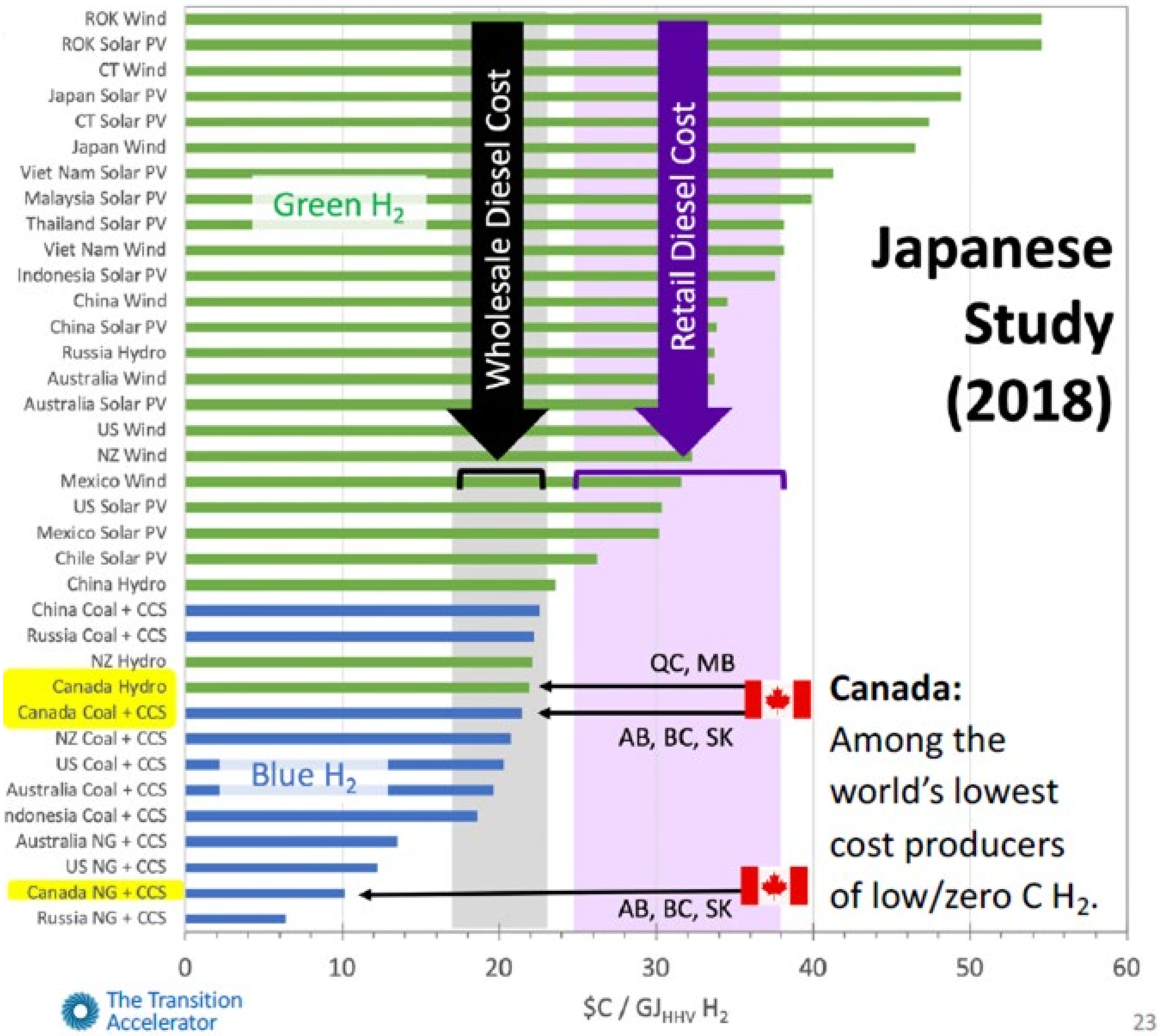


Figure showing the cost of blue and green H_2 production in different countries

Small Modular Reactors

Small Modular Reactors

Overview

As opposed to large scale nuclear plants, small modular reactors (SMRs) have been developed to reduce the total capital costs with shorter lead times and technologies that improve the operating flexibility of nuclear power plants to allow for the integration with renewable capacity into the electricity system.

Due to lowering capital costs, R&D and investment in SMRs and other advanced reactors are being encouraged through public-private partnerships (currently mainly in the US)

SMR technology is very relevant for the mining industry (also mentioned in the Canadian SMR Roadmap released in 2018 [1]) and is set to reach commercialization in the next few decades.

At a glance

Applicability:	*Electricity Generation*	**TRL:**	*5-8*
Cost	*0.085 $/kWh (2020)* *0038-0.067 $/kWh (2030/40)*	**Carbon Footprint:**	*~ 4-8.7* gCO_2*/kWh (2020) expected to reduce by 2035*
Scale:	*Upto 190 MWth (2020) -* *upto 300 MWth (2030/40)*	**Hurdles:**	*Lack of safety certifications and regulations, high R&D costs (US DoE has invested $ 317 million in R&D already)*
Advantages:	*Higher operational flexibility, potential for use of innovative fuels, safer, cheaper than conventional nuclear, more compatible with renewables*		

Small Modular Reactors

Key takeaways for IMII

As the supply of RE grows, SMRs are expected to handle its intermittent nature much better as they are easier to turn on and leave running.

Canada's SMR Action Plan (was set to release in the fall of 2020) will provide more details [12].

