Hydrogen Technologies

Salt Cavern Storage

PSI

sweet swiss energy research for the energy transition

PATHFNDR

ETH zürich Empa PAUL SCHERRER INSTITUT PSI zhaw HOCHSCHULE LUZERN UNIVERSITÉ DE GENÈVE EPFL TU Delft

Agenda

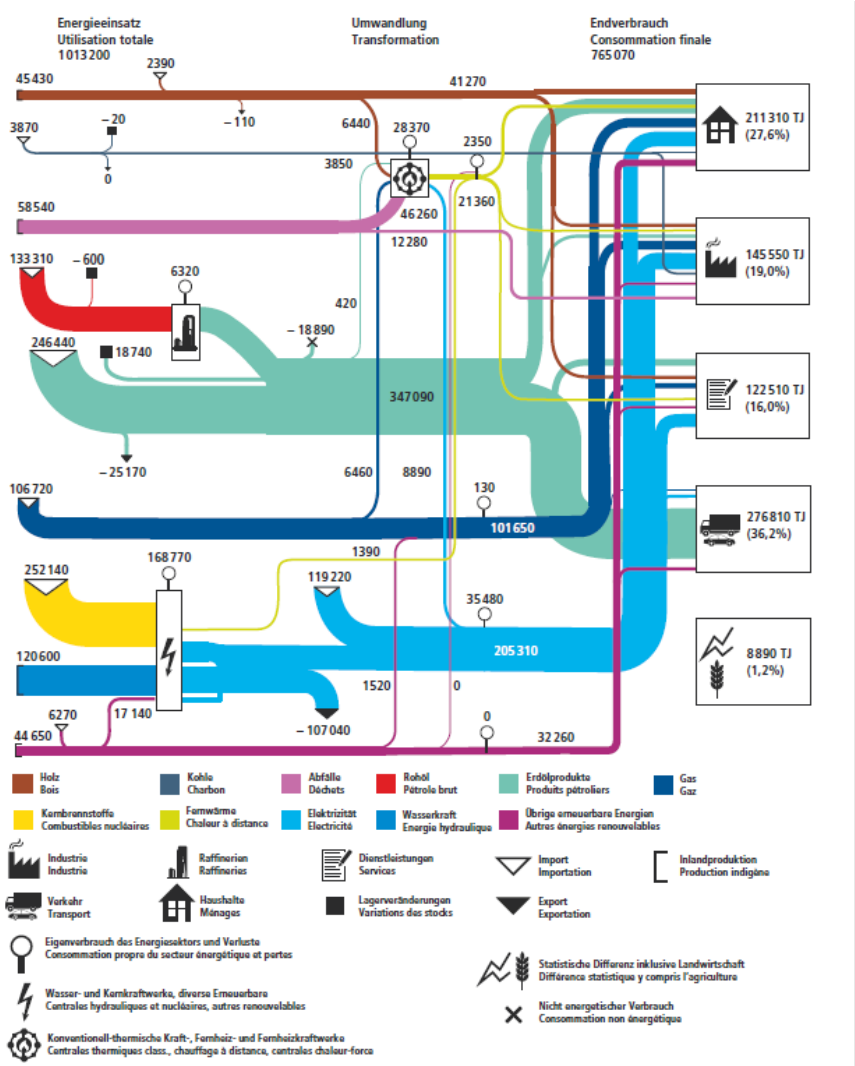
1. Motivation
2. Underground Storage in Europe
3. Salt Cavern Model
4. Salt Deposits in Switzerland
5. Sites
6. Summary & Outlook

Motivation: Energy transition and sector coupling

- Swiss Energy Statistics from the year 2022

- End consumption : 765070 TJ -> 213 TWh
- Total consumption: 1013200 TJ -> 281 TWh
- El. Consumption: ~60TWh

- Hydrogen
  - allows sector coupling
  - seasonal energy storage



BFE. (2022). *SCHWEIZERISCHE GESAMTENERGIE STATISTIK*.

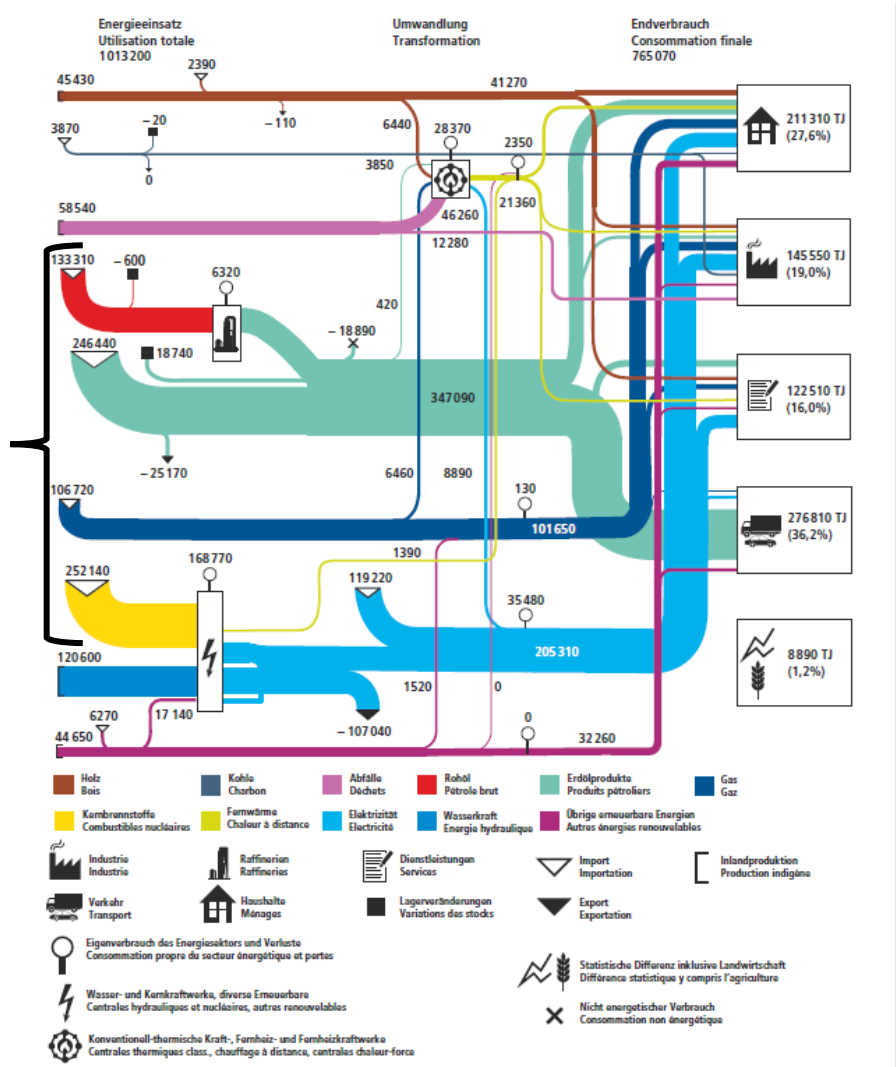
Motivation: Energy transition and sector coupling

- Swiss Energy Statistics from the year 2022

- End consumption : 765070 TJ -> 213 TWh
- Total consumption: 1013200 TJ -> 281 TWh
- El. Consumption: ~60TWh

- Hydrogen
  - allows sector coupling
  - seasonal energy storage

Storage capacity mandatory



BFE. (2022). *SCHWEIZERISCHE GESAMTENERGIE STATISTIK*.

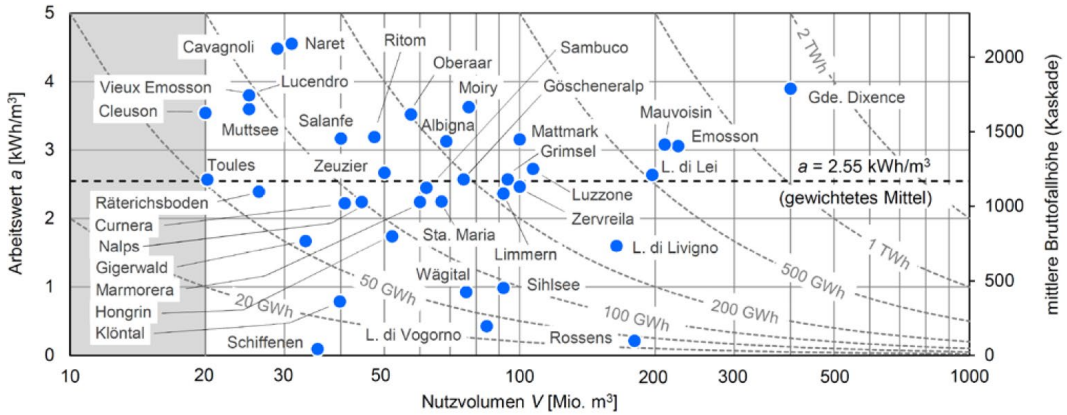
Eidgenössisches Departement für Wirtschaft (2023) Bericht zur Vorratshaltung 2023.

Motivation: Bulk energy storage

Hydro- Storage

Krummenacher J (2016). Höher, grösser, teurer NZZ. 13. Sept., Grande Dixance

Plant: ~10GWh bis TWh



Felix D (2020). Ausbaupotential der bestehenden Speicherseen in der Schweiz. Waser Energie Luft

Expansion limited (~+2TWh)

Battery storage

Liste von Batterie-Speicherkraftwerken. (2024). Wikipedia. https://de.wikipedia.org/wiki/Liste_von_Batterie-Speicherkraftwerken

Plant: ~10MWh bis GWh
~ 20 Projects

- Expensive for high energy demand
- Scarcity of resources

Motivation: Bulk energy storage

Pipe Storage

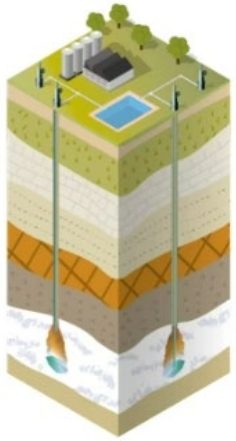
bis-austria.bilfinger.com
Urdorf

~GWh bis ~10GWh

swiss center of excellence on net zero emissions
SCENE

https://www.scene-project.ch

Salt Cavern (SC)

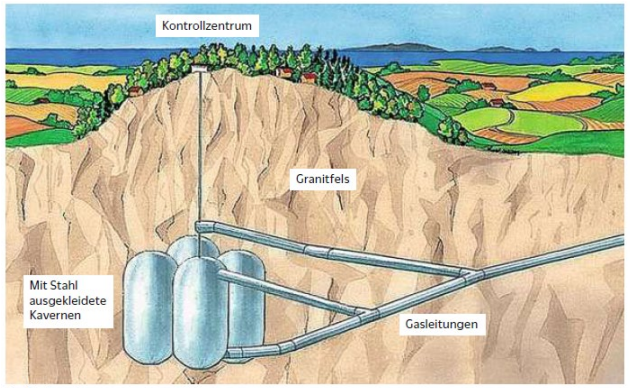


~100GWh bis TWh

sweet swiss energy research for the energy transition
PATHFNDR

https://sweet-pathfndr.ch

Lined Rock Cavern (LRC)



