

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

*Original*

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

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**POLITECNICO  
DI TORINO**

## Problematic

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



*Kuujjuaq*

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



*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

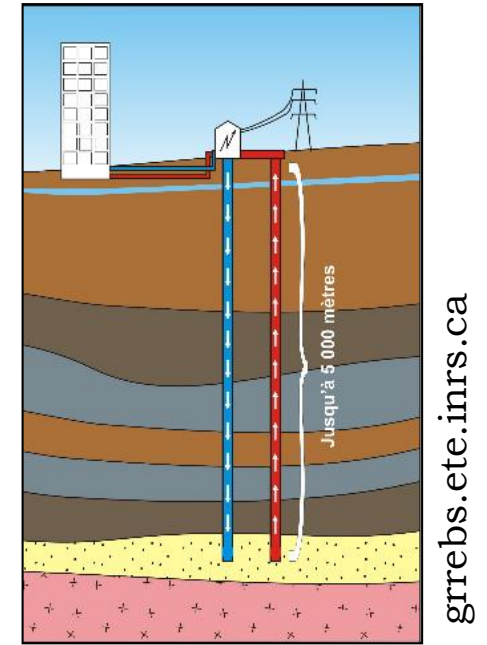
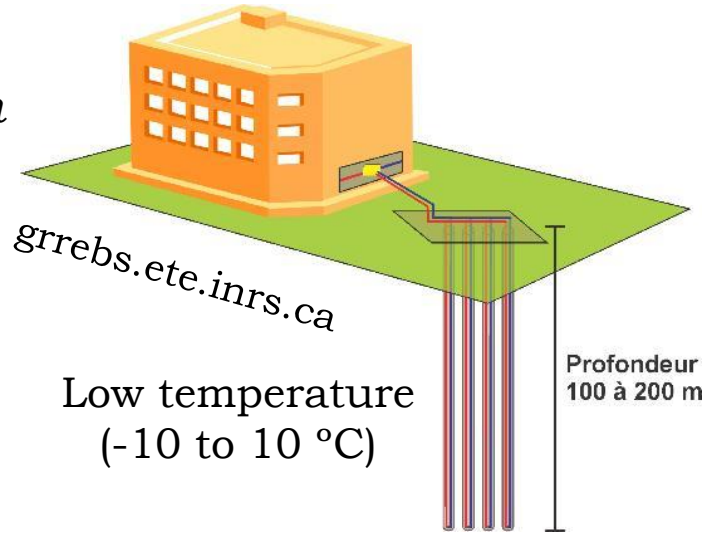
# General objective

## Is geothermal energy a viable alternative for Nunavik?

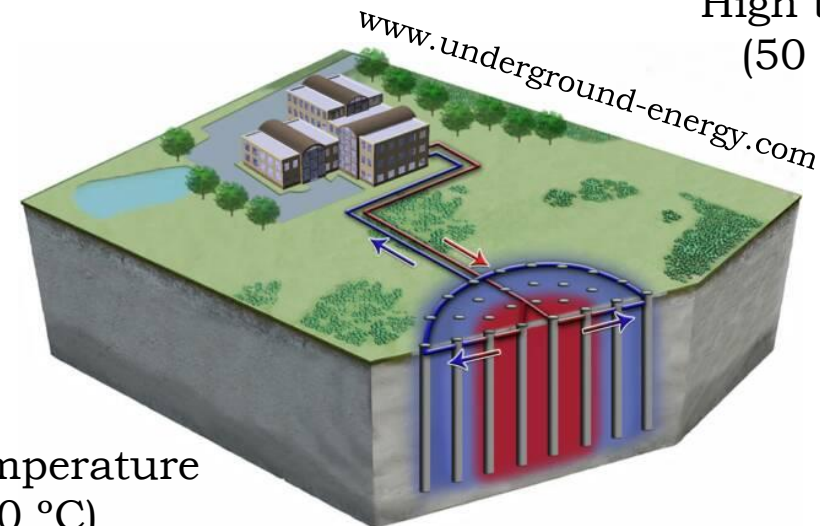
*Alternatives to fossil fuels for heat production*

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

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



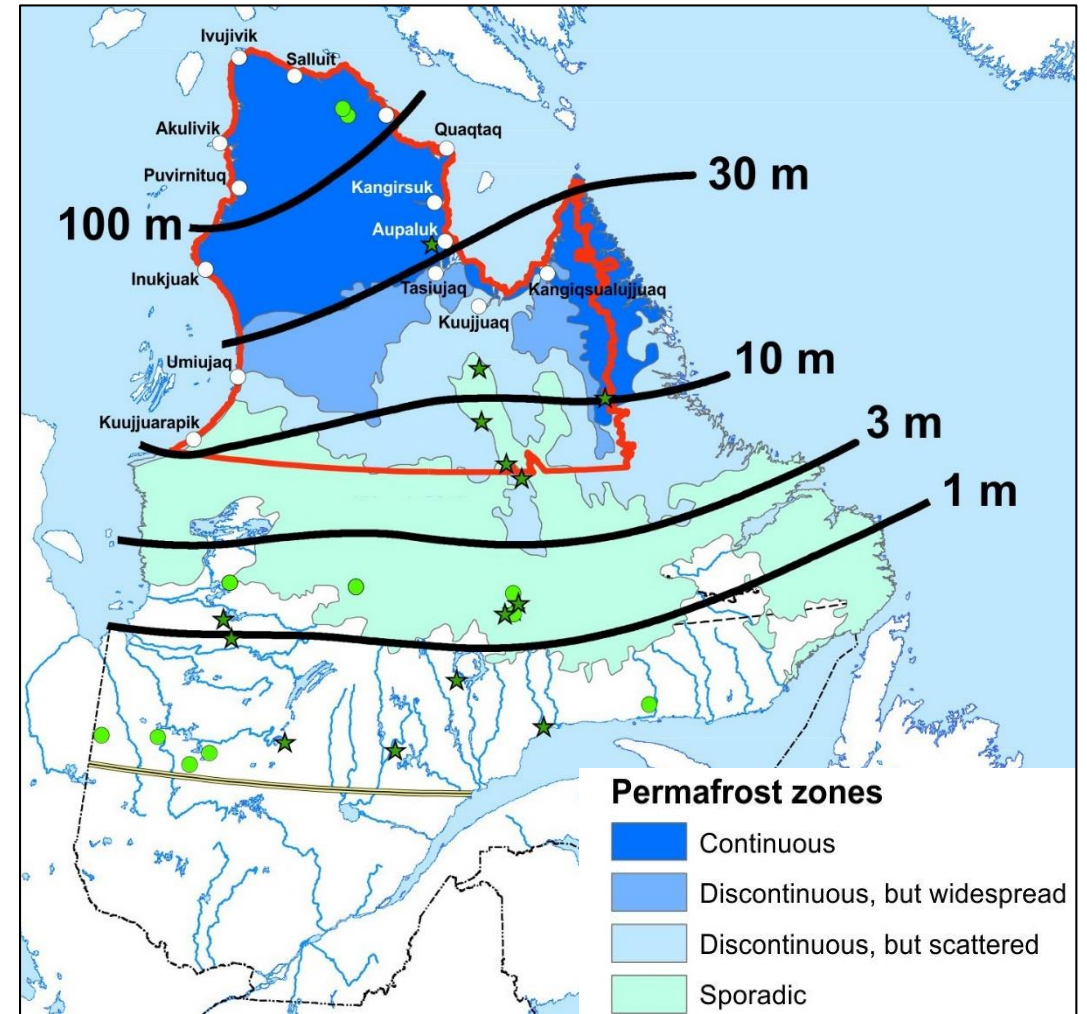
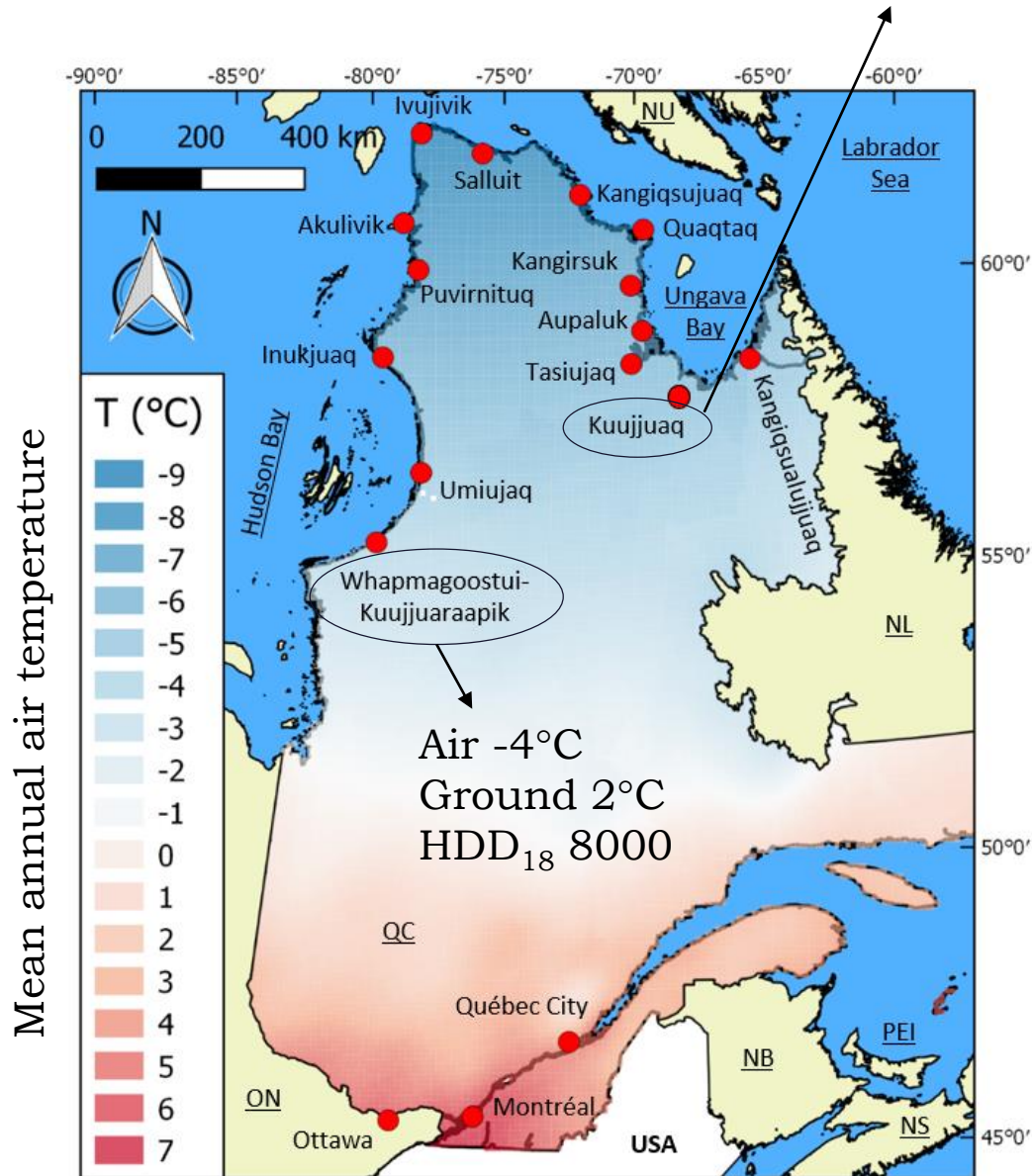
High temperature  
(50 to 100 °C)



Moderate temperature  
(10 to 50 °C)

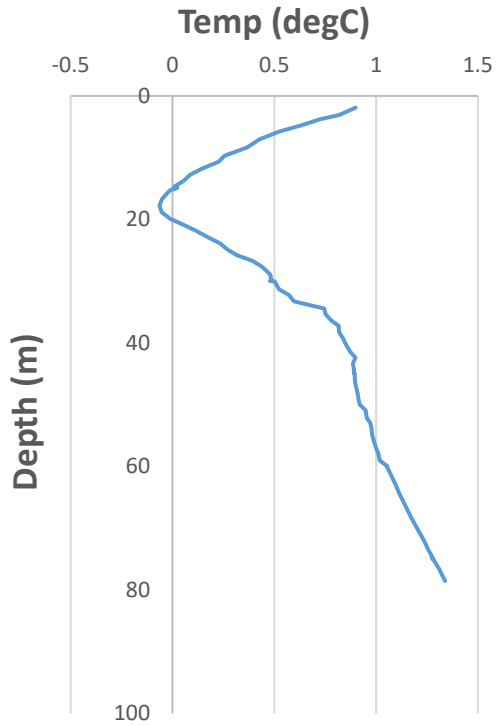
# Geographical setting

Mean annual air temperature  $-5.8^{\circ}\text{C}$   
 Ground temperature  $1^{\circ}\text{C}$   
 Heating degree days  $\text{HDD}_{18}$  8500

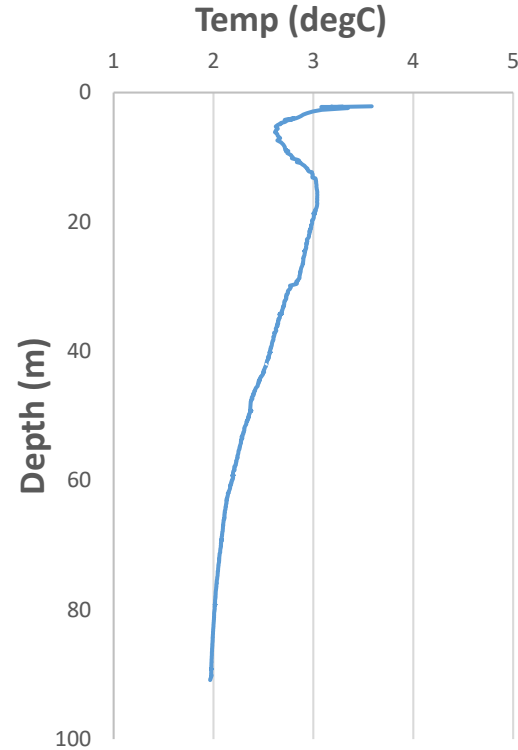


Allard and Lemay (2012)  
 Lemieux et al. (2016)

