Shallow geothermal technology as alternative to diesel heating of subarctic off-grid autochthonous communities in Northern Quebec (Canada)

EGU General Assembly 2020
Online | 4–8 May 2020

Award Roland Schlich Early Career Scientist's Travel Support

Funding

Institut nordique du Québec
Together for the North

LabEx DRIIHM

OHMI Nunavik

Shallow geothermal technology as alternative to replace diesel heating in subarctic off-grid Aboriginal communities of Northern Québec (Canada)

Nicolò Giordano[1], Evelyn Gunawan[1,2], Félix-Antoine Comeau[1], Mafalda Miranda[1], Hubert Langevin[1], Matteo Covelli[3], Paul Piché[4], Stéphane Gibout[4], Didier Haillot[4,5], Alessandro Casasso[6], Jessica Chicco[3], Giuseppe Mandrone[3], Cesare Comina[3], Richard Fortier[7], Jasmin Raymond[1]

[1]Centre Eau Terre Environnement, Institut national de la recherche scientifique, Québec, Canada
[2]Reykjavik University, Iceland School of Energy, Reykjavik, Iceland
[3]Dipartimento di Scienze della Terra, Università degli Studi di Torino, Italia
[4]Laboratoire de Thermique, énergétique et procédés, Université de Pau et des Pays de l'Adour, Pau, France
[5]Département de génie mécanique, École de Technologie Supérieure, Montréal, Canada
[6]Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino, Torino, Italia
[7]Département de géologie et génie géologique, Université Laval, Québec, Canada

POLITECNICO DI TORINO

INRS Institut national de la recherche scientifique

Centre d'études nordiques

HÁSKÓLINN Í REYKJAVÍK
REYKJAVIK UNIVERSITY

Dipartimento di Scienze della Terra, Università degli Studi di Torino

UNIVERSITÉ DE PAU ET DES PAYS DE L'ADOUR

UNIVERSITÉ LAVAL

ÉTS Le génie pour l'industrie

Problematic

Nunavik is the northern region of Québec. It hosts 14 Inuit villages (around 12,300 people), Kuujjuaq is the regional capital

Electricity production by off-grid diesel power plants (Hydro-Québec)

Kuujjuaq

Kuujjuaq

Space heating and domestic hot water needs covered by individual diesel furnaces

This implies

- High costs (0.86 CAD$/kWh electricity production, 0.16 CAD$/kWh space heating, subsidies for residents (0.8 CAD$/kWh, 0.4 CAD$/litre, fuel transport…)
- Environmental impact with high annual GHGs emissions, pollution (oil spills)
- Dependency on fluctuation of oil products price

INRS

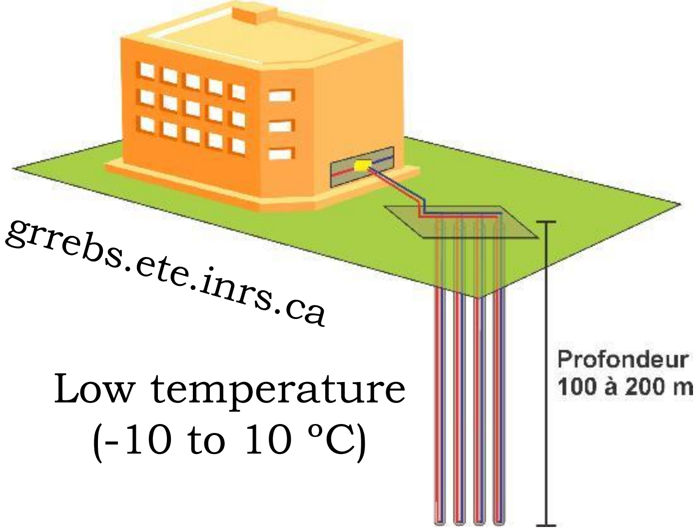
General objective

Is geothermal energy a viable alternative for Nunavik?

Alternatives to fossil fuels for heat production

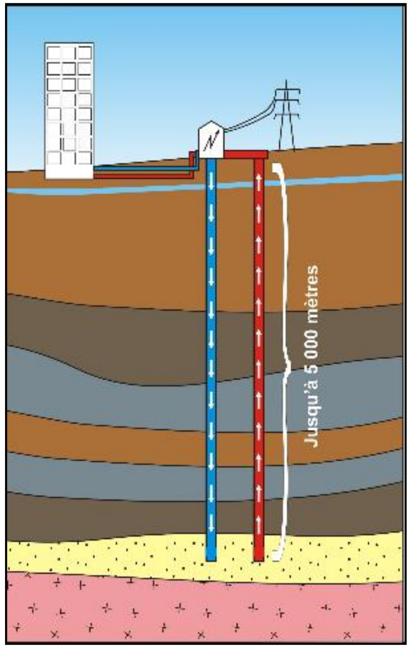
- Heat recovery
- Biomass
- Waste to energy
- Geothermal energy

  - Ground source heat pump (GSHP)
  - Underground thermal energy storage (UTES)
  - Enhanced geothermal system (EGS)



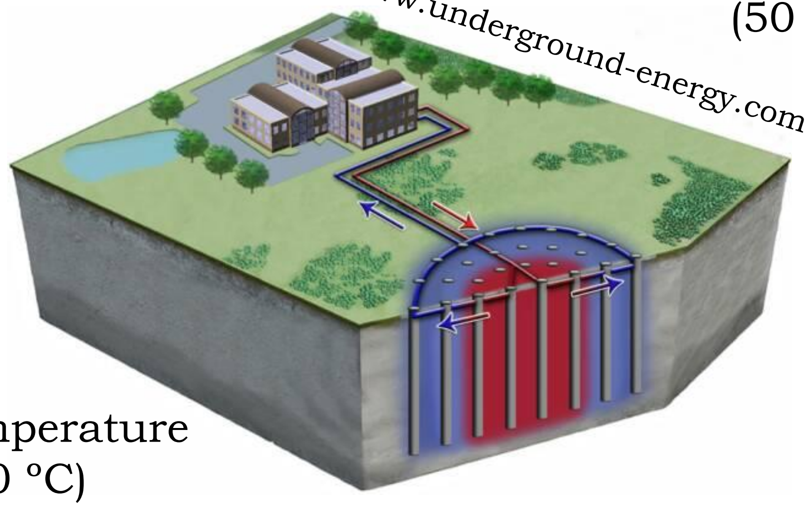
grrebs.ete.inrs.ca

Low temperature
(-10 to 10 °C)



grrebs.ete.inrs.ca

High temperature
(50 to 100 °C)



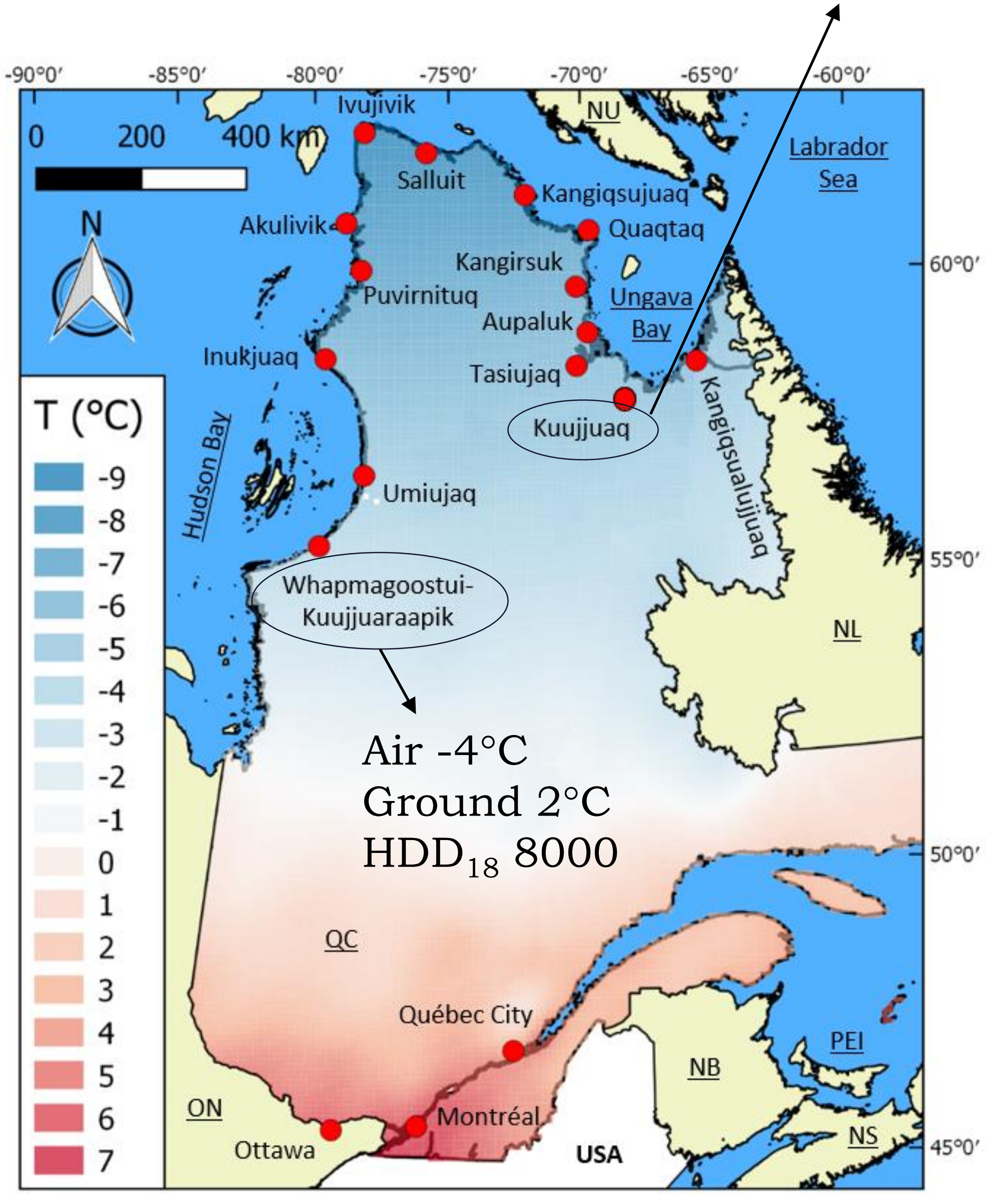
www.underground-energy.com

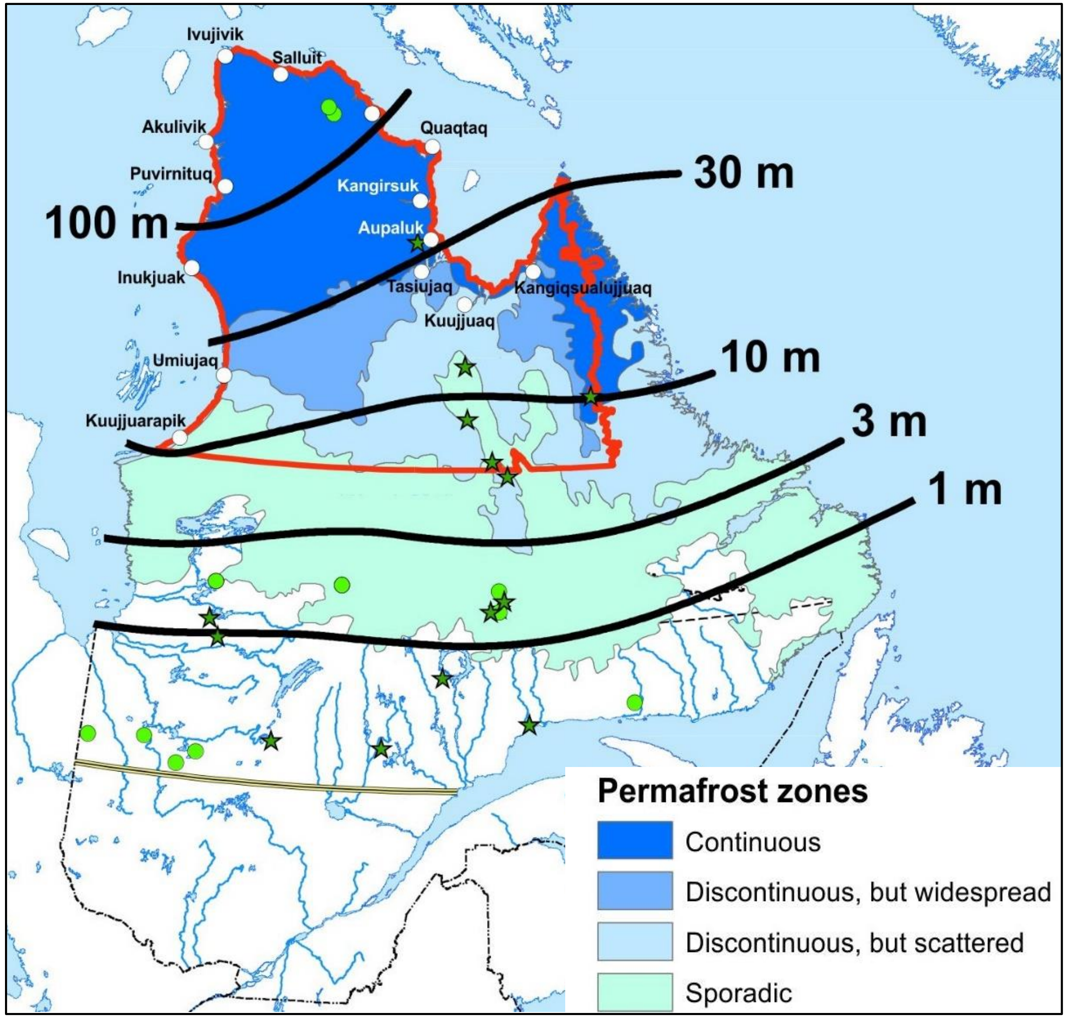
Moderate temperature
(10 to 50 °C)

Geographical setting

Mean annual air temperature -5.8°C
Ground temperature 1°C
Heating degree days HDD_{18} 8500