Quelle: Gaznat

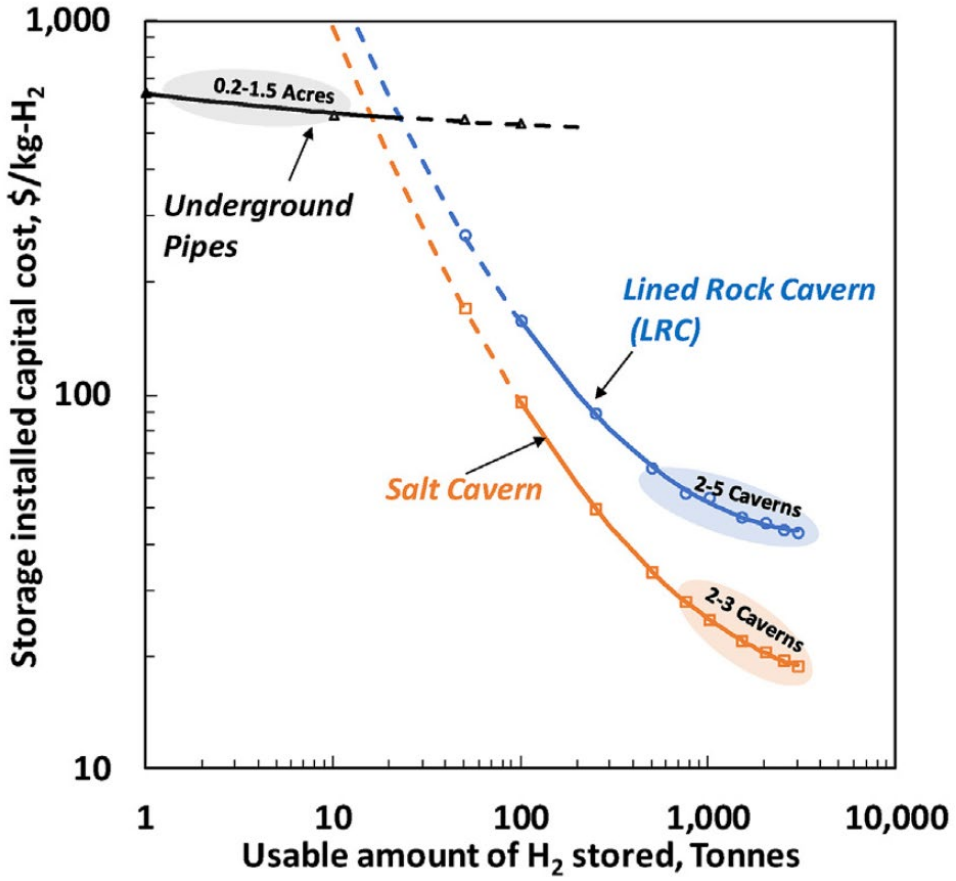
~100GWh bis TWh

sweet swiss energy research for the energy transition
SURE

https://sweet-sure.ch/

22.07.2024

Motivation: Bulk energy storage – cost



Papdias D (2021). Bulk storage of hydrogen, International journal o f hydrogen energy

Natural gas underground storage in Europe

Underground Gas Storage Capacity (TWh) **# Facilities**

	operational	under constr.	planned	TOTAL	TOTAL
Austria	95,2			95,2	9
Belgium	9,0			9,0	1
Bulgaria	5,8		4,8	10,6	1
Croatia	5,2		0,3	5,5	2
Czech Republic	43,1	0,8	0,4	44,4	9
Denmark	10,5			10,5	2
France	132,3		4,1	136,4	17
Germany	260,5		5,9	266,4	60
Greece			3,9	3,9	1
Hungary	69,6			69,6	5
Ireland					
Italy	195,4	8,6	40,7	244,7	21
Latvia	24,2			24,2	1
Lithuania					
Netherlands	144,6			144,6	5
Poland	38,4	0,7	9,0	48,1	10
Portugal	3,6			3,6	1
Romania	33,0		12,5	45,5	7
Slovakia	43,4		3,6	47,1	3
Spain	34,2			34,2	4
Sweden	0,1			0,1	1
EU	1148,2	11,1	85,2	1243,5	160
Belarus	15,3	5,5		20,8	3
Russian Fed.	23,8			23,8	3
Serbia	4,5			4,5	1
Turkey	35,0		43,2	78,3	4
Ukraine	327,9			327,9	13
UK	17,5	0,4	35,3	53,2	12
non EU	424,1	5,9	78,6	508,6	36
TOTAL EUROPE	1572,2	16,0	163,8	1752,0	196

*Note : Number of planned and under construction facilities on

Europe total gas consumption: 4509TWh in 2022

Gas Infrastructure Europe (2022). Storage Map 2022, https://www.gie.eu/

Natural gas underground storage in Europe

Underground Gas Storage Capacity (TWh) **# Facilties**

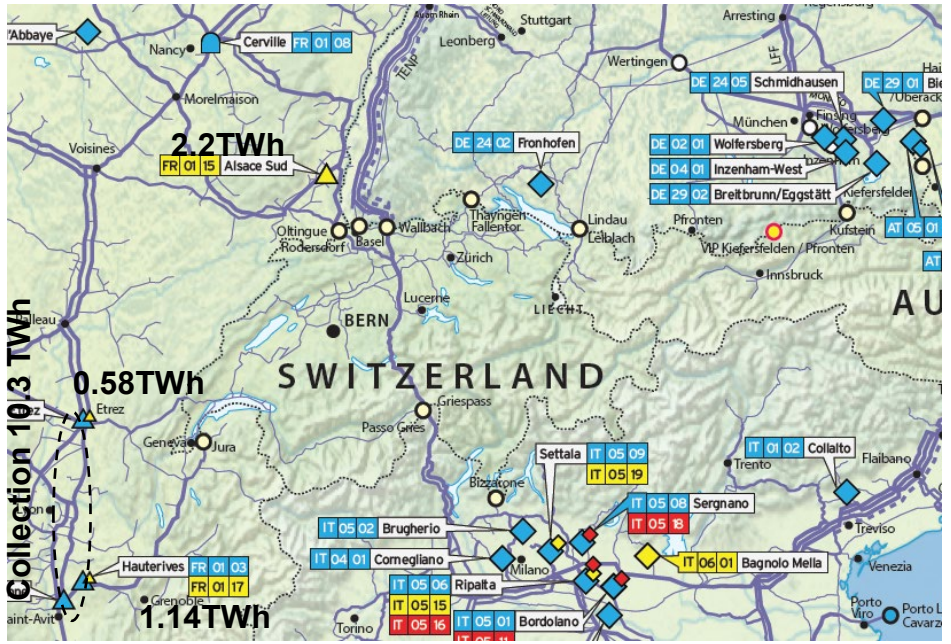
	operational	under constr.	planned	TOTAL	TOTAL
Austria	95,2			95,2	9
Belgium	9,0			9,0	1
Bulgaria	5,8		4,8	10,6	1
Croatia	5,2		0,3	5,5	2
Czech Republic	43,1	0,8	0,4	44,4	9
Denmark	10,5			10,5	2
France	132,3		4,1	136,4	17
Germany	260,5		5,9	266,4	60
Greece			3,9	3,9	1
Hungary	69,6			69,6	5
Ireland					
Italy	195,4	8,6	40,7	244,7	21
Latvia	24,2			24,2	1
Lithuania					
Netherlands	144,6			144,6	5
Poland	38,4	0,7	9,0	48,1	10
Portugal	3,6			3,6	1
Romania	33,0		12,5	45,5	7
Slovakia	43,4		3,6	47,1	3
Spain	34,2			34,2	4
Sweden	0,1			0,1	1
EU	1148,2	11,1	85,2	1243,5	160
Belarus	15,3	5,5		20,8	3
Russian Fed.	23,8			23,8	3
Serbia	4,5			4,5	1
Turkey	35,0		43,2	78,3	4
Ukraine	327,9			327,9	13
UK	17,5	0,4	35,3	53,2	12
non EU	424,1	5,9	78,6	508,6	36
TOTAL EUROPE	1572,2	16,0	163,8	1752,0	196

*Note : Number of planned and under construction facilities on

Europe total gas consumption: 4509TWh in 2022

Gas Infrastructure Europe (2022). Storage Map 2022, https://www.gie.eu/

Country: # Facilities / Energy / Type UGS (existing / plan SC)
Germany: # 60 / 260 TWh / all kinds (44/2 salt cavern fac.)
Austria: # 9 / 95 TWh / all depleted fields
France: #17/ 132 TWh / all kind (4/3 salt cavern fac.)
Italy: # 21 / 195 TWh
Switzerland: 0



- Depleted field
- Salt cavern

Natural gas underground storage in Europe

Underground Gas Storage Capacity (TWh) **# Facilties**

	operational	under constr.	planned	TOTAL	TOTAL
Austria	95,2			95,2	9
Belgium	9,0			9,0	1
Bulgaria	5,8		4,8	10,6	1
Croatia	5,2		0,3	5,5	2
Czech Republic	43,1	0,8	0,4	44,4	9
Denmark	10,5			10,5	2
France	132,3		4,1	136,4	17
Germany	260,5		5,9	266,4	60
Greece			3,9	3,9	1
Hungary	69,6			69,6	5
Ireland					
Italy	195,4				
Latvia	24,2				
Lithuania					
Netherlands	144,6				
Poland	38,4				
Portugal	3,6				
Romania	33,0				
Slovakia	43,4				
Spain	34,2				
Sweden	0,1				
EU	1148,2				
Belarus	15,3				
Russian Fed.	23,8				
Serbia	4,5				
Turkey	35,0				
Ukraine	327,9			327,9	13
UK	17,5	0,4	35,3	53,2	12
non EU	424,1	5,9	78,6	508,6	36
TOTAL EUROPE	1572,2	16,0	163,8	1752,0	196

*Note : Number of planned and under construction facilities on

Country: # Facilities / Energy / Type UGS (existing / plan SC)
Germany: # 60 / 260 TWh / all kinds (44/2 salt cavern fac.)
Austria: # 9 / 95 TWh / all depleted fields
France: #17/ 132 TWh / all kind (4/3 salt cavern fac.)
Italy: # 21 / 195 TWh
Switzerland: 0

Theoretical example:

Schweizer Salinen AG produces 400e3t to 600e3t salt per year corresponding to a volume of 185e3m^3 to 278 m^3 -> 20-30 GWh (@f = 0.8, P_{Min}= 30bar, P_{Max}=73bar, real Gas, H2)