# Temperature at depth

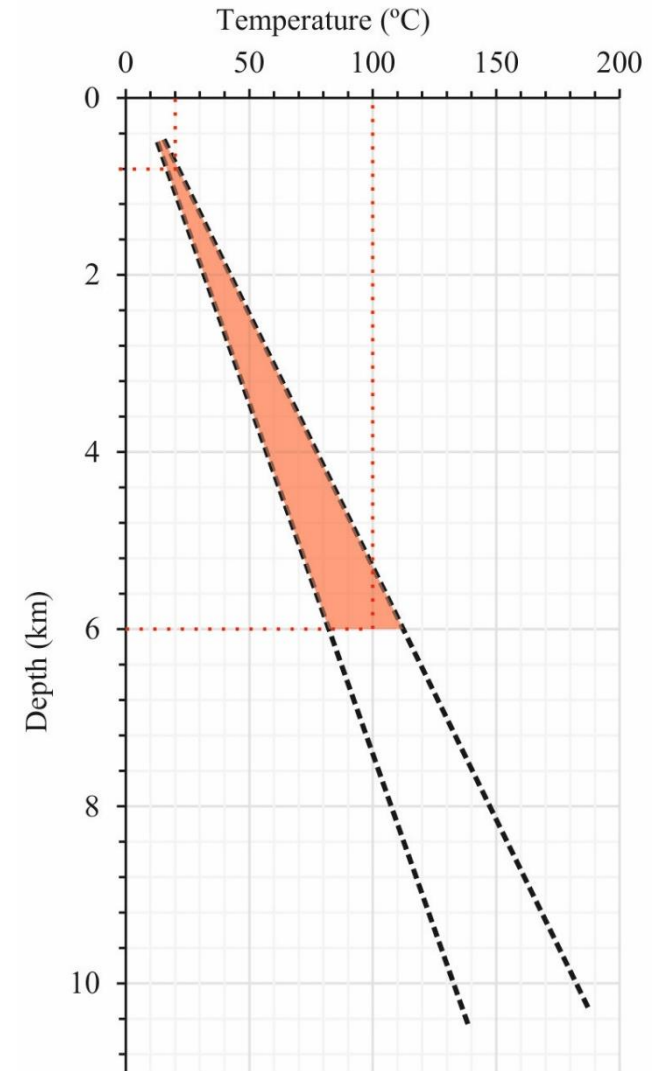


**Kuujuuaq**



**Whapmagoostui-Kuujuarapik**

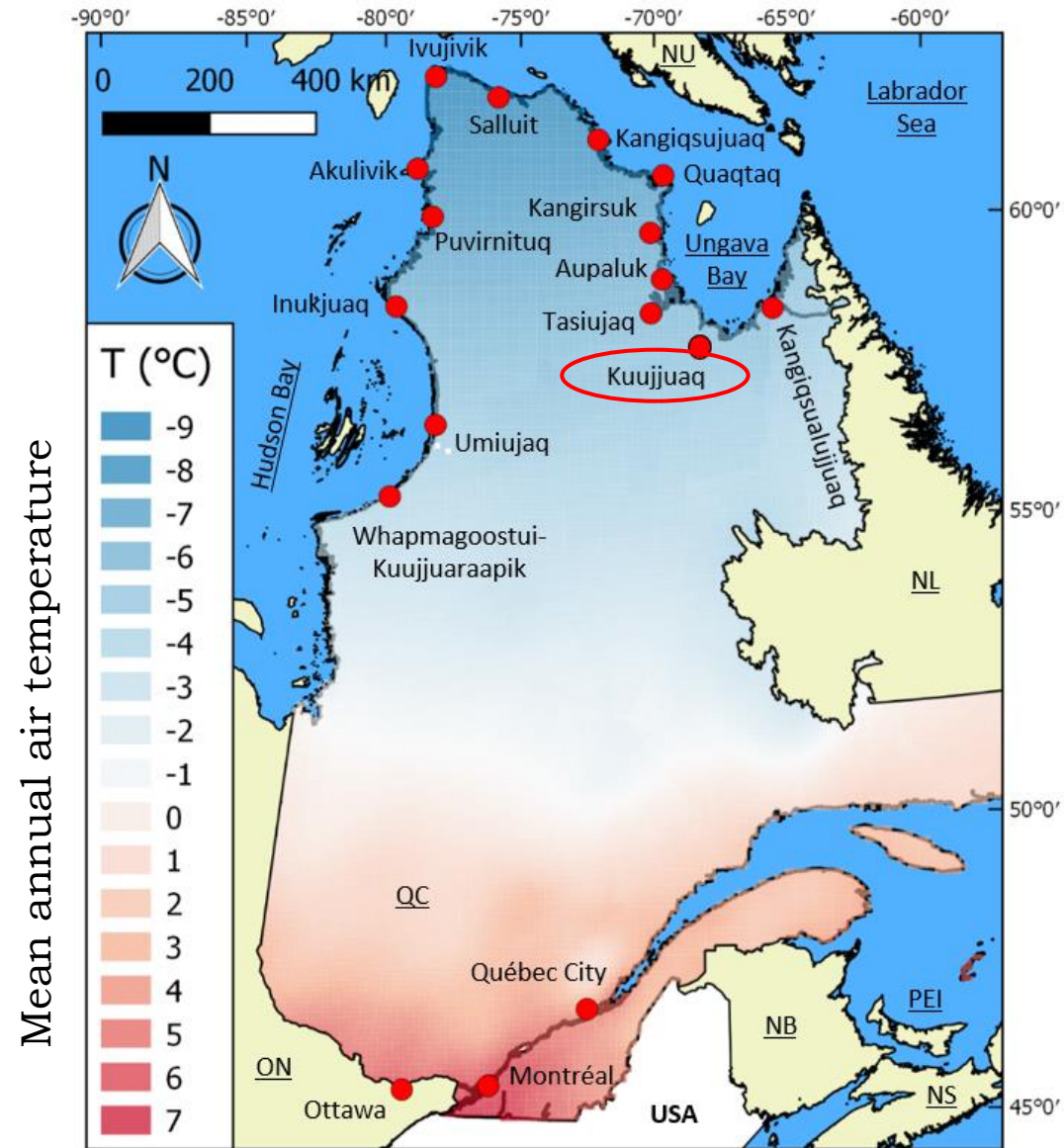
Geothermal gradient  $\sim 15$  °C/km  
Surface heat flow  $\sim 40$  mW/m<sup>2</sup>



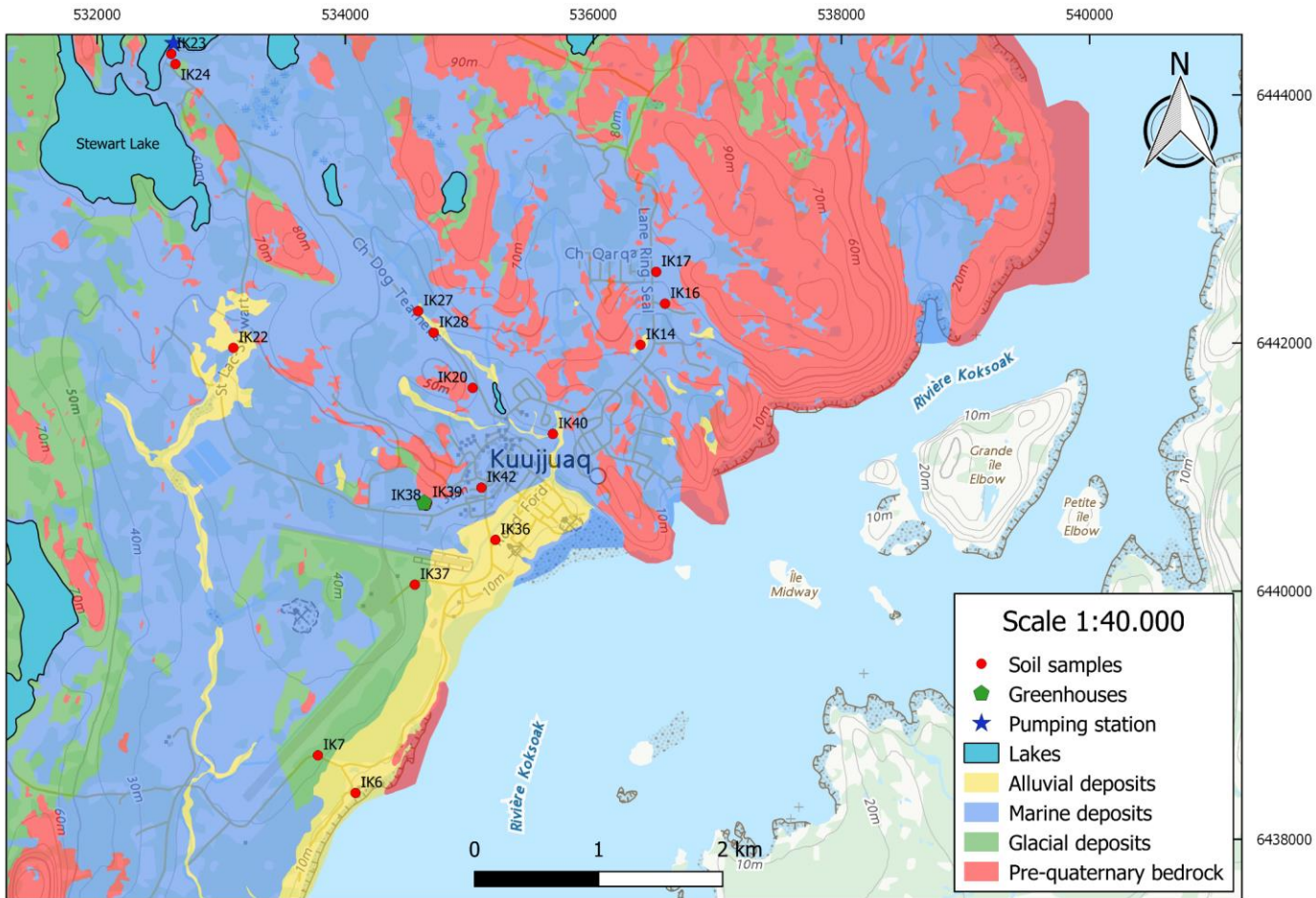
Inferred  
temperature  
at depth

Miranda et al. (2019)