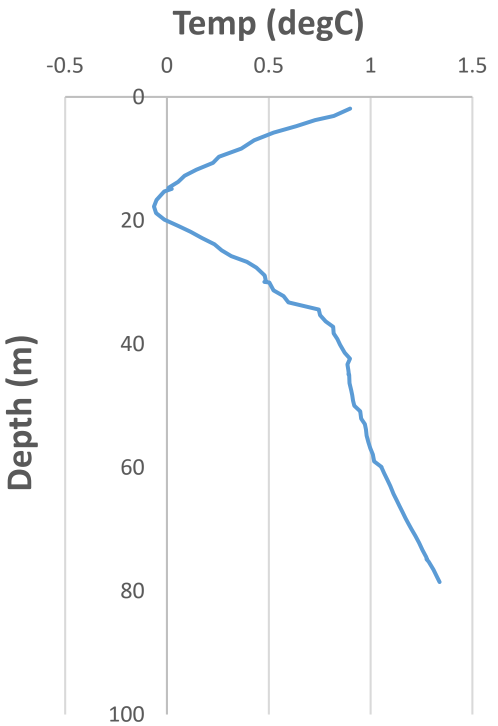
Mean annual air temperature



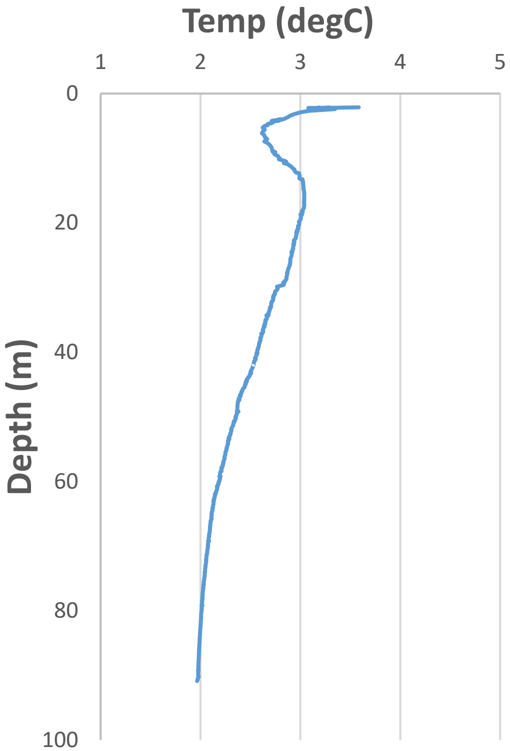


Allard and Lemay (2012)
Lemieux et al. (2016)

Temperature at depth

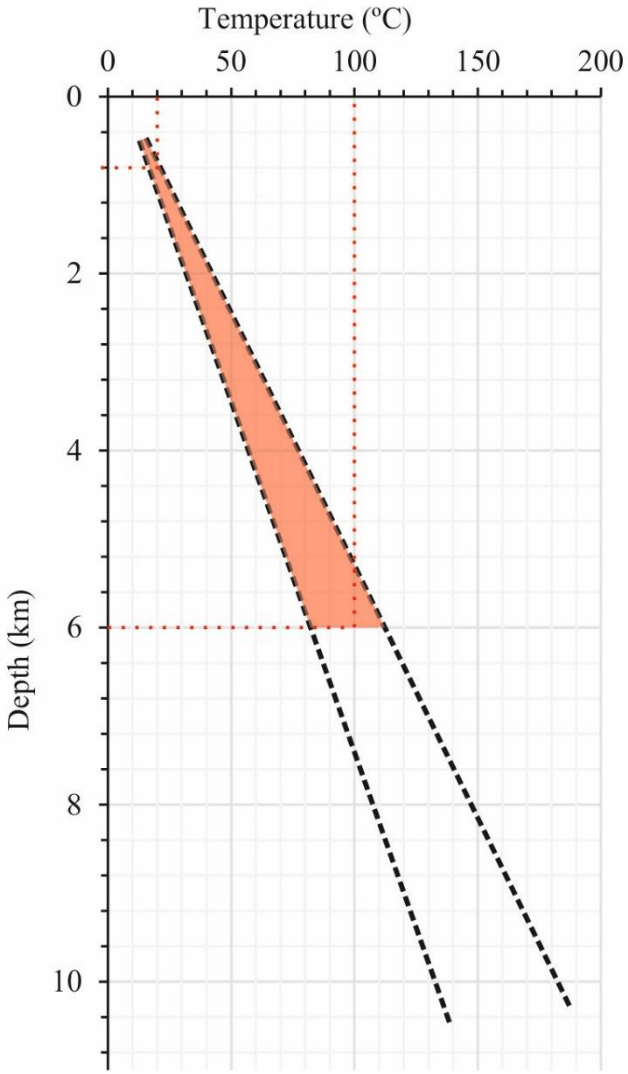


Kuujjuaq



Whapmagoostui-Kuujjuarapik

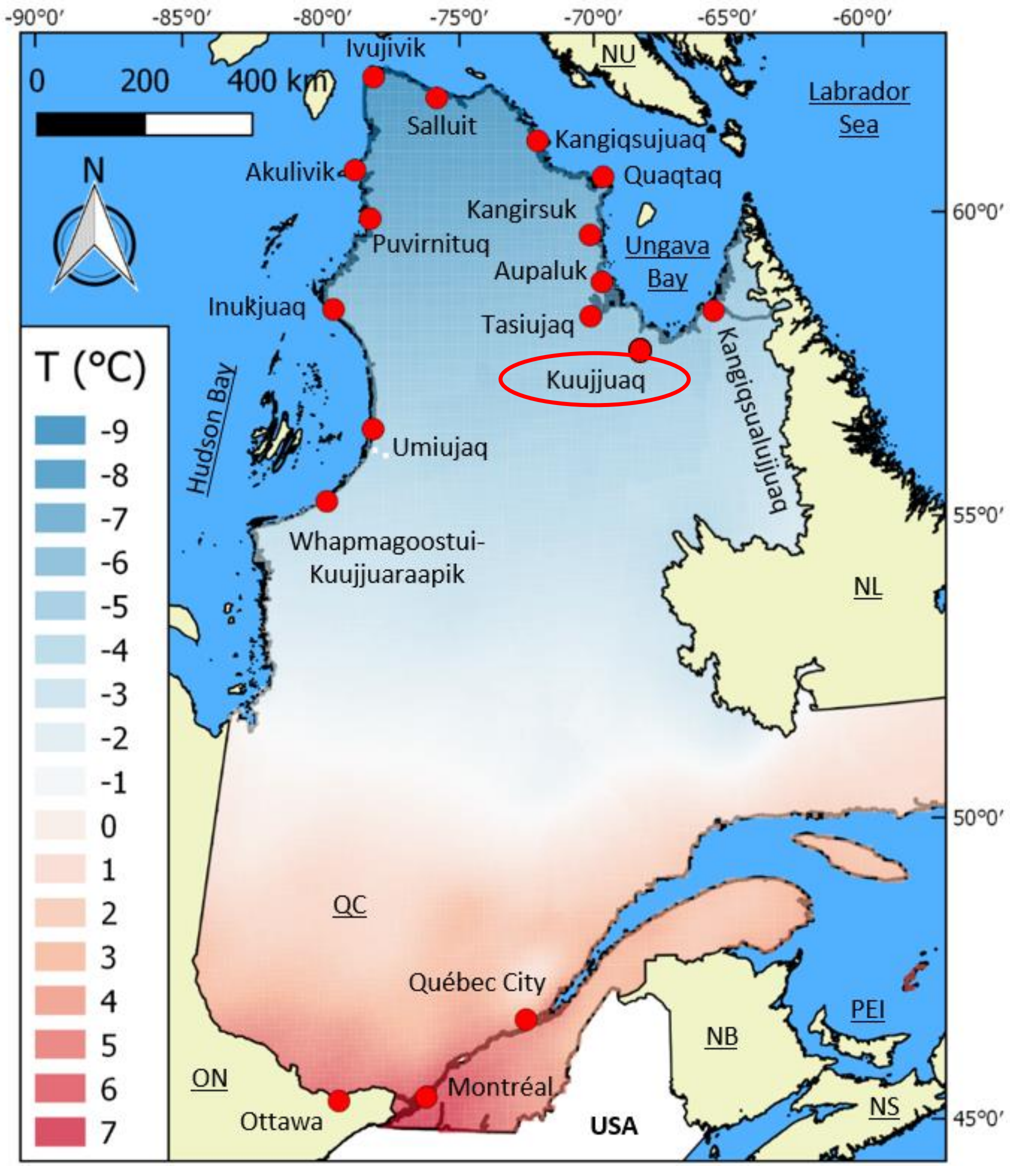
Geothermal gradient ~15 ºC/km
Surface heat flow ~40 mW/m²



Miranda et al. (2019)

