

Minus CO2 Challenge 2023 – Student teams tackle load-balancing via compressed air and hydrogen storage in Carboniferous salt caverns: Cumberland County, Nova Scotia, Atlantic Canada

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Competition results

Congratulations to the five teams who prepared technical reports and gave excellent online presentations in the final round of the 2023 Minus CO2 Challenge. We also congratulate the two leading teams who presented in person at the opening session of the Global Energy Transition Conference (GET) in Paris in November 2023 (Figure 1). Edward Wiarda, President of the EAGE, kindly presented the prizes. A special mention goes to Lucia Manuel Varela, who singlehandedly represented her team.

The teams list is:

- (1) ‘DECARBO-NOMADS’ University of M’hamed Bougara, Boumerdes, Algeria (UMBB)
- (2) ‘The CarbonBusters’ IFP School, Paris (IFP)
- (3) ‘NetZero Heroes’ Clausthal University of Technology, Germany (TUC)
- ‘GAIA TEAM’ Federal University of Bahia, Salvador, Brazil (UFBA)
- Kuwait University Team, Kuwait City, Kuwait (KU)

Introduction

The Cumberland Basin project (location in Figure 2) is the third of three successive Minus CO2 Challenges set in Nova Scotia, and the 18th EAGE student competition since 2010 (world map of all participant universities in Figure 3). It follows a carbon storage assessment of the Scotian Shelf (Chakraborty et al, 2022) and carbon-neutral development of a hypothetical oil field at Penobscot near Sable Island (Haemmerlein et al., 2023). The 2023 competition was stimulated by an online news article (Dusseault and Wach, 2020) and regional geocellular-geothermal modelling of the Cumberland Basin at the Nova Scotia Department of Natural Resources and Renewables that includes major salt deposits (Cen & Richards – in preparation).

The Cumberland Basin (Waldron et al, 2005 & 2013) is an intermontane Mississippian-Pennsylvanian basin located main-



Figure 1 Imad Smaini, Ahmed Guembour, Edward Wiarda, Lucia Varela, Bill Richards, Ibrahim Elkhallil Hadjadj.

ly in Cumberland County which includes much of the Isthmus of Chignecto that connects Nova Scotia to mainland Canada. It is one of a number of basins within the overall Maritimes Basin (Gibling et al, 2019) that, along with American and European coal basins, formed during the late stages of the assembly Pangea (Figure 4). The Cumberland Basin is dominated by deposition of continental clastics, punctuated in the Viséan by marine incursions, with deposition of limestones and extensive evaporites of the Windsor Group. Subsequent diapirs have driven a major salt industry where they reach the surface near coastal ports. In addition, a major salt diapir brings Westphalian bituminous coals to the surface at Springhill. In this town, five vertically stacked coal mines were worked from 1873 to 1959, down dip from surface outcrops to ~1300m depth. Subsequent water wells down to 200 m provide district heating and cooling (Jessop et al., 1995).

Teams were charged with developing 300 MW of green-field renewable energy from wind, solar or hydro-electric sources (but not tidal) and to guarantee a consistent base load capability using either CAES (compressed air energy

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storage) or UHS (underground hydrogen storage) in salt caverns.

In North America and Europe, operational facilities at Huntorf, McIntosh and Goderich provide CAES analogues with UHS analogues in the UK, Texas, and Germany (Table 1).

The teams needed to address three additional tasks.

1. To place the project in the United Nations Framework Classification for Resources (United Nations, 2019). It ranked very high, based on technical feasibility, geologic knowledge, and socio-economic viability. UMBB assessed it '122' out of 1-4 in each category. KU placed it '222'.
2. To consider community involvement – in view of a recently terminated methane salt cavern storage project at Alton (Ryan, CBC News, 2021). Teams focused on early engagement and participation, with UMBB envisaging interaction with indigenous communities through the Mi'kmaw Kina'matnewey initiative.
3. To discuss how this type of project might play out in their countries. TUC presented leading developments in wind and hydrogen storage technology in Germany. UMBB highlighted abundant solar, wind and salt diapirism in Algeria; KU emphasised undeveloped wind potential on Kuwait's offshore islands and UFBA stressed the economic attractiveness given Brazilian energy tariffs.