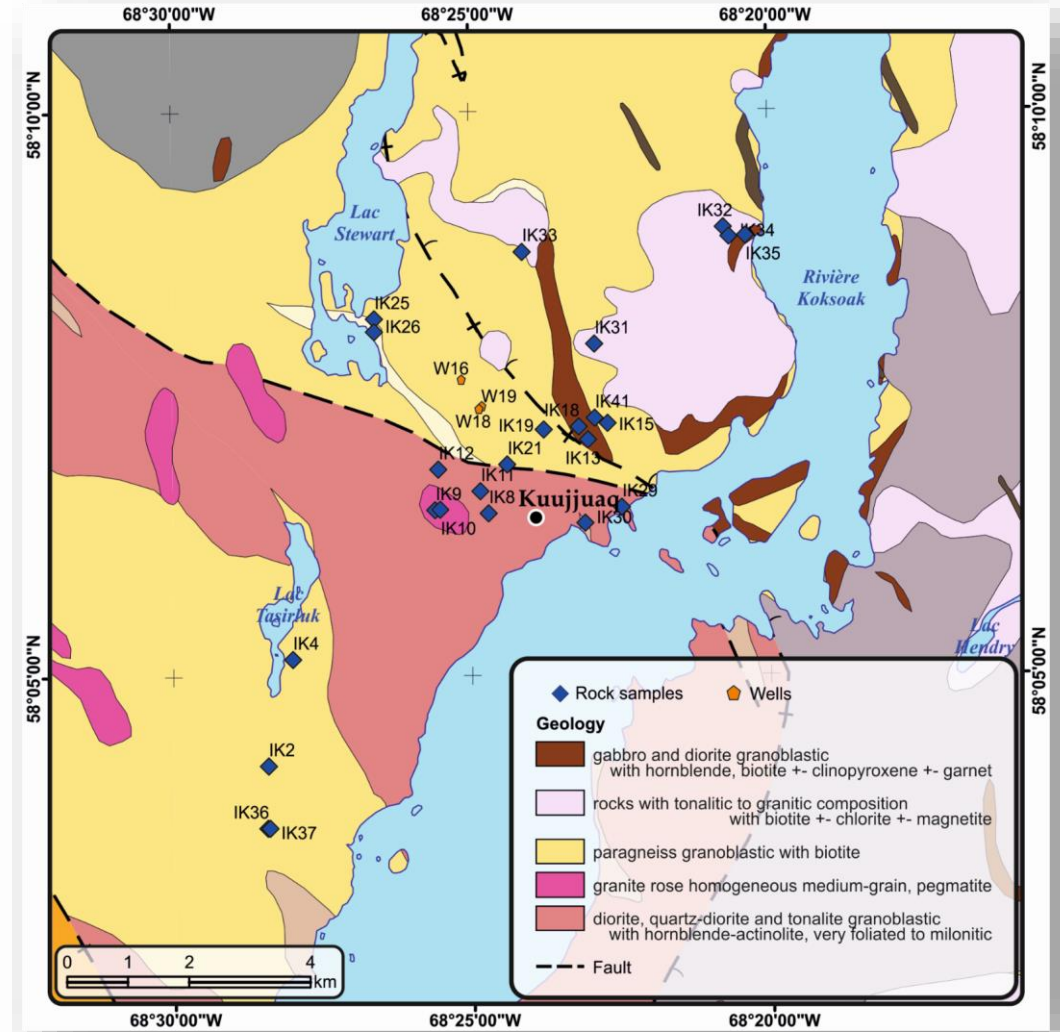
# Kuujuuaq



# Geological setting



Quaternary  
sediments

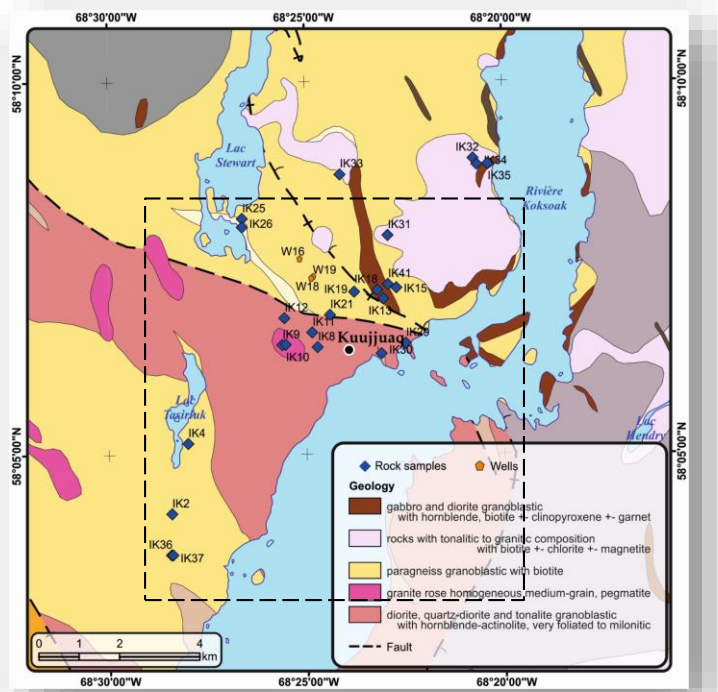


Bedrock

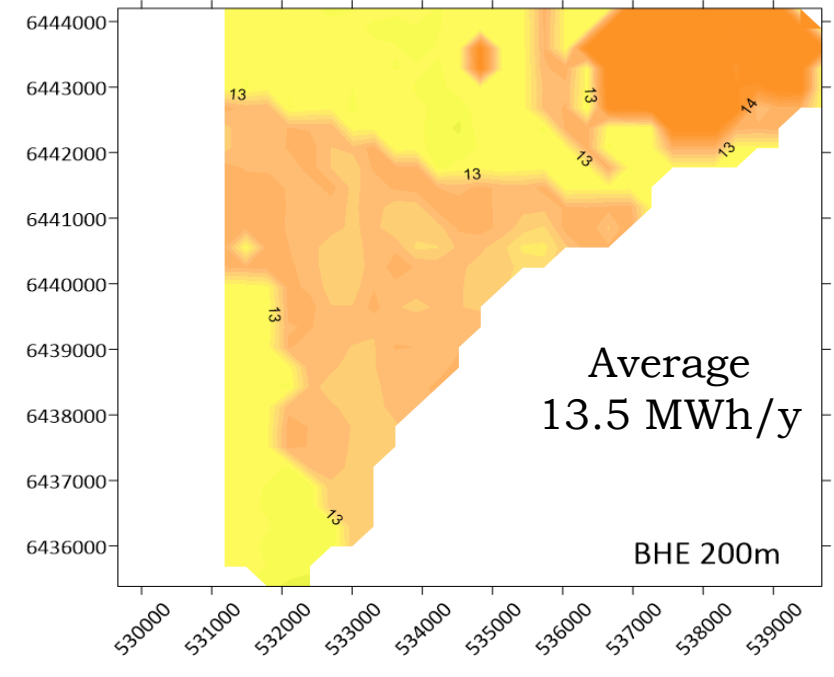
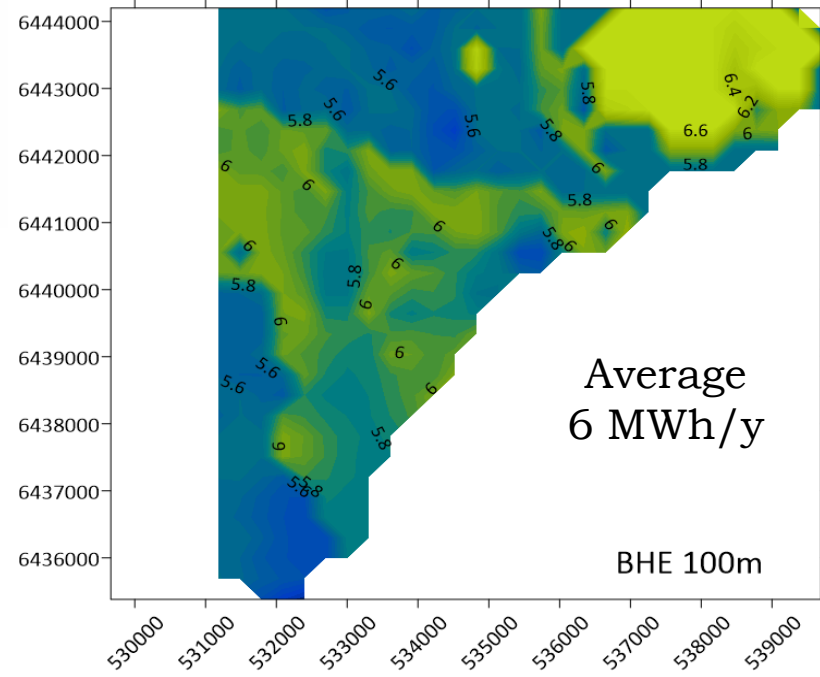
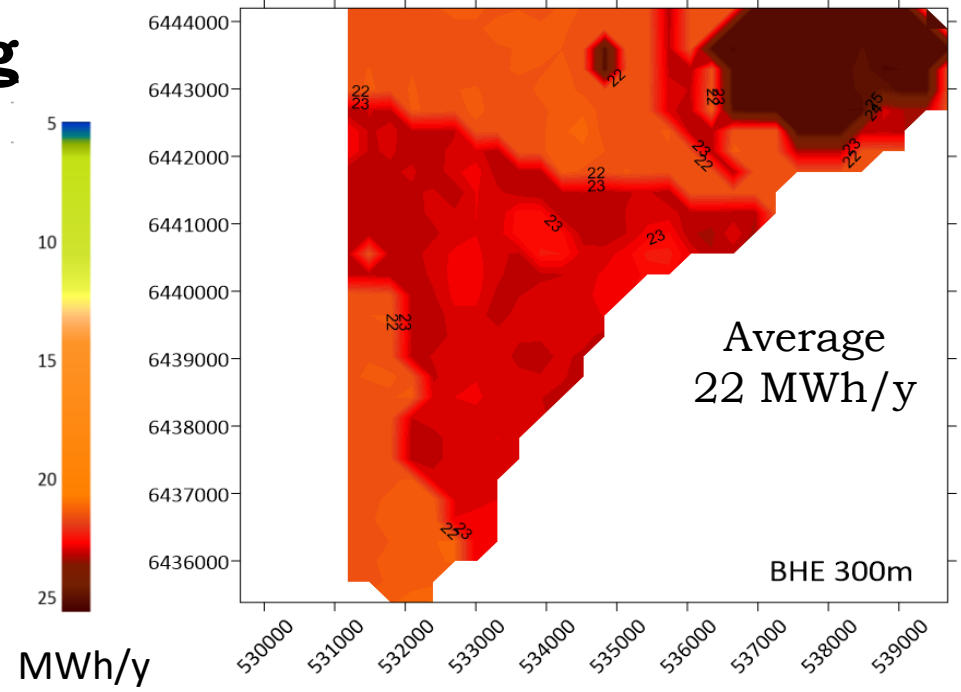
# Ground-source heat pump systems

# Ground-source heat pump potential mapping

G.POT Approach (Casasso and Sethi, 2016)



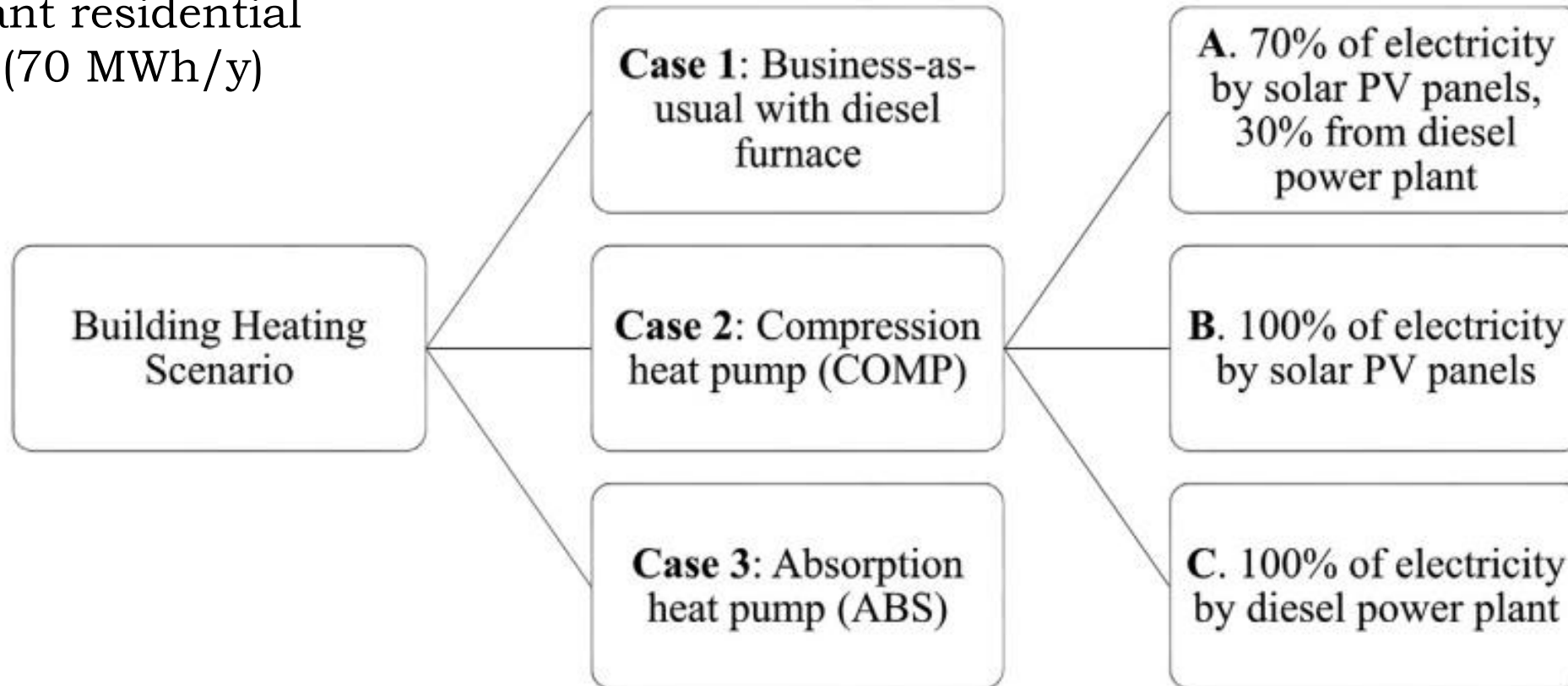
**Thermal properties and ground temperature** are key-factors to define shallow geothermal potential



Gunawan et al. (2020)

# Life-cycle cost analysis of GSHP compared to diesel

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

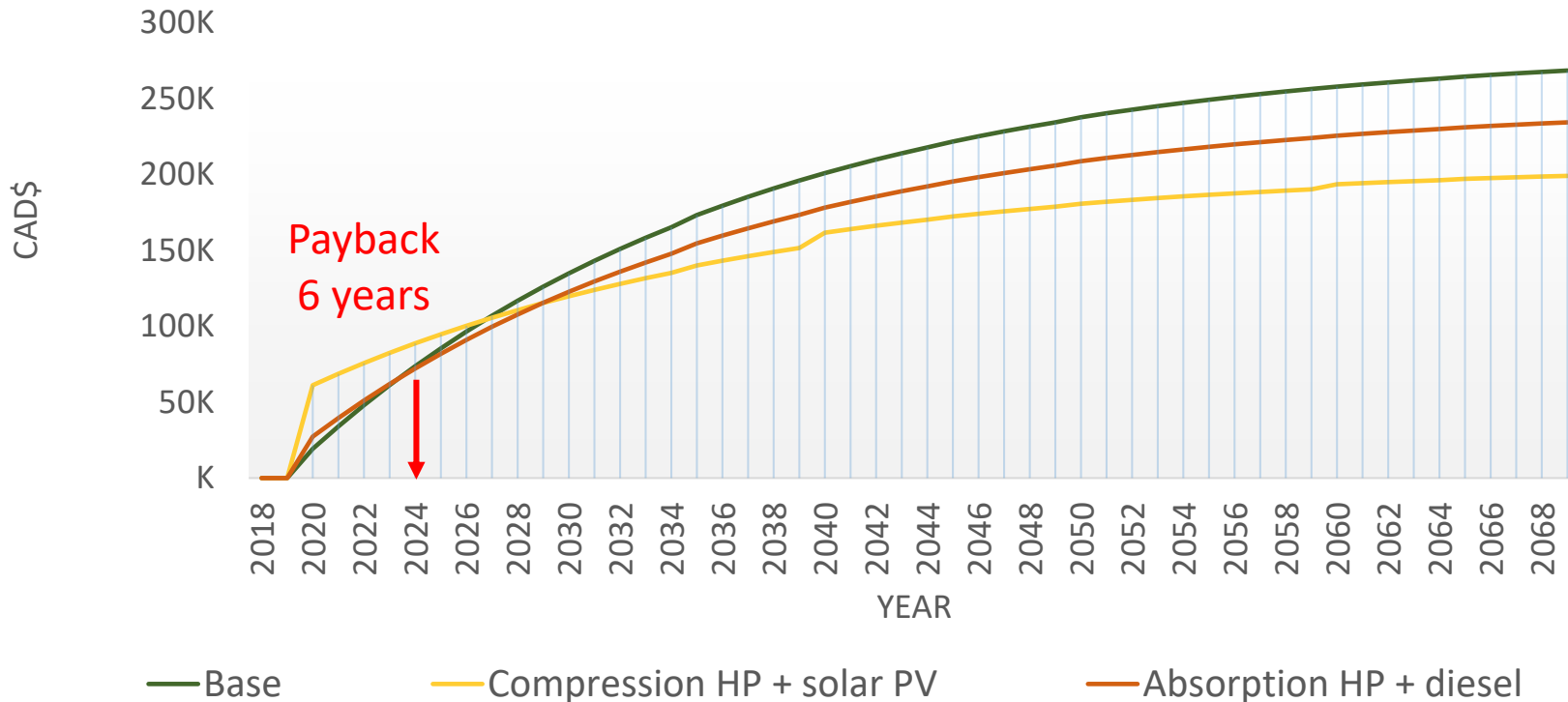


**Fig. 3.** Building heating scenarios.

Gunawan et al. (2020)