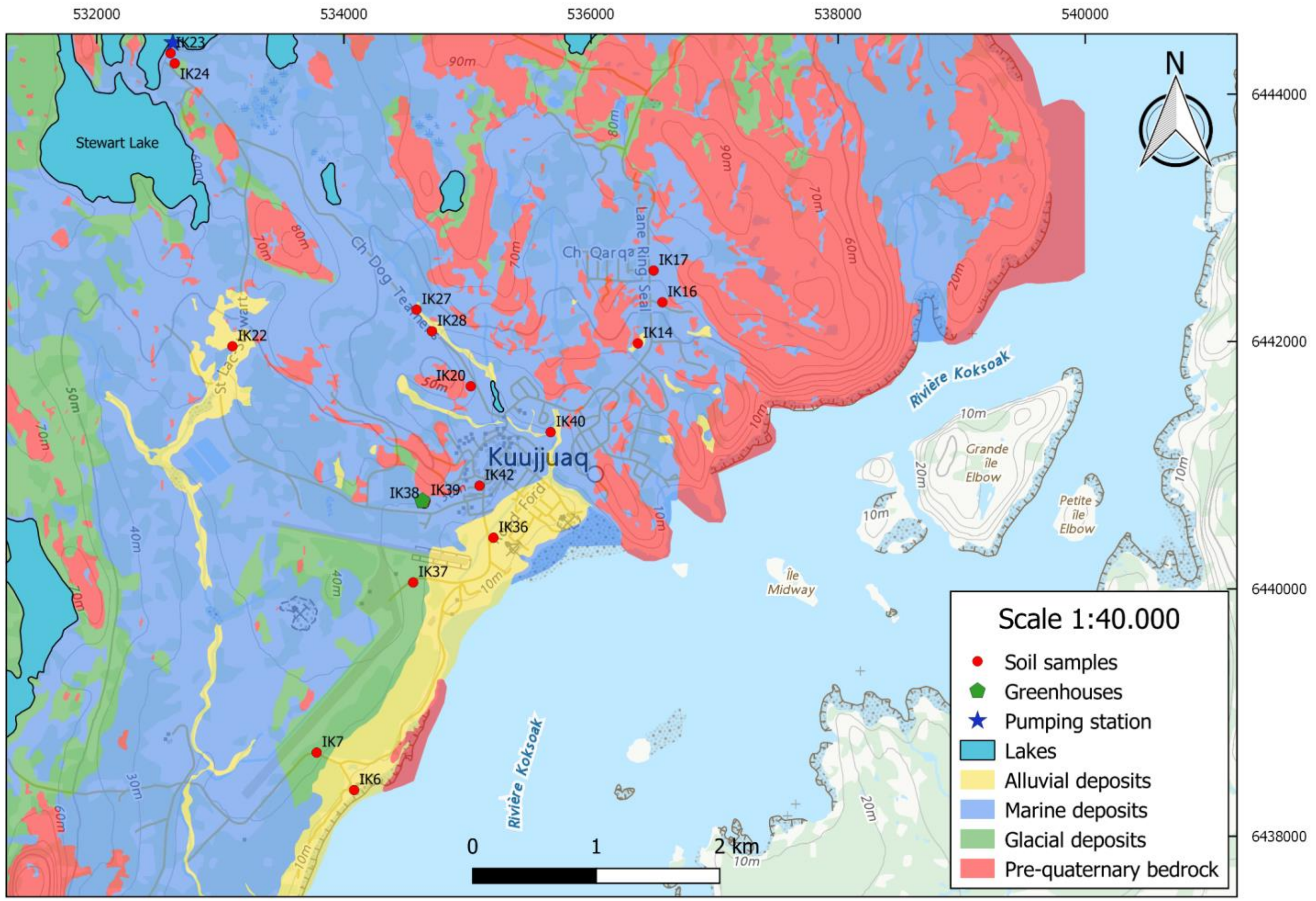
Inferred temperature at depth

Kuujjuaq

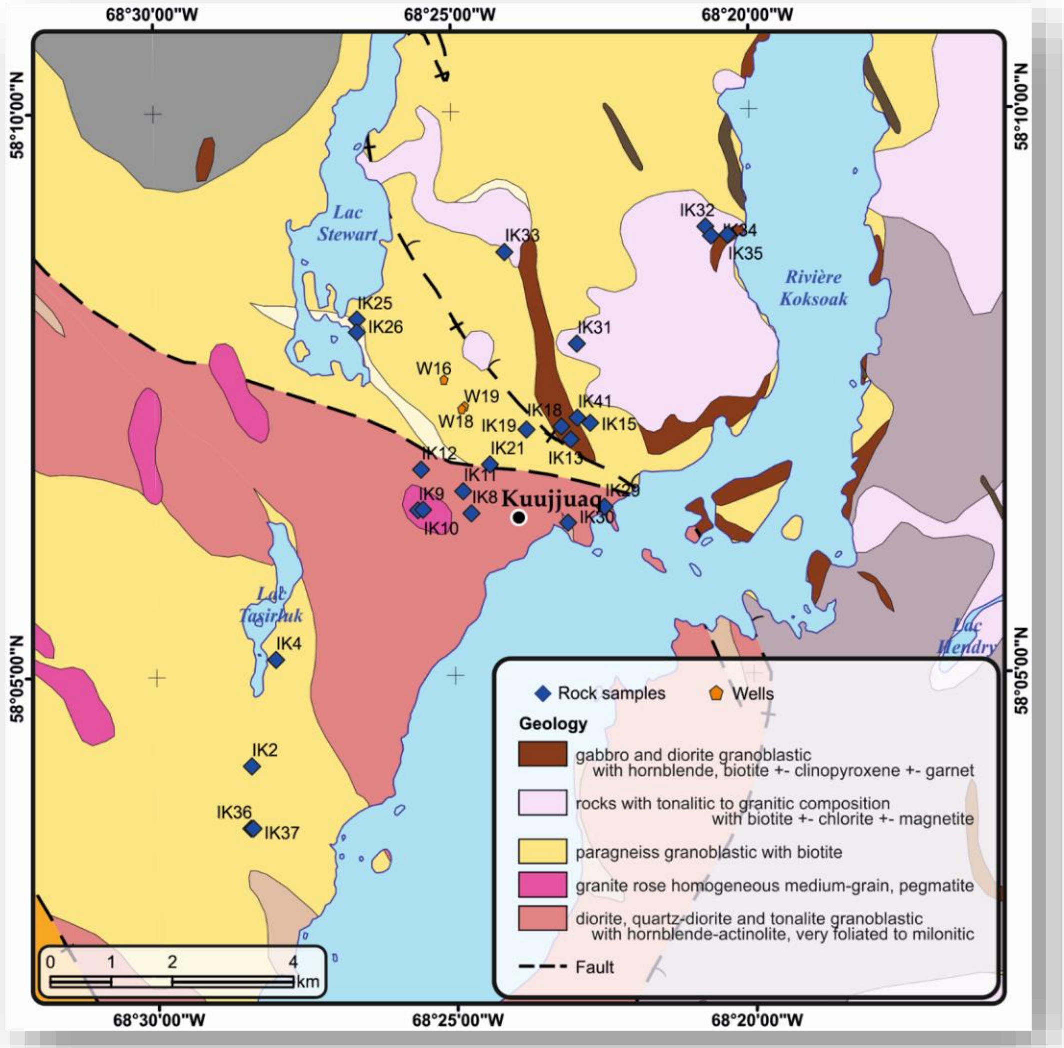


Mean annual air temperature

Geological setting



Quaternary sediments



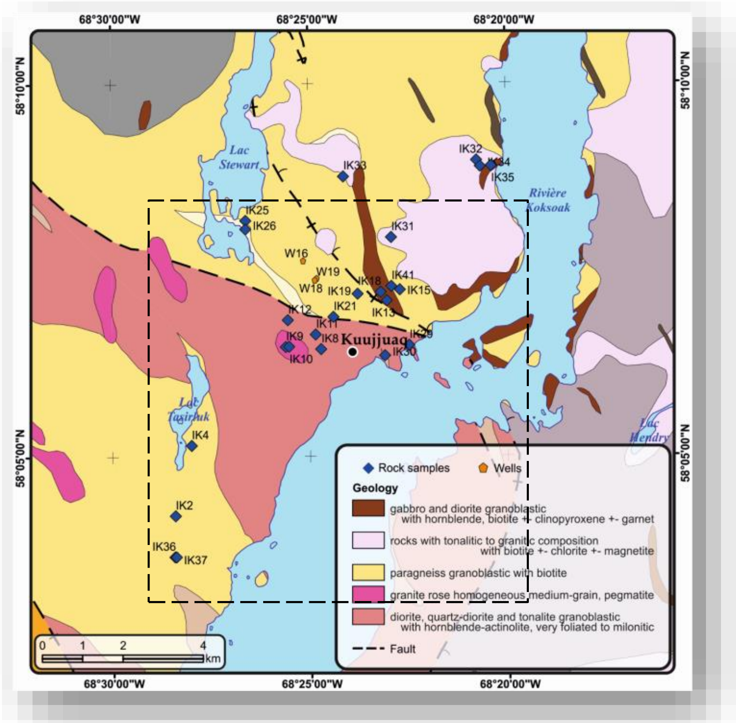
Bedrock

Ground-source heat pump systems

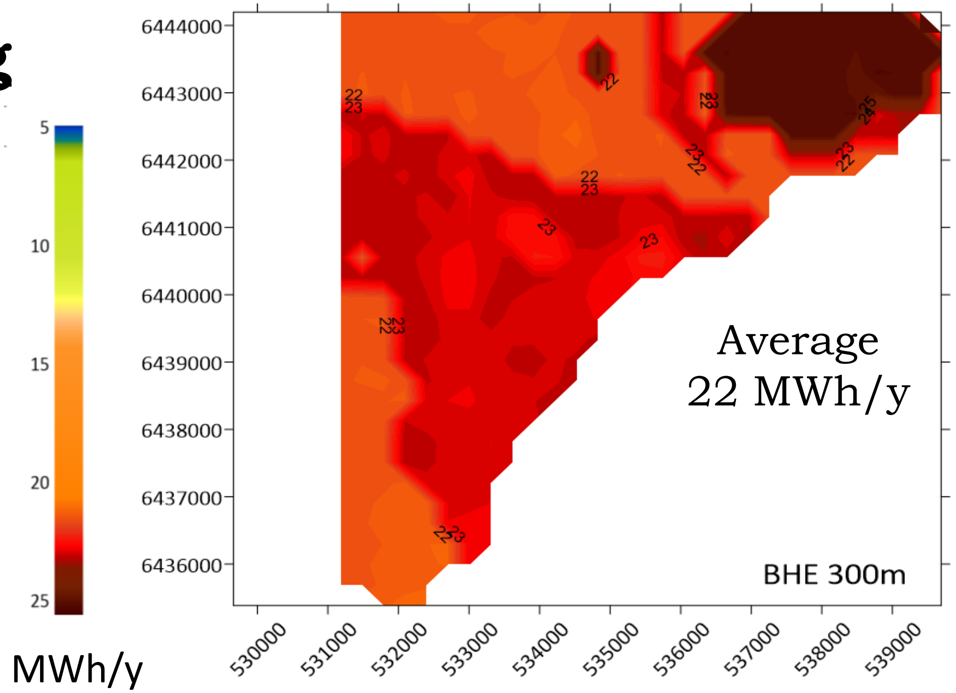
INRS

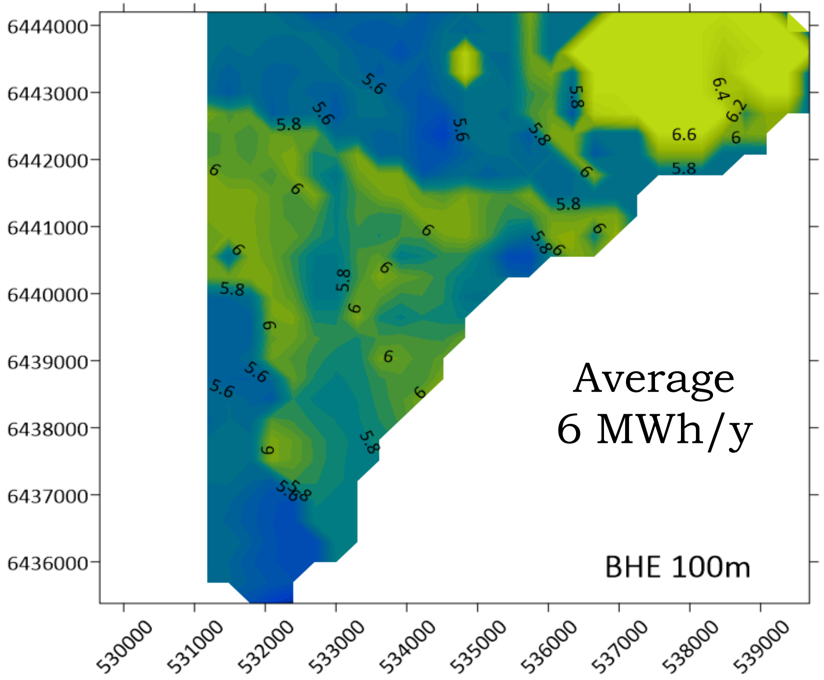
Ground-source heat pump potential mapping

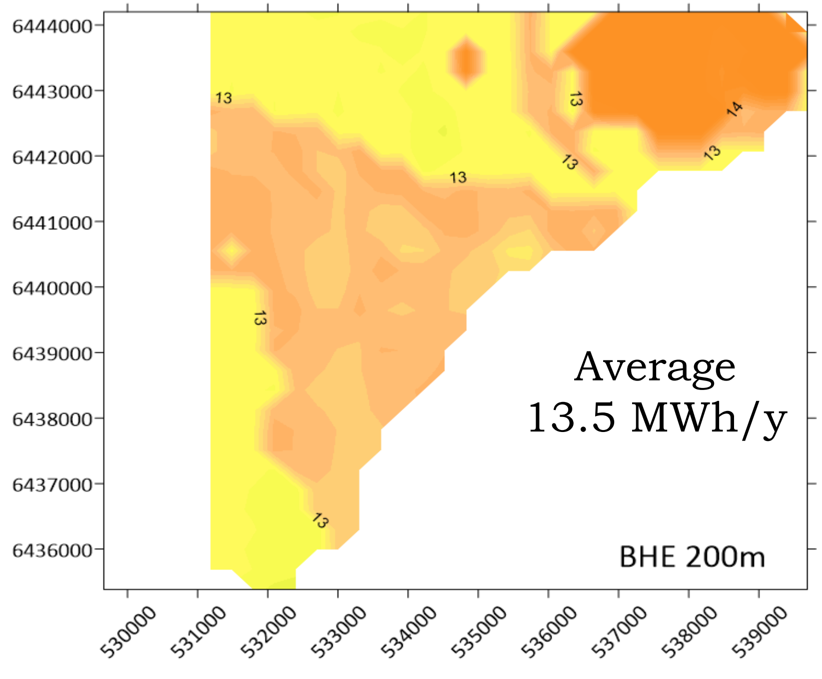
G.POT Approach (Casasso and Sethi, 2016)



Thermal properties and **ground temperature** are key-factors to define shallow geothermal potential







Gunawan et al. (2020)

Life-cycle cost analysis of GSHP compared to diesel

Heating scenario for a 5-occupant residential building (70 MWh/y)

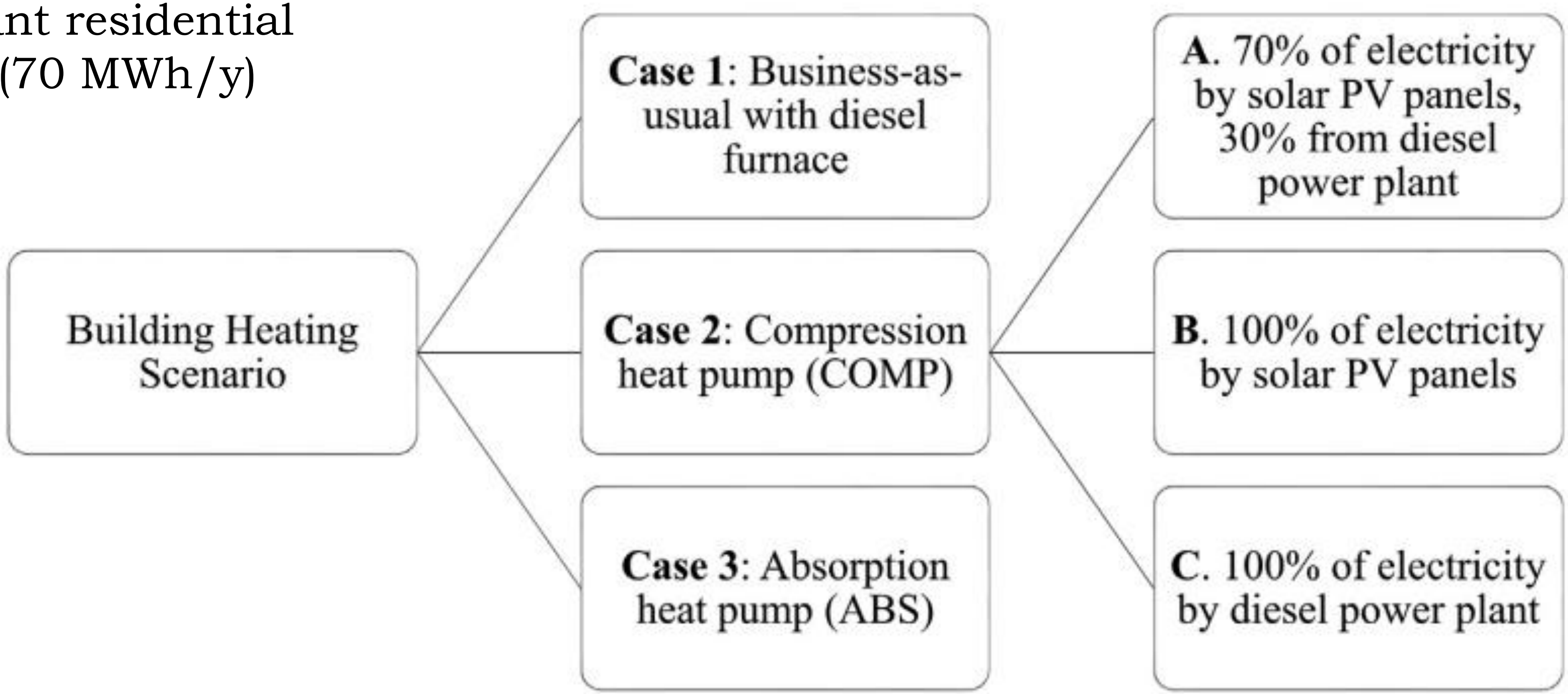
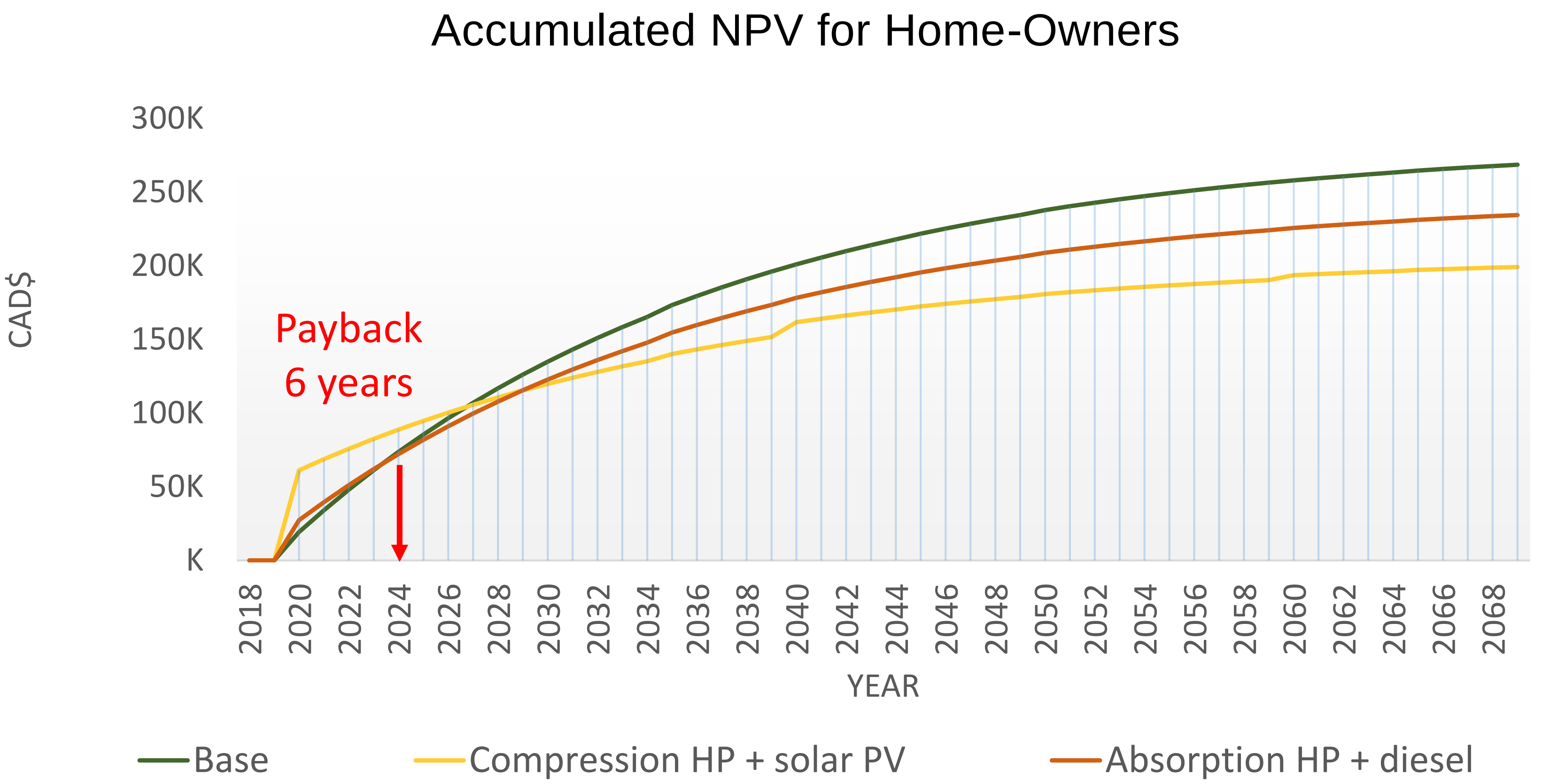


Fig. 3. Building heating scenarios.