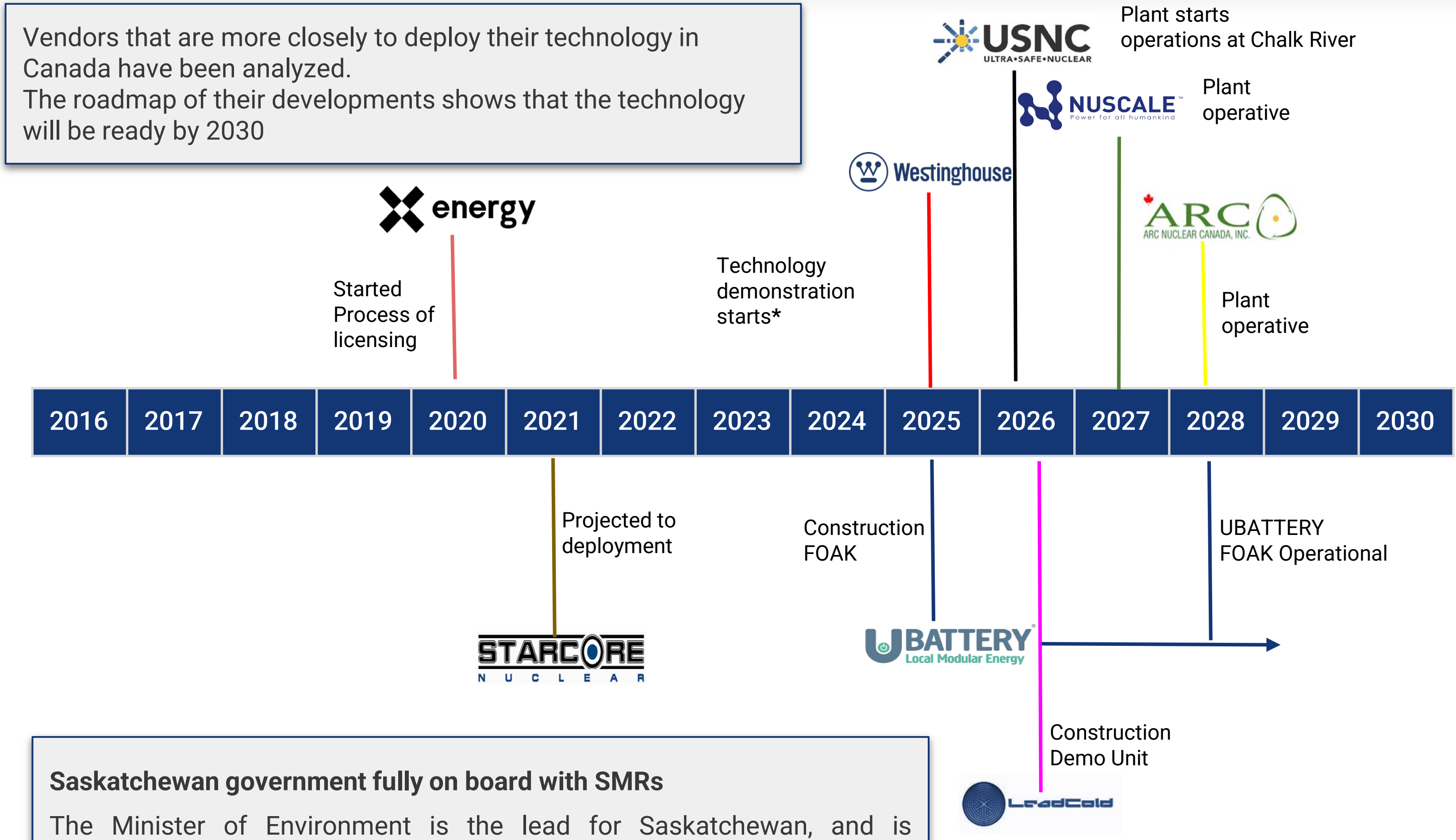
Comprehensive list of the proposed SMR designs/lab-scale modelling and operational prototypes was published by IAEA in Sep 2020 [13].

References:

1. Canadian Small Modular Reactor (SMR) Roadmap Steering Committee, 2020
2. International Energy Agency, 2019
3. Carnegie Mellon University, 2016
4. SMR Roadmap Technology working group, 2018
5. Carbon Brief (UK based website), 2017
6. Department of Civil EngineeringAalto University, Finland, 2020
7. World Nuclear Association, 2020
8. Nuclear Energy Agency, 2016
9. Ontario Newsroom, Office of the Premier, 2019
10. Yale School of Environment, 2020
11. NuScale Power YouTube, 2018
12. Government of Canada, 2020
13. International Atomic Energy Agency, 2020

SMR’s development in Canada: Overview

Vendors that are more closely to deploy their technology in Canada have been analyzed.
The roadmap of their developments shows that the technology will be ready by 2030