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

Accumulated NPV for Home-Owners



Government's NPV = \$8,231.76  
Government's NPV = \$9,026.42  
Government's NPV = \$40,891.82

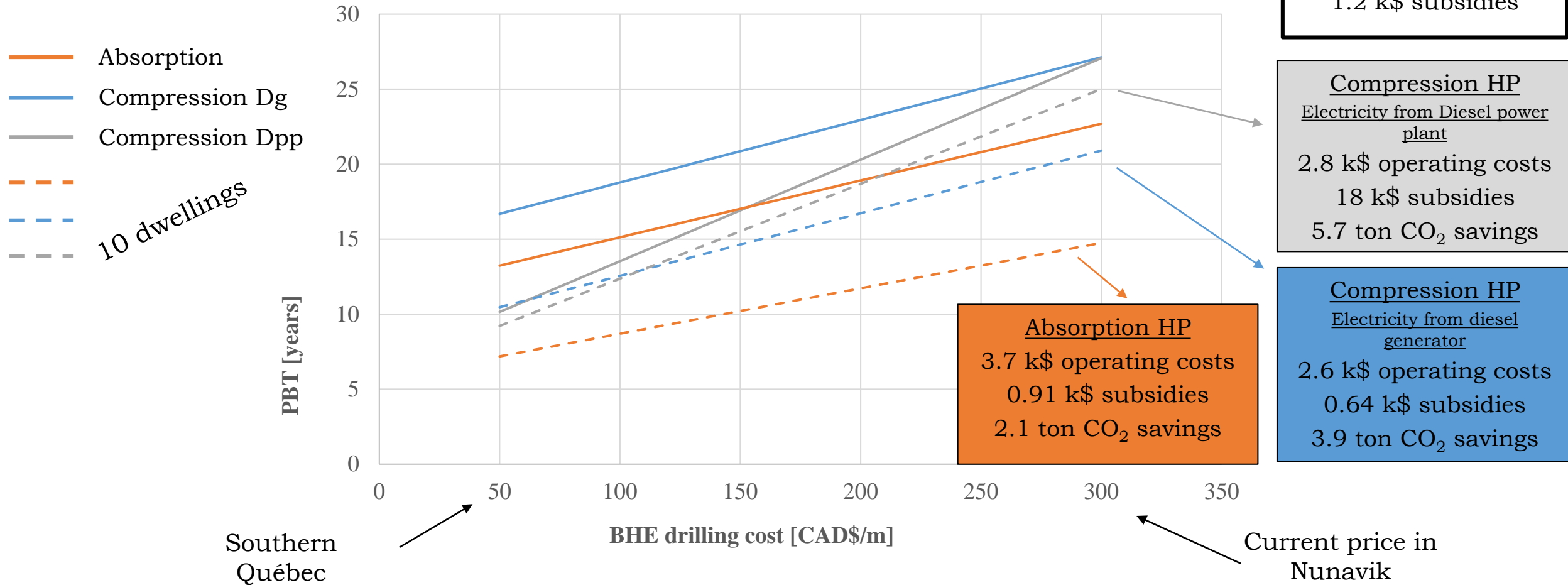
## Government scheme:

- 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<sub>2</sub> emission

Gunawan et al. (2020)

# Payback time vs. Drilling cost

Home-owner pay-back time (PBT) of the three scenarios (single and 10 dwellings)



Southern Québec

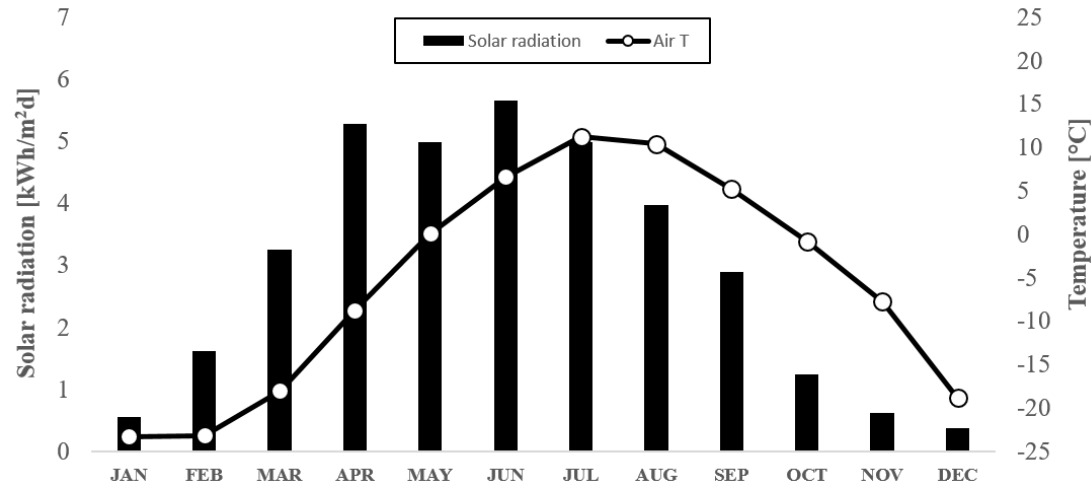
Current price in Nunavik

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

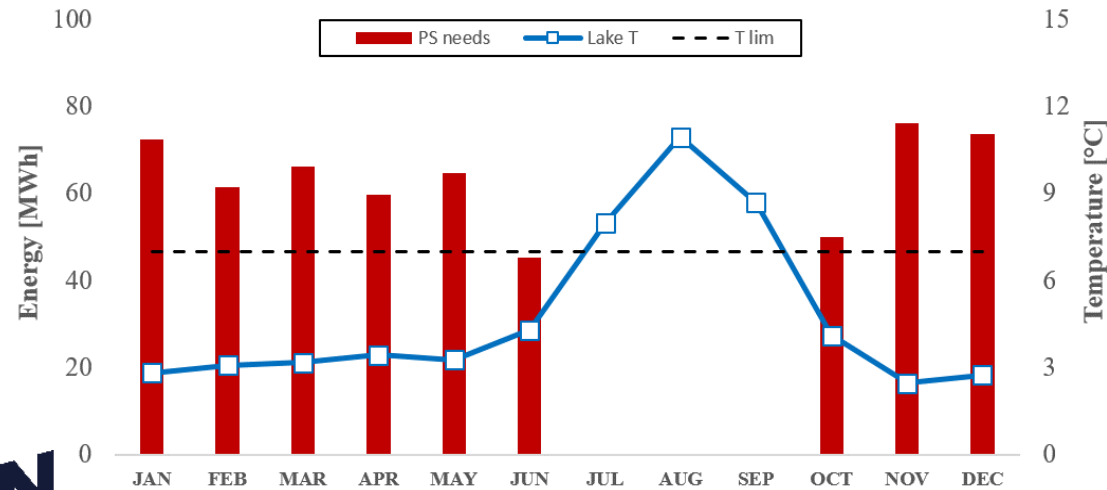
Giordano et al. (2019)

# Underground thermal energy storage systems

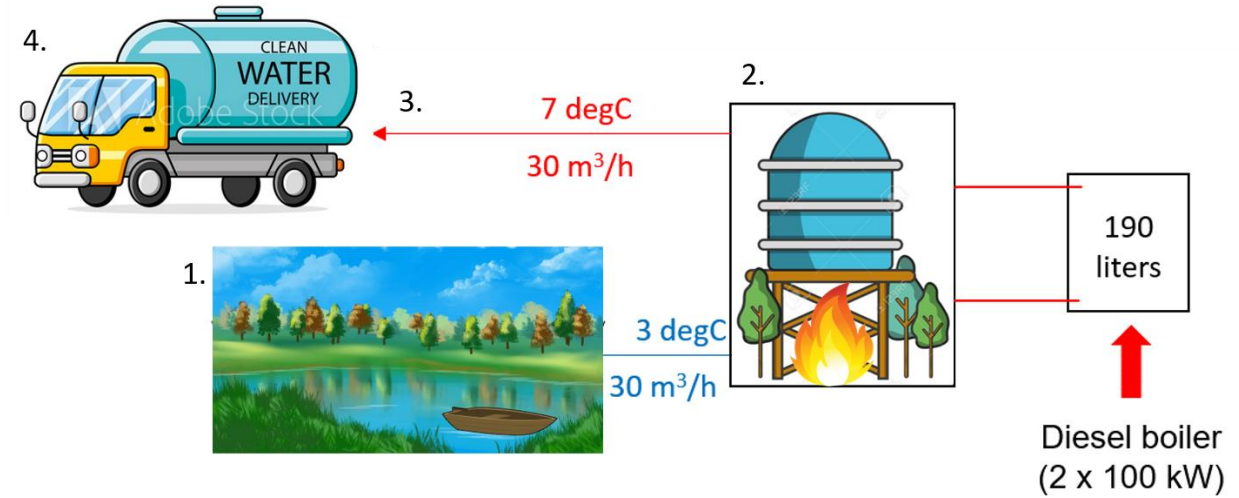
# Pumping station of the drinking water network