Dataset

The project was conceived and organised by the Nova Scotia Department of Natural Resources and Renewables (DNRR) who, in addition to public access to their extensive online resources, provided digital copies of online data: geologic cross-sections and geologic maps (notably NS DNNR, 2006; Keppie J.D.); well reports and LAS files; a regional salt horizon (from geocellular modelling); seismic images; and key publications such as 'Salt and Potash Deposits in Nova Scotia' (Boehner, 1986).

Figure 5a and 5b show, respectively, an annotated map view of surface salt distribution and mines (Boehner, 1986) adjacent to a 3D perspective view from the 2022 geocellular model. The geocellular model (Figure 6) was constructed via surface geology, wells, and good quality 2D seismic data. Initial complex interpretations by John Waldron at the DNRR (Waldron et al., 2005 & 2013) were simplified for modelling purposes and geothermal calculations were undertaken using a procedure published by Bedard et al. (2020) in the St. Lawrence Lowlands sedimentary basin. A representative seismic line is shown in Figure 7.

Power generation

The teams considered wind, solar, and hydro-electric power generation with consensus that onshore wind provides the best opportunities based on abundant wind, costs, and the

CAES	Huntorf Germany	McIntosh Alabama	Goderich Ontario		
Company	Uniper	Power S.	Hydrostor		
Date	1978	1991	2019		
Caverns*	2	1	1		
Depth (m)	650	450	NA		
Height (m)	150	NA	NA		
Diameter (m)	50	NA	NA		
Volume m³	310.000	583.000	NA		
Pressure (bar)	43-70	45-76	NA		
Power	290 MW	110 MW	2.2 MW		
Energy	580 MWh	2.86 GWh	10 MWh		
Sources	* 1 unless known otherwise. NA= not available. He et al., 2017; Wang et al., 2022; Polanski, 2019.				
UHS	Teesside UK	Keil Germany	Clemens Dome Texas	Moss Bluff Texas	Spindletop Texas
Company	SABIC	NA	Praxair	Conoco-Phillips	Air Liquide
Date	1972	1971	1986	2007	2017
Caverns*	3	1	1	1	1
Depth (m)	350-400	1335	850	823	1128
Height (m)	15-40	80-100	300	579	518
Diameter (m)	70	NA	49	60	76
Volume m³	70.000	32.000	580.000	566.000	NA
Pressure (bar)	45-50	80-100	70-135	55–152	up to 150
Power	NA	NA	NA	NA	NA
Energy	25 GWh	NA	92 Gwh	120 GWh	>120 Gwh
Sources	* 1 unless known otherwise. Pnafilov, 2016; GaffneyCline, 2022; Williams et al.; 2022, Jahanbakhsh et al., 2024.				

Table 1 Operational CAES & UHS facilities in Europe and North America.

complexities of offshore ice in the Northumberland Strait and Bay of Fundy (plus famous tides). None of the teams pursued onshore hydro-electricity, mainly due to costs and lack of suitable new potential sites. UMBB augmented 200 MW of wind power with solar to cope with slack wind periods of 10-20 days, mostly in the summer when daylight approaches 16 hours.

The design of wind power facilities comprised several stages, influenced by proximity to suitable storage sites.

Potential locations were assessed based on online wind maps (Figure 8, Global Wind Atlas, from the UFBA report)