Plant starts operations at Chalk River

Plant operative

Started Process of licensing

Technology demonstration starts*

Plant operative

Projected to deployment

Construction FOAK

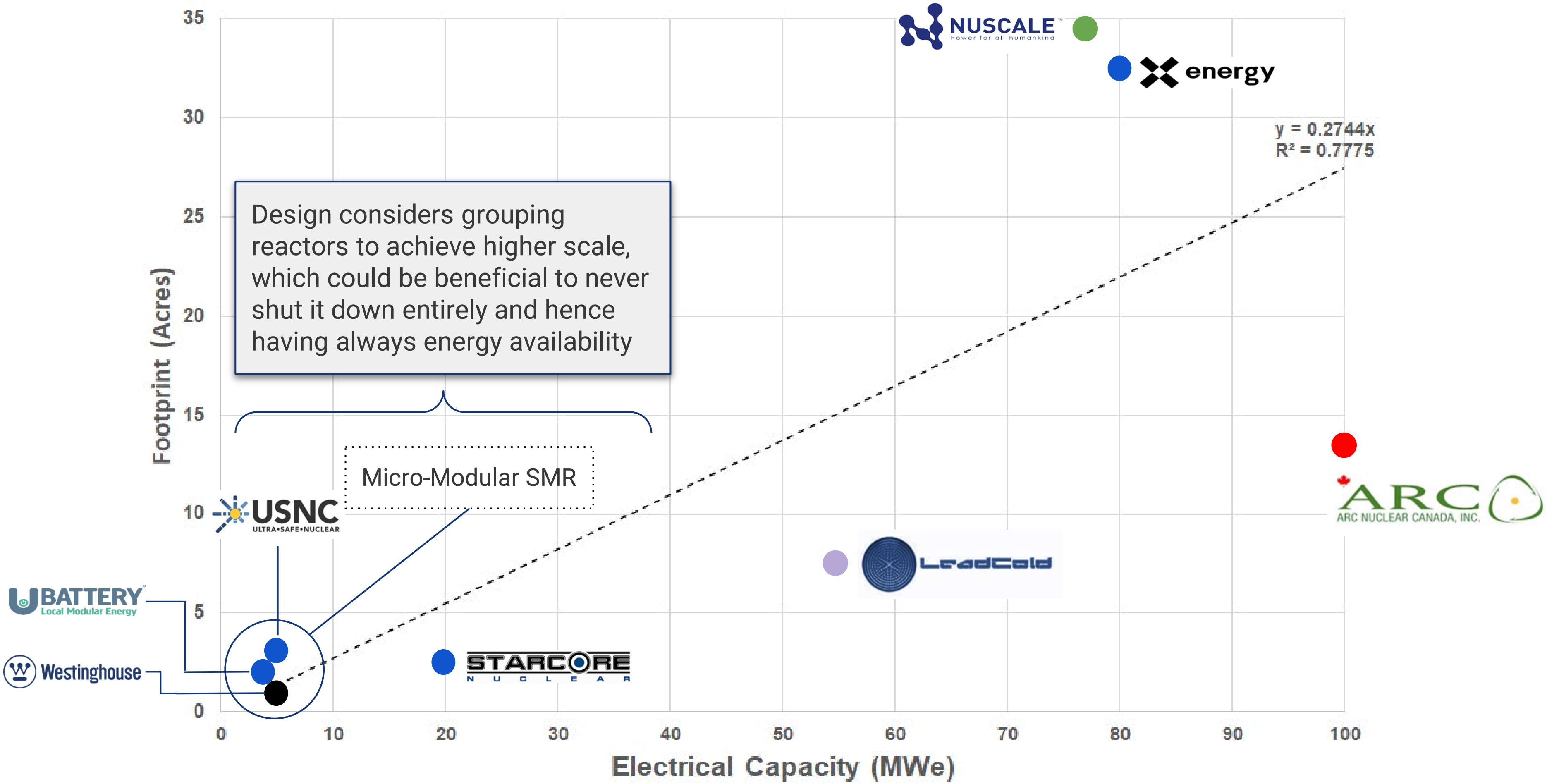
UBATTERY FOAK Operational

Construction Demo Unit

Saskatchewan government fully on board with SMRs

The Minister of Environment is the lead for Saskatchewan, and is supported by a new Small Modular Reactor (SMR) Unit in the Climate Change and Adaptation Division that is responsible for coordinating a provincial approach with other ministries and SaskPower.

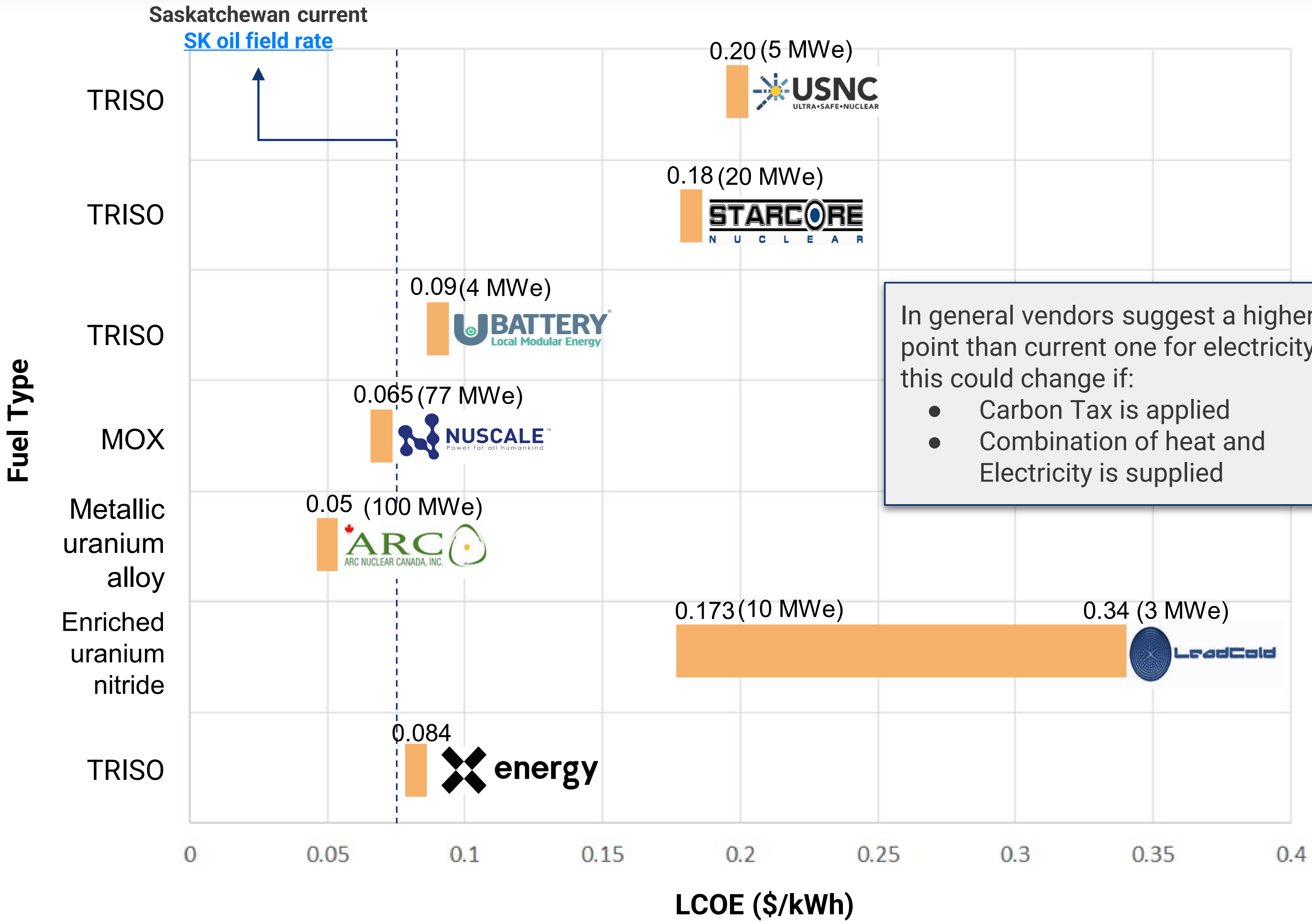
SMR’s Capacity



Design considers grouping reactors to achieve higher scale, which could be beneficial to never shut it down entirely and hence having always energy availability