Solar radiation and air temperature



Pumping station energy needs and lake T



Energy consumption 570 MWh/y

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

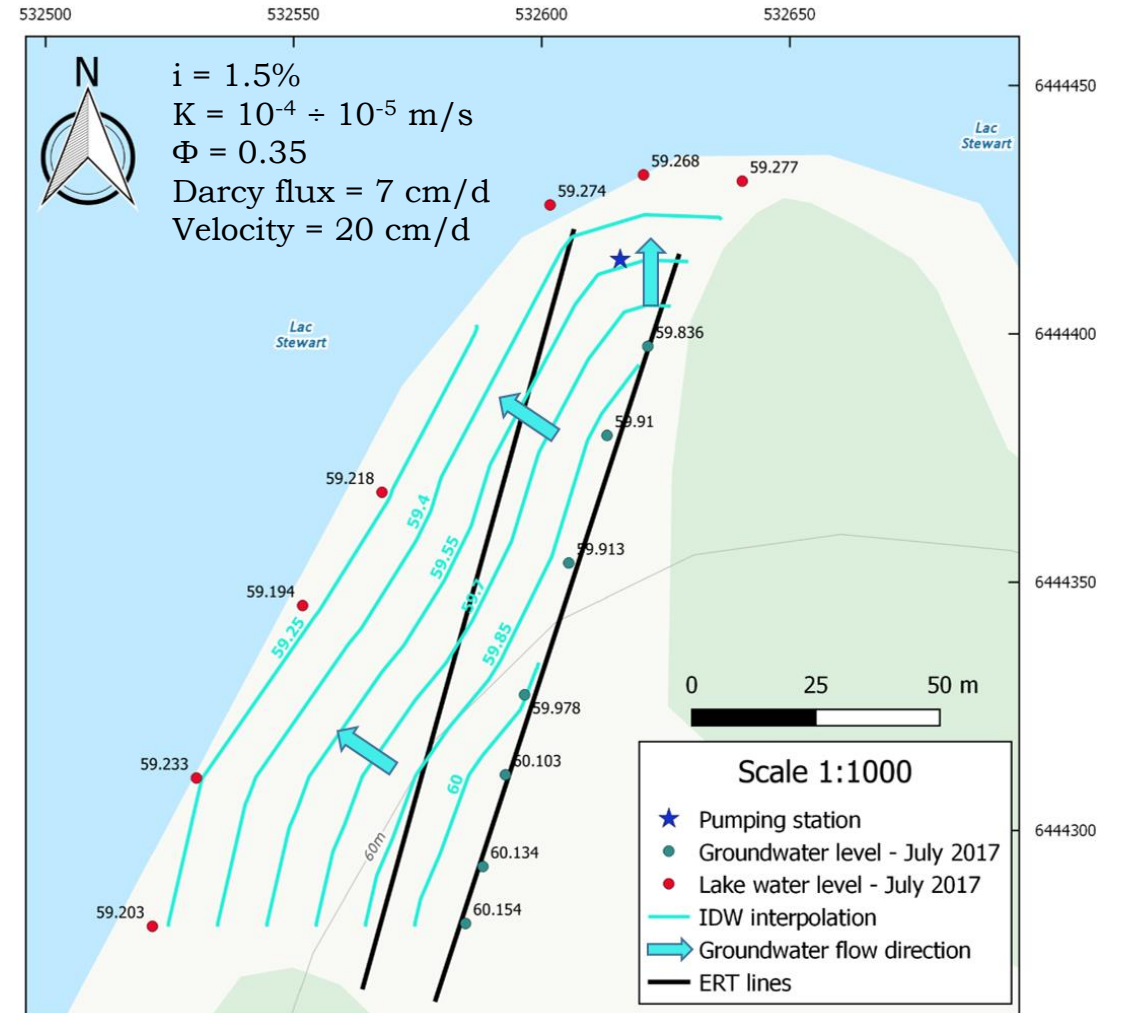
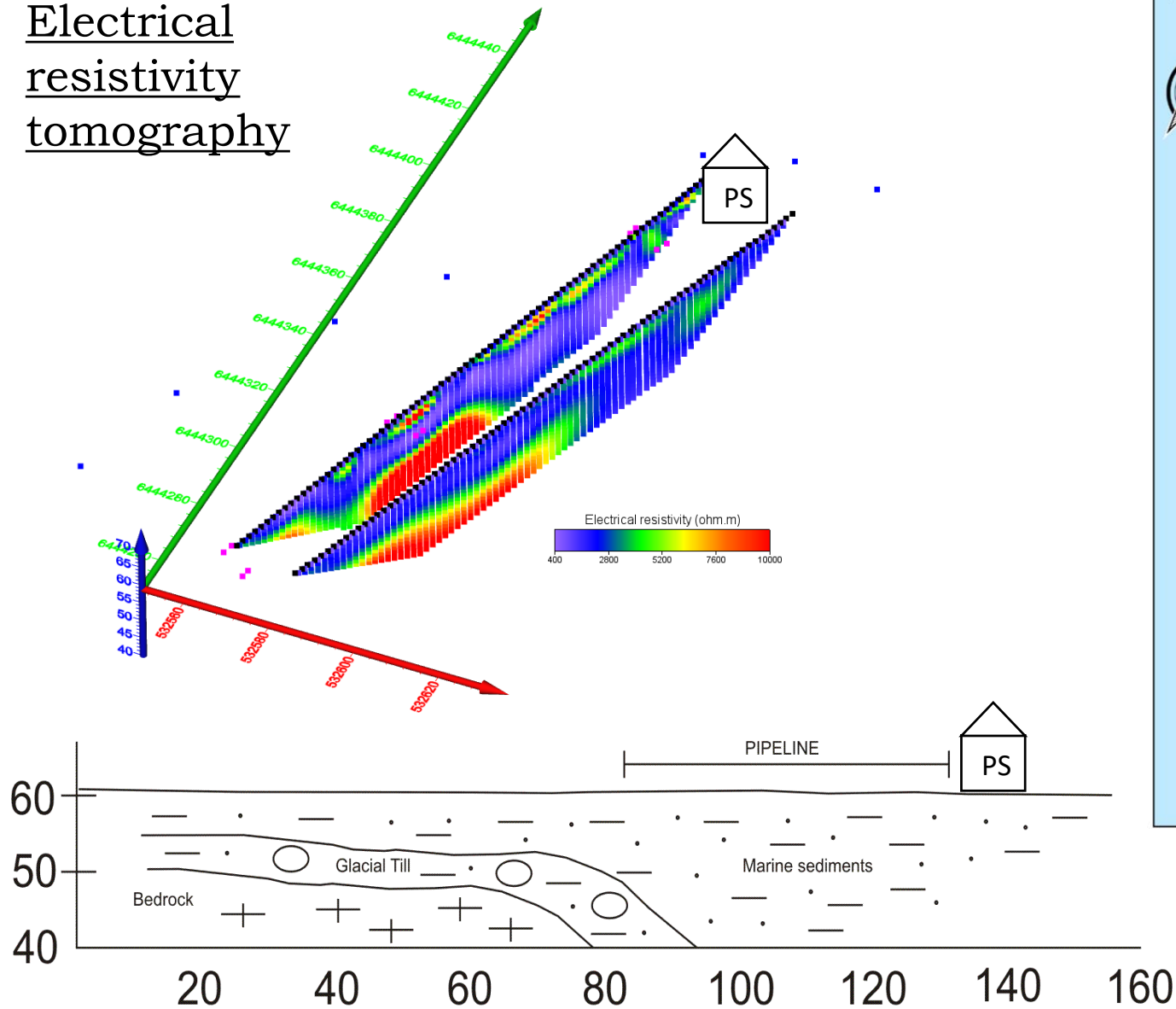
## Drinking water network in Kuujjuaq:

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

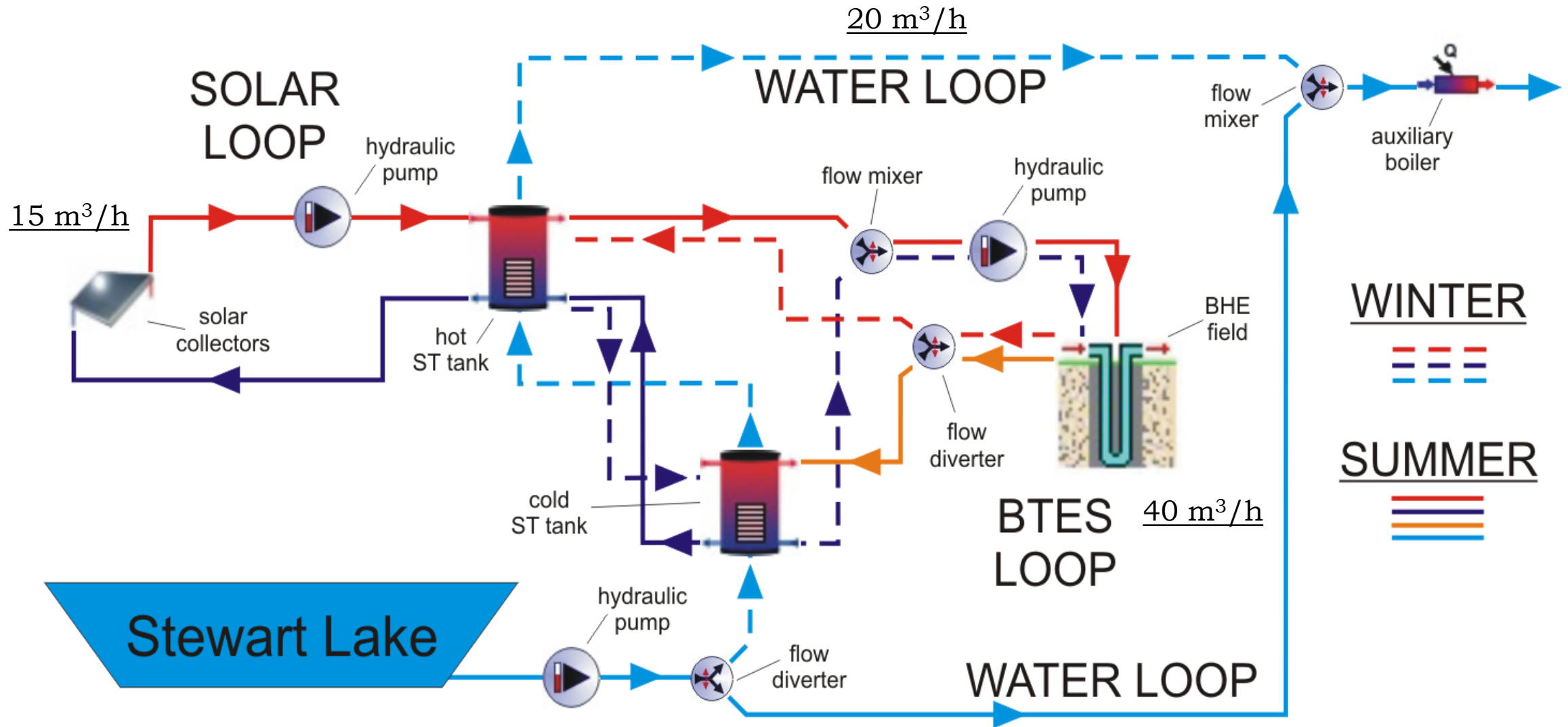
# Geological and hydrogeological characterization