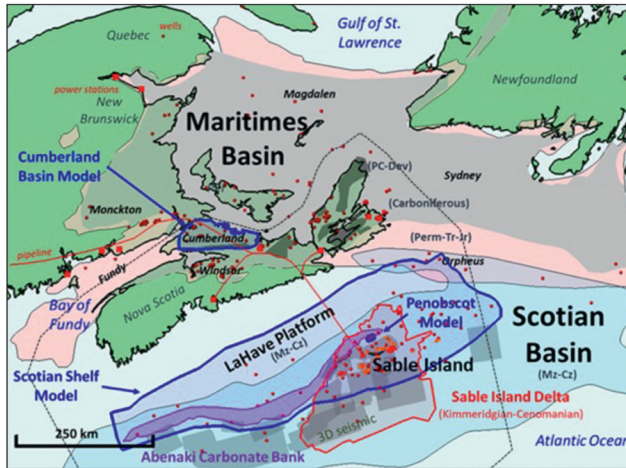


Figure 2 Location of the Cumberland Basin Project within the Maritimes Basin (2023 Minus CO2 Challenge); the Penobscot Project (2022 Minus CO2 Challenge); the Scotian Shelf Project (2021 Minus CO2 Challenge). Basins from GSC and CNSOPB publications.

and open-source software that provides yearly/hourly wind data worldwide with power generation capability based on the number, type, height, and nominal capacity of turbines (Figure 9, with data from windatlas.xyz: Hayes et.al., 2021).

The next step was estimating the power production to storage ratio, allowing for inefficiencies in both storage and retrieval. Teams typically estimated that ~100 MW continuous production is sustainable with storage above that, up to the design capacity of 300 MW (Figure 9).

Specific wind-farm plans ranged from 20 to 165 turbines matched to local conditions. UMBB proposed 80 x 2.5 MW turbines on the North Shore near Malagash for 200 MW (+100 MW solar). IFP proposed 45 x 6.6 MW turbines for 300 MW near Oxford. TUC proposed 150 x 2 MW turbines at Nappan. UFBA (reasonably) interpreted the objective as 300 MW of guaranteed base load capacity and designed a 700 MW wind-farm in the Springhill area (the area also selected by KU). UMBB designed a 100 MW solar farm at Amherst using Solar HiKu 350-watt panels. Average solar irradiance in Nova Scotia is shown in Figure 10.

Energy storage

Two teams opted for CAES: IFP at Oxford, and UTC at Nappan, with UMBB opting for an A-CAES (Adiabatic) system with a new 200,000m³ solution-mined cavern to meet daily needs and a UHS system in a new 600,000 m³ solution-mined cavern to meet seasonal, mostly winter, shortfall. Two teams opted for UHS: UFBA with a 500,000 m³ cavern and UTC with a development in the Nappan area. Similar to power generation, some teams