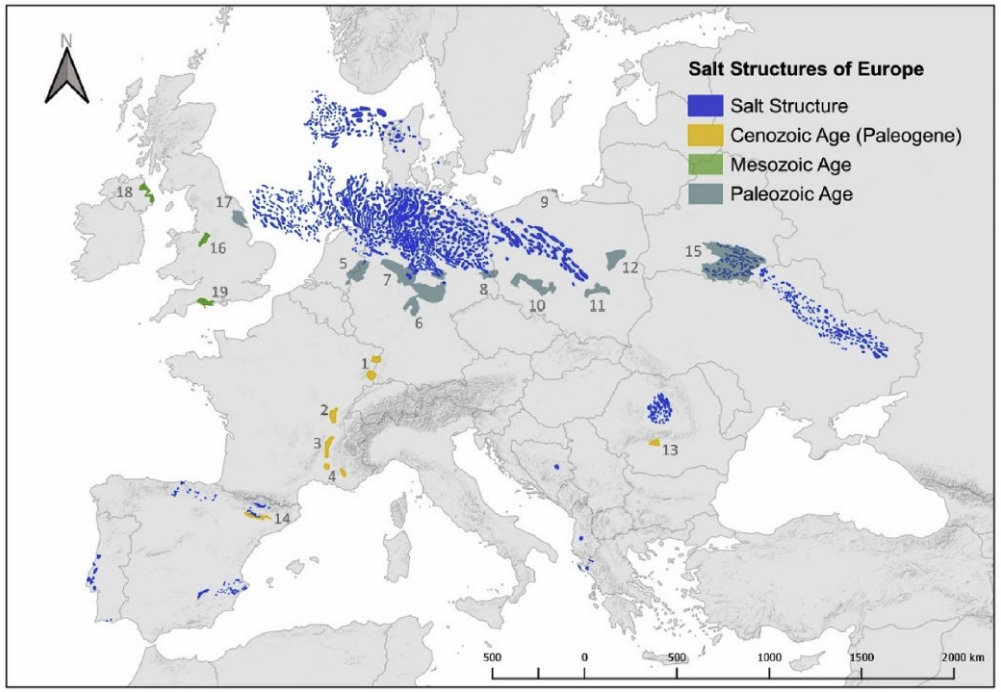
- Depleted field
- Salt cavern

Europe total gas consumption:
4509TWh in 2022

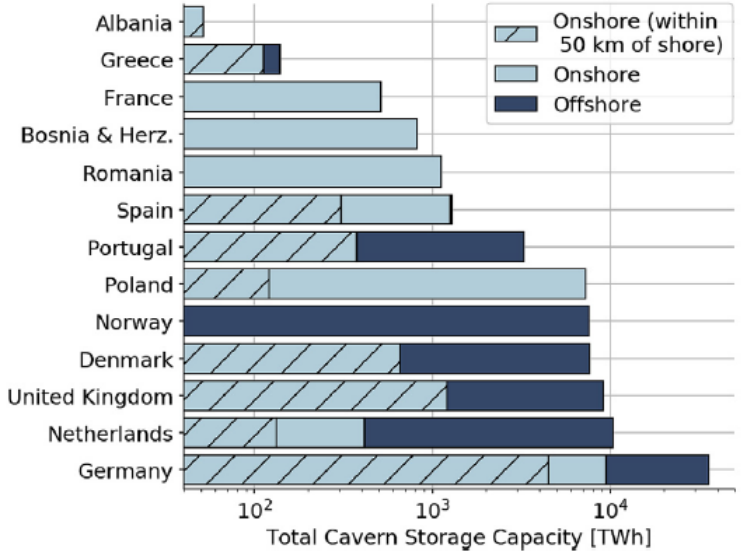
Gas Infrastructure Europe (2021). Storage Map 2021, https://www.gie.eu/

Ref Gie

Potential of salt caverns in Europe



Suitable salt deposits for underground H2 storage



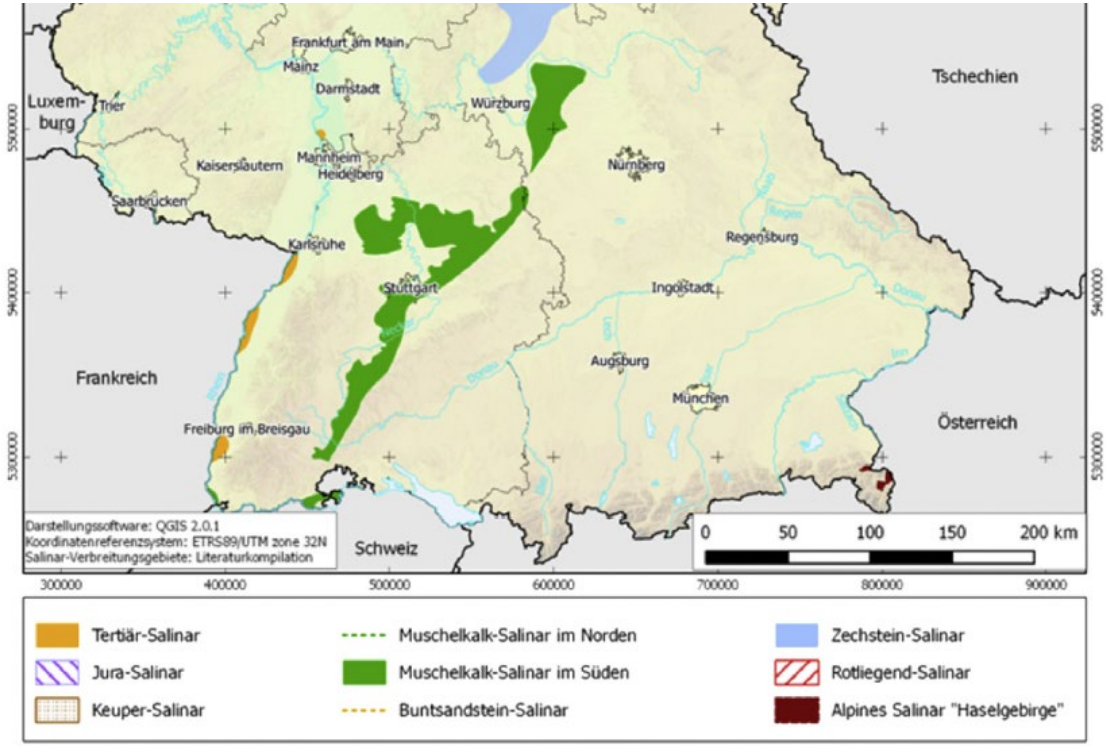
- EU Storage Potential 84.8 PWh_{H2}
- Onshore 23.2 PWh_{H2}
- DE: 35.6 PWh_{H2}
- Fr: 510 TWhH2 -> Todays consumption ~430TWh (Natural Gas)

Caglayan D (2020). Technical potential of salt caverns for hydrogen storage in Europe, International journal o f hydrogen energy

Potential of salt caverns in Europe

- Gradual introduction of H2 -> gradual increase of storage
- Repurposing of exiting salt caverns used for natural gas storage -> Potential 27TWh

- In both studies Switzerland is gray! Why? Both studies show salt around Switzerland, and we have local salt production.



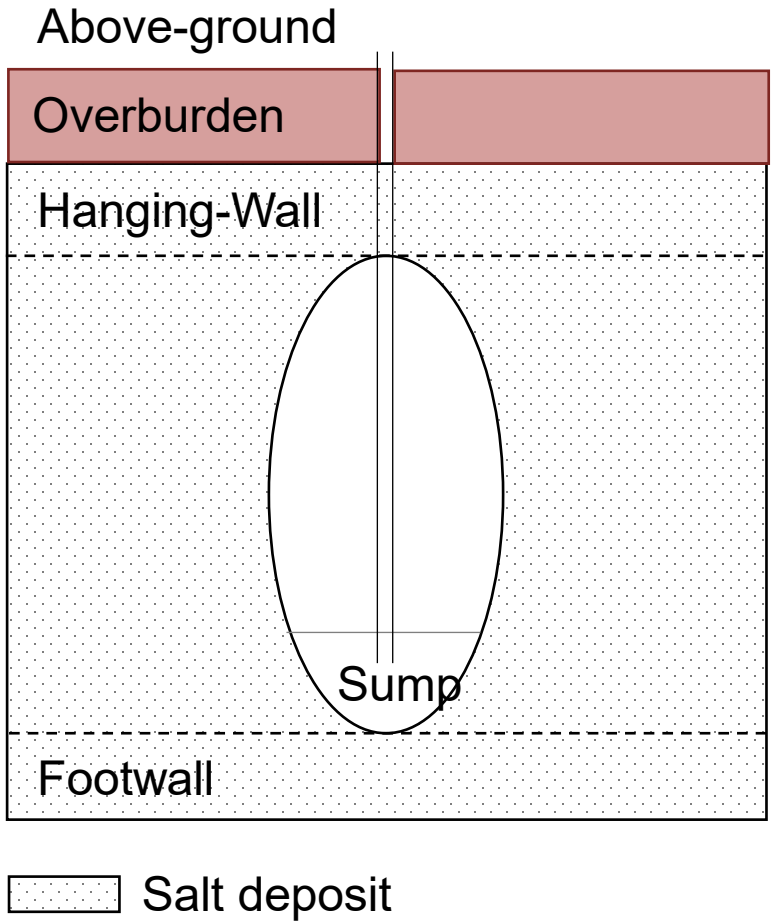
Michalski J (2017). Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems
aspects with regard to the German energy transition, International journal o f hydrogen energy

Salt cavern model

- Salt cavern potential analysis based on empirical formulas
- Cavern design based on simulations using data from underground drilling samples

Salt cavern model

- Potential salt cavern analysis based on empirical formulas
- Cavern design based on simulations using data from underground drilling samples



After: Caglayan D (2020). Technical potential of salt caverns for hydrogen storage in Europe, International journal o f hydrogen energy