Blue = High-Temperature He-Cooled SMR
Black = Heat Pipe-Cooled SMR
Purple = Lead-Cooled SMR
Green = Integral Pressurized Heavy Water SMR
Red = Liquid metal (Sodium) cooled fast reactor

SMR Levelized Cost of Electricity and Fuel Type



In general vendors suggest a higher price point than current one for electricity, but this could change if:

- Carbon Tax is applied
- Combination of heat and Electricity is supplied

Regulatory Landscape SMR in Canada

Overview

The Canadian Nuclear Safety Commission (CNSC) regulates all nuclear activities and facilities in Canada. The CNSC is also in charge of regulating the operation of SMRs (although licenses have not yet been issued to any companies yet).

Through the pre-licensing vendor design review process, the CNSC provides assessments to SMR vendors so that they can meet the regulatory requirements and identify potential design issues at early stages. Based on this initial assessment, vendors can submit a licence application. Applications for SMRs follows the same procedures as an application for any other nuclear facility. The CNSC's primary role is to ensure that an applicant can demonstrate they will operate their reactor safely.

At a glance

Regulatory body:	*Canadian Nuclear Safety Commission (CNSC)*	**Main Regulations for SMRs:**	*REGDOC-2.5.2, Design of Reactor Facilities: Nuclear Power Plants, Design of Small Reactor Facilities (RD-367)*
Permits required:	*Vendor license for operating a nuclear facility*	**Timeline:**	*Vendor Design Review process Phase 1 takes 12-18 months, Phase 2 takes 24 months. Licensing application is variable but includes a 4 month long public hearing and 3 month decision period*
Advantages:	*Pre-licensing Vendor Design Review (VDR) process by CNSC helps companies identify regulatory lapses early on in the design stages*	**Hurdles:**	*Obtaining a license can take a long time and is dependent on many factors that are reactor and location specific, gaining public acceptance could be tricky*

Regulatory Landscape SMR in Canada

Key takeaways for IMII

It appears that the regulatory framework for obtaining an SMR license from the Canadian Nuclear Safety Commission is clear and streamlined but is very time-intensive. The pre-licensing vendor design review (VDR) process, provides a lot of value addition to SMR vendors so that they can better understand the regulatory requirements and identify potential design issues early on during the design process. Going by the list of companies under a VDR service agreement currently, it can be seen that many of them are taking advantage of this process (since irrespective of the reactor design, if the regulations are not in sync, it is better for the vendor to know this in the early design stage). Although no SMR licenses have been issued yet, many vendors and companies are in various stages of the VDR assessment process. SK seems to be suitable for location-specific CNSC regulations. The hurdles appear to be in the long timelines required for a license to be issued and gaining public acceptance for the set up of the facilities.

References:

1. CNSC, SMRs, 2020
2. CNSC, Prelicensing VDR, 2020
3. University of Regina, SK, 2021
4. CNSC, RD-367, 2014
5. CNSC compliance, 2015
6. CNSC, SMRs, 2019
7. CNSC, 2019
8. CNSC New Reactor FAQs, 2020
9. SK Govt., 2019
10. Nuclear Safety Act, CNSC, 2021