Gunawan et al. (2020)

INRS

Life-cycle cost analysis – Net present value (NPV)



Government's NPV = $8,231.76

Government's NPV = $9,026.42

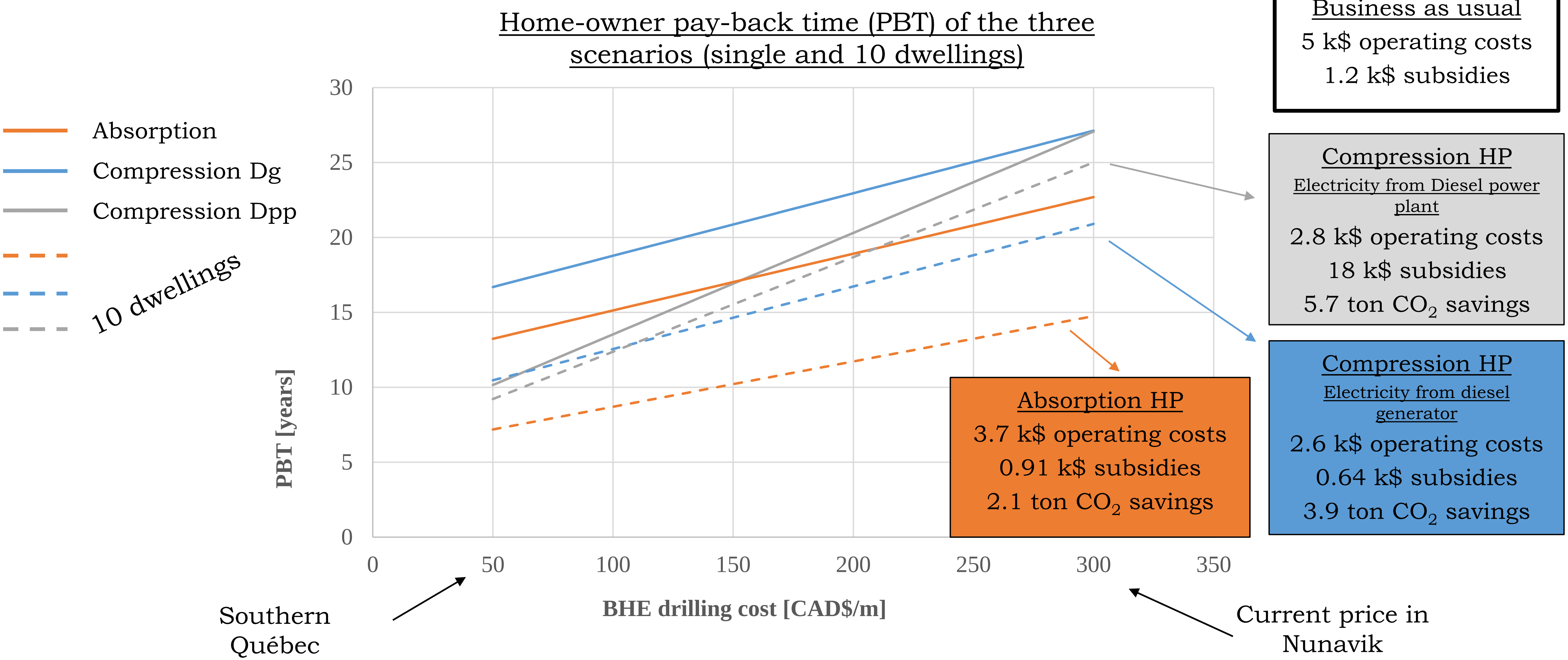
Government's NPV = $40,891.82

Government scheme:

1) Government pays for 50% of heat pump and solar PV panels costs
2) No subsidy on diesel and electricity
3) Government supports drilling industry with cost of drilling 50 CAD$/m
4) 19.4 $/ton of CO_2 emission

Gunawan et al. (2020)

Payback time vs. Drilling cost

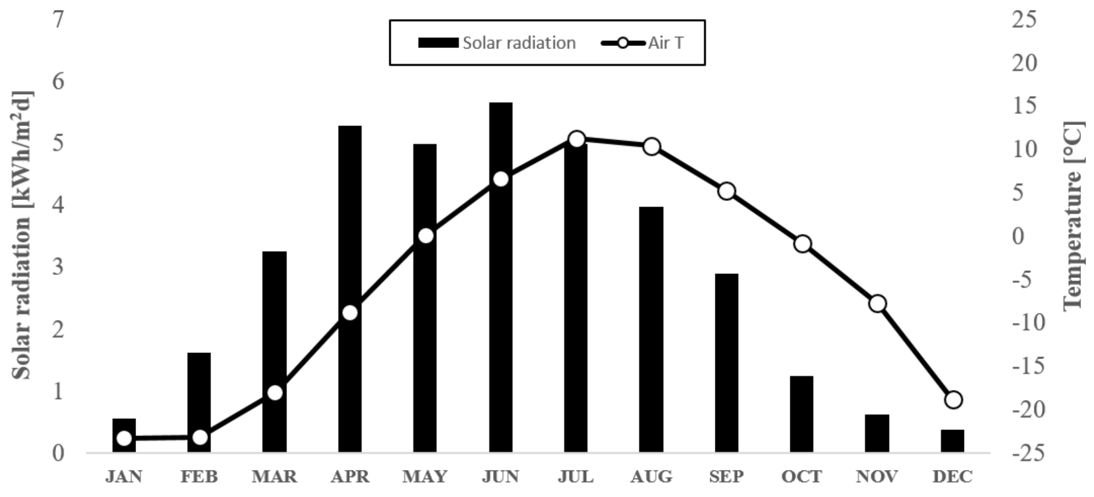


1) Interesting paybacks under 150 CAD$/m
2) Economy of scale → 10 dwellings better than 1

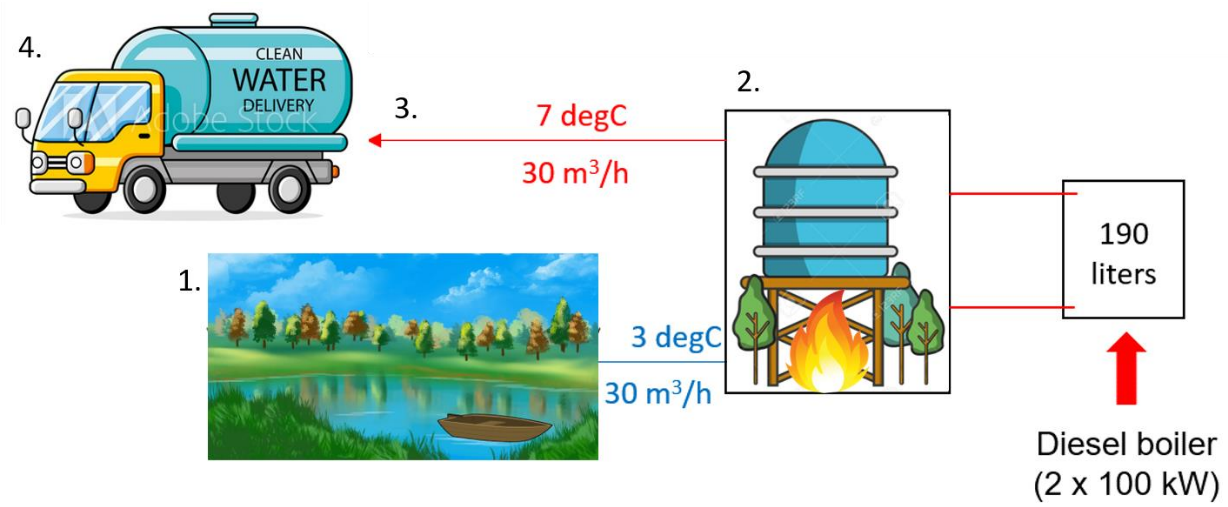
Giordano et al. (2019)

Underground thermal energy storage systems

Pumping station of the drinking water network

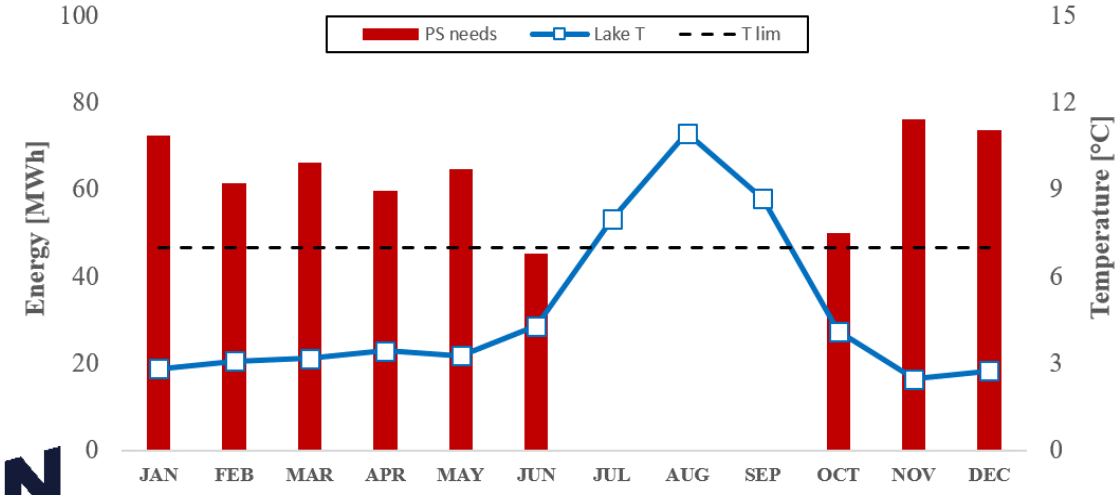


Solar radiation and air temperature



Energy consumption 570 MWh/y

Cost 100,000 $CAD/year (diesel 1.9 $CAD/litre)



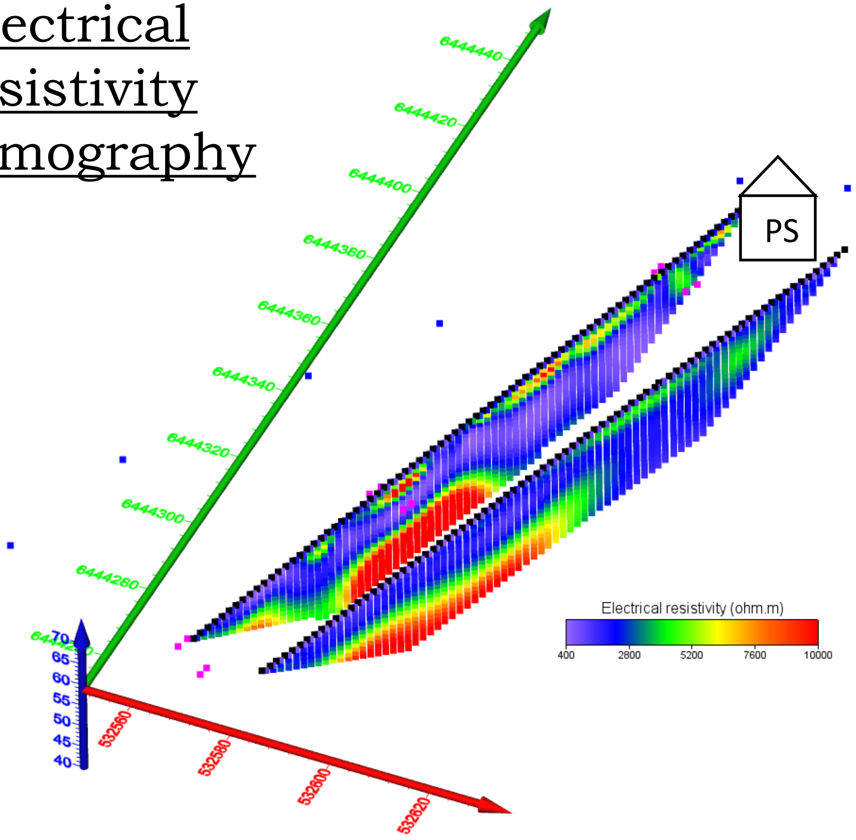
Pumping station energy needs and lake T

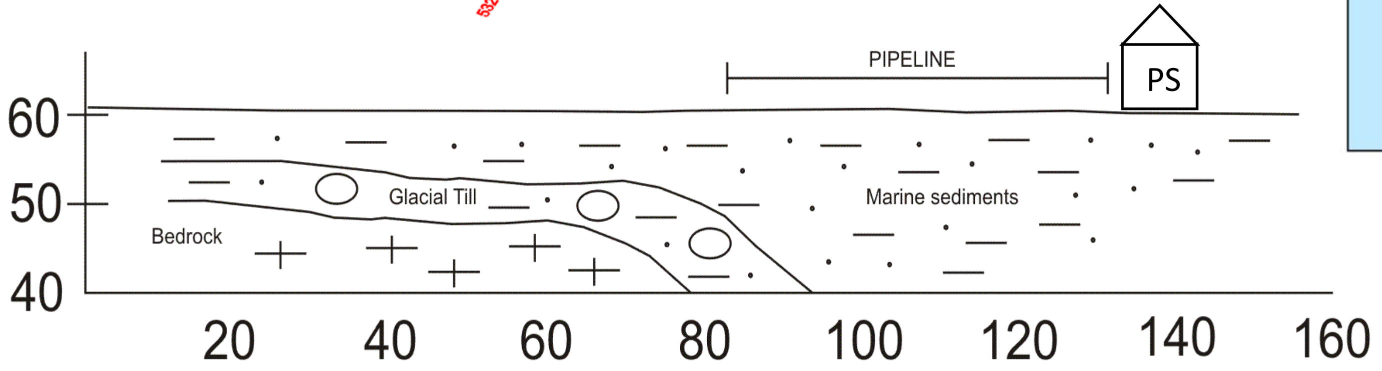
Drinking water network in Kuujjuaq:

1. Water pumped from Lake Stewart
2. Heated to prevent freezing
3. Pumped in a 5 km pipeline to the village
4. Distributed to each house by truck