Salt cavern model - archetype

Geological Data
- Geomechanical assessment

Salt formation
- Location
- Thickness
- Depth
- Insoluble parts

Salt cavern

- Dimension
- Shape
- Filling factor
- Gas

- Distance between caverns

Energy

Operating pressure

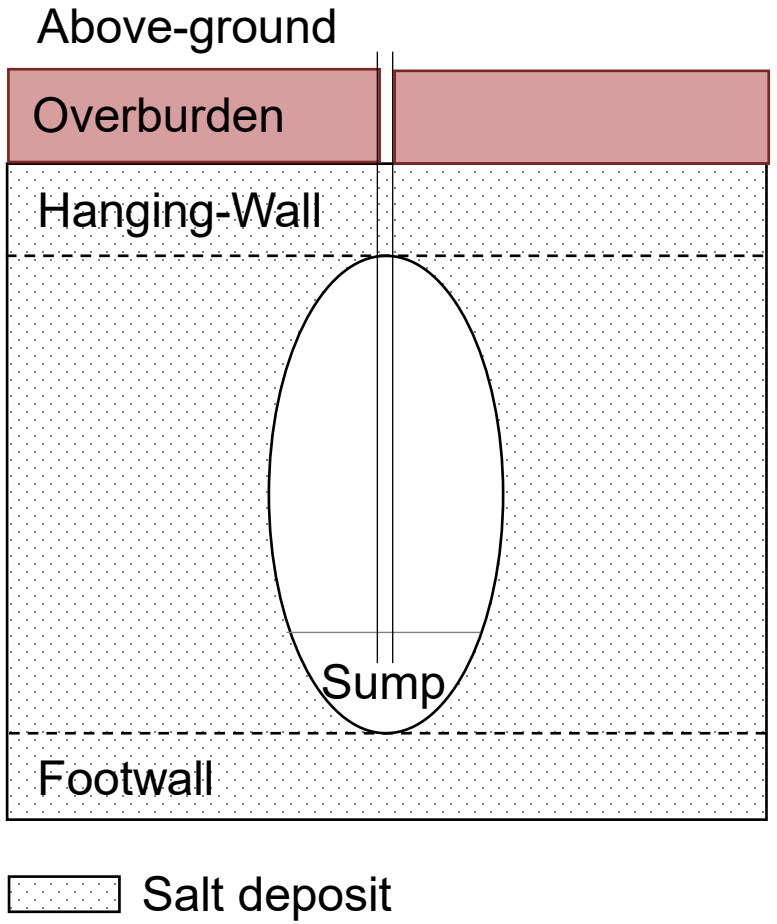
Impurities

Losses

Location

Charging, discharging time

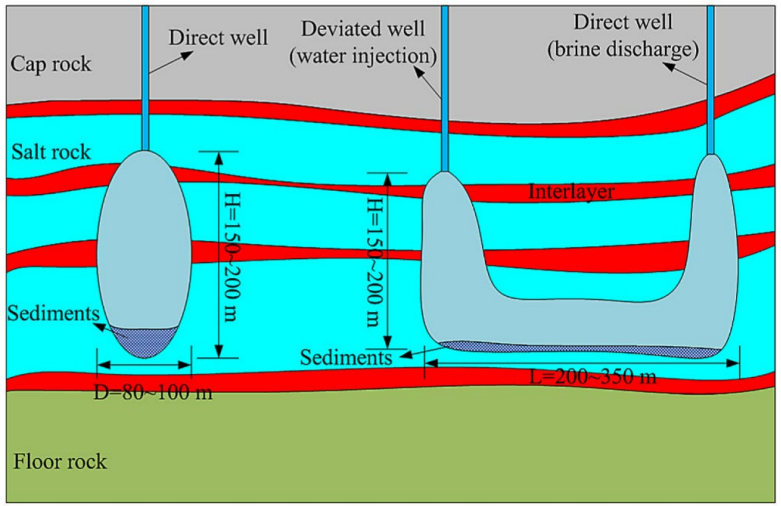
Time to build



After: Caglayan D (2020). Technical potential of salt caverns for hydrogen storage in Europe, International journal o f hydrogen energy

Salt cavern model – demanding environment conditions

Caverns in thin salt beds with interlayers

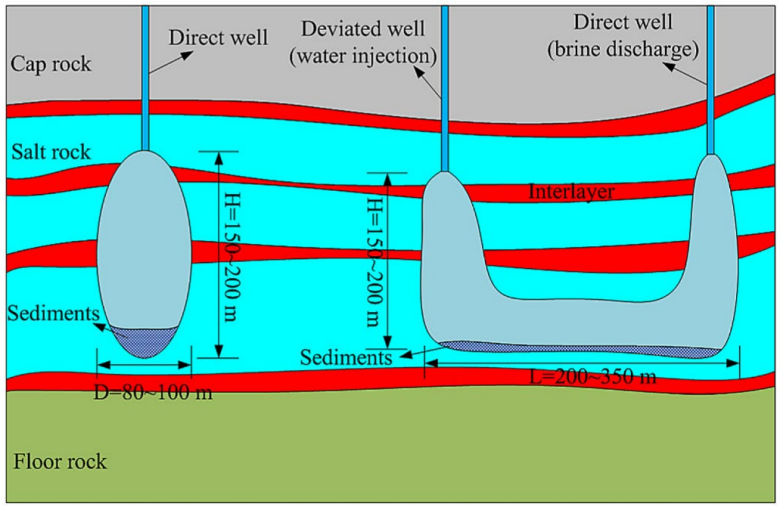


- Stability issues
- Decrease cavern volume due to insoluble parts

Peng L (2021).
Stability analysis of U-shaped horizontal salt cavern for underground natural gas storage , International Journal of Energy Storage

Salt cavern model – demanding environment conditions

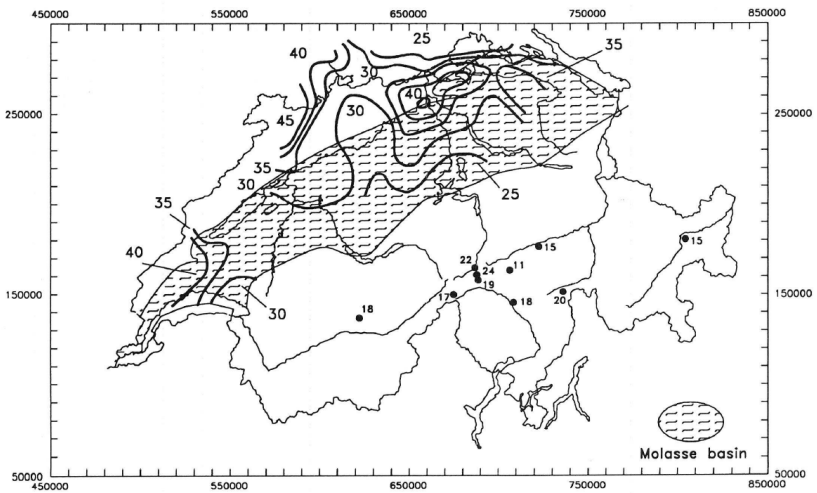
Caverns in thin salt beds with interlayers



- Stability issues
- Decrease cavern volume due to insoluble parts

Peng L (2021). Stability analysis of U-shaped horizontal salt cavern for underground natural gas storage , International Journal of Energy Storage

Deep salt cavern



Rybach L (1992). Geothermal potential of the Swiss Molasse Basin, Eclogae Geologicae Helvetiae

- Map of geothermal gradient increase with depth in °C/km
- Salt creep rate increases exponentially with temperature Cavern volume loss increased

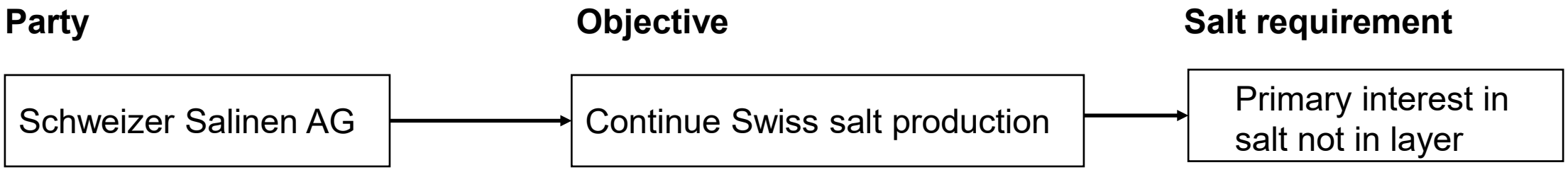
Lux KH (1984). Gebirgsmechanischer Entwurf und Felderfahrungen im Salzkavernenbau, Ferdinand Engke Verlag Stuttgard,

Salt cavern model – costs

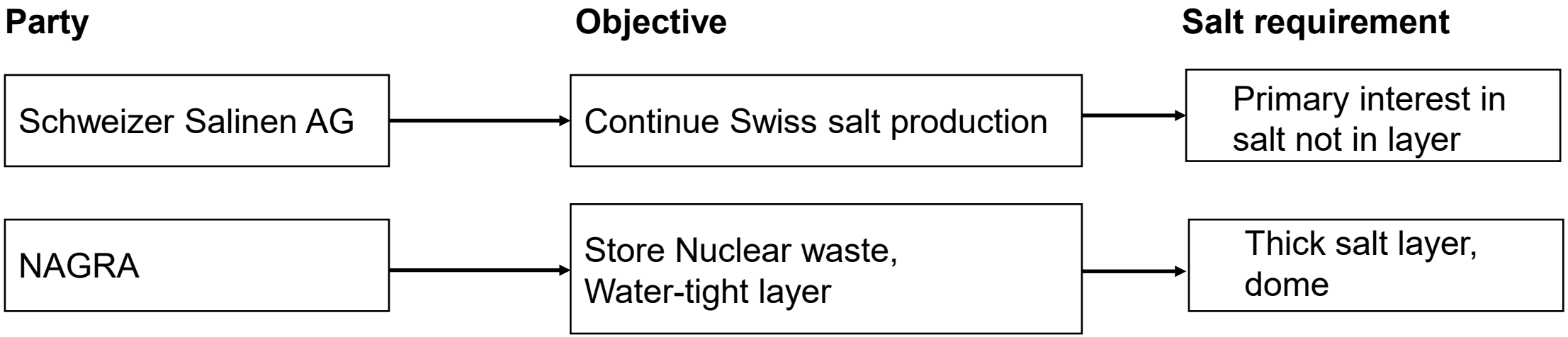
	**Drilling Cost**
	Drill+ Casing, Leaching, Mechanical integrity Test
	**Engineering Cost**
	Geological survey, Engineering, Contingency, Permitting
	**Brine Disposal Cost**
	Transportation, Disposal
	**Above Ground Cost**
	Compressor, Piping, Instrumentation, Cushion gas, Land cost

After: Papdias D (2021). Bulk storage of hydrogen, International journal o f hydrogen energy

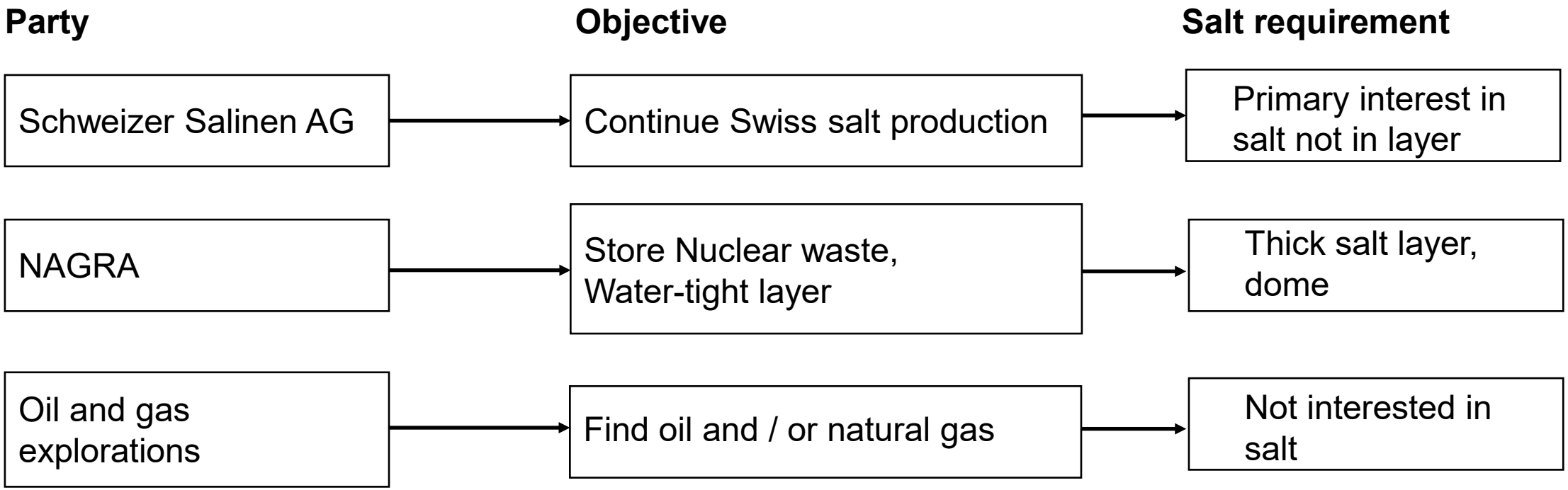
Analysis of salt deposits in Switzerland