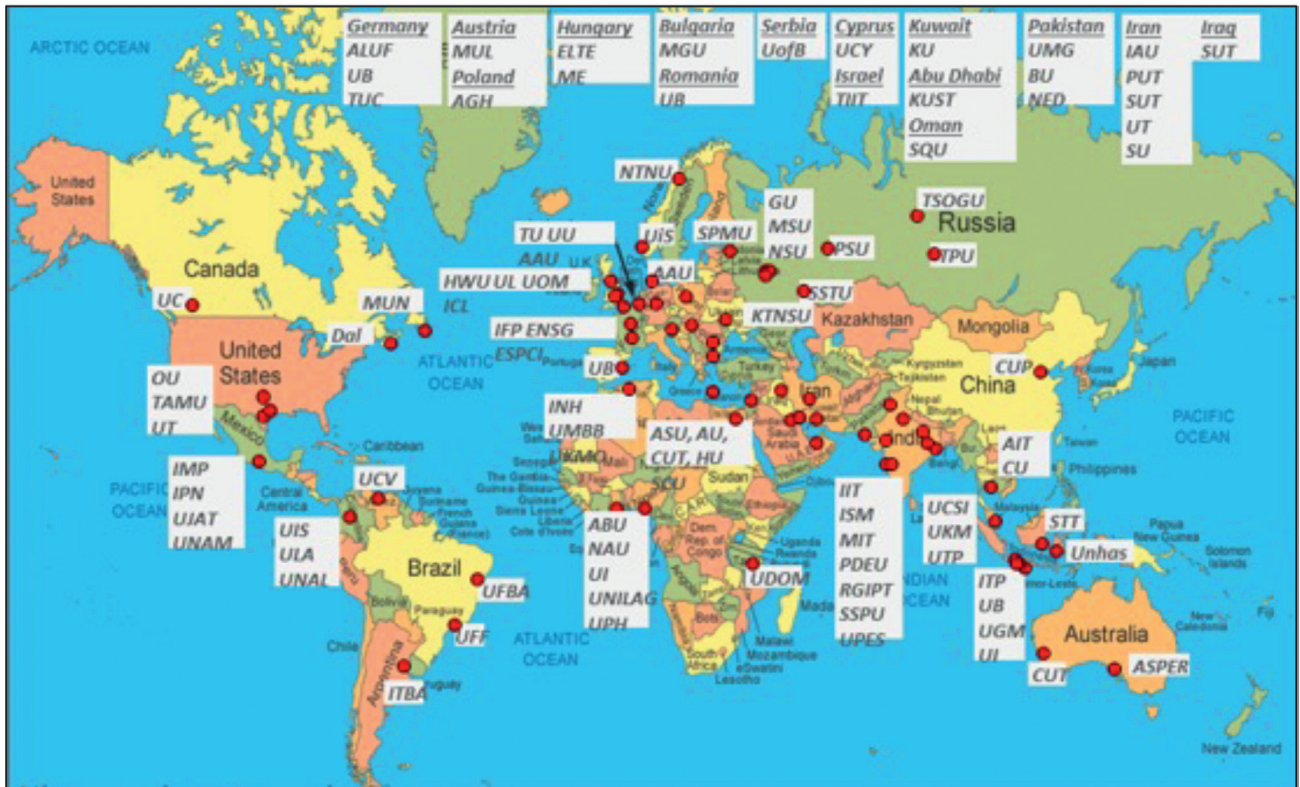


Figure 3 Locations of universities that have participated in the Laurie Duke & Minus CO2 Challenges since 2010. Many thanks to organisations that have provided data sets, software, and sponsorship. (From EAGE records & Roger Clark's personal records).



Figure 4 Tectonic setting of the Maritimes Basin within collisional area of Gondwana and Laurasia in the final stages of Pangean assembly (summarised from Gibling et al, 2019).

put very detailed effort into specific technical aspects: IFP on the geomechanics of salt cavern design and UTC on energy conversion to hydrogen through different electrolysis methods.

The differing selections of CAES versus UHS were based on safety (favouring compressed air over small-molecule, potentially leaky, flammable, hydrogen) or based on energy density, movability and storage duration (favouring hydrogen).

Costs, revenues and economics

The two leading teams, UMBB and IFP, presented economic analyses aligned with the organisers, with costs sourced from IRENA (2022) and the Pacific Northwest National Laboratories (2021) and revenues from Nova Scotia Power (<https://www.nspower.ca/>) and Energy Nova Scotia (<https://energy.novascotia.ca>). Five recent wind projects, majority-owned by Mi'kmaw communities, are expected to generate at an average cost of \$53.17 / MWh (Smith, CBC News, 2022). UMBB estimated CAPEX at \$826 million with wind and solar facilities at \$627 million. At \$164 / MWh revenue (Nova Scotia Power standard residential rate) UMBB calculated an IRR of 21% at 20 years.

IFP had CAPEX at \$557 million (wind-farm \$390 million; caverns \$160 million) and positive economics with a consumer price of \$132 / MWh and a 12% hurdle rate. However at wholesale prices as low as \$40 / MWh (from purchase agreements) the project would require support to be competitive.

These results should be seen in the context of Nova Scotia abandoning the proposed Atlantic Loop linkage to hydro-electric power in Labrador that costs 250-300 /MWh (Withers, CBC News, October 2023). One thousand MW of onshore wind is planned by 2030 including battery storage.