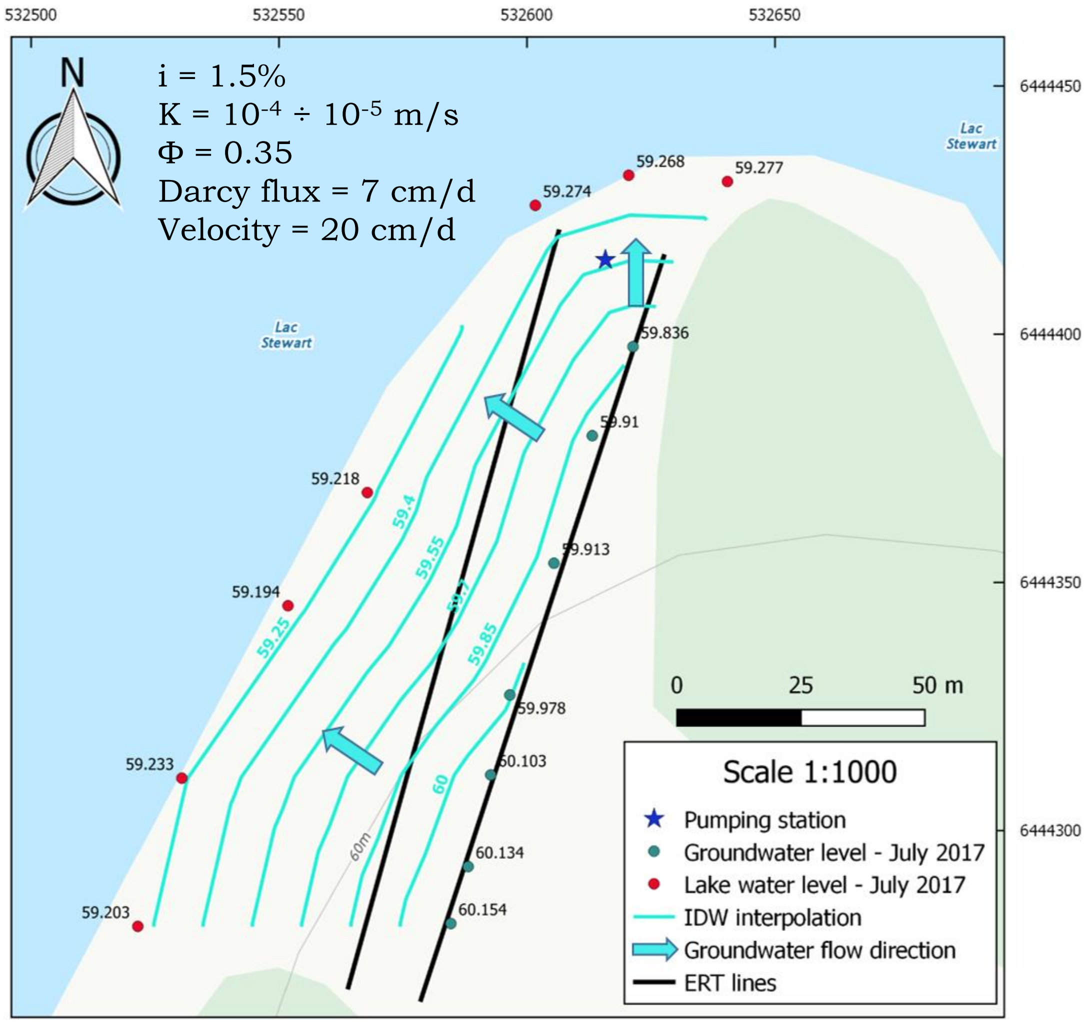
Geological and hydrogeological characterization

Electrical resistivity tomography

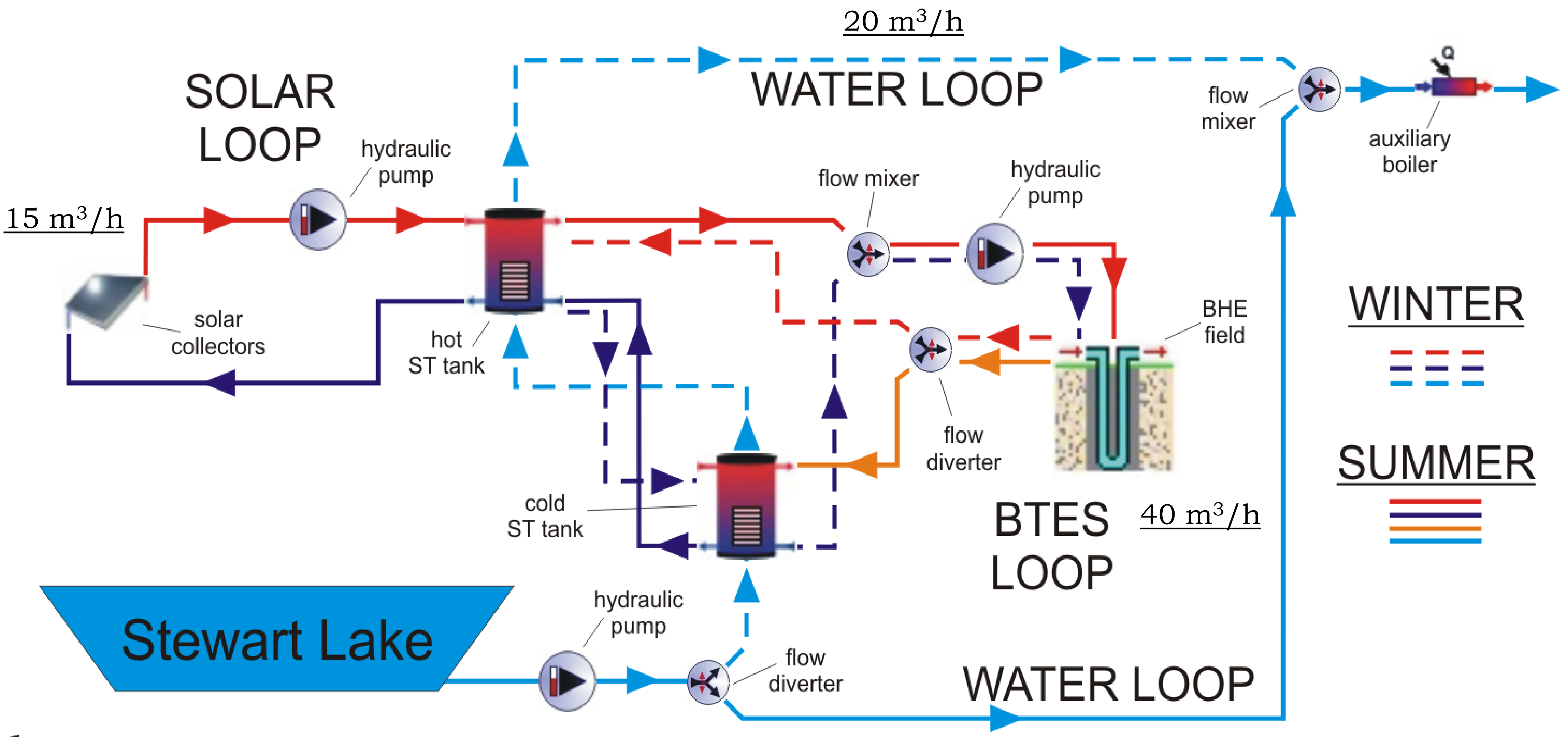




Local groundwater



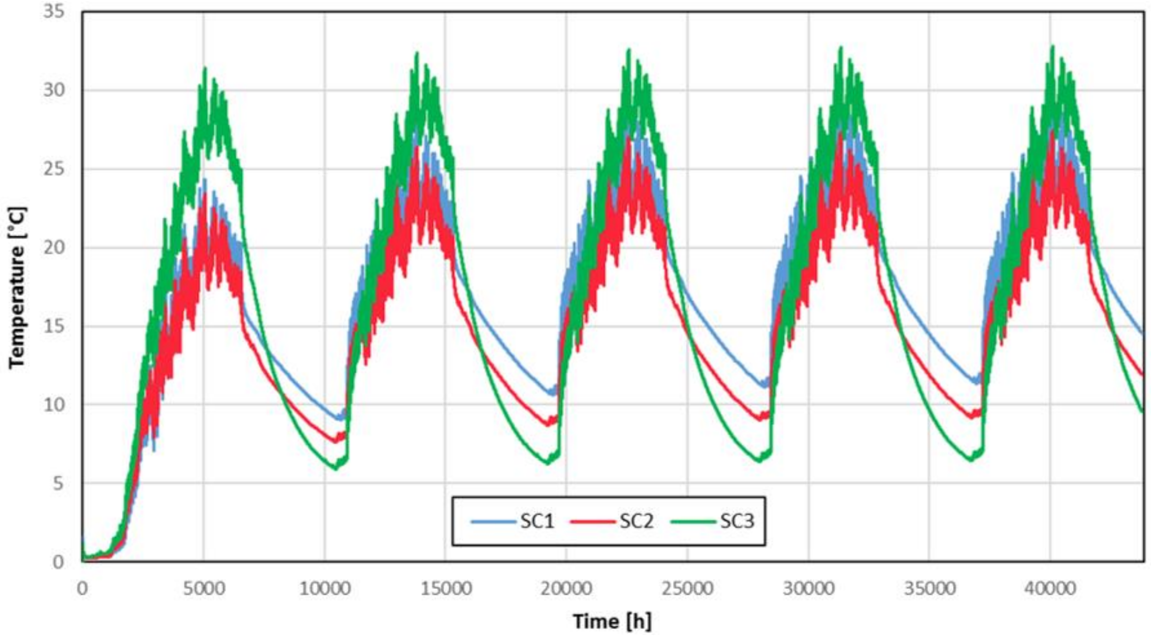
UTES system design



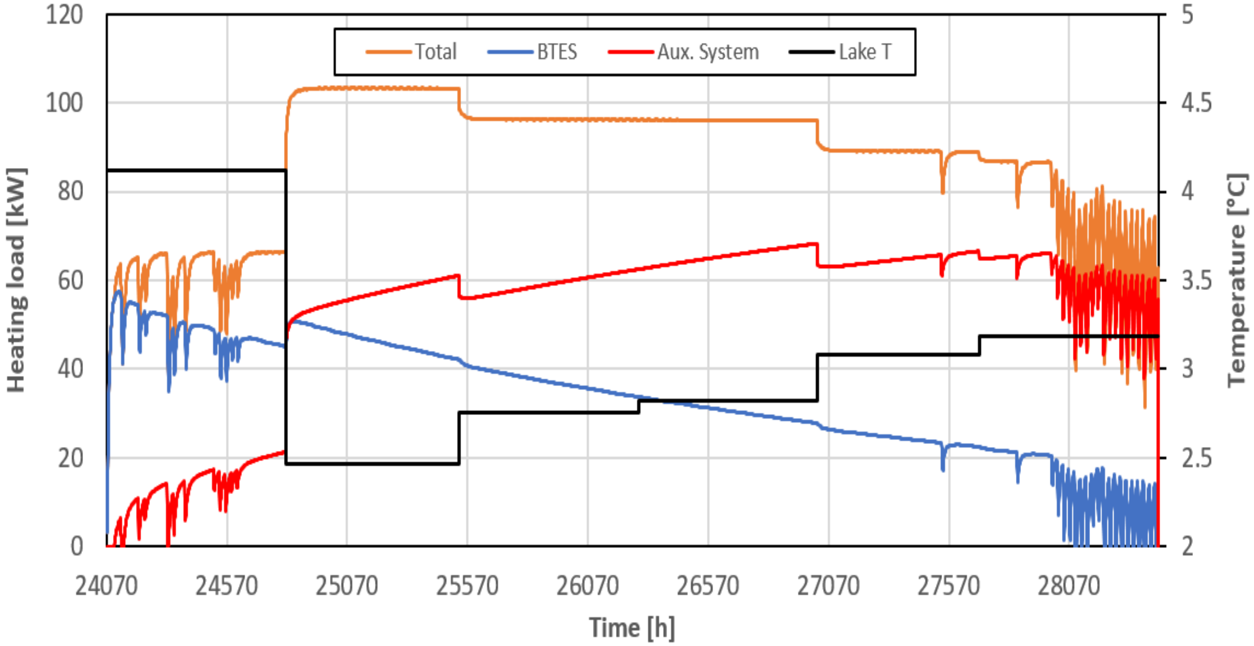
Giordano and Raymond (2019)

Simulations results

Temperature in the centre of the BTES (5 years simulation)



3rd year discharge SC2



OCT | NOV | DEC | JAN | FEB | MAR

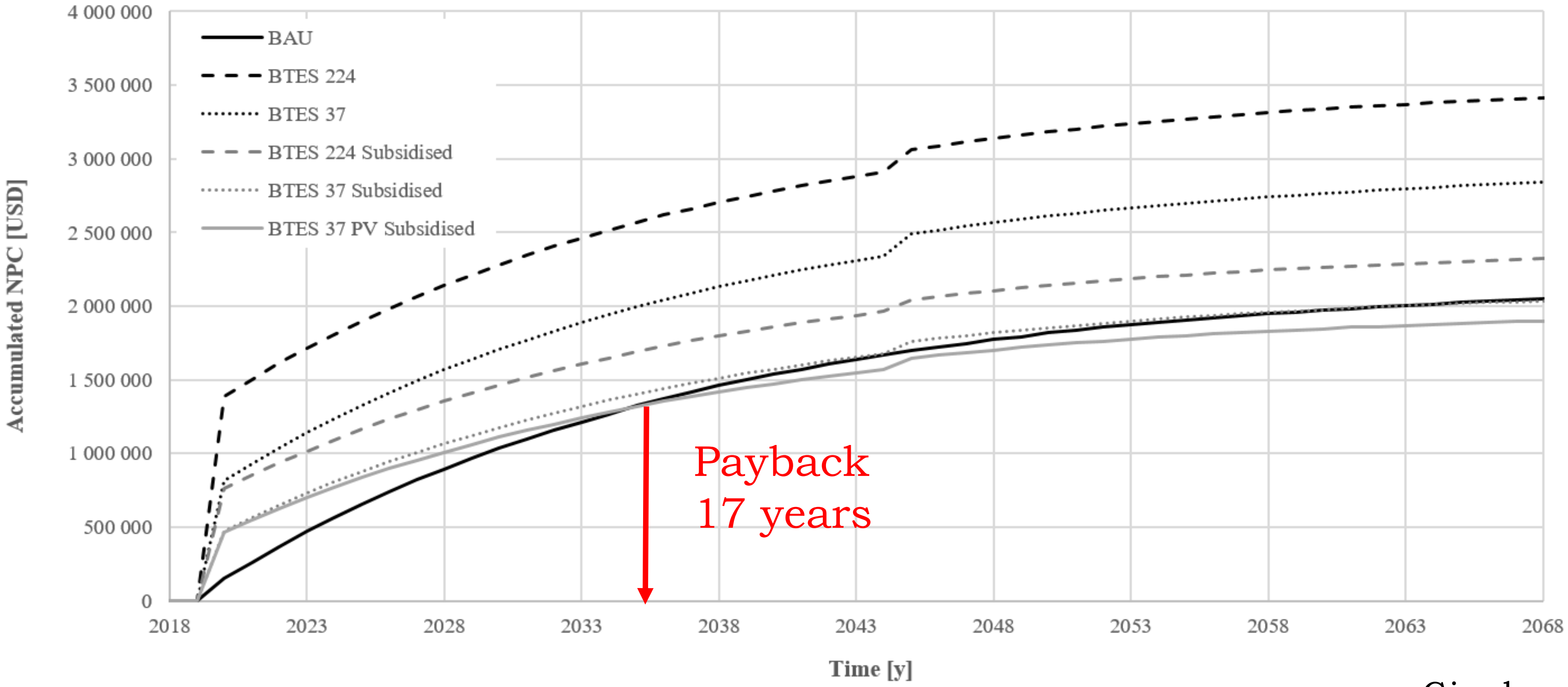
- Borehole thermal energy storage system (BTES) provides **45-50 % of total energy need**
- Equilibrium is reached after 3-4 years
- **Challenges**: permafrost, limited solar radiation, heat losses due to advection