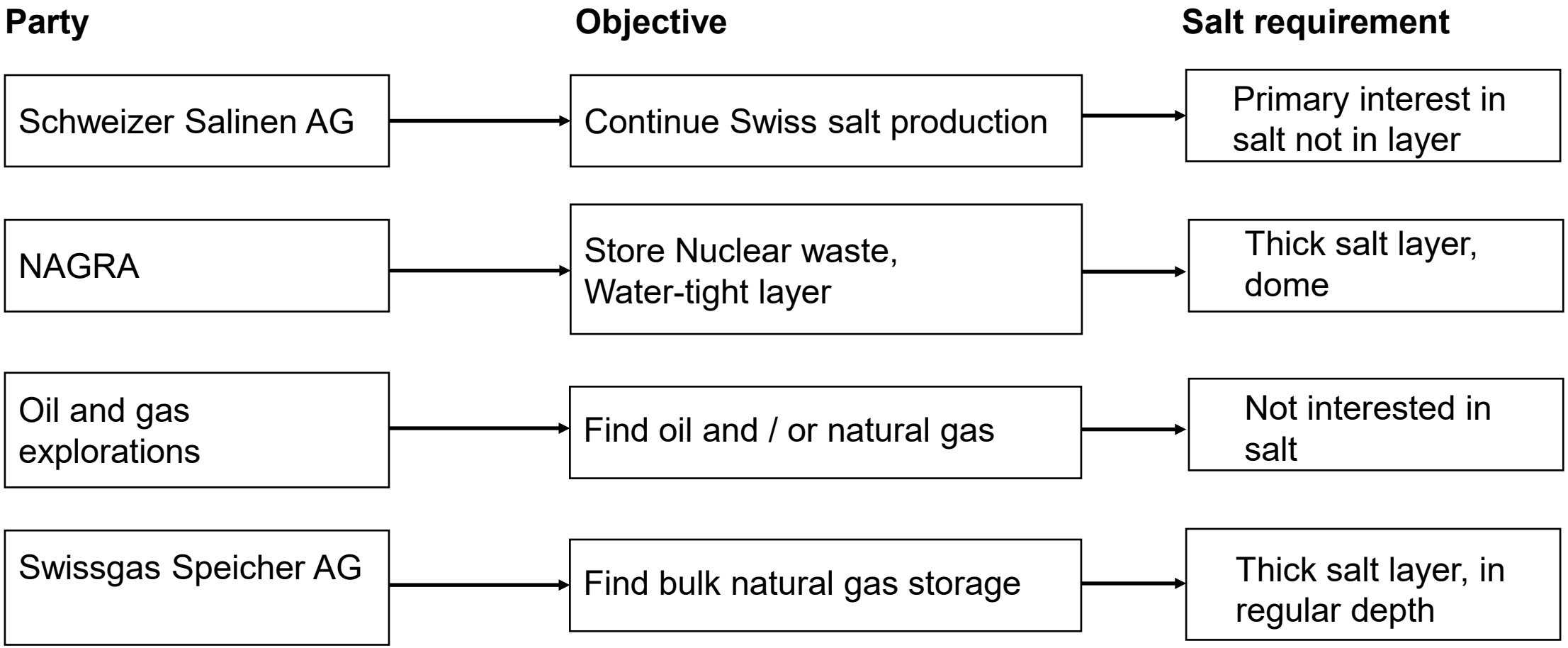
Analysis of salt deposits in Switzerland



Analysis of salt deposits in Switzerland



Analysis of salt deposits in Switzerland



Analysis of salt deposits in Switzerland

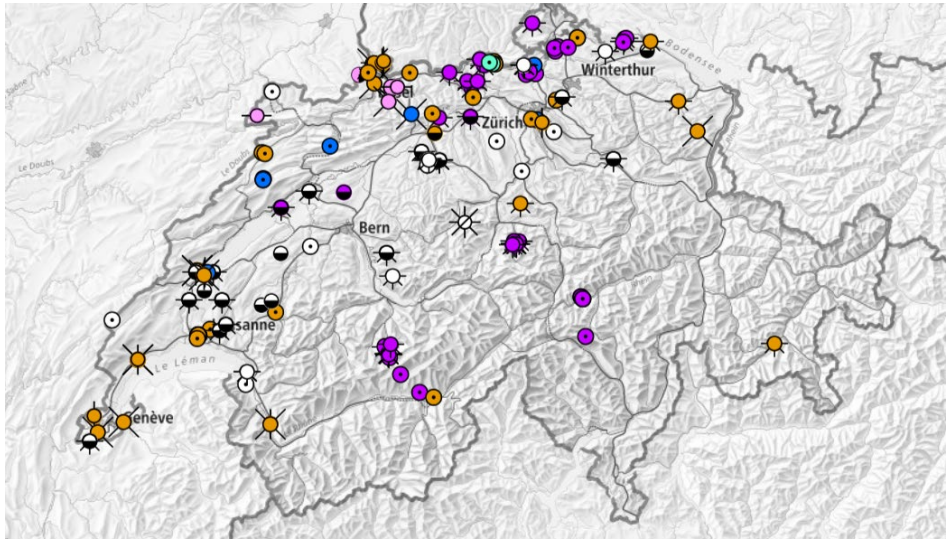
Leads to:

- Investigation of thin bedded salt layer
- Deep salt layers
- Salt layers with interlayers
- or a combination of disadvantages

- Which make an **economic perspective very difficult without additional motivation**

Analysis of salt deposits in Switzerland -public data

Boreholes



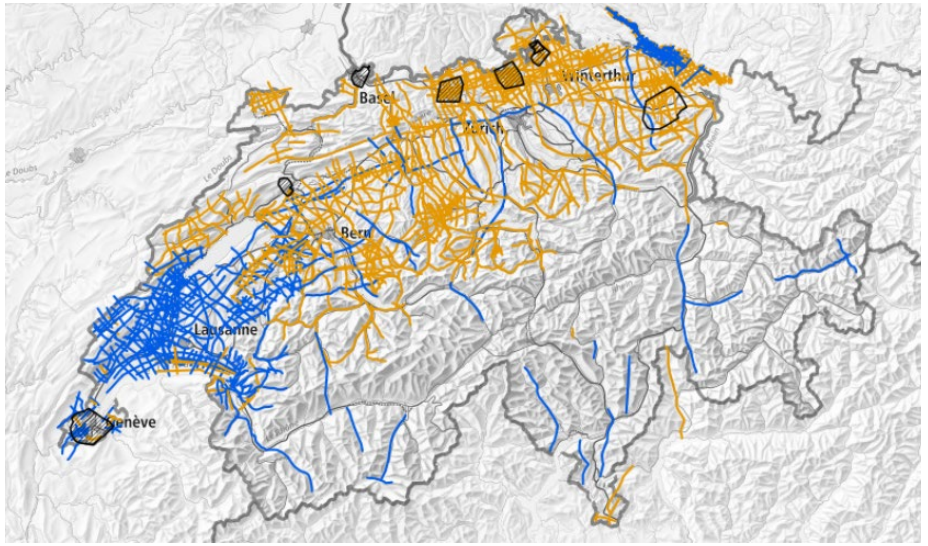
Purpose

- Infrastructure & research
- Geothermal energy
- Hydrocarbons
- Salt
- Groundwater
- No data

Discovery

- Gas production, depleted
- Gas shows
- Oil and gas shows
- Oil shows
- Tar
- Salt
- Groundwater
- Dry
- No data

Seismic measurements



2D reflection seismic

- Public data
- Data currently not public

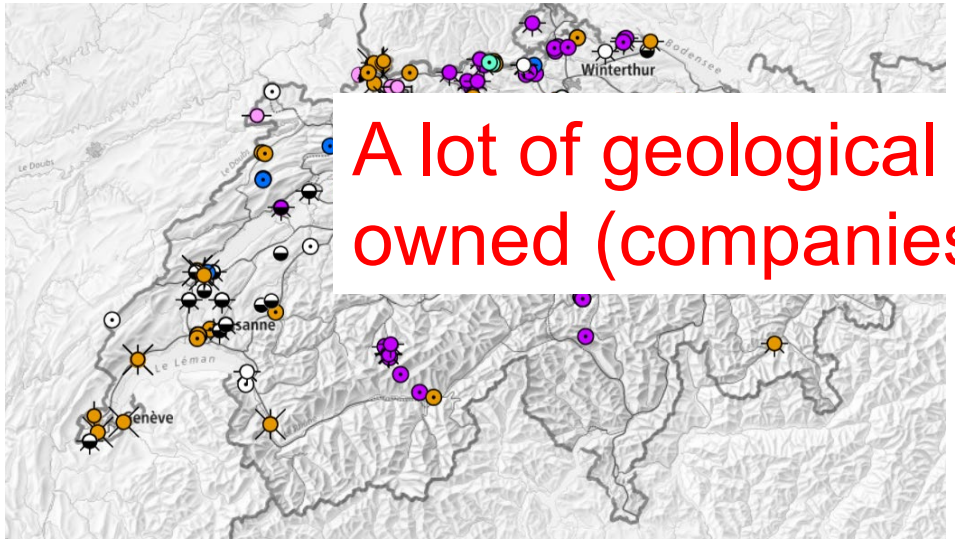
3D reflection seismic

- Public data
- Data currently not public

Schweizerische Eidgenossenschaft. (2019). *Swiss Geoportal*. https://map.geo.admin.ch/

Analysis of salt deposits in Switzerland -public data

Boreholes



Purpose

- Infrastructure & research
- Geothermal energy
- Hydrocarbons
- Salt
- Groundwater
- No data

Discovery

- Gas production, depleted
- Gas shows
- Oil and gas shows
- Oil shows
- Tar
- Salt
- Groundwater
- Dry
- No data

A lot of geological data is privately owned (companies) and not public!