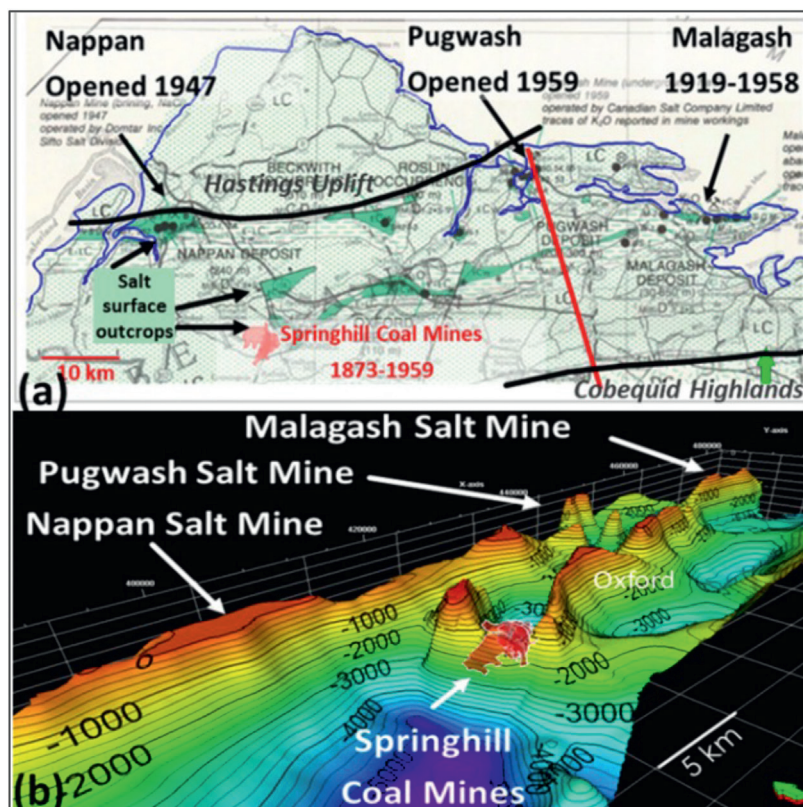


Figure 5 (a) The Cumberland Basin, bounded by the Hastings Uplift and Cobequid Highlands. Salt deposit surface outcrops are shown in green (Boehner, 1986). 5 (b) Perspective view of Top Windsor Salt horizon (Cen & Richards - Nova Scotia DNNR model) with outlines of the Springhill coal mines.

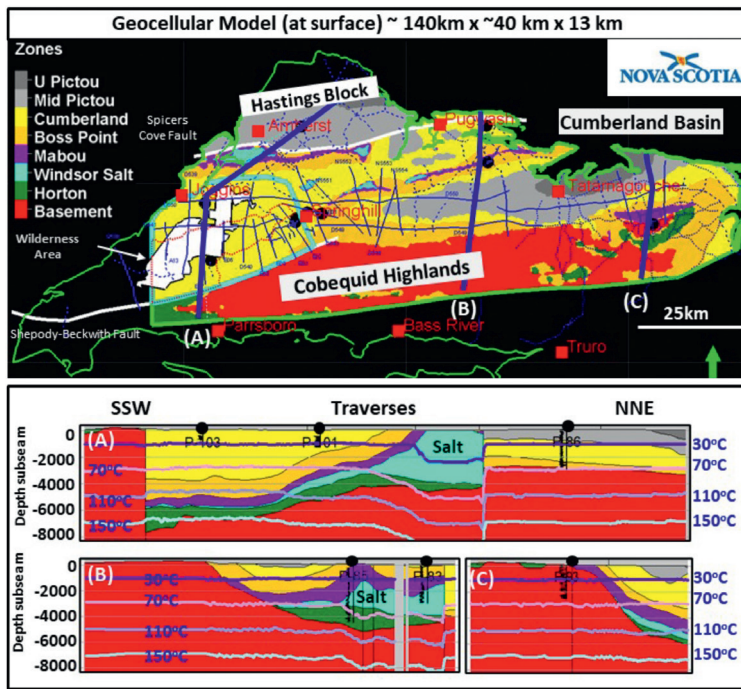


Figure 6 (a). Nova Scotia DNRR geocellular/geothermal model of the Cumberland Basin. Map view of surface geology. Coastline (green), towns (red), wells (black), surface geology, seismic lines (blue). Figure 6 (b). Traverses A,B,C with wells, gamma ray logs and isotherms extracted from temperature model.