Carbon Capture

Carbon capture, storage and utilization

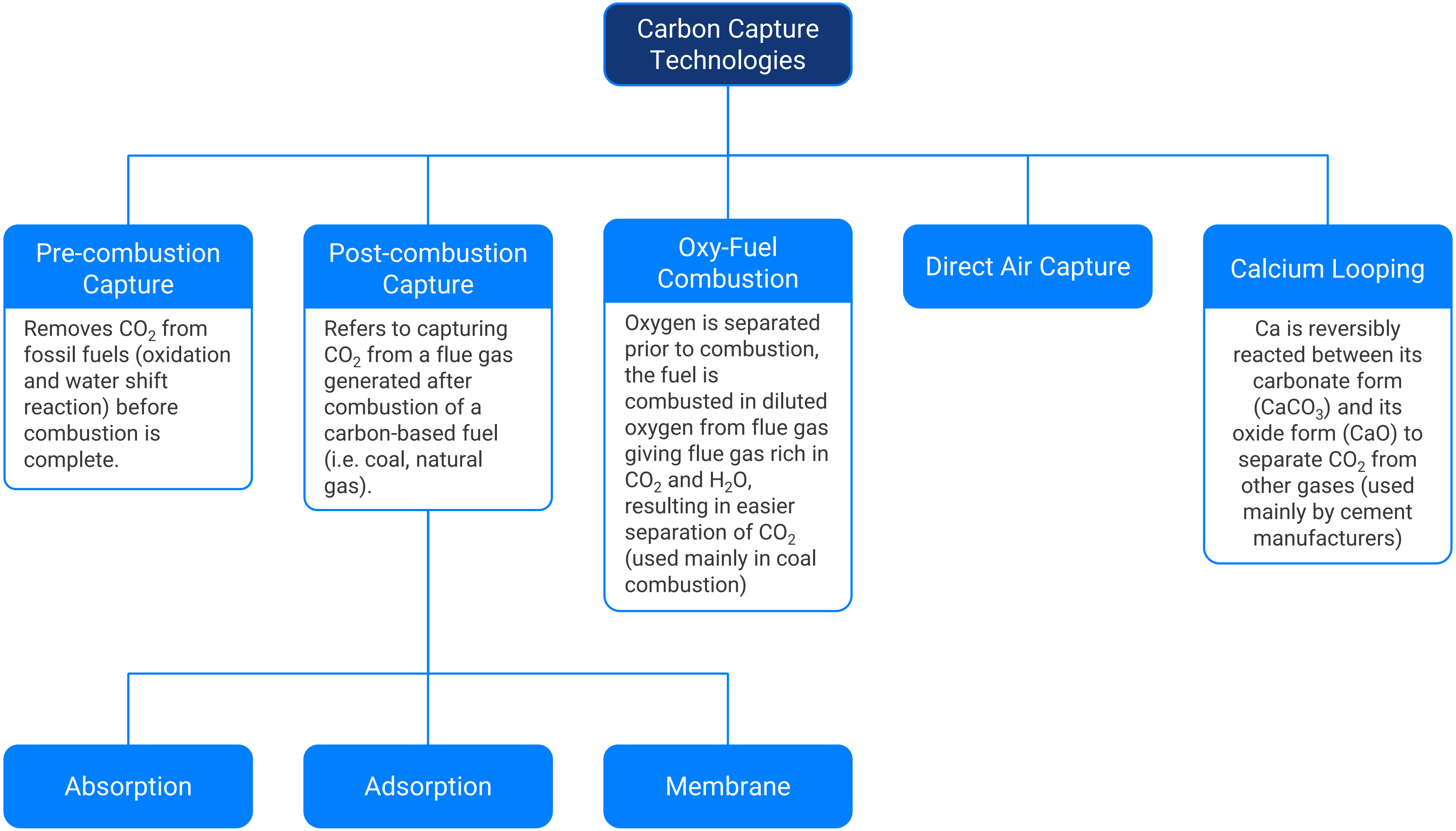
Overview

By incorporating a “utilization” option within a “storage” concept, captured CO_2 can be used as a feedstock for making products, products in which CO_2 gas is sequestered permanently. This unison is known as carbon capture, utilization, and storage (CCUS) [1]. CCUS is the only group of technologies that contributes both to reducing emissions in key sectors directly and to removing CO_2 to balance emissions that are challenging to avoid – a critical part of “net” zero goals [1, 2].

At a glance

Applicability:	*Heating and steam generation*	**TRL:**	*4-8*
Cost	*\$65/t (2020) (Power generation)* *\$50/t (2040) (Power generation)*	**Carbon Footprint:**	*14–20% mitigation of total anthropogenic CO_2 emissions in 2050*
Scale:	*1.9 Mt/y (2020) - 3.12 Mt/y (2025)*	**Hurdles:**	*There is no benchmark against which costs of new technologies or improvements to current technologies can be made, making the choice of technology less clear for investors.*
Advantages:	*CCUS contributes both to reducing emissions directly and to removing CO_2 to balance emissions that cannot be avoided.*		

Carbon Capture Technologies: Overview



Carbon Capture Technologies

Pre-combustion Capture

Removes CO_2 from fossil fuels (oxidation and water shift reaction) before combustion is complete.

Post-combustion Capture

Refers to capturing CO_2 from a flue gas generated after combustion of a carbon-based fuel (i.e. coal, natural gas).

- Absorption
- Adsorption
- Membrane

Oxy-Fuel Combustion

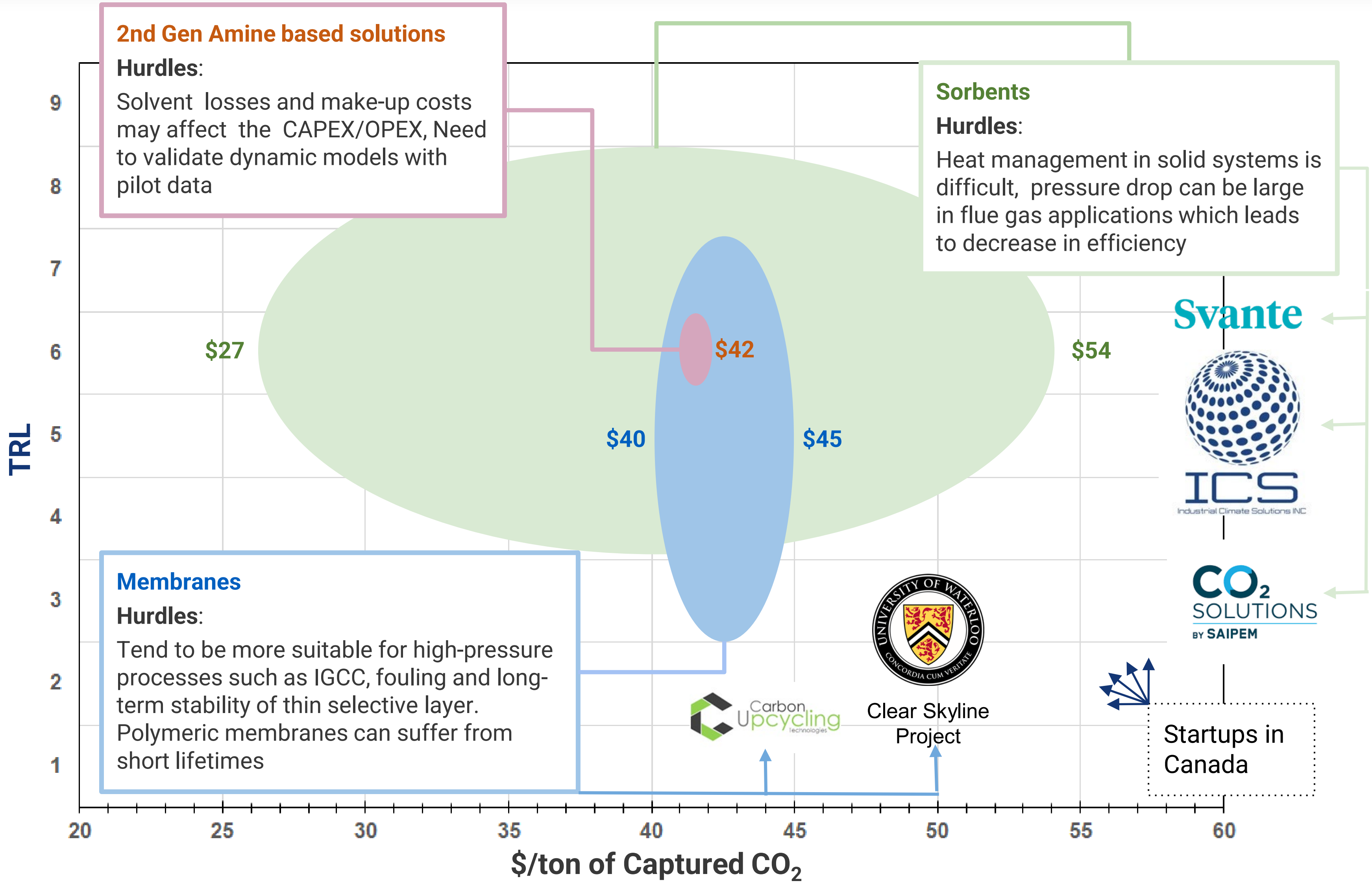
Oxygen is separated prior to combustion, the fuel is combusted in diluted oxygen from flue gas giving flue gas rich in CO_2 and H_2O, resulting in easier separation of CO_2 (used mainly in coal combustion)