INRS

Giordano and Raymond (2019)

Life-cycle cost analysis – Net present cost (NPC)

BAU = business as usual (diesel)



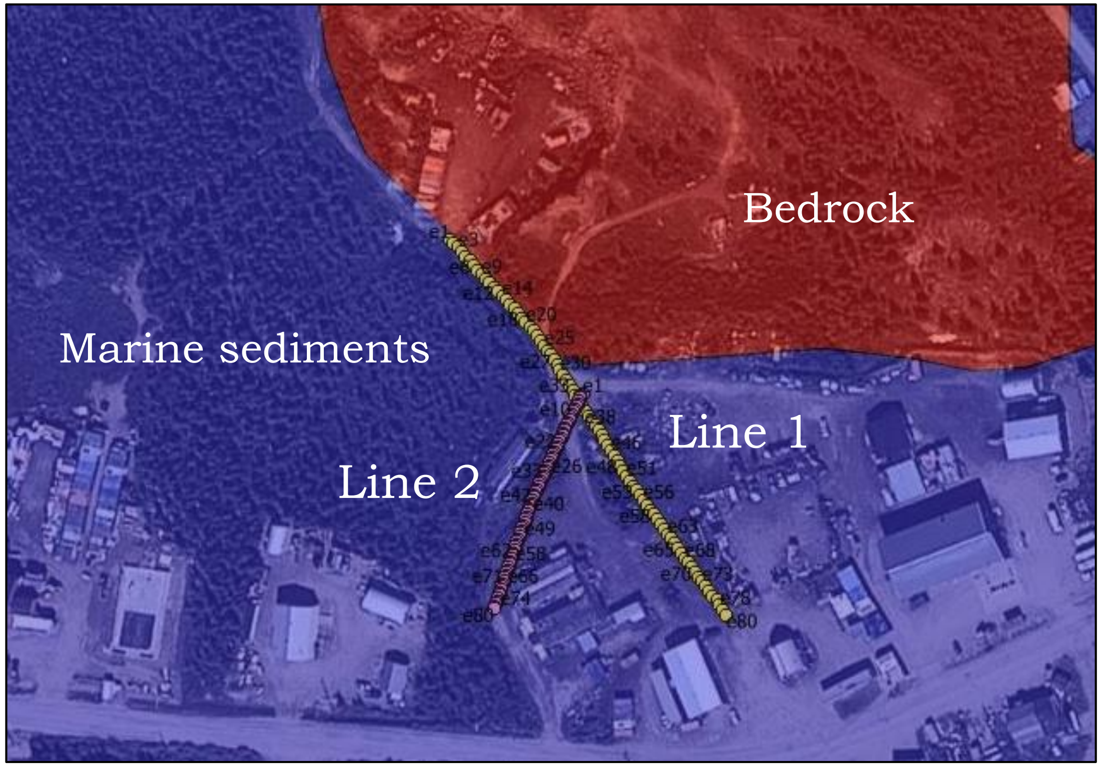
Giordano and Raymond (2019)

Best scenario could help saving **15,000 $CAD/y** and **19 tons of CO_2eq/y**

INRS

Coupled daily and seasonal energy storage for greenhouses

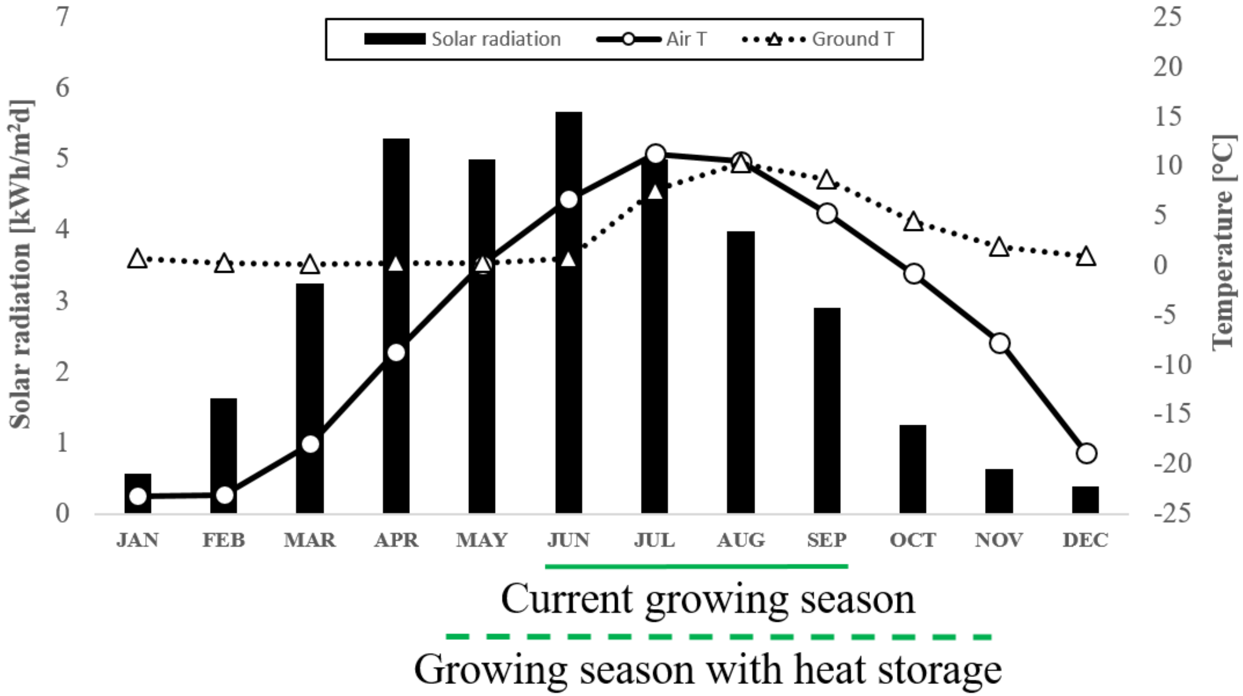
Greenhouses in Kuujjuaq

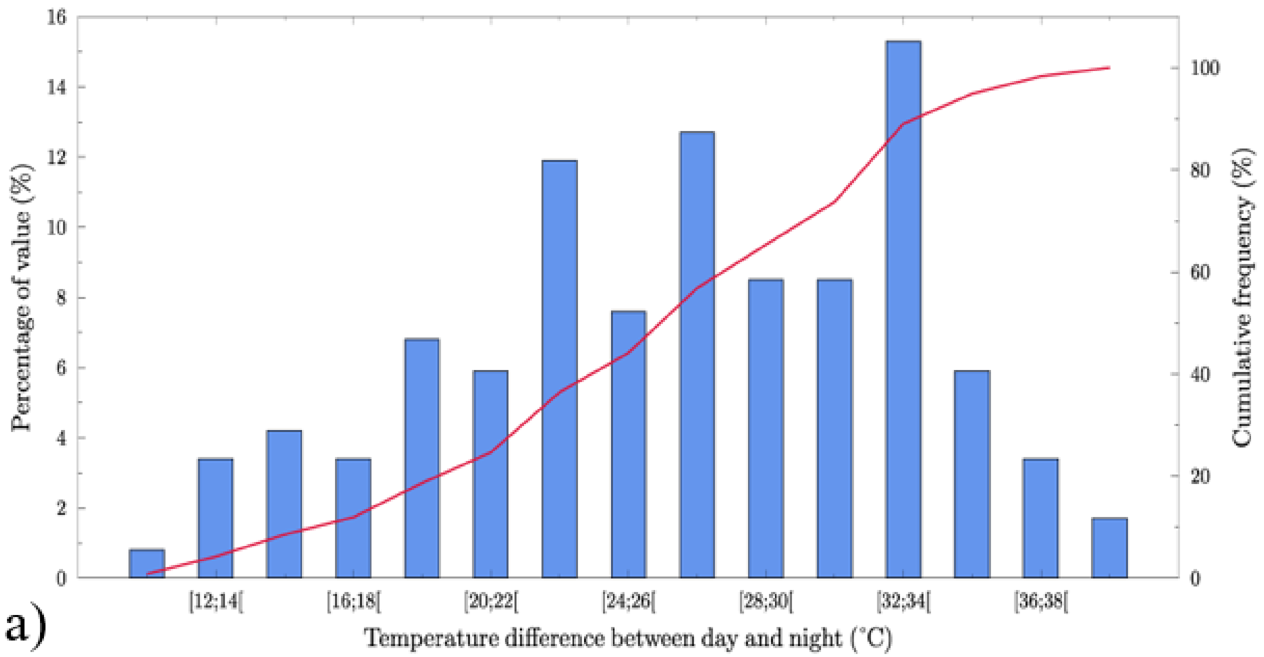


Electrical resistivity tomographies

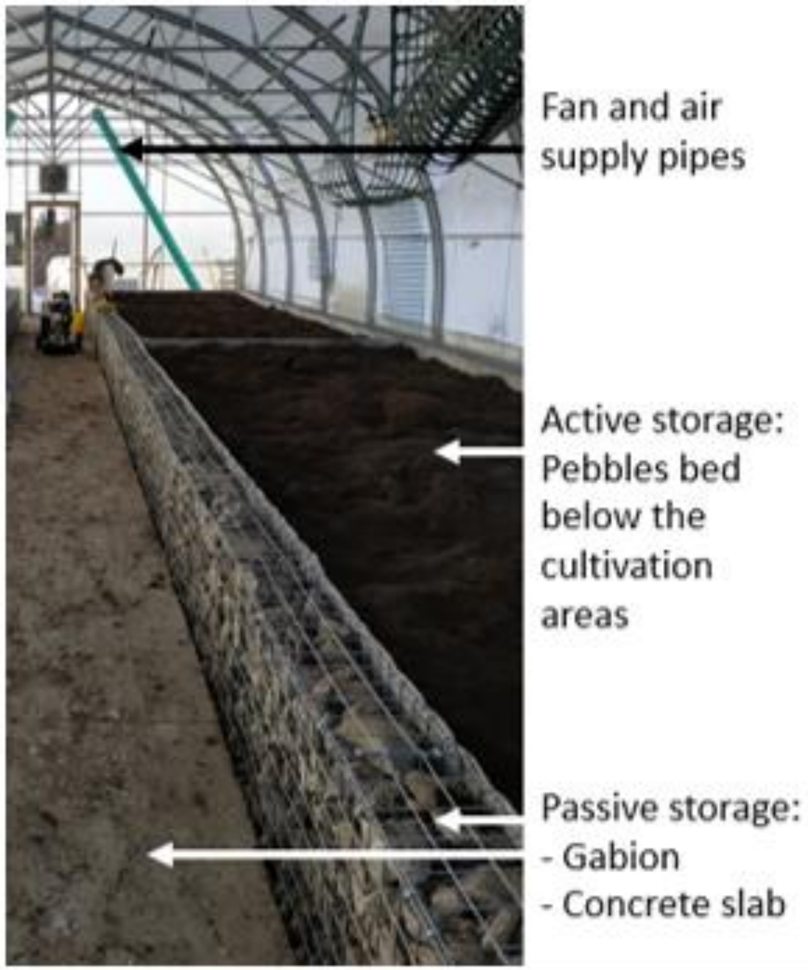
INRS

Daily heat storage



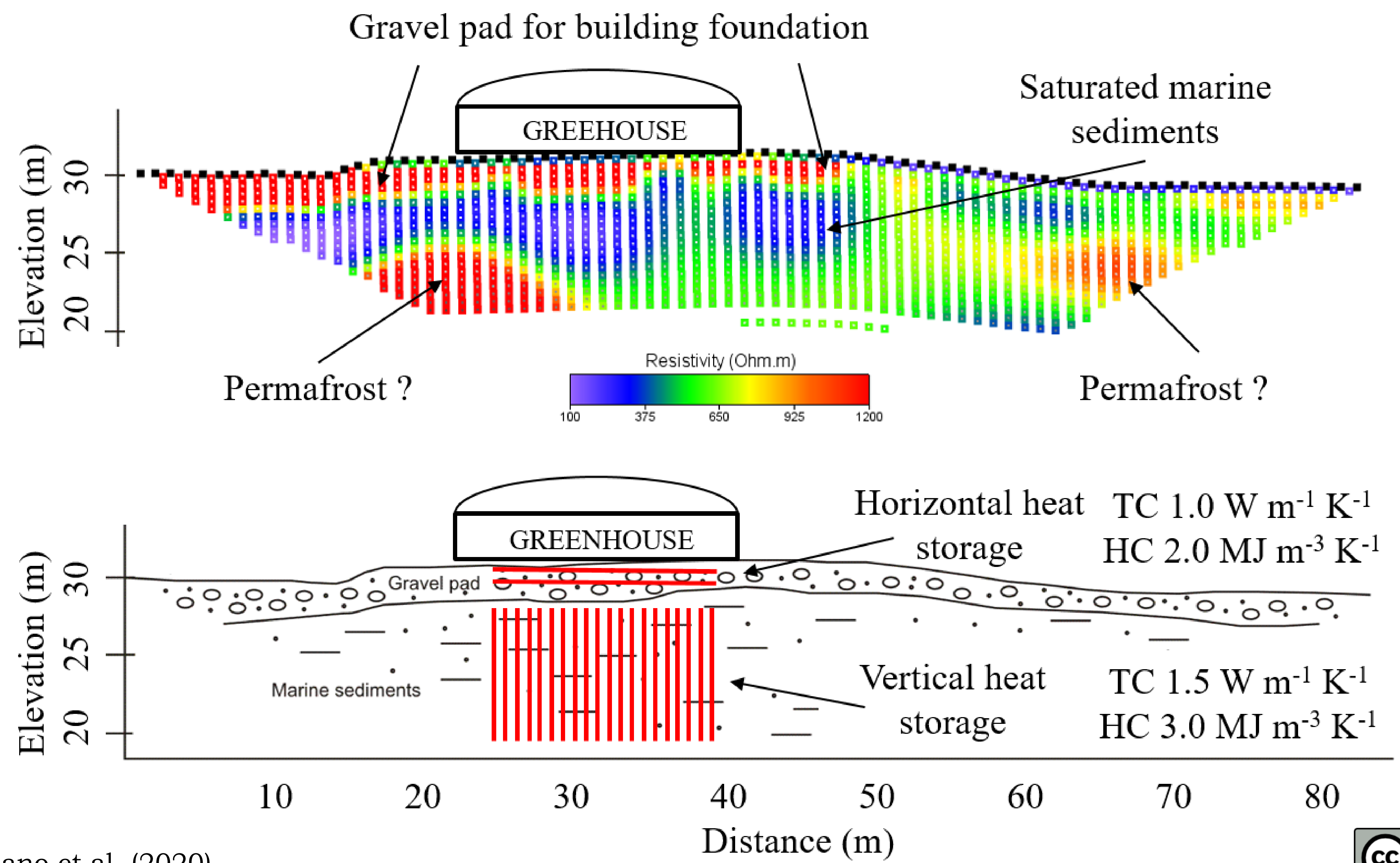


a)