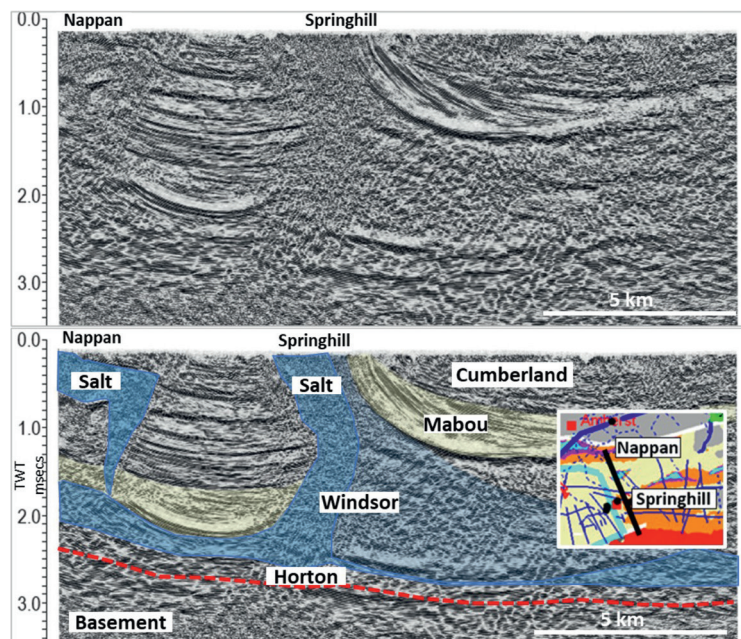


Figure 7 2D seismic line through Nappan and Springhill salt diapirs (based on Waldron, 2013)

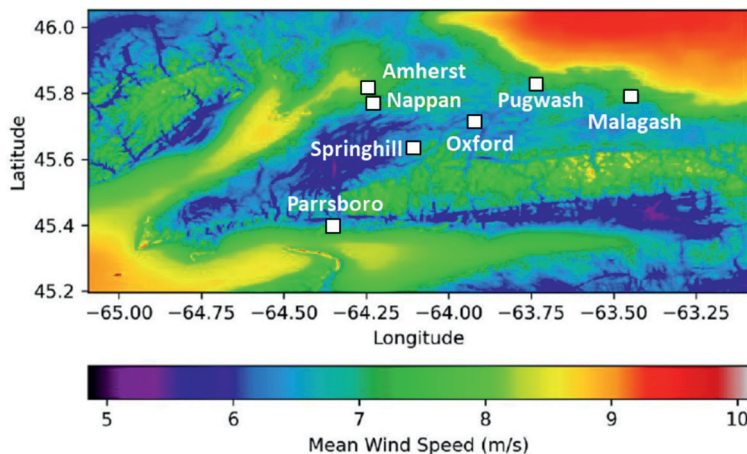


Figure 8 Mean Wind Speed (from the UFBA report), <https://globalwindatlas.info/en>.

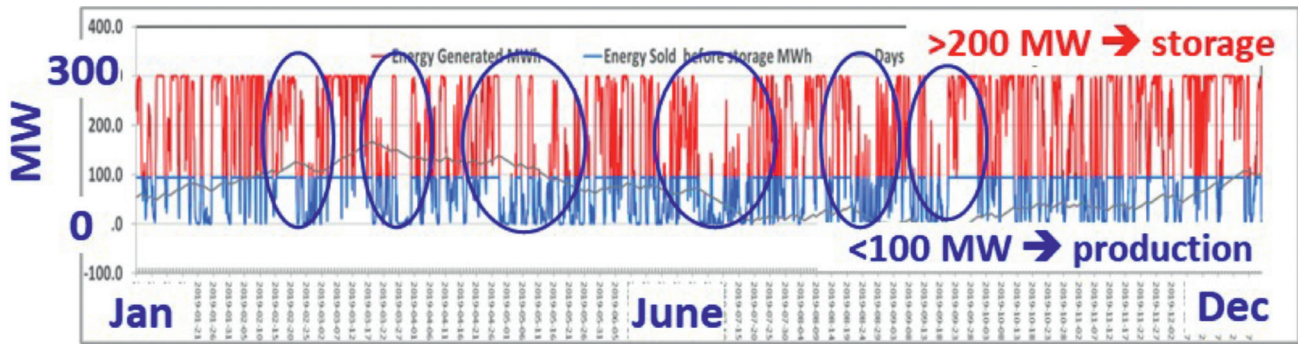


Figure 9 Wind power production versus storage. //windatlas.xyz/about/.