## Local groundwater

### Electrical resistivity tomography

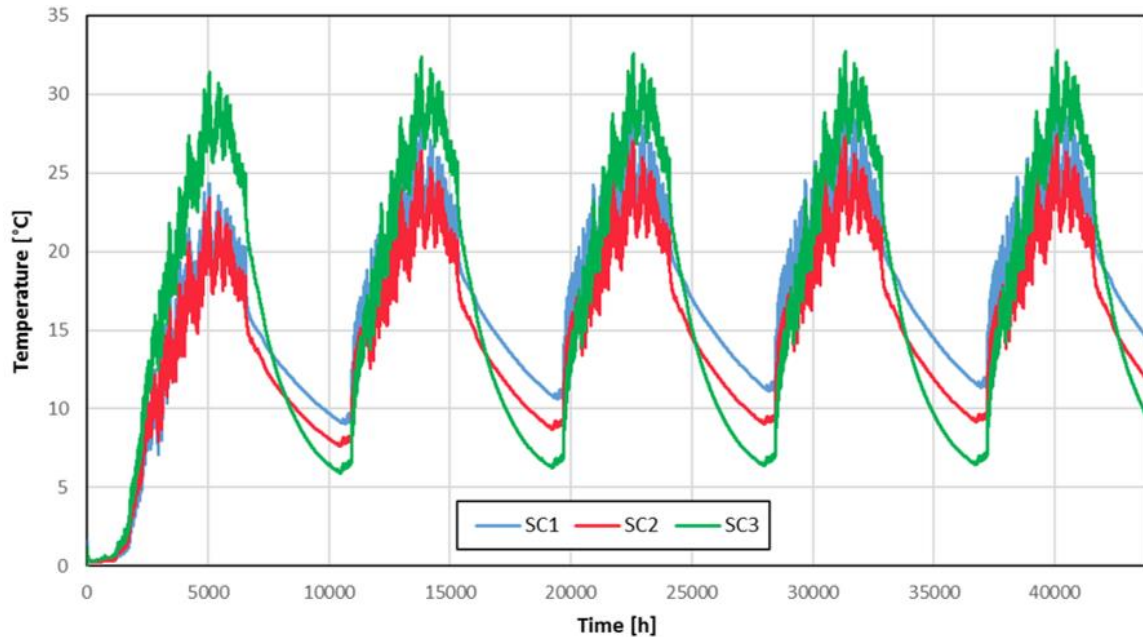


# UTES system design

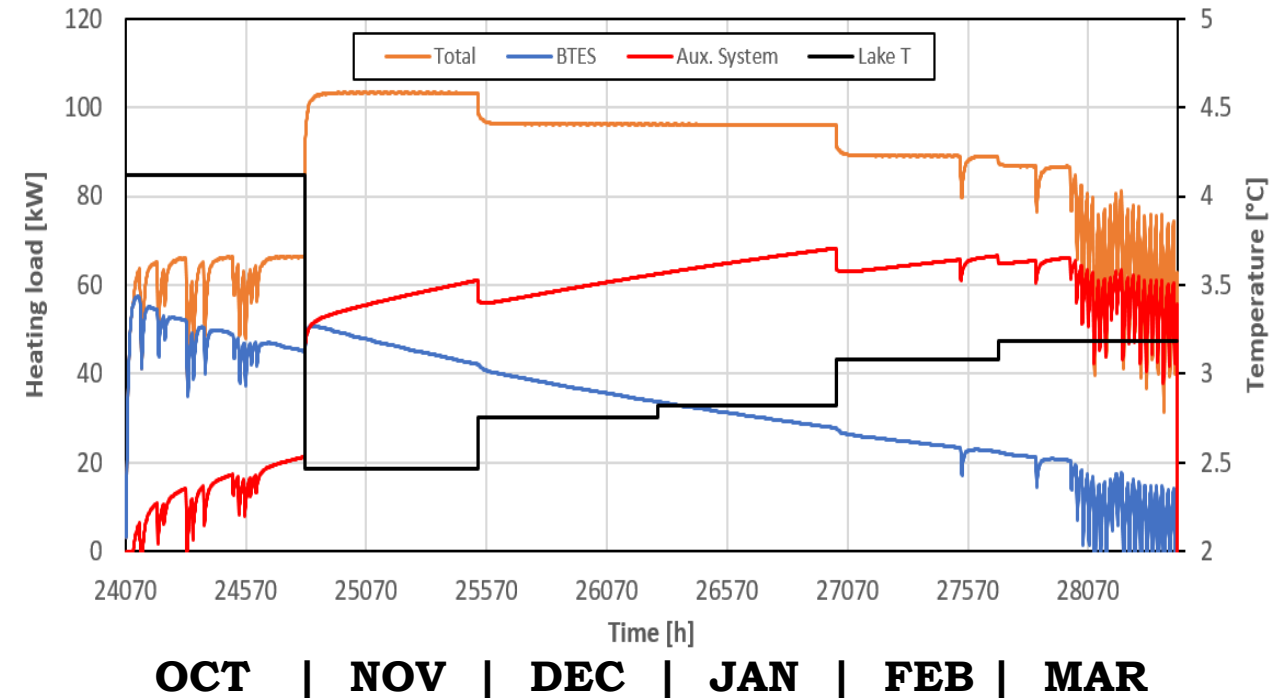


# Simulations results

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



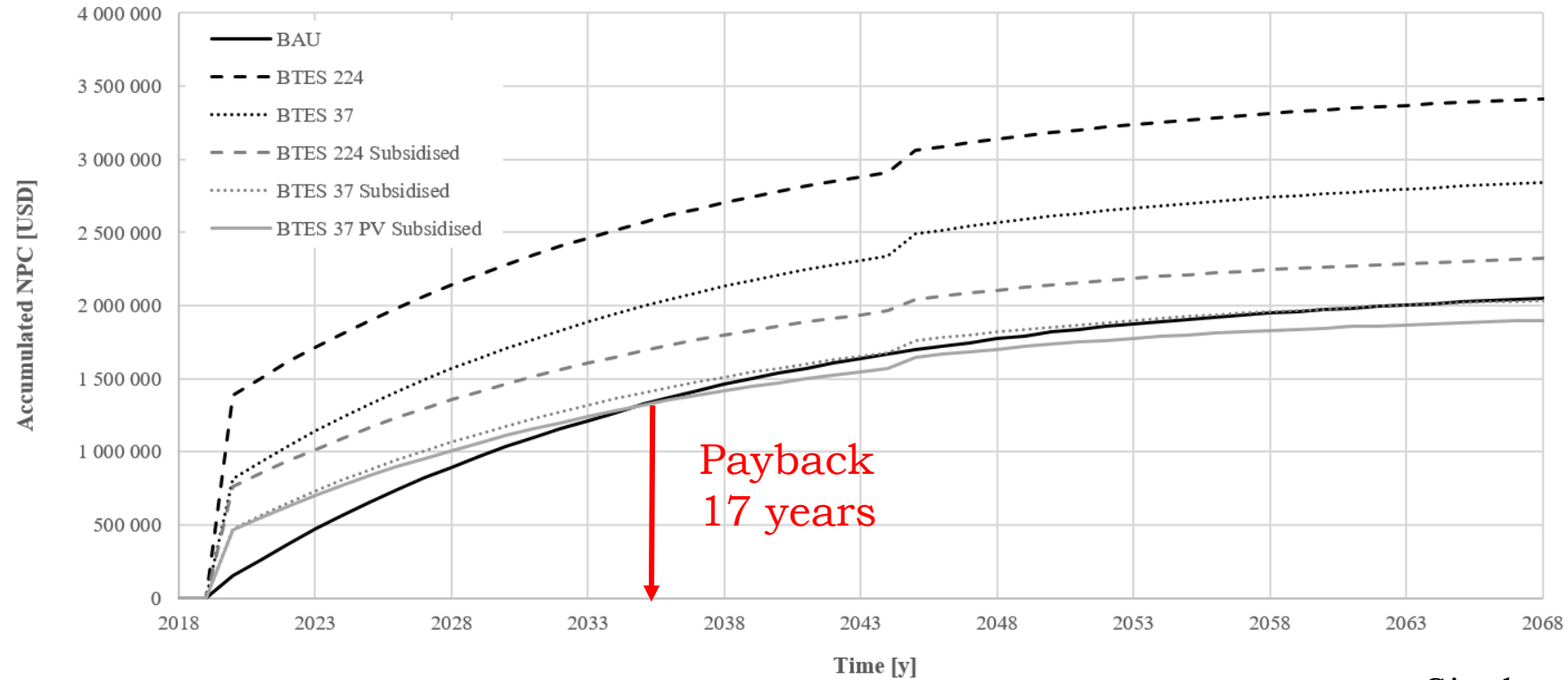
3<sup>rd</sup> year discharge SC2



- 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

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

BAU = business as usual (diesel)

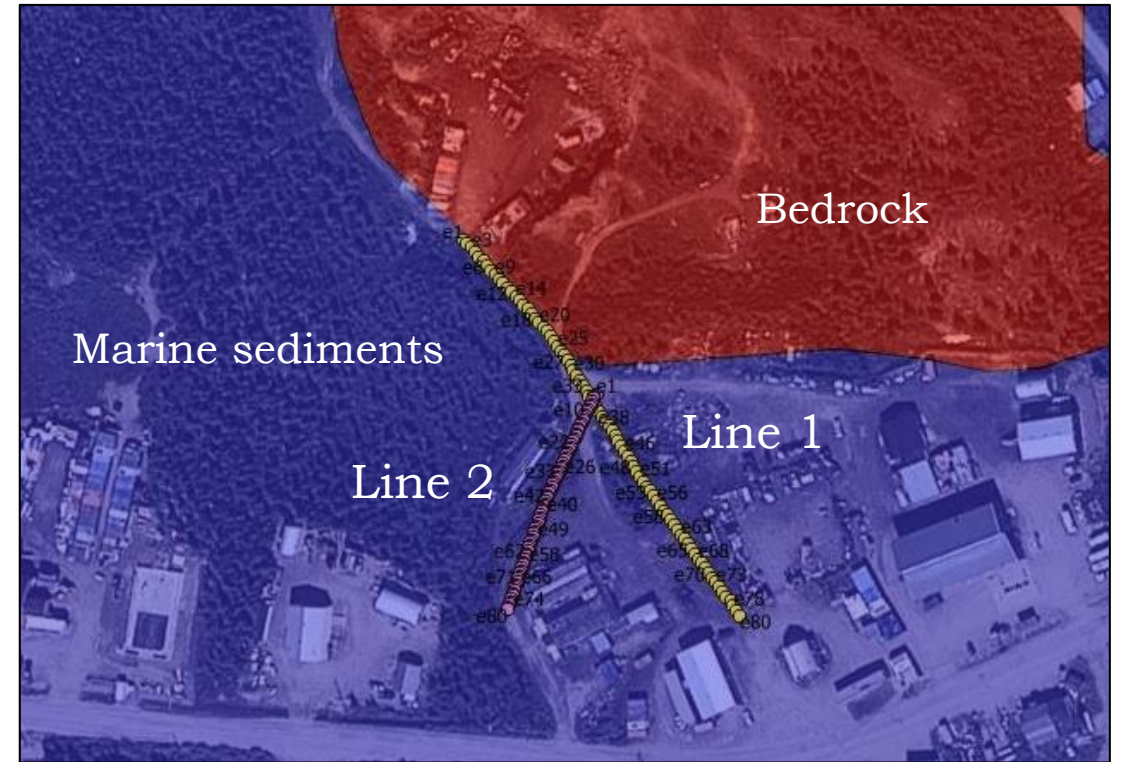


Giordano and Raymond (2019)

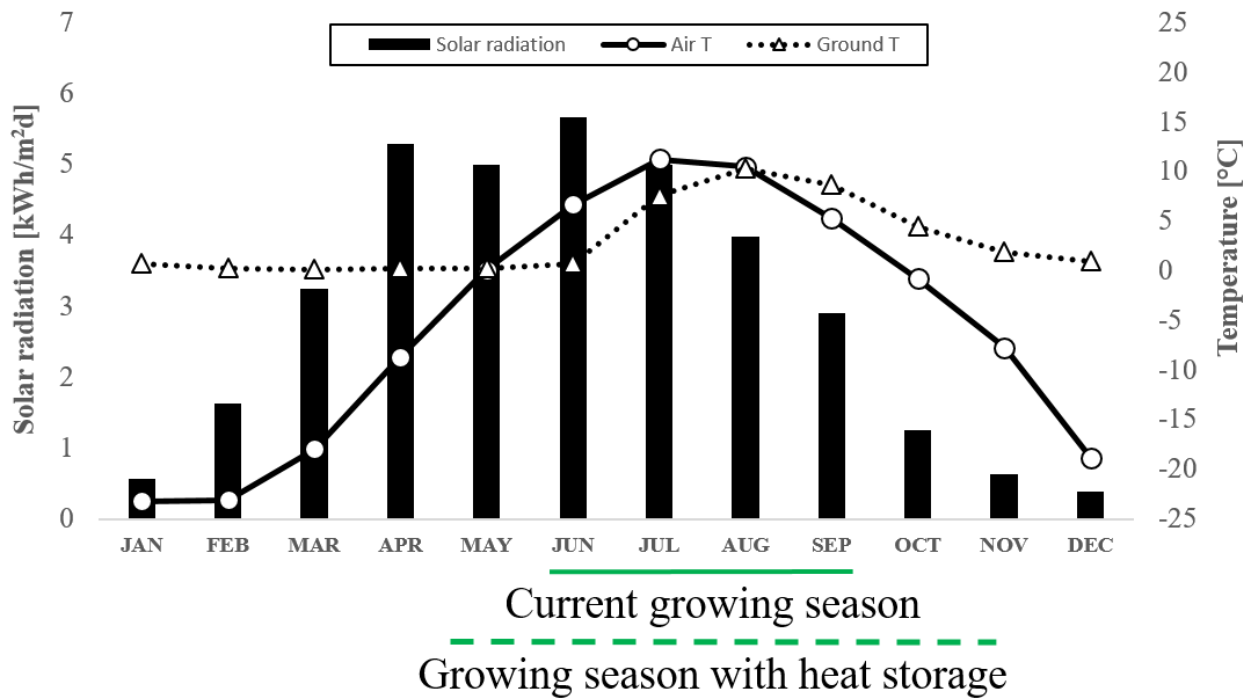
# Coupled daily and seasonal energy storage for greenhouses



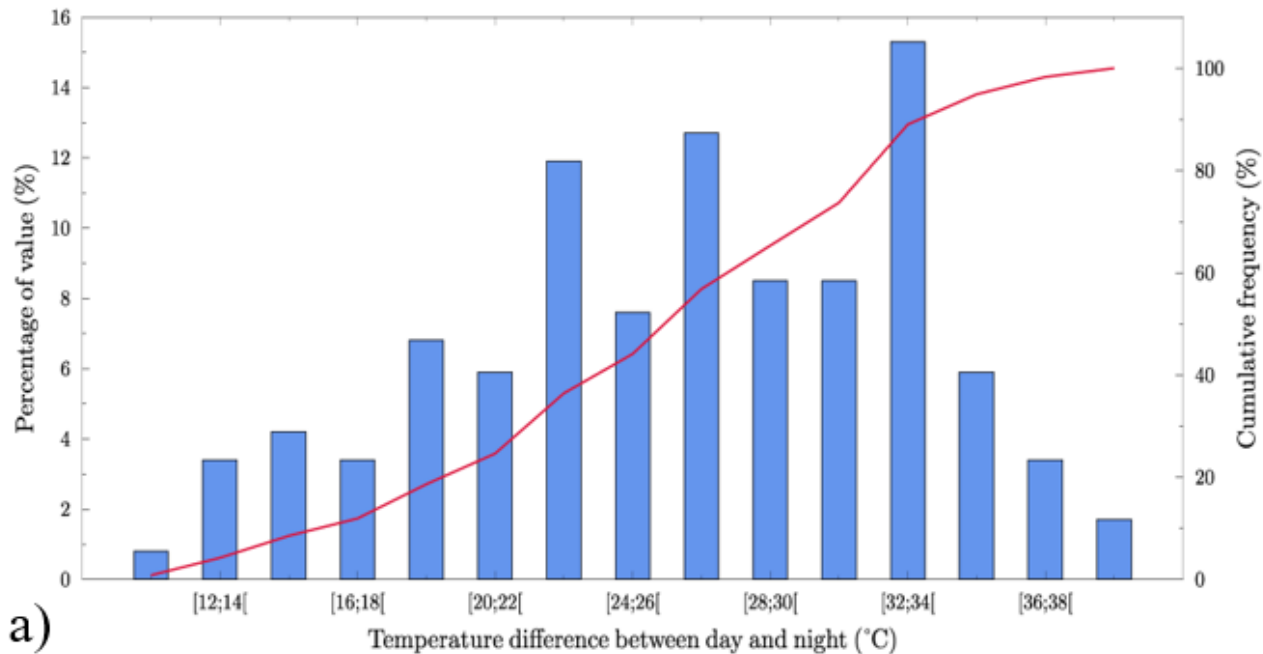
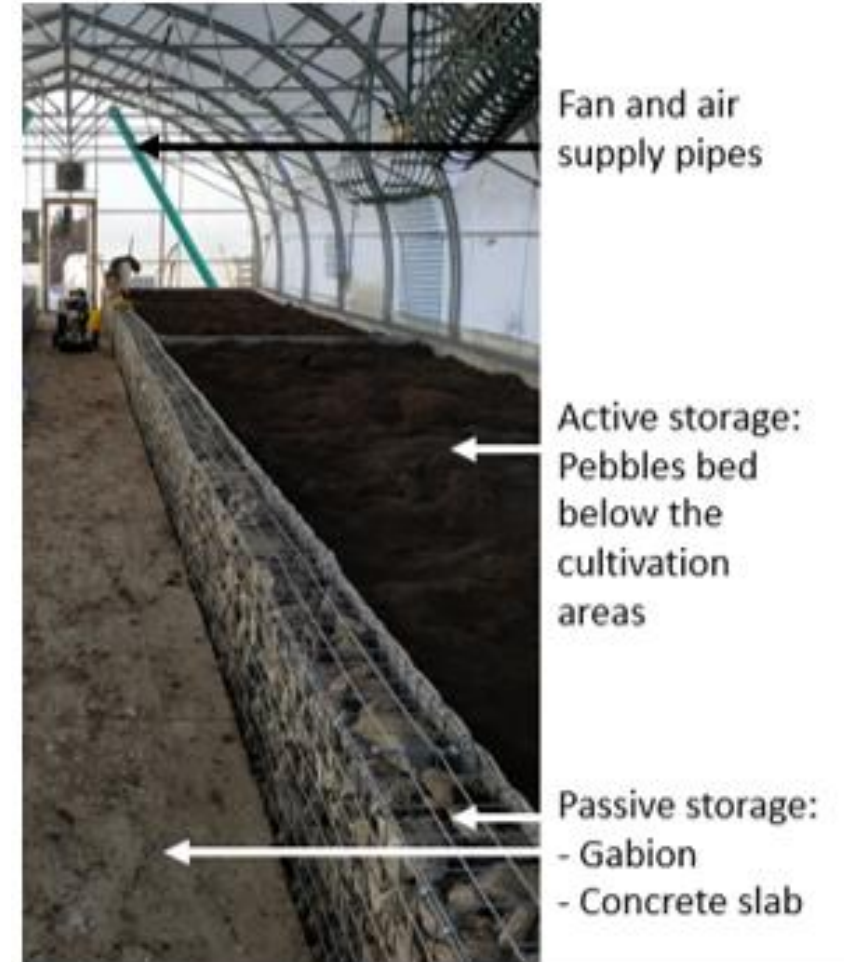
Greenhouses in Kuujuaq