Seismic measurements

2D reflection seismic

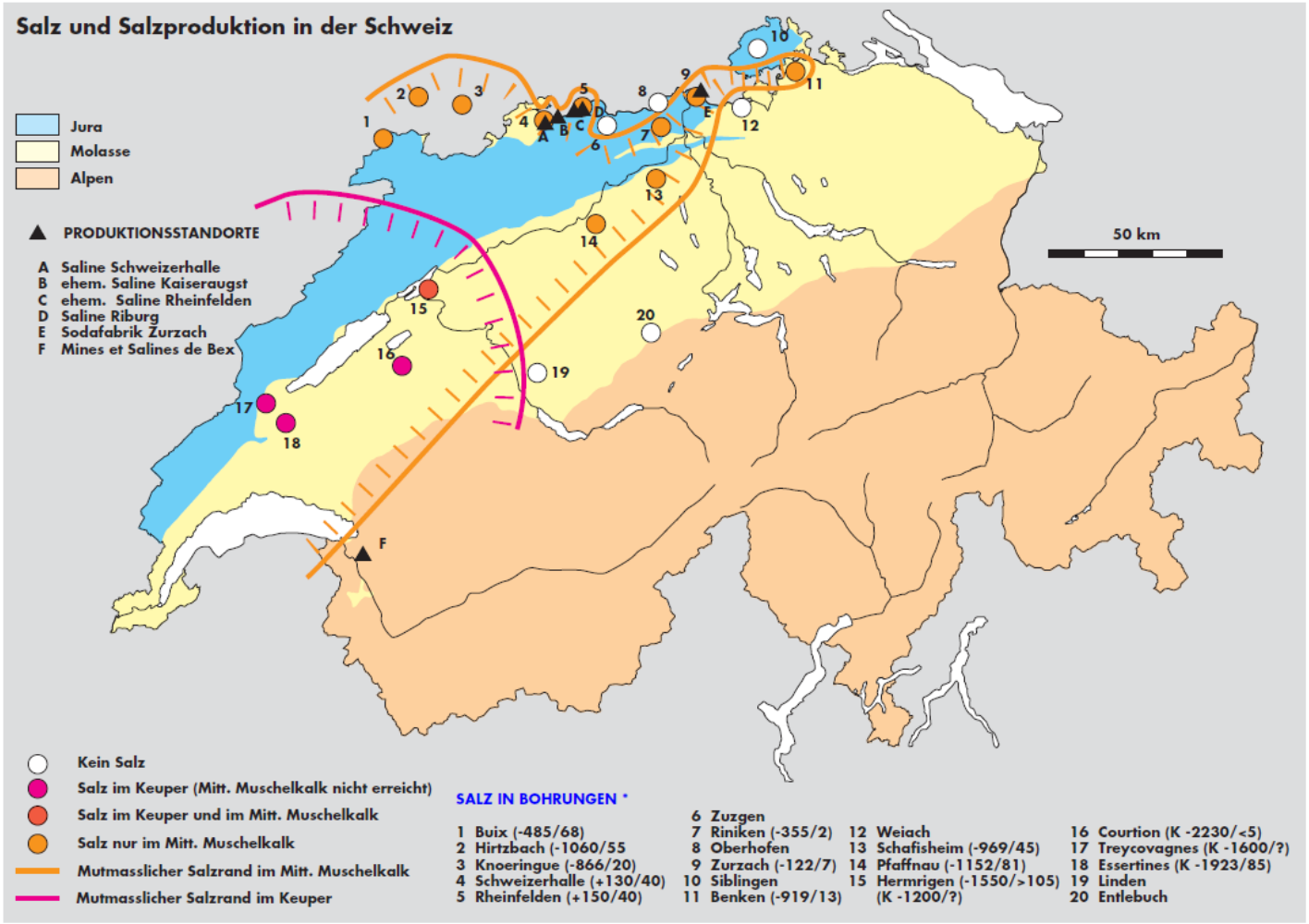
- Public data
- Data currently not public

3D reflection seismic

- Public data
- Data currently not public

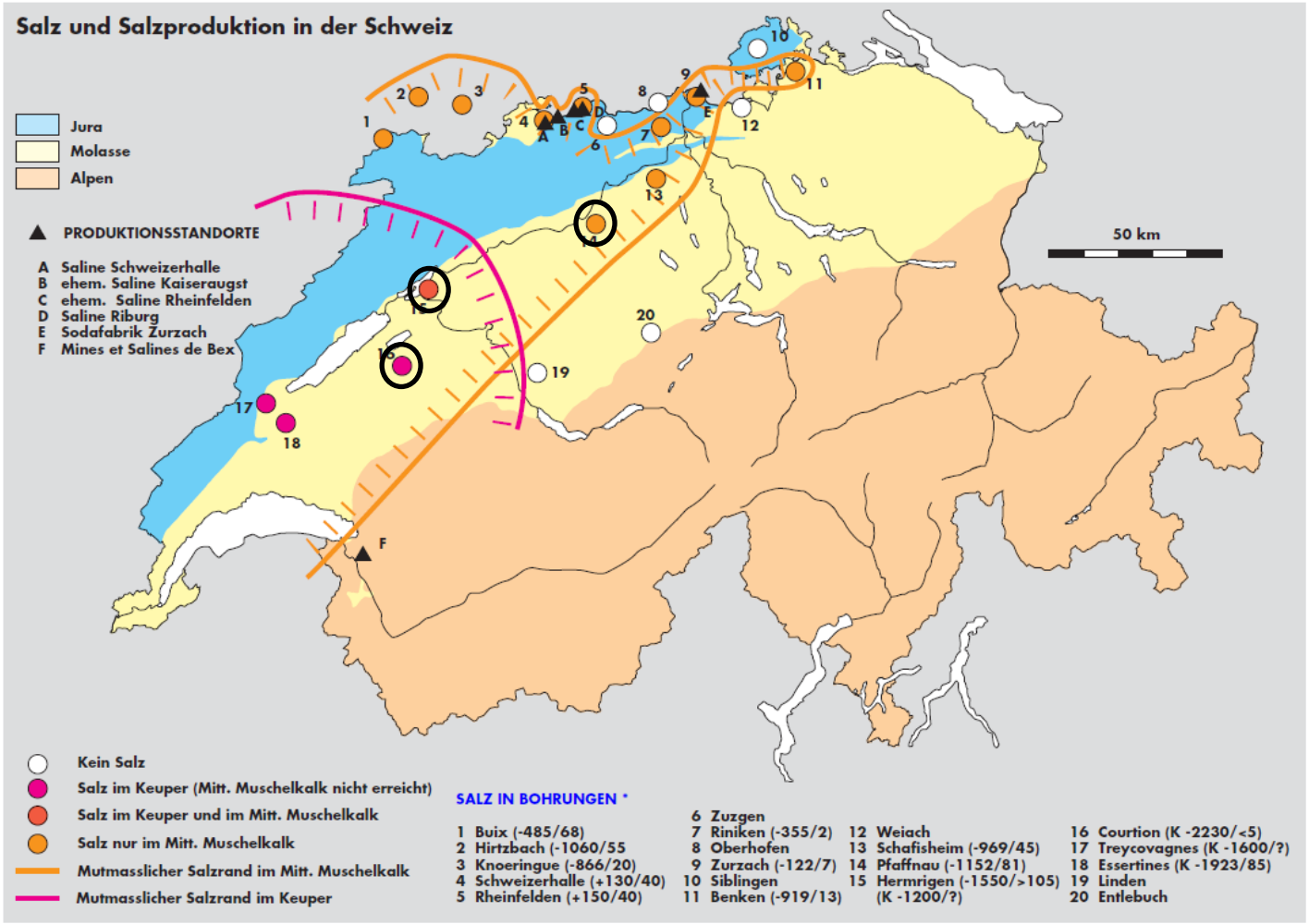
Schweizerische Eidgenossenschaft. (2019). *Swiss Geoportal*. https://map.geo.admin.ch/

Analysis of salt deposits in Switzerland - salt map



Kündig R, et. al. (1997) Die Mineralischen Rohstoffe der Schweiz,

Analysis of salt deposits in Switzerland - salt map



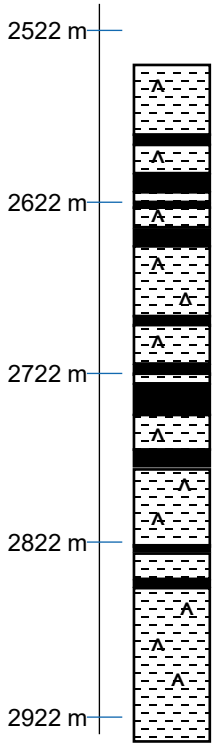
Kündig R, et. al. (1997) Die Mineralischen Rohstoffe der Schweiz,

Sites:

- Essertine
- Hermrigen
- Pfaffnau

Sites: Stratigraphic column of Essertine, Hermrigen, Pfaffnau

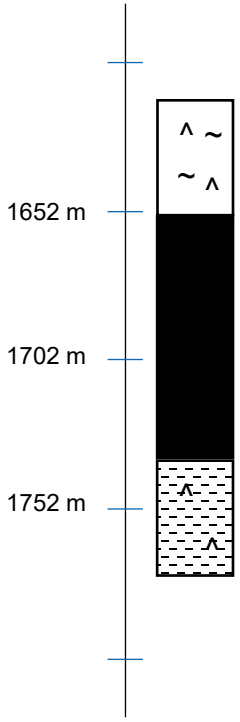
Borehole depth



Salt containing: 350m
Rock salt: 85m

Essertine

Borehole depth



Salt 1652 m – 1733m
Rock salt: 81m

Report on Salt content
1652 – 1655m Salt (no val.)
- 1660m Salt: 30%
1665 – 1730m Salt: 85-95 %

1734-1740m Anhydrite 95%,
Salt (no val.)