Yearly/hourly wind converted to power and separated into storage and production. Low wind periods are highlighted. The optimum guaranteed baseload (~ 100 MW) can be estimated iteratively keeping the cumulative sum of production and storage positive. This can be adjusted seasonally or with input from secondary sources such as solar.

Month	kWh/kW
January	66
February	89
March	105
April	98
May	106
June	112
July	111
August	111
September	102
October	82
November	56
December	52
Annual Total	1090

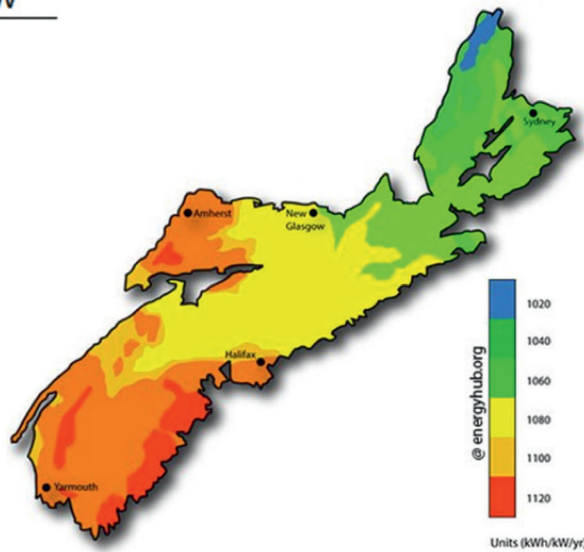


Figure 10 Provincial Solar Energy Map (www.energyhub.org).



Figure 11 Strengths Weaknesses Opportunities and Threats (SWOT analysis): IFP School.

Environmental and demographic risks and mitigation

IFP summarised strengths, weaknesses, opportunities, and threats in a SWOT analysis (Figure 11), while more broadly, UMBB embraced the UNFC classification and SDGs, aligning the project with goals 17, 13, 9 and 7 (Figure 12). At a detailed level IFP School tabulated risks, mitigation (and monitoring) strategies in the key areas of Health and Safety, Environmental, Social and Community, Economic and Financial (reproduced here as Figure 13). Most important are geo-mechanical and operational monitoring that impact safety.

Conclusions & Acknowledgments

From the perspective of the Nova Scotia DNRR this has been a very useful exercise, with many sets of eyes and multi-disciplinary teamwork moving an idea in a 2020 news article forward to wide-ranging analyses and concrete plans. We hope the teams found this an exciting and interesting project and we thank them – and the EAGE judges – for their enthusiasm and hard work. The EAGE would like to thank Fraser Keppie and Natasha MacAdam from the NS DNRR for participating as judges.

The 'Minus CO2 Challenge 2023' Top 5 Teams, Judges, and Administrators

First Place – University M'hamed Bougara of Boumerdes, Algeria

- Merouane Sbahi
- Imad Smaini
- Ahmed Guembour
- Ibrahim Elkhailil Hadjadj
- Wassim-Allalouche

Second Place – IFP School, France

- DRI Juan Manuel
- LENCINAS PUPKIEWICZ Santiago
- MIRANDA PINTO Lucas
- SEPULVEDA Pablo
- VARELA Lucia
- Advisor: TORRES Arnaud

Third Place – Clausthal University of Technology, Germany

- Waithera Gakio
- Jonathan Heetlage
- Mahmoodzia Zamaninia
- Supervisor: Prof. Dr. Philip Jaeger

Runner Up – Federal University of Bahia, Salvador, Brazil

- Filipe de Moura Antônio Cordeiro
- João Pedro Silva Gomes
- Matheus Radames Silva Barbosa
- Vinicius Carneiro Santana
- Mentor: Alexsandro Guerra Cerqueira