Direct Air Capture

Calcium Looping

Ca is reversibly reacted between its carbonate form ($CaCO_3$) and its oxide form (CaO) to separate CO_2 from other gases (used mainly by cement manufacturers)

TRL and Cost



2nd Gen Amine based solutions

Hurdles:

Solvent losses and make-up costs may affect the CAPEX/OPEX, Need to validate dynamic models with pilot data

Sorbents

Hurdles:

Heat management in solid systems is difficult, pressure drop can be large in flue gas applications which leads to decrease in efficiency

Membranes

Hurdles:

Tend to be more suitable for high-pressure processes such as IGCC, fouling and long-term stability of thin selective layer. Polymeric membranes can suffer from short lifetimes

Supplementary Information

Concentrated Solar Power (CSP) technology

Thermal Energy Storage (TES) technologies

Redox Flow Battery in Salt Caverns

UPHS technologies

Concentrated Solar Power (CSP) technology

Overview

Process heat demand is one of the major energy consuming processes within the mining industry. The growing renewable energy industry has mainly been focused on electricity production and grid integration, while technology solutions designed for other industrial processes are still nascent. Unlike photovoltaic (PV) panel technologies, Concentrated Solar Power (CSP) has an inherent capacity to store heat energy for limited intervals of time for later conversion into electricity [1].

At a glance

Applicability:	*Heating*	**TRL:**	*5-9*
Cost	*\$0.29 (2020) - \$0.05/Kilowatt-Hour (2030)*	**Carbon Footprint:**	*Emissions are in the range of 15-20 gCO$_2$eq/kWh*
Scale:	*550 °C (2020) - >1000 °C (2030)* *4.9 GW (2017) - need to reach 8GW (2030)*	**Hurdles:**	*An impediment is the availability of land where to establish renewable energy facilities. Another limitation is the distance required of the CSP plants and the consumption site. High water requirements.*
Advantages:	*The use of CSP technology could help to reduce fossil fuel dependency in high-temperature process for heat production. In contrast to Photovoltaic energy, CSP can be stored.*		

Concentrated Solar Power (CSP) technology

Other Information

CSP water requirements are relatively high: about 3 000 L/MWh [1]. The NREL claimed that mining operations that require fossil fuels as a feedstock are usually hard to fully decarbonize with current renewable technologies. Technology advancement is still needed to allow for higher penetration levels. The renewable installation by mining companies has increased from 42 MW of annual installation in 2008 to 3,397 MW of annual installations in 2019 [1].

Key takeaways for IMII

The use of renewable energy technology can reduce the need for carbon-based energy use at mines. Particularly, Concentrated Solar Power (CSP) technology is showing promising results but will require larger land availability and sufficient solar resources.

References:

1. NREL. 2020
2. Energysage. 2019.
3. Simona, 2019
4. IEA. 2020.
5. NREL, 2019

Thermal Energy Storage (TES) technologies

Overview

Thermal Energy Storage (TES) is an established concept for balancing the mismatch in demand and supply for heating or cooling, offsetting differences in time and magnitude of heat/cooling production. TES can help improve system performance by balancing supply and demand and system temperature fluctuations, as well as improving the reliability of the heating and/or cooling source. TES supports the wider take-up of renewable heating in particular interseasonal storage of solar heat and the electrification of heat using heat pumps coupled with thermal storage technologies [1].

At a glance

Applicability:	*Heating and cooling applications. Replacing gas-based heating.*	**TRL:**	*9 (TTES - Tank systems) and 1 (THS - Thermochemical Heat Storage)*
Cost	*25 - 90 USD/kWh (2018) - <15 - 160 USD/kWh (2030)*	**Carbon Footprint:**	*Currently, information is limited to the development and global deployment of the technology and not in the environmental impact.*
Scale:	*TES with CSP - Energy density* *2018: Sensible: 70 -200 kWh/m^3; Latent: 30-85 kWh/m^3; and Thermochemical: 800-1200 kWh/m^3. 2030: Sensible: Value dependent on the material selection. For latent and thermochemical, there aren't projected changes.*		
Advantages:	*TES reduces the need for costly grid reinforcements, helps to balance seasonal demand and supports the shift to a predominantly renewable-based energy system.*	**Hurdles:**	*Market barriers: For PCM products, upper end TRL of available technologies still lack of proper supply chain. Low renewable heat penetration.*

Thermal Energy Storage (TES) technologies

Other Information

One of the main objectives of lowering the Levelized cost of electricity of CSP is to reduce the cost of the thermal storage asset employed by the plant. Furthermore, to improve the overall economics of the plant, one of the principal objectives is to increase the operating temperature. High operating temperatures improve the thermal-to-electric efficiencies of CSP plants [5].

Key takeaways for IMII

One potential option to reduce emissions from process heat is to displace natural gas with renewables coupled with thermal energy storage (TES). Investments to drive technological development and measures to enhance market pull, combined with a holistic energy policy aimed at scaling up renewables and decarbonising energy use, can unlock rapid growth in TES deployment.