Electrical resistivity tomographies

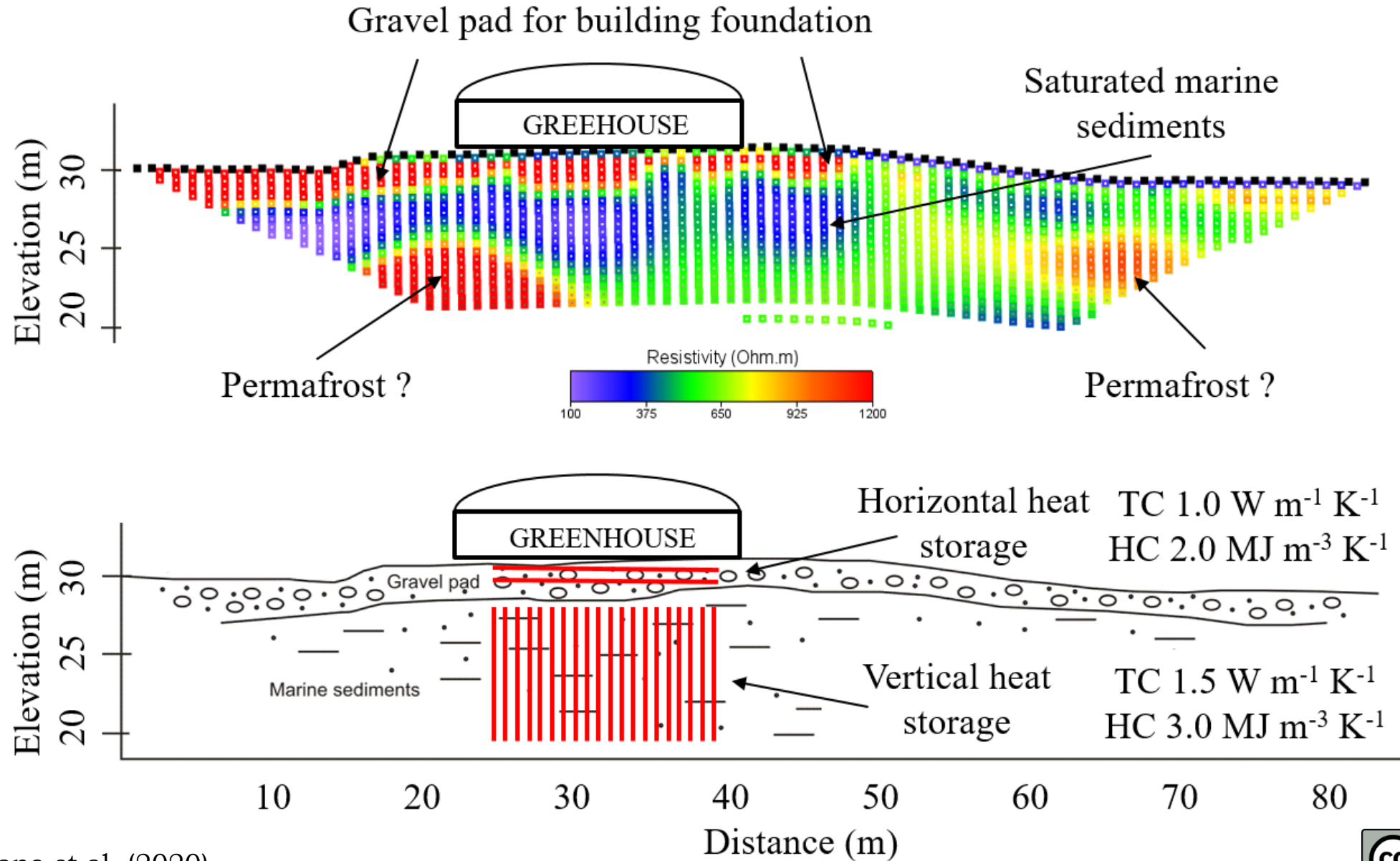


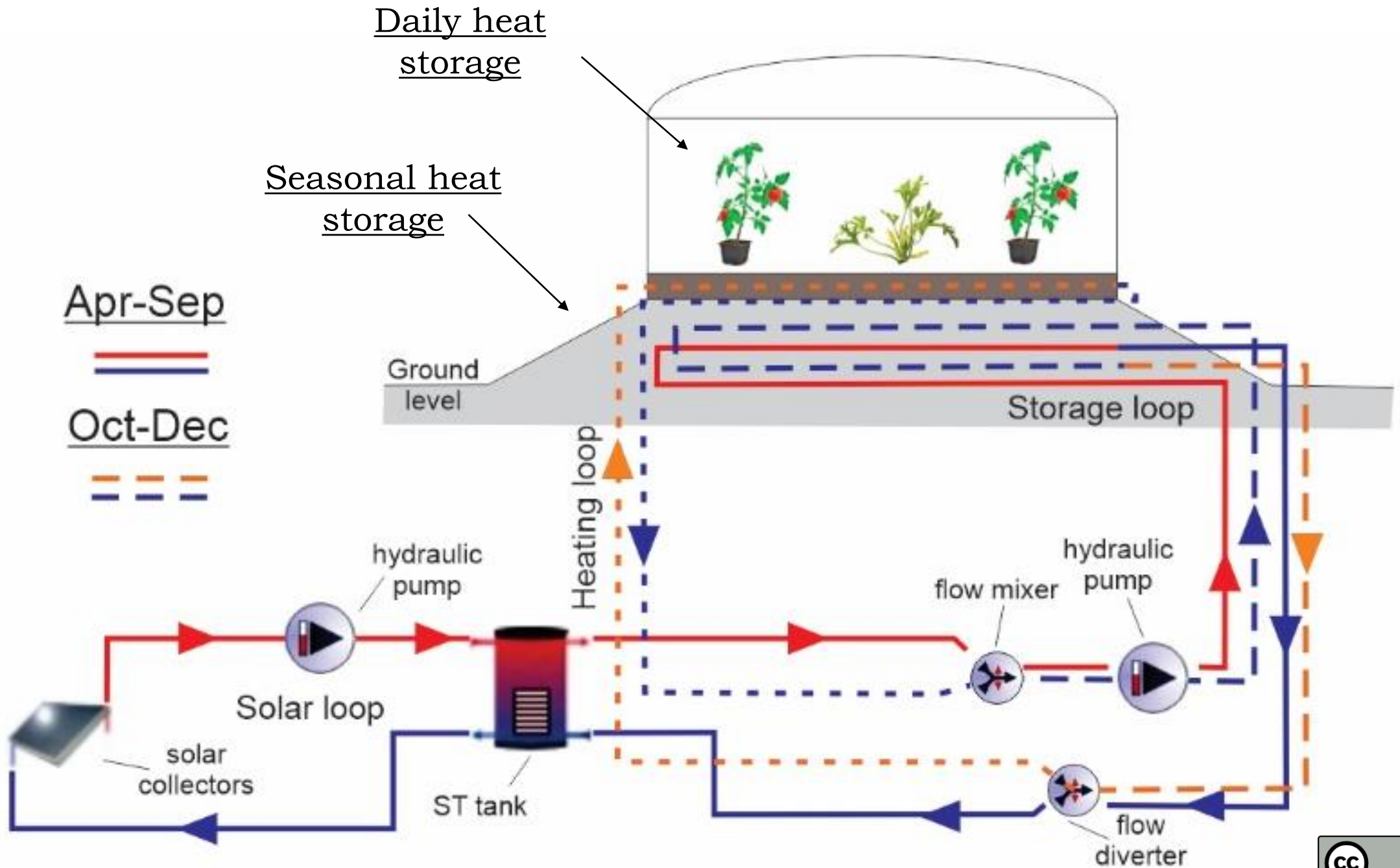
# Daily heat storage



Piché et al. (2020)