Runner Up – Kuwait University Team, Kuwait

- Reem Al-Subaie
- Sultan K. Dwier
- Nuwyer Al-Azmi

Judges and Administrator

- Fraser Keppie and Natasha MacAdam (Nova Scotia Department of Resources and Renewables)
- Giancarlo Bernasconi (Politecnico di Milano)
- Roger Clark (University of Leeds)
- Thomas Finkbeiner (King Abdullah University of Science and Technology)
- Karine Labat (IFP School)
- Antonia Hardwick (Lithothermal Resources Ltd., Hardwick Geophysical Ltd., Rejuvenate Energy)
- Carla Skinner (Geological Survey of Canada)
- Bill Richards (Dalhousie University and NS DNRR)
- Maria Jose Rodriguez (EAGE Administrator)

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- Our project adopts the rigorous United Nations Framework Classification (UNFC)
- **Socioeconomic** (1-3): Aligned with UN SDGs #7, #9, #13, and #17 - Rating of "1"
- **Technical** (1-4): Proven technologies but complex integration - Rating of "2"
- **Geologic** (1-4): Good foundation but more study needed - Rating of "2"
- Current overall rating of "122"



Figure 12 'Meeting the UNFC Evaluation Standards' (UMBB).

Health and Safety Risks:	
Potential Risks	Mitigation Strategies
Construction and Operation Hazards	Establish strict safety protocols and training for the personnel.
	Conduct regular inspections and audits to ensure compliance with safety standards and early identification of potential risks.
	Maintain a strong safety culture and promote individual and collective responsibility.
Workplace Accidents and Injuries	Implement specific safety measures, such as personal protective equipment, safe work procedures, and first aid training.
Emergency Response and Evacuation	Establish an incident reporting and tracking system.
	Develop detailed emergency response plans that address a variety of scenarios, such as fires, chemical spills, or extreme weather events.
	Conduct periodic evacuation and emergency response drills with the community and personnel involved in the project.
Environmental Risks	
Potential Risks	Mitigation Strategies
Ecological and Biodiversity Impacts	Conduct comprehensive environmental assessments to identify and mitigate potential impacts.
	Design mitigation and compensation measures, such as habitat restoration and protection of sensitive areas.
	Establish long-term monitoring plans.
Water and Soil Contamination	Implement proper management measures to prevent contamination during construction and operation.
	Perform regular testing and analysis to monitor water and soil quality.
Social and Community Risks	
Potential Risks	Mitigation Strategies
Conflict with Mi'kmaq Community	Establish direct and respectful communication with the Mi'kmaq communities in Cumberland Basin.
	Include Mi'kmaq representatives in project discussions and decisions.
	Develop educational and engagement programs to promote mutual understanding and cultural respect.
Resistance from Local Community	Conduct education and awareness campaigns about the economic, social, and environmental benefits of green energy projects.
	Demonstrate how green energy can create jobs, benefit the state, and reduce electricity costs in the community.
	Facilitate educational visits and tours to green energy facilities to highlight their operation and its benefits.
Health and Safety Concerns	Conduct comprehensive environmental and health impact assessments to address and mitigate community health and safety concerns.
	Implement safety measures and emergency response protocols to ensure the safety of locals.
Visual and Landscape Impact	Work with architects and landscape designers to minimize the visual impact of green energy installations on the local landscape.
Economic and Financial Risks	
Potential Risks	Mitigation Strategies
Construction Cost Changes	Conduct detailed cost-benefit analyses and consider financial contingencies.
	Work closely with suppliers and contractors to ensure efficient cost management.
	Maintain constant cost monitoring throughout all project stages.
Electricity Price Fluctuations	Evaluate and analyze scenarios of electricity price fluctuations and develop mitigation strategies, such as long-term power purchase agreements (PPAs) or price adjustment mechanisms.
	Explore the possibility of negotiating preferential rates with local utility companies due to the project's ability to provide a consistent and predictable supply of energy.
Long-Term Financial Viability	Conduct detailed financial analysis considering investment costs, projected revenue, and operating expenses.
	Explore financing options and collaborations to ensure financial stability.

Figure 13 Potential Risks and Mitigations: IFP School.

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