References:

1. Delta Energy & Environment Ltd. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf
2. NREL. https://www.nrel.gov/docs/fy20osti/76156.pdf
3. Barbara Hardy Institute. https://www.sciencedirect.com/science/article/pii/S0960148118308826?via%3Dihub
4. DIOPMA. https://doi.org/10.1016/j.solener.2019.01.050
5. IRENA. https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage

Redox Flow Battery in Salt Caverns

Overview

Redox flow battery technology basically stores energy in liquid electrolytes. When these electrolytes are based on recyclable polymers which can dissolve in salt water, they can be used in salt caverns (which acts as the reservoir) to form really large-scale environment-friendly batteries (up to GWh capacities). This technology is currently being developed by researchers at the University in Jena and a system is under construction by a German utility subsidiary company, EWE, under the **"brine4power"** project in Germany. It is expected to be operational by 2023. There is also another pilot plant being developed for testing in Germany by a gas storage company (RWE).

At a glance

Relationship to mining:	*Energy storage*	**TRL:**	5-6
Cost:	*Data not available*	**Carbon Footprint:**	No emissions
Scale:	*700 MWh at an output of 120 MW (2023 - planned year of operation)* *Potentially scalable to GWh level depending on size of salt cavern (2030/40)*		
Advantages:	*Useful in situations that require regular cycling throughout the day (like with RE sources), environmentally friendly, high efficiency, long duration storage, potentially low costs, non-flammable, components can be recycled*	**Hurdles:**	Still in development stages, cost data not available, only two plants are currently under construction so not much overall data is known yet

Redox Flow Battery in Salt Caverns

Other Information

Apart from the technological aspects, the policy aspect is also important for this technology. Currently, in Germany, there is a lack of a definition and legal framework for large-scale energy storage facilities. Under energy laws, only NG storage sites are defined as “storage facilities”. This means that the battery energy storage facilities are currently classified as energy end-users, and therefore operators are generally required to pay all end-user fees such as the network fee, RE levy and electricity tax in order to operate the storage facility or connect it to the grid (for charging) [6].

Key takeaways for IMII

Most of the companies (utilities in Germany) that are exploring this technology are ones that already own salt caverns which are currently used for NG storage. This technology seems to make more sense for utility-scale projects and grid power balancing as a long duration storage application rather than for specific industry-scale applications. But given that SK has many salt mines, this is definitely an important technology to look out for in the coming decade as it has potential to be integrated with the grid. It could subsequently also help drive the mining industry by aiding with clean energy storage and supply.

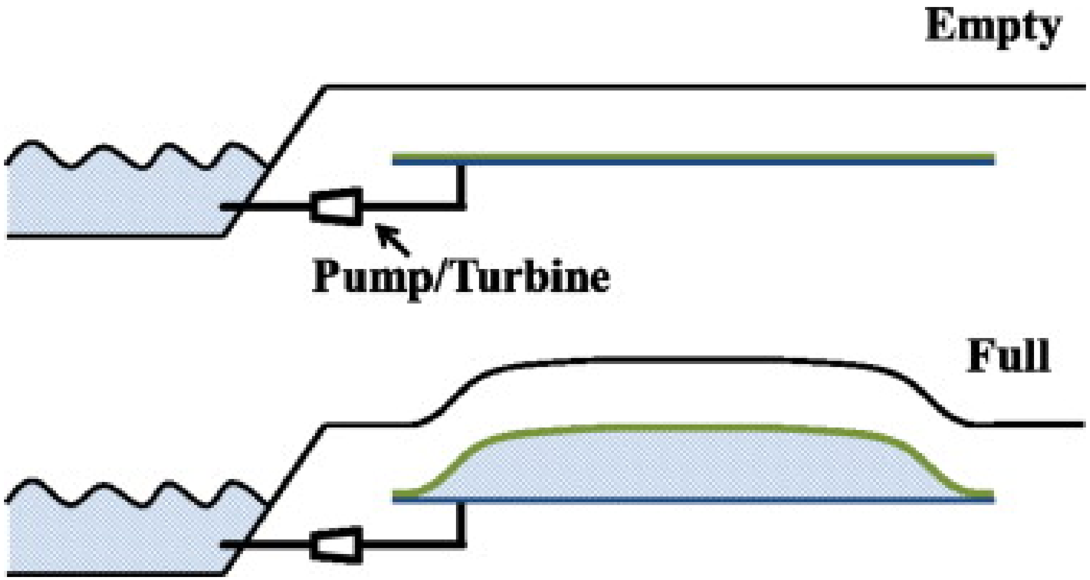
References:

1. *Friedrich Schiller University News, 2020*
2. *Friedrich Schiller University, Jena, 2020*
3. *TechXplore, 2017*
4. *New Atlas, 2017*
5. *ReCharge, 2020*
6. *EWE Gasspeicher, 2020*

Underground Pumped Hydroelectric Storage

1. The UPHS technology was developed in 2010 by JolTech ApS. The UPHS stores energy by lifting a mass of soil through the pumping of water into an underground cavity. The cavity is formed by two impermeable membranes welded along the edges. The technology is based on both visco-elastic and plastic effects for the cyclic loading of the soil.