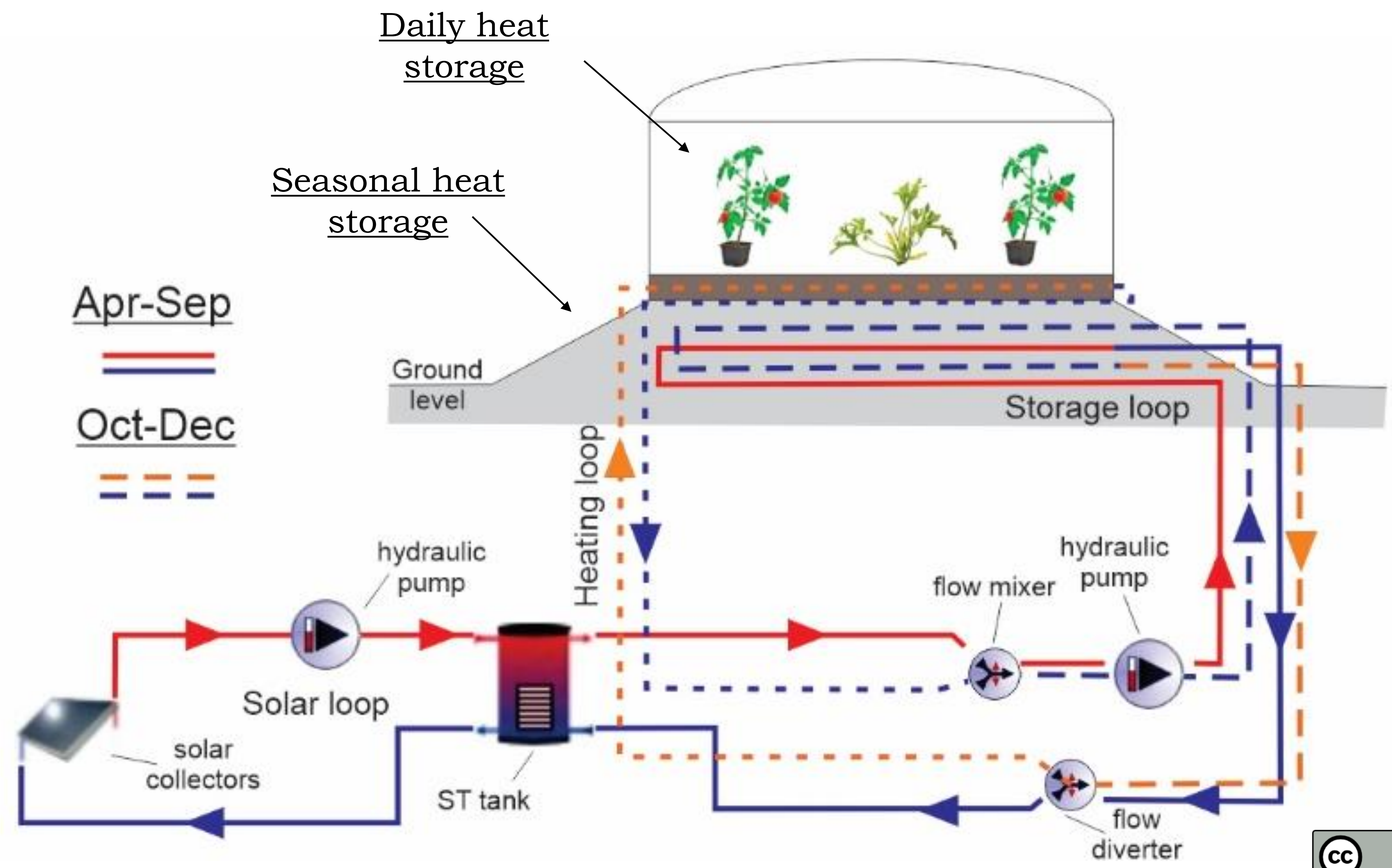


Piché et al. (2020)

Seasonal heat storage



Giordano et al. (2020)



Giordano et al. (2020)

Conclusions - Kuujjuaq

Technical results

- **GSHP** and **UTES** are **promising alternative technologies for heating purposes** in Nunavik;
- **GSHP** can provide **10 to 40 % energy savings** whether if **absorption** or **compression** technology is used;
- **UTES** can guarantee **50% energy savings**, **thermal recovery is similar to other operating plants** around the world even in this subarctic climate

Financial results

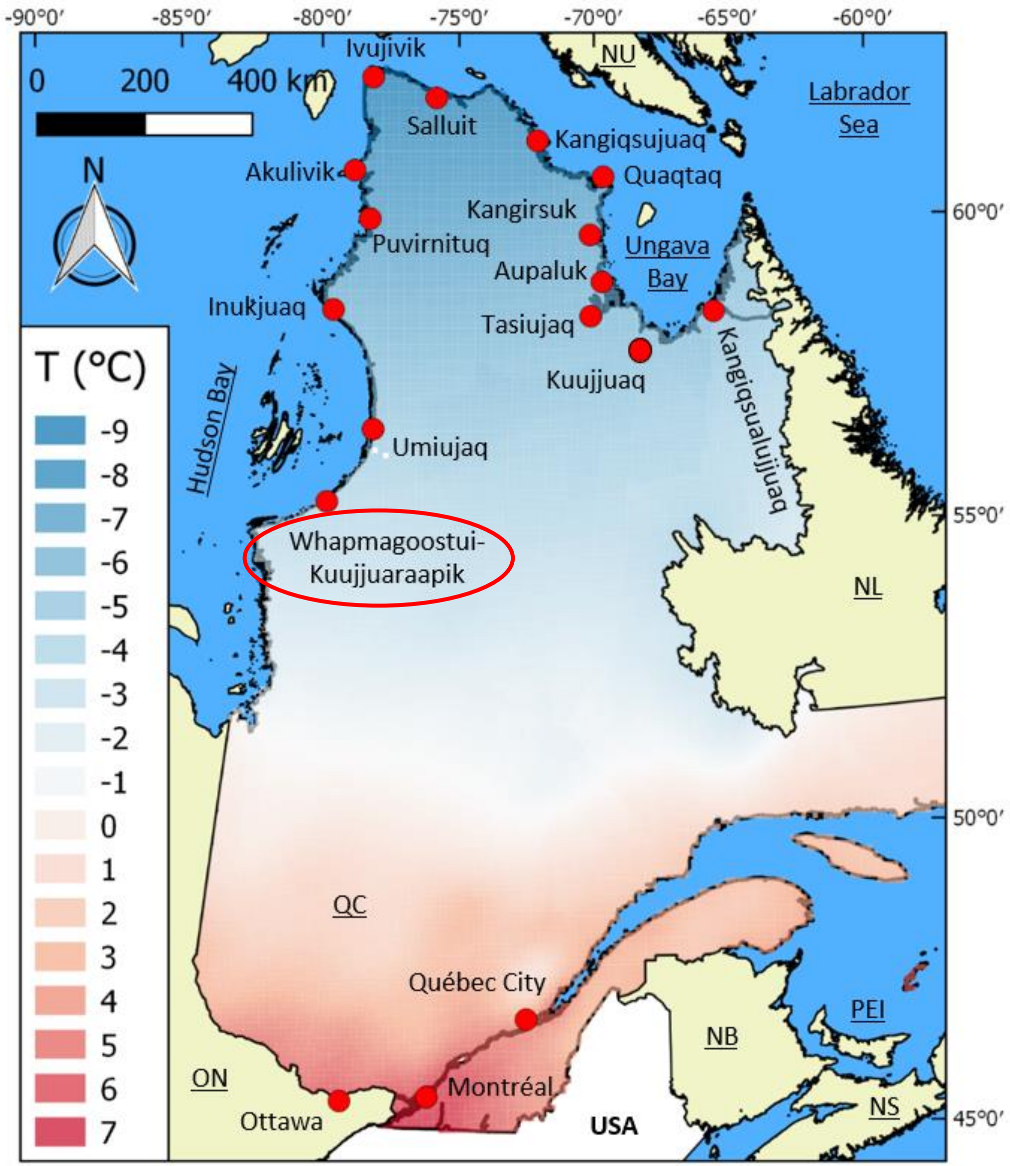
- A decrease of the **BHE drilling and installation cost** is crucial to aim at a **widespread utilization** of these technologies in Nunavik. A cost of **150 CAD$/m** has been defined as a threshold for getting interesting pay-back time compared to the BAU scenario → technological transfer will be a key element to achieve this value in the future
- **Government subsidies** could be shifted from **oil products to renewable energy** to guarantee **sustainability** of the communities

Future activities

- Demonstration plant of horizontal GSHP in summer 2020
- Integration with solar and wind to feed the compression HP

Whapmagoostui- Kuujjuaraapik (W-K)

Mean annual air temperature

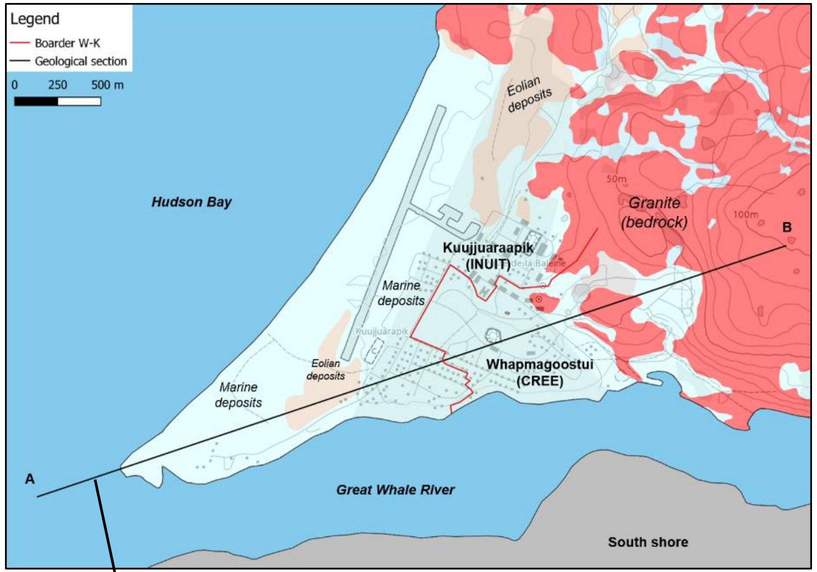


Geological setting

Comeau et al. (2020)

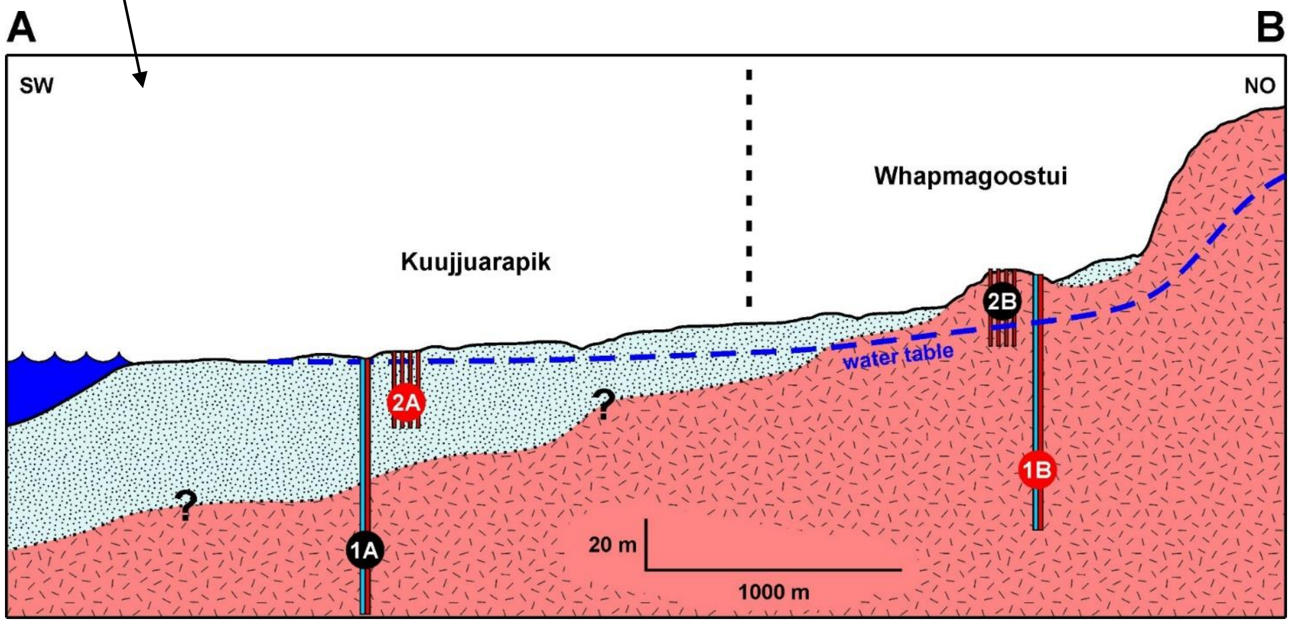
The Inuit population lives in the western and north part of the village, while the Cree population occupies the south-eastern part. The granitic bedrock is highlighted in red. The unconsolidated deposits of the river delta that mainly host the village can be differentiated into marine and eolian deposits (Fortier et al. 2011).

Ground-source heat pumps



For a reference building of 70 MWh/y, optimistic (1B) and pessimistic (1A) scenarios have been estimated.

According to the G.POT method (Casasso and Sethi, 2016) 4 and 5 vertical ground heat exchangers would be necessary to feed a ground-source heat pump.