# Seasonal heat storage





# Conclusions - Kuujuaq

## 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

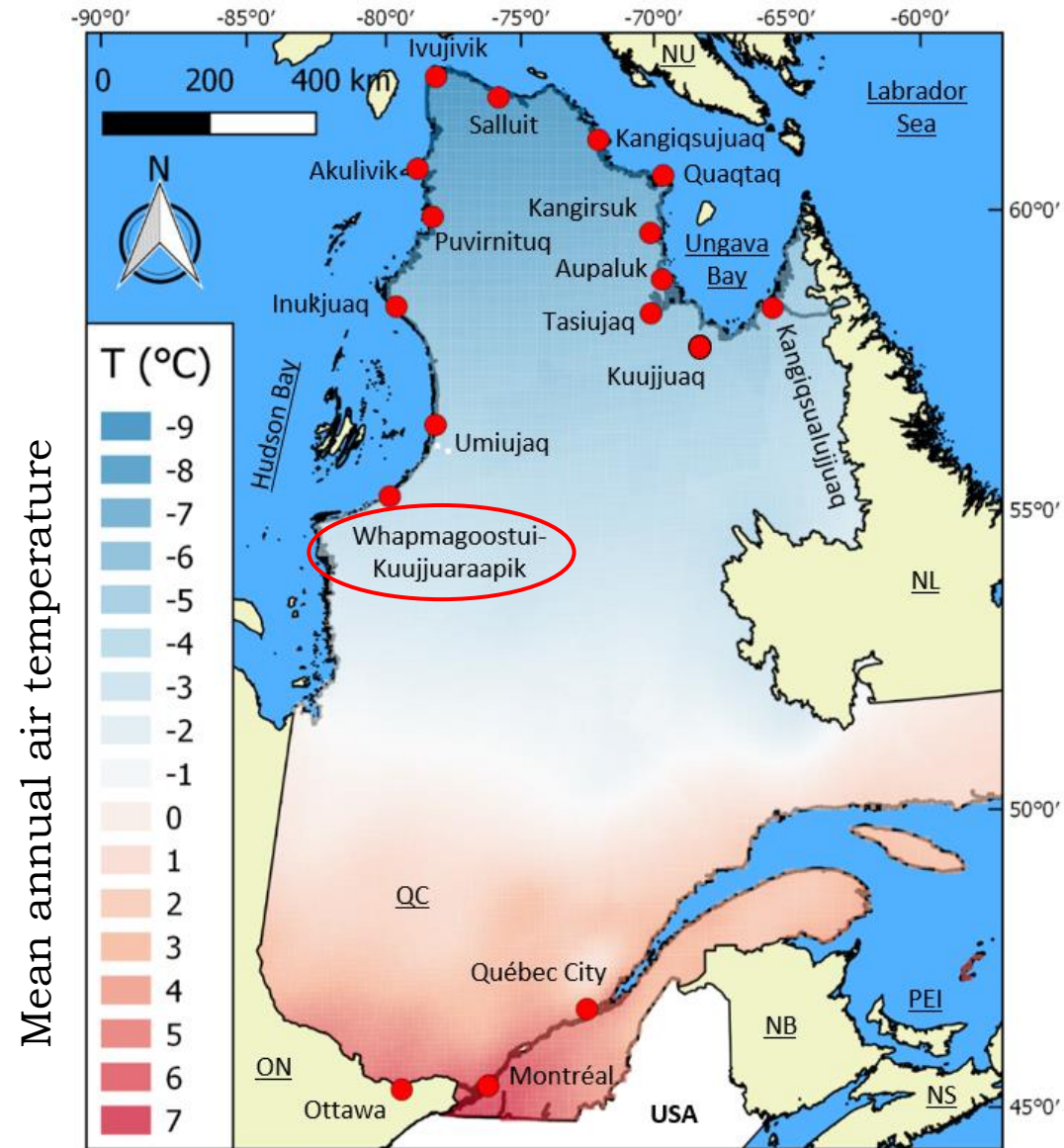
## Financial results

- 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

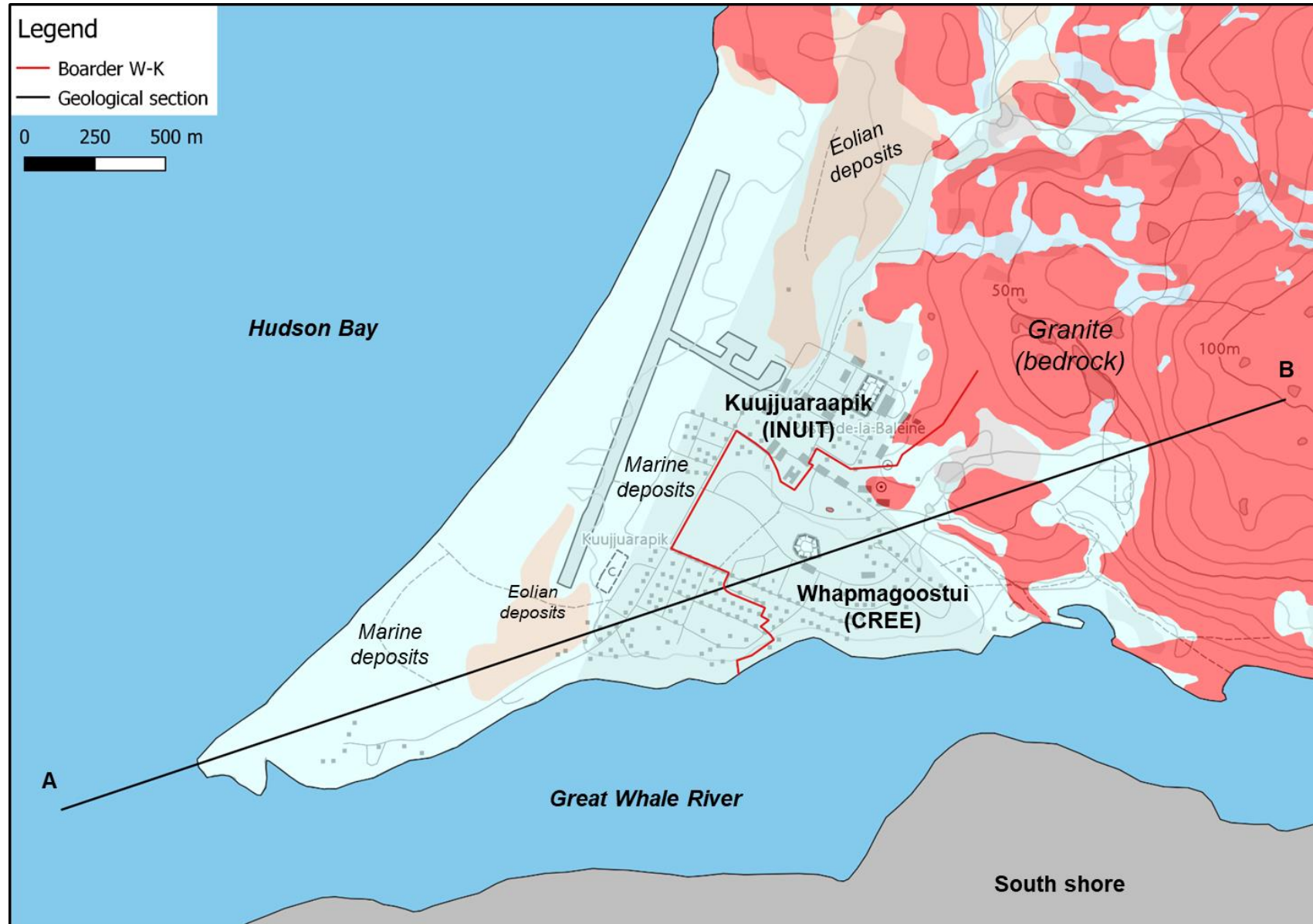
## Future activities

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

# Whapmagoostui- Kuujjuaraapik (W-K)

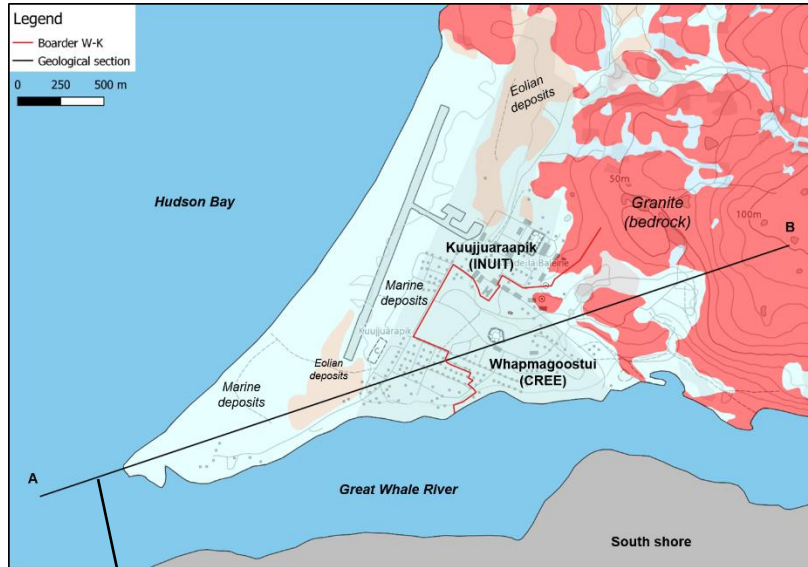


# Geological setting



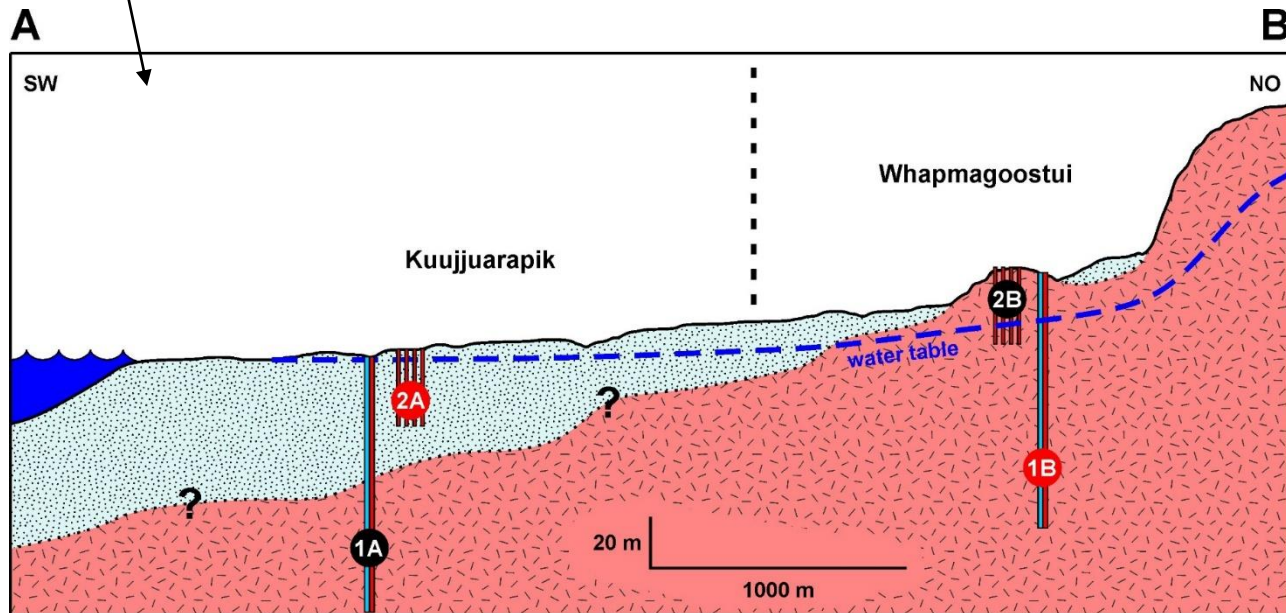
The Inuit population lives in the western and north part of the village, while the Cree population occupies the south-eastern part. The granitic bedrock is highlighted in red. The unconsolidated deposits of the river delta that mainly host the village can be differentiated into marine and eolian deposits (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	$\lambda$	3,00 W m <sup>-1</sup> K <sup>-1</sup>	2,35 W m <sup>-1</sup> K <sup>-1</sup>
Ground heat capacity	$\rho c$	2,30 J m <sup>-3</sup> K <sup>-1</sup>	2,50 J m <sup>-3</sup> K <sup>-1</sup>
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	$\lambda_{bf}$	1,50 W m <sup>-1</sup> K <sup>-1</sup>	1,50 W m <sup>-1</sup> K <sup>-1</sup>
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
Borehole thermal resistance	$r_{p,eq}$	0,02	0,02
	$R_b$	0,12 m K W <sup>-1</sup>	0,12 m K W <sup>-1</sup>
Closed-loop potential energy	$P_{BHE}$	13,23 MWh y <sup>-1</sup>	10,69 MWh y <sup>-1</sup>
Reference building	$P_{building}$	70 MWh y <sup>-1</sup>	70 MWh y <sup>-1</sup>
Coefficient of performance	$COP$	3,00	3,00
Total geothermal energy	$P_{ground}$	46,67 MWh y <sup>-1</sup>	46,67 MWh y <sup>-1</sup>
Number of boreholes needed		4	5

Comeau et al. (2020)



# UTES potential mapping – STOREmap method

**Energy stored**

$$Q_{STO} = f(\lambda, \rho c) \left\{ \begin{array}{l} \lambda = f(\text{bedrock and groundwater depth}) \\ \rho c = f(\text{bedrock and groundwater depth}) \end{array} \right.$$

**Heat losses**

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

**Available energy**

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

**Thermal recovery**

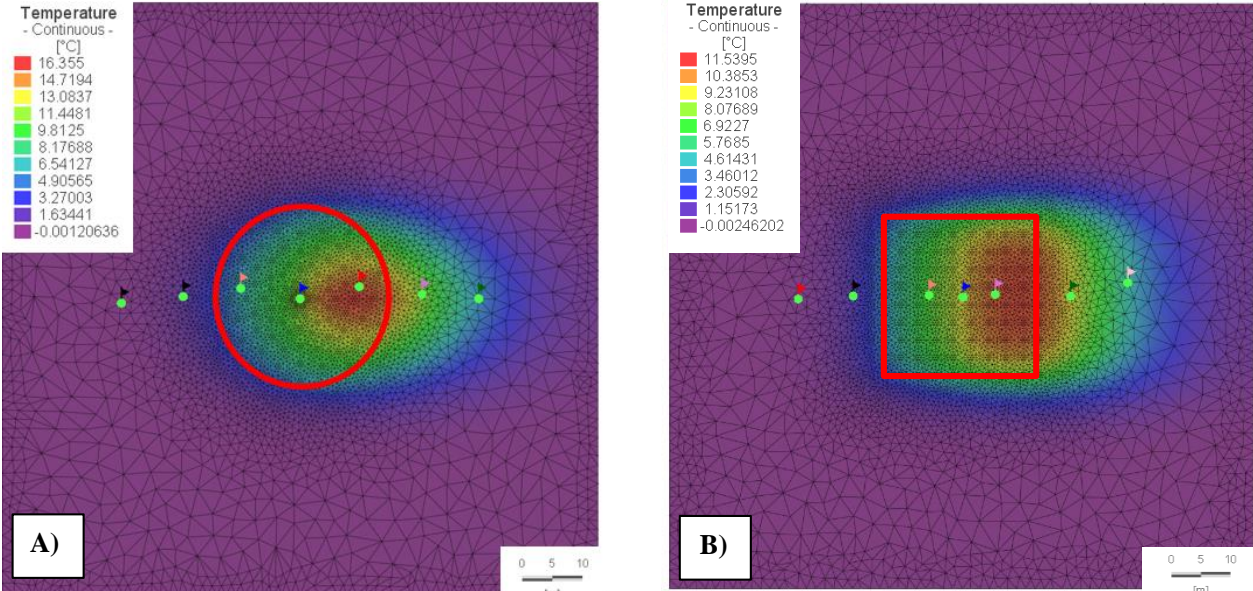
$$\eta = Q_{REC} / Q_{STO}$$

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  $10^{-6} \text{ m s}^{-1}$ , **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 ( $\eta$ ) 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).



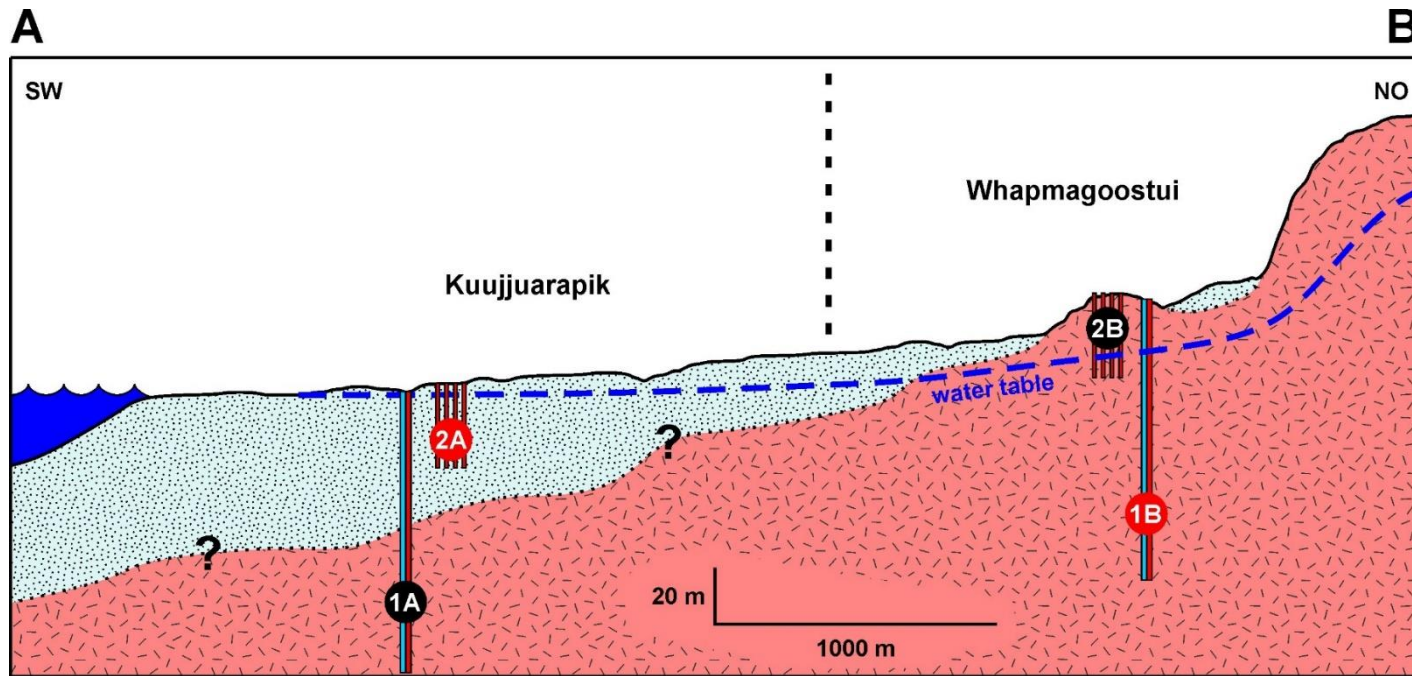
Giordano and Raymond (2019)



# Underground thermal energy storage systems

## Underground thermal energy storage (UTES)

		Thermal conductivity	Heat capacity	Thermal diffusivity	Storage volume	Average temperature	$\eta$	$Q_{STO}$	$Q_{REC}$	$Q_{LOST}$	Coverage
<b>Scenario 2A</b>	%	$W m^{-1} K^{-1}$	$MJ m^{-3} K^{-1}$	$m^2 s^{-1}$	$m^3$	$^{\circ}C$	%	GJ	GJ	GJ	%
Unconsolidated sediments	100	1.70	2.70	0.63	24000	15.2	55%	935	510	425	54%
<b>Scenario 2B</b>											
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)

# Conclusions – Whapmagoostui-Kuujuaraapik

## 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...)

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