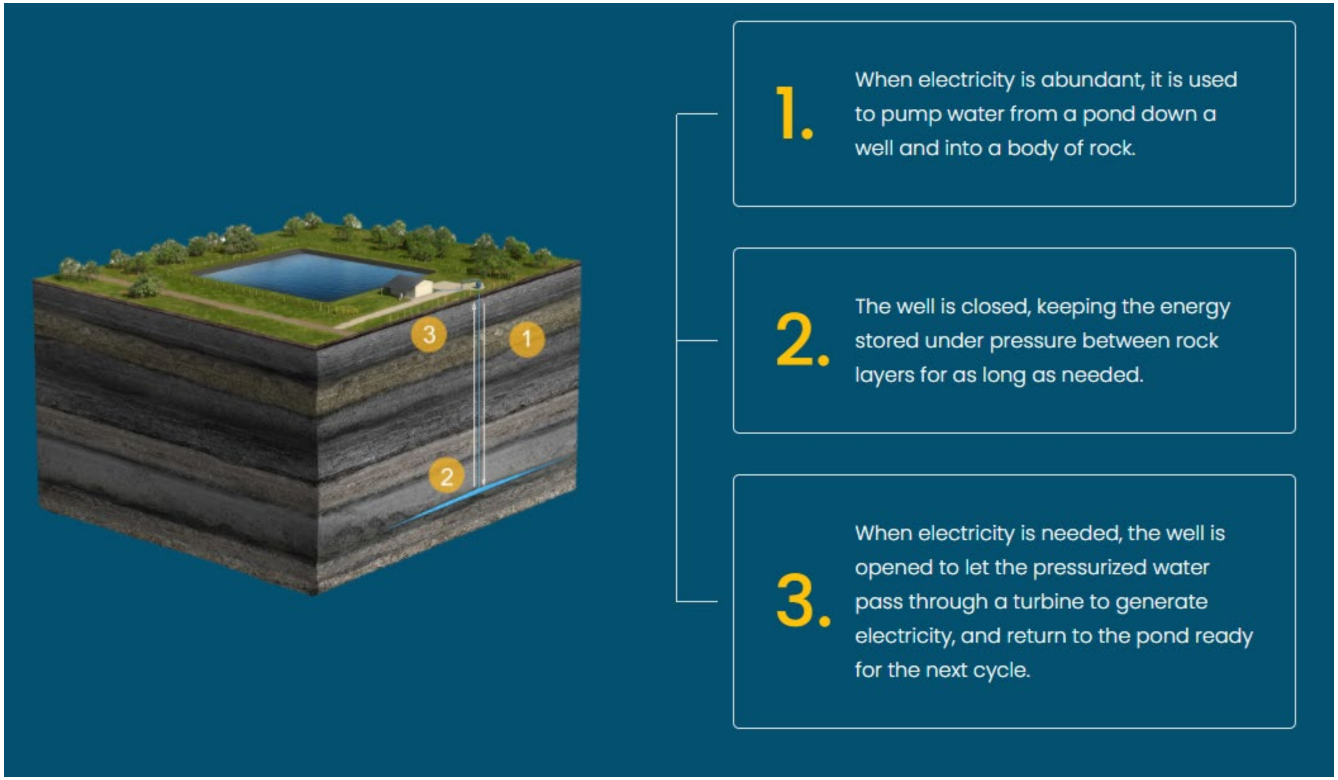
   The field test in Denmark indicated that the technology would be very close to produce a full scale system of **30 MW** power and 200 MWh capacity (similar to traditional Pump Hydro Storage). Unfortunately, the **company and partners disappeared** and cannot be linked to any additional project.



UPHS technology

Underground Pumped Hydroelectric Storage

2. Quidnet Energy (US startup) has developed a variant of UPHS known as “Geomechanical Pumped Storage” A Modular system that can be deployed across diverse geographic areas on small footprints. **1-10 MW modules**.



1. When electricity is abundant, it is used to pump water from a pond down a well and into a body of rock.
2. The well is closed, keeping the energy stored under pressure between rock layers for as long as needed.
3. When electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity, and return to the pond ready for the next cycle.

Geomechanical Pumped Storage technology

Next Steps

Next Steps

SOME POSSIBILITIES THAT PRESCOUTER CAN OFFER FOR CONTINUATION OF OUR RELATIONSHIP

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- ☑ **TECHNOLOGY & PATENT LANDSCAPING**
- ☑ **MARKET RESEARCH & ANALYSIS**
- ☑ **TRENDS MAPPING**
- ☑ **REVIEW BEST PRACTICES**
- ☑ **PATENT COMMERCIALIZATION STRATEGY**
- ☑ **DATA ANALYSIS & RECOMMENDATIONS**
- ☑ **ACQUIRE NON-PUBLIC INFORMATION**
- ☑ **SUPPLIER OUTREACH & ANALYSIS**
- ☑ **CONSULT WITH INDUSTRY SUBJECT MATTER EXPERTS**
- ☑ **INTERVIEWING COMPANIES & EXPERTS**

WE CAN ALSO DO THE FOLLOWING

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- ✓ **WRITING ARTICLES:** Write technical or more public facing articles on your behalf.
- ✓ **WORKING WITH A CONTRACT RESEARCH ORGANIZATION:** Engage with a CRO to build a prototype, test equipment or any other related research service.

For any requests, we welcome your additional questions and custom building a solution for you.

TRL Rating Scale

The Technology Readiness Level (TRL) Scale is an industry standardized metric by which PreScouter evaluates technologies for each client. Based on the constraints on the innovation challenge, PreScouter assigns a TRL number to each identified academic, company or patent.

This process allows each solution to be easily identified for commercialization potential.

Higher number TRL's do not always equate to the best technology – for example, most late stage academic technology is best suited for optimization and integration, but would have a TRL between 2-4.

TRL 9	**Systems operation -** Actual system operated over full range of expected conditions
TRL 8	**System commissioning -** Actual system completed and qualified through demonstrate tests
TRL 7	**System commissioning -** Full-scale, similar prototype demonstration in relevant environment
TRL 6	**Technology demonstration -** Engineering / pilot scale prototype testing in relevant environment
TRL 5	**Technology development -** Lab-scale validation in relevant environment
TRL 4	**Technology development -** Component or system validation in lab environment
TRL 3	**Research to prove feasibility -** Analytical/experimental test of critical function - proof of concept
TRL 2	**Basic technology research -** Technology concept and/or application formulated
TRL 1	**Basic technology research -** Basic principles observed and reported

About the Authors

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Professional Summary:

Christian is one of PreScouter's Technical Directors. He has helped many clients in the Natural Resources and Energy vertical by bringing solutions that align with their sustainability, efficiency and financial goals. He ensures PreScouter clients receive the latest insights into any disruptive or ground-breaking technologies within Carbon Capture & Utilization, Waste Management, Biofuel Developments, O&G, Mining, Renewable Energy generation and storage, among others. Christian has a background in Materials Engineering and Science and brings to PreScouter years of experience in the energy industry in aging management, failure analysis and testing, as well as technical consultancy and troubleshooting for special alloys manufacturing.

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