Pfaffnau

Legend:

- Rock salt
- Clay stone
- Marl stone
- Anhydrite

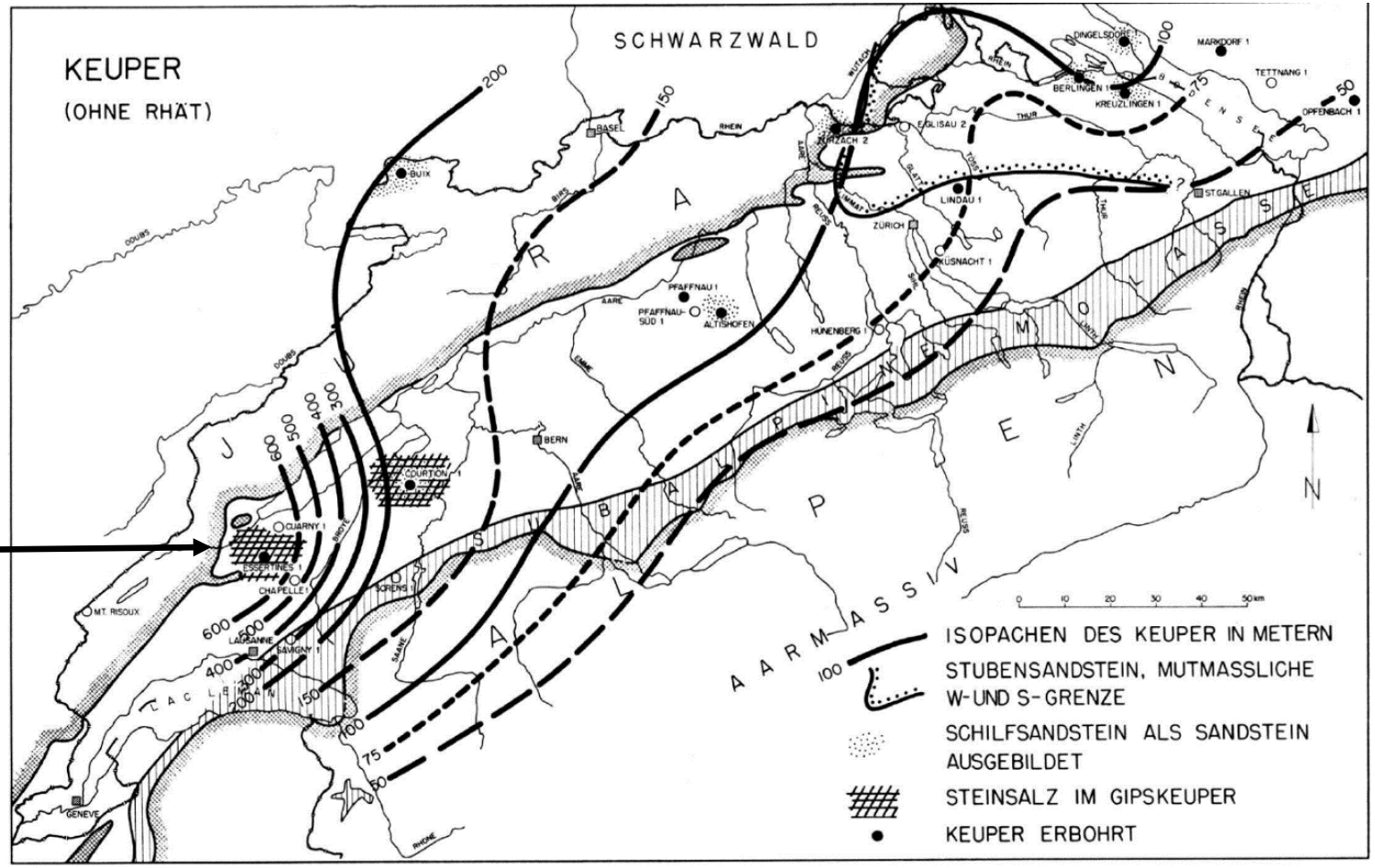
Rock salt: 114m
Depth: 2310m
In a block

Hermrigen

Büchi P, et. al. (1965) Geologische Ergebnisse der Erdölexploration auf das Mesozoikum im Untergrund des schweizerischen Molassebeckens, Bulletin der Vereinigung Schweiz. Petroleum-Geologen und -Ingenieure

Sites: Area containing the salt layer

Essertine
~10x15km

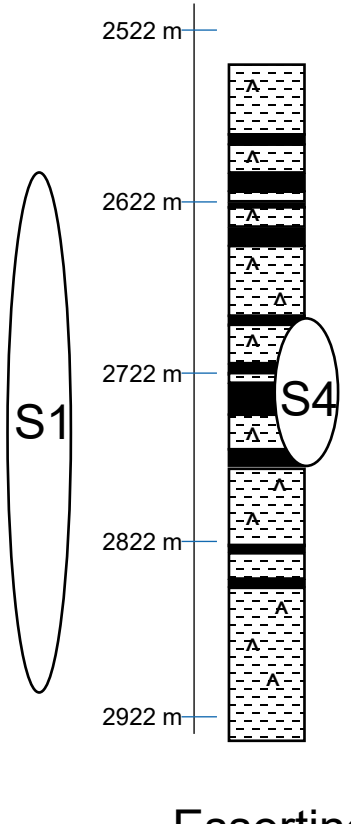


- No data found for Hermrigen and Pfaffnau
- No data found on the evolution of thickness for Essertine
- Potential calculation per km^2

Büchi P, et. al. (1965) Geologische Ergebnisse der Erdölexploration auf das Mesozoikum im Untergrund des schweizerischen Molassebeckens, Bulletin der Vereinigung Schweiz. Petroleum-Geologen und -Ingenieure

Sites: Scenarios of Essertine

Scenario (S)	1	2	3	4	5	6
Cavern						
Cavern height	- Design for full salt layer 350m	- For 270m salt layer	- Stable middle layer, 80m salt layer	- Like S3, 1cavern = collective of 3 parallel caverns	- Like S4, limiting P_{min}, P_{max}	- Like S5, constant pressure
Drawback Unlikely due to:	- Geology	- Geology	- economy	- operations	- economy	- TRL? - Brine



Essertine

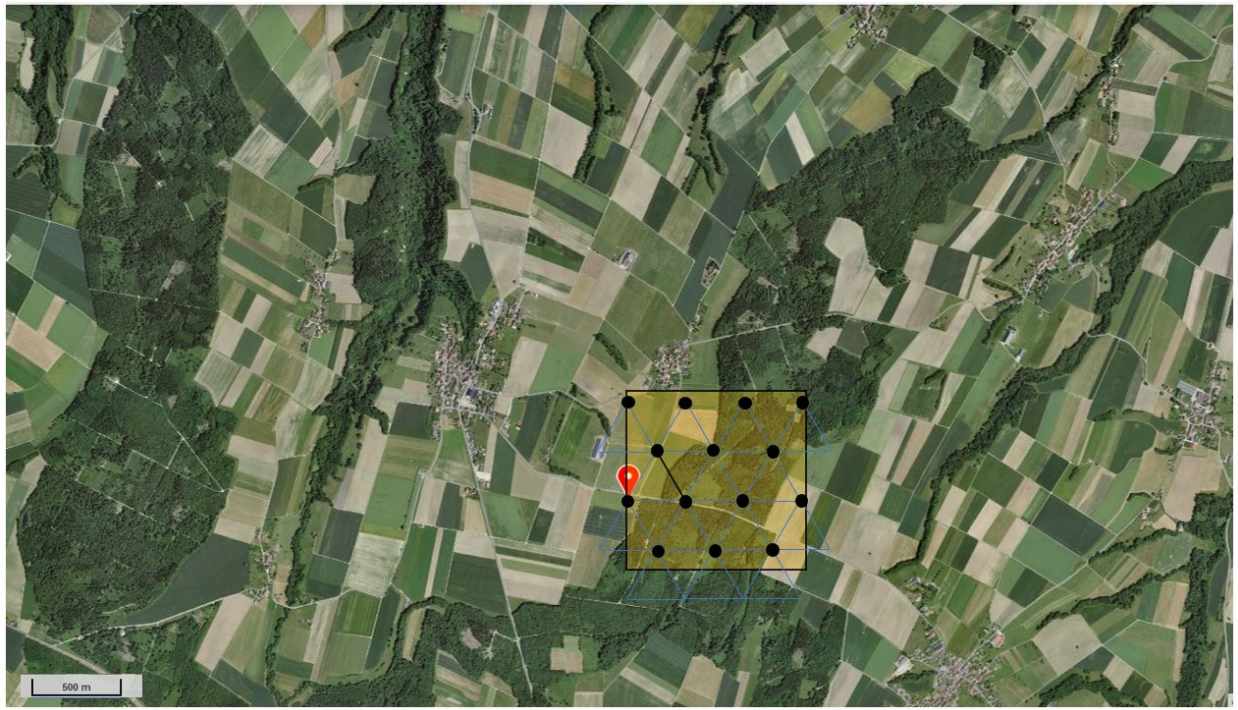
Source or Reference: APA citation style

Sites: Key data

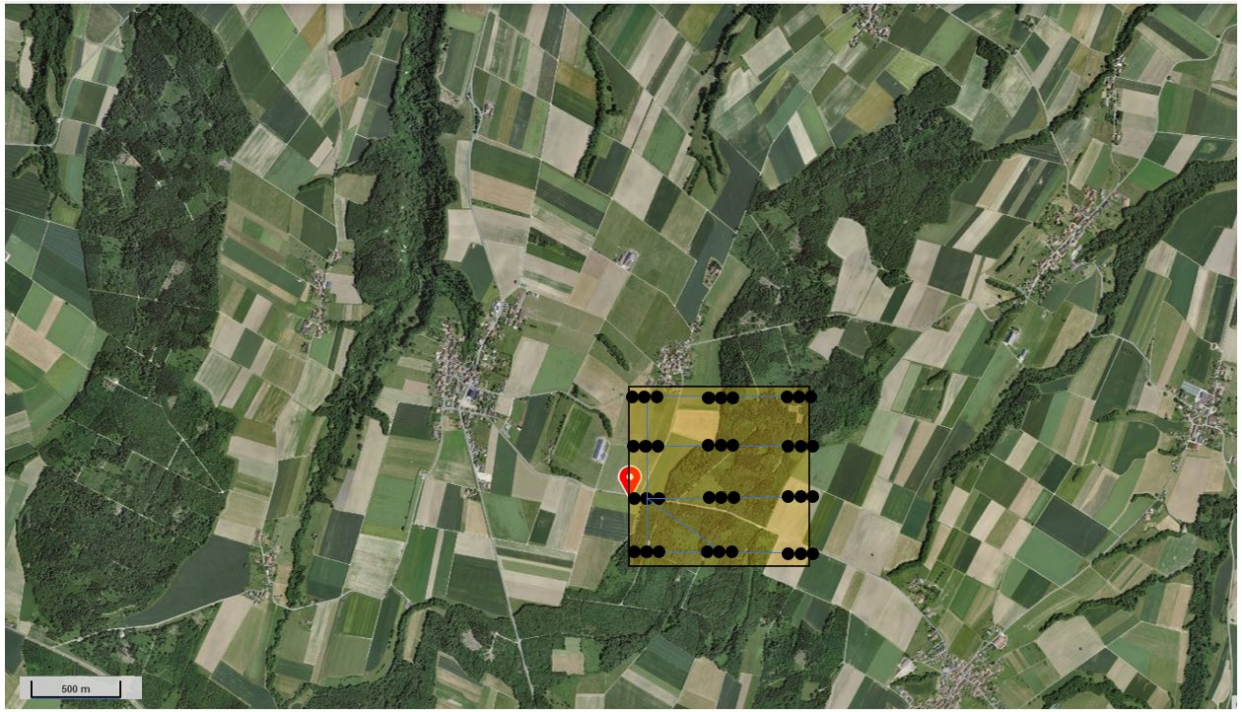
	Essertine			Hermrigen	Pfaffnau
Scenario	1	4	6	4	4
# of || caverns for 1 site	1	3	3	3	5
Volume [m^3]	~880e3	~600e3	~600e3	330e3	~170e3
Time to drill [year]	~12	~3	~3	1.5	~0.5
Filling factor	0.5	0.5	0.5	0.8	0.8
P_{Min} – P_{Max} [bar]	175-465	178-475	360 (const.)	154-413	111-295
Energy / cav. [GWh_{LHVH2}]	195	135	168	110	47
CAPEX [CHF]	113e6	105e6	88e6	78e6	30e6
CAPEX [CHF/MWh_{LHVH2}]	575	773	526	716	1300
# cav./km^2	14	12	12	12	12
# TWh/km^2	2.7	1.6	2.0	1.3	0.6

Sites: Scenarios of Essertine

Scenario 1,2, 3



Scenario 4, 5, 6



Initial borehole Essertine

Area of 1km^2

Salt cavern

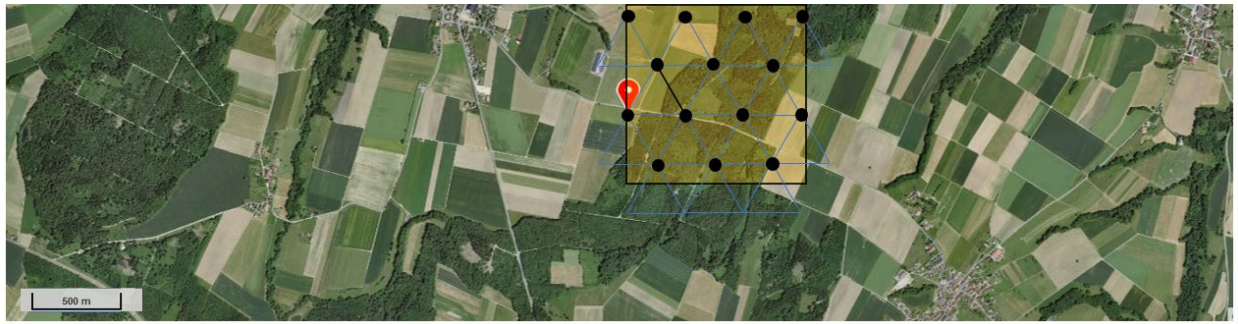
Distance between caverns

Google Maps. (2024). Google Maps. Google Maps; Google. https://www.google.com/maps

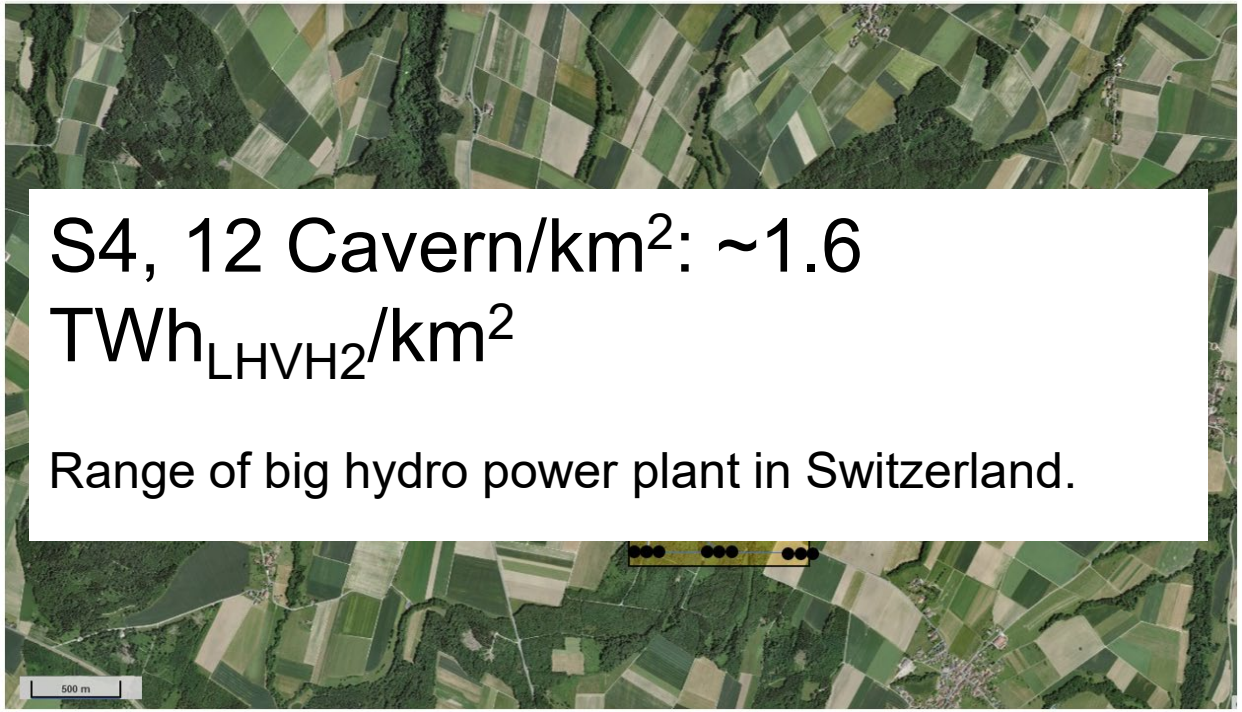
Sites: Scenarios of Essertine

Scenario 1,2, 3

S1, 14 Cavern/km^2:
~2.7 TWh_{LHVH2}/km^2



Scenario 4, 5, 6



S4, 12 Cavern/km^2: ~1.6
TWh_{LHVH2}/km^2

Range of big hydro power plant in Switzerland.

Initial borehole Essertine

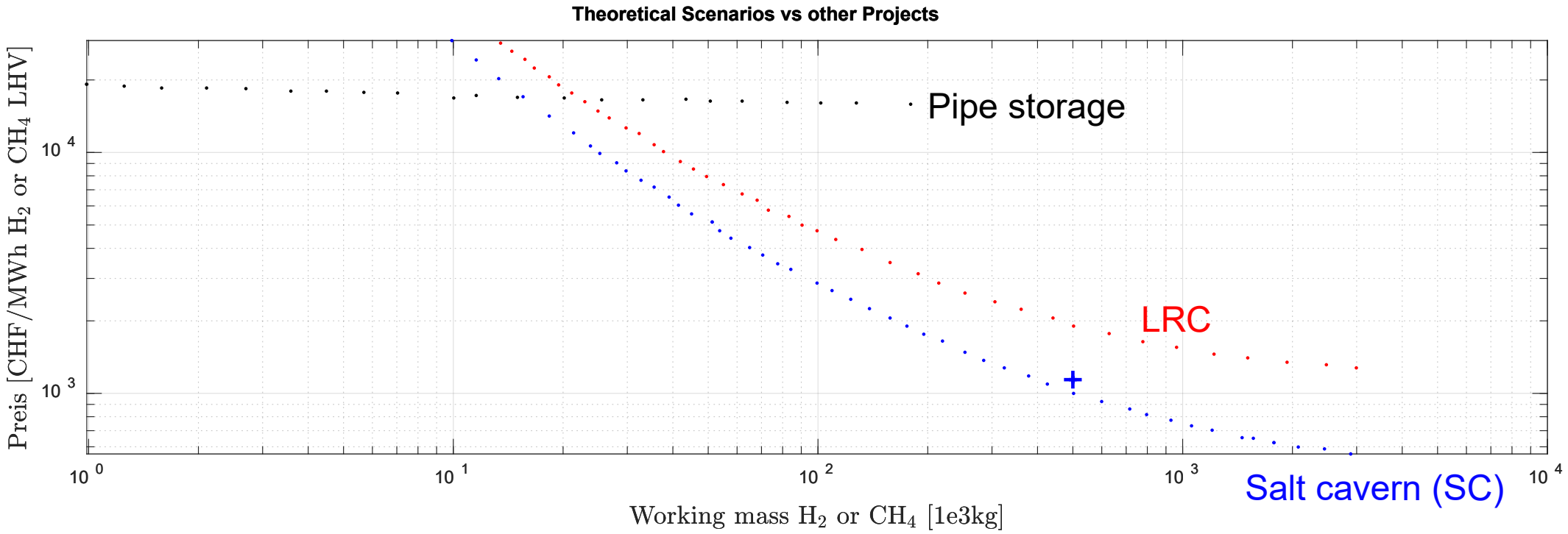
Area of 1km^2

Salt cavern

Distance between caverns

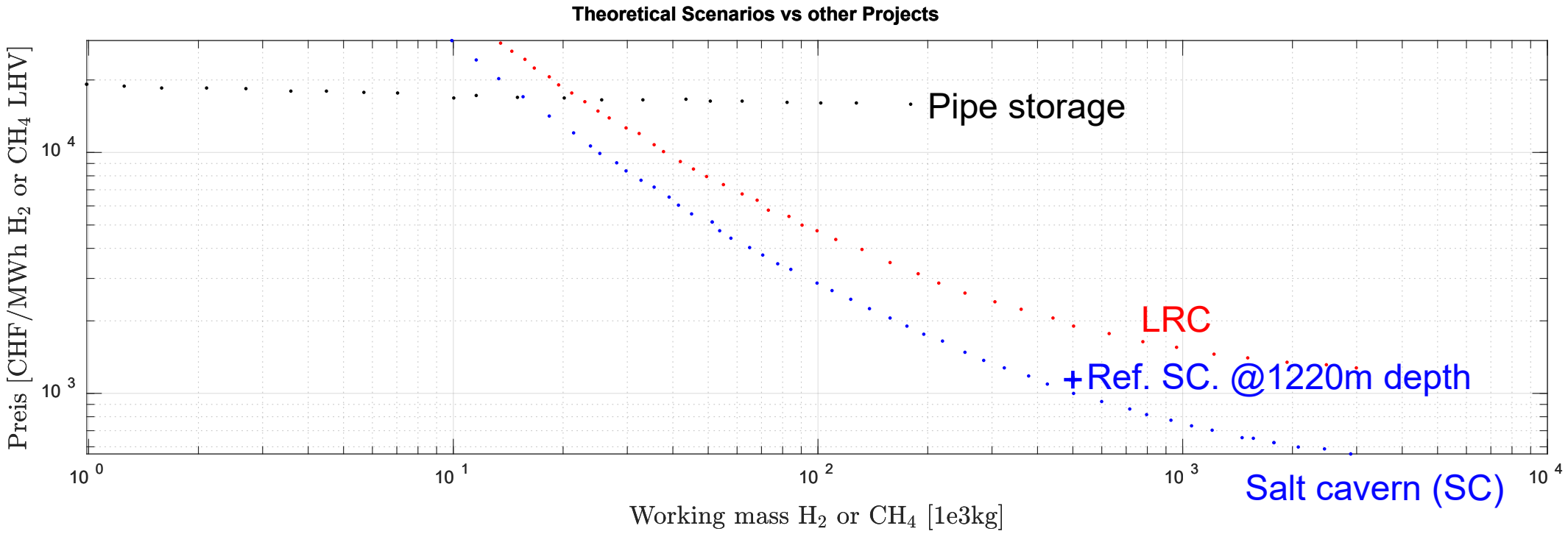
Google Maps. (2024). Google Maps. Google Maps; Google. https://www.google.com/maps

Sites: Evaluation