		1B Optimistic		1A Pessimistic	
Initial ground temperature	T_o	2		2	°C
Minimum fluid temperature	T_{lim}	-5	°C	-5	°C
Ground thermal conductivity	λ	3,00	$W\ m^{-1}\ K^{-1}$	2,35	$W\ m^{-1}\ K^{-1}$
Ground heat capacity	ρc	2,30	$J\ m^{-3}\ K^{-1}$	2,50	$J\ m^{-3}\ K^{-1}$
Borehole length	L	100	m	100	m
Borehole radius	r_b	0,076	m	0,076	m
Length of heating season	t_c	365	days	365	days
Year	t_y	365	days	365	days
Simulation time (lifetime)	t_s	25	years	25	years
Grout thermal conductivity	λ_{bf}	1,50	$W\ m^{-1}\ K^{-1}$	1,50	$W\ m^{-1}\ K^{-1}$
Number of pipes	n	2	-	2	-
Pipe radius	r_p	0,017	m	0,017	m
	t'_c	1,00		1,00	
	u'_c	0,00		0,00	
	u'_s	0,00		0,0001	
	G_{max}	9,59		9,25	
	$r_{p,eq}$	0,02		0,02	
Borehole thermal resistance	R_b	0,12	$m\ K\ W^{-1}$	0,12	$m\ K\ W^{-1}$
Closed-loop potential energy	P_{BHE}	13,23	$MWh\ y^{-1}$	10,69	$MWh\ y^{-1}$
Reference building	$P_{building}$	70	$MWh\ y^{-1}$	70	$MWh\ y^{-1}$
Coefficient of performace	COP	3,00		3,00	
Total geothermal energy	P_{ground}	46,67	$MWh\ y^{-1}$	46,67	$MWh\ y^{-1}$
Number of boreholes needed		4		5	

Comeau et al. (2020)

UTES potential mapping – STOREmap method

Energy stored

$$Q_{STO} = f(\lambda, \rho c) \quad \begin{cases} \lambda = f(bedrock\ and\ groundwater\ depth) \\ \rho c = f(bedrock\ and\ groundwater\ depth) \end{cases}$$

Heat losses

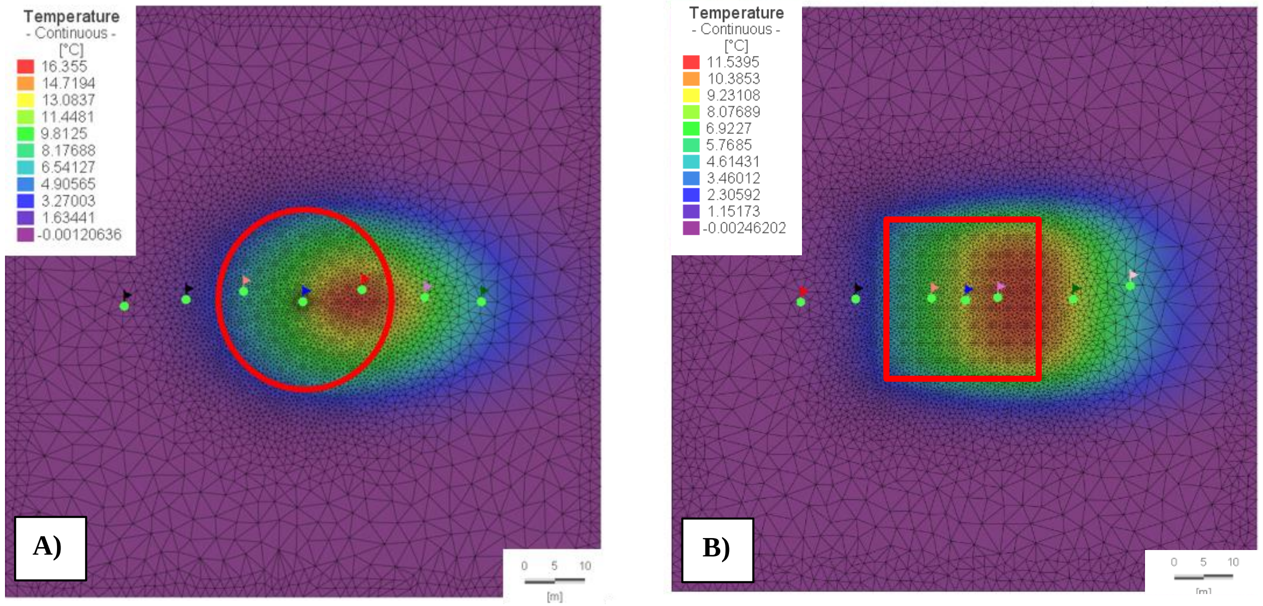
$$Q_{LOST} = f(\lambda, \rho c, groundwater\ depth\ and\ Darcy\ velocity)$$

Available energy

$$Q_{REC} = Q_{STO} - Q_{LOST}$$

Thermal recovery

$$\eta = Q_{REC}/Q_{STO}$$



Giordano and Raymond (2019)

The STOREmap method has been proposed to **evaluate the effectiveness of UTES systems in different geological settings** (Comeau et al., 2020). It takes into account the subsurface thermal and physical properties to evaluate the amount of energy that can be stored into the underground (Q_{STO}).

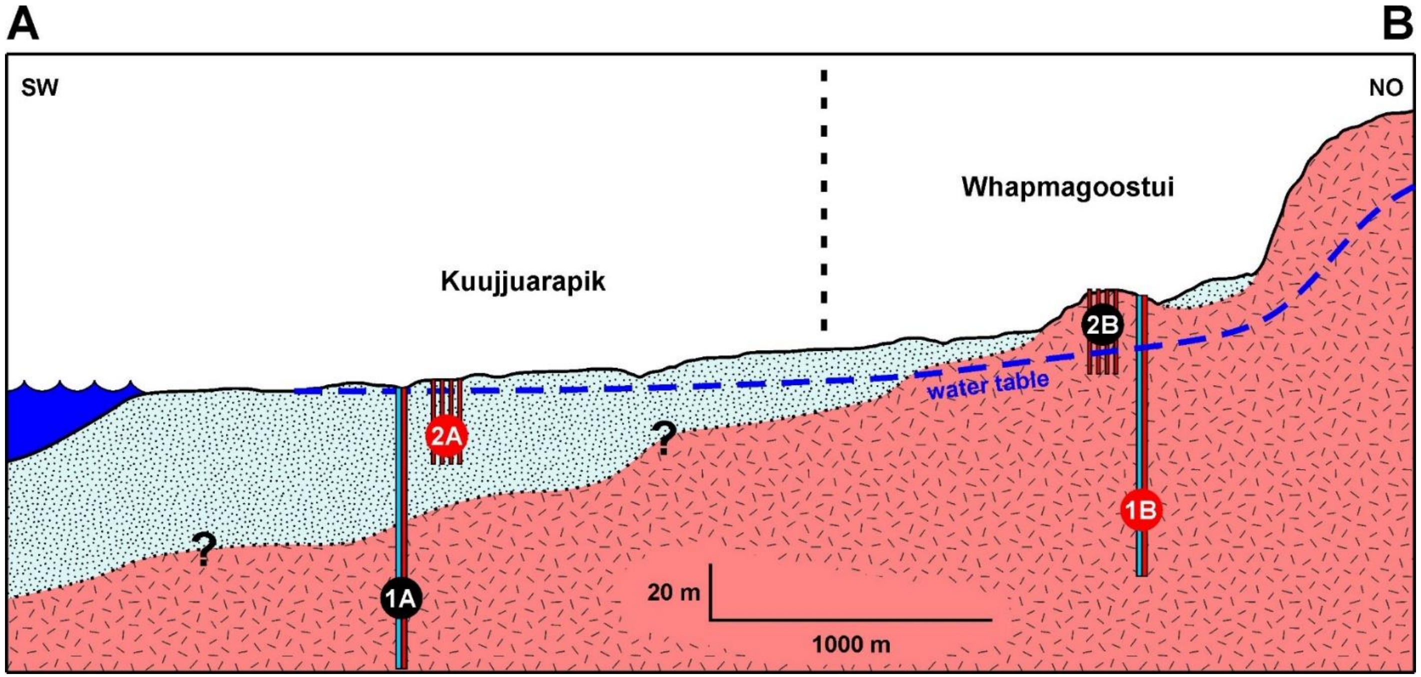
This amount is strongly related to the **depth of the bedrock** and the **groundwater table** when considering only conduction. These parameters also impact the amount of energy that would be lost during the charge of the system (Q_{LOST}). But the most important element is actually the **Darcy velocity**. Indeed, if the groundwater is moving due to the hydraulic head distribution, the system is not only controlled by heat conduction. The heat transport caused by advection must thus be taken into account, because this is significantly more important than the heat transfer occurring by conduction only. Unfortunately, the Darcy velocity is one of the most difficult parameters to evaluate in the field, because at least three wells are necessary to define the main direction of the flow and then quantify its magnitude.

According to numerical simulations performed by Giordano and Raymond (2019), with a Darcy velocity of 10^{-6} m s^{-1}, **the heat transport by advection contributes with an additional 10 % to the total Q_{LOST}**. Once Q_{STO} and Q_{LOST} are evaluated, the thermal recovery (η) can be estimated and different layouts of the underground storage volume can be tested to optimize the system and increase the overall effectiveness.

Numerical simulations of the thermal energy storage systems in the underground allow quantifying for the heat lost owing to the groundwater flow. The losses can be reduced by optimizing the volume of storage, which can be either of circular (A) or square shaped (B) (Giordano and Raymond, 2019).

Underground thermal energy storage systems

Underground thermal energy storage (UTES)		Thermal conductivity	Heat capacity	Thermal diffusivity	Storage volume	Average temperature	η	Q_{STO}	Q_{REC}	Q_{LOST}	Coverage
Scenario 2A	%	$W\ m^{-1}\ K^{-1}$	$MJ\ m^{-3}\ K^{-1}$	$m^2\ s^{-1}$	m^3	°C	%	GJ	GJ	GJ	%
Unconsolidated sediments	100	1.70	2.70	0.63	24000	15.2	55%	935	510	425	54%
Scenario 2B											
Bedrock	100	3.00	2.30	1.30	24000	17.5	50%	917	454	463	48%



For UTES, we consider a total energy need of 350 MWh/y, corresponding to a complex of 5 buildings in a small district heating network.

This system would be able to cover 54% in the optimistic (2A) scenario and 48% in the pessimistic one (2B) of the energy demand of the building complex.

Comeau et al. (2020)

INRS

Conclusions – Whapmagoostui-Kuujjuaraapik

Technical results

- For the ground-source heat pump (GSHP), **one 100-m-deep borehole can guarantee 13.2 MWh/y**, which is 25 % more than the worst scenario, where the unconsolidated sediments are expected to be the thickest (around 50 m).
- According these scenarios, **4 and 5 boreholes are anticipated to be necessary to cover the total heating need of the reference building (70 MWh/y)** with a compression heat pump (COP of 3).
- For the underground thermal energy storage (UTES), the best configuration is completely in the saturated unconsolidated sediments, that guarantee **a thermal recovery of 55 %**. The worst-case scenario (in the bedrock) can however allow to recover 50 % of the energy stored during the charge phase.
- The **total heating need of a small district heating system** (5 reference buildings, 350 MWh/y) can be covered at **54 % and 48 % by a UTES system installed in the saturated unconsolidated sediments and in the bedrock**, respectively.

Future activities

- Demonstration plant (GSHP vertical or horizontal, UTES)
- Comparison with other renewable sources (solar, wind, biomass etc…)

INRS

References

Allard M., Lemay M. (2012) Nunavik and Nunatsiavut: From science to policy. An Integrated Regional Impact Study (IRIS) of climate change and modernization, Québec.

Casasso A., Sethi R. (2016) G.POT: A quantitative method for the assessment and mapping of the shallow geothermal potential, Energy, 106: 765-773, doi: 10.1016/j.energy.2016.03.091.

Comeau F-A., Giordano N., Raymond J. (2020) Shallow geothermal potential of the northern community of Whapmagoostui-Kuujjuaraapik. Institut national de la recherche scientifique, Centre Eau Terre Environnement, Québec, R1927.

Fortier R., Allard M., Lemieux J-M., Therrien R., Molson J., Fortier D. (2011) Cartographie des dépôts quaternaires des villages nordiques de Whapmagoostui-Kuujjuarapik, Umiujaq, Salluit et Kuujjuaq. Rapport de synthèse de la Phase 1 Stratégie de déploiement du réseau Immatsiak, Québec, GM65971.

Giordano N., Raymond J. (2019) Alternative and sustainable heat production for drinking water needs in Nunavik (Canada): borehole thermal energy storage to reduce fossil fuel dependency in off-grid communities. Applied Energy, 252: 113463, doi: 10.1016/j.apenergy.2019.113463.

Giordano N., Riggi L., Della Valentina S., Casasso A., Mandrone G., Raymond J. (2019) Efficiency evaluation of borehole heat exchangers in Nunavik, Québec, Canada. Proceedings of 25th IIR International Congress of Refrigeration, August 24-30, Montréal, Canada, doi: 10.18462/iir.icr.2019.547.

Giordano N., Piché P., Gibout S., Haillot D., Arrabie C., Lamalice A., Rousse D.R., Py X., Raymond J. (2020) Daily and seasonal heat storage for greenhouse food production in Nunavik (Canadian Arctic). Proceedings World Geothermal Congress, April 26 - May 2, Reykjavik, Iceland, 9 pp.

Gunawan E., Giordano N., Jensson P., Newson J., Raymond J. (2020) Alternative heating systems for northern remote communities: Techno-economic analysis of ground-source heat pumps in Kuujjuaq, Nunavik, Canada. Renewable Energy, 147(1): 1540-1553, doi: 10.1016/j.renene.2019.09.039.

Lemieux J-M., Fortier R., Talbot-Poulin M-C., Molson J., Therrien R., Ouellet M., et al. (2016) Groundwater occurrence in cold environments: examples from Nunavik, Canada. Hydrogeology Journal, 24: 1497–513, doi:10.1007/s10040-016-1411-1.

Miranda M., Giordano N., Raymond J., Kanzari I., Dezayes C. (2019) Past and present climate variations recorded by subsurface temperature: an example from northern Québec (Canada) and its geothermal implications. International Meeting on Paleoclimate, June 17-19, Coimbra, Portugal.

Piché P., Haillot D., Gibout S., Arrabie C., Lamontagne M.A., Glbert V., Bédécarrats J-P. (2020) Design, construction and analysis of a thermal energy storage system adapted to greenhouse cultivation in isolated northern communities. Solar Energy (in press).

INRS

EGU General Assembly 2020

Online | 4–8 May 2020

Award Roland Schlich Early Career Scientist's Travel Support

Funding

Institut nordique du Québec
Together for the North

LabEx DRIIHM

OHMI Nunavik

Contact

Nicolò Giordano
Pot-doc Research Fellow
Institut national de la recherche scientifique
Centre Eau Terre Environnement
490, rue de la Couronne
Québec (Québec) G1K 9A9 CANADA

Tel. 418-654-2652
nicolo.giordano@ete.inrs.ca
Skype: nicolo.giordano@tiscali.it

Google Scholar
https://scholar.google.it/citations?hl=it&user=OQo1SO8AAAAJ&view_op=list_works&sortby=pubdate

CEN Member
http://www.cen.ulaval.ca/membre.php?id=6193446&cat=22&membre=ngiordano

Politecnico di Torino

Université Laval

Université de Pau et des Pays de l'Adour

Centre d'études nordiques

Dipartimento di Scienze della Terra – Università degli Studi di Torino

INRS Institut national de la recherche scientifique

Háskólinn í Reykjavík – Reykjavik University

ÉTS – Le génie pour l'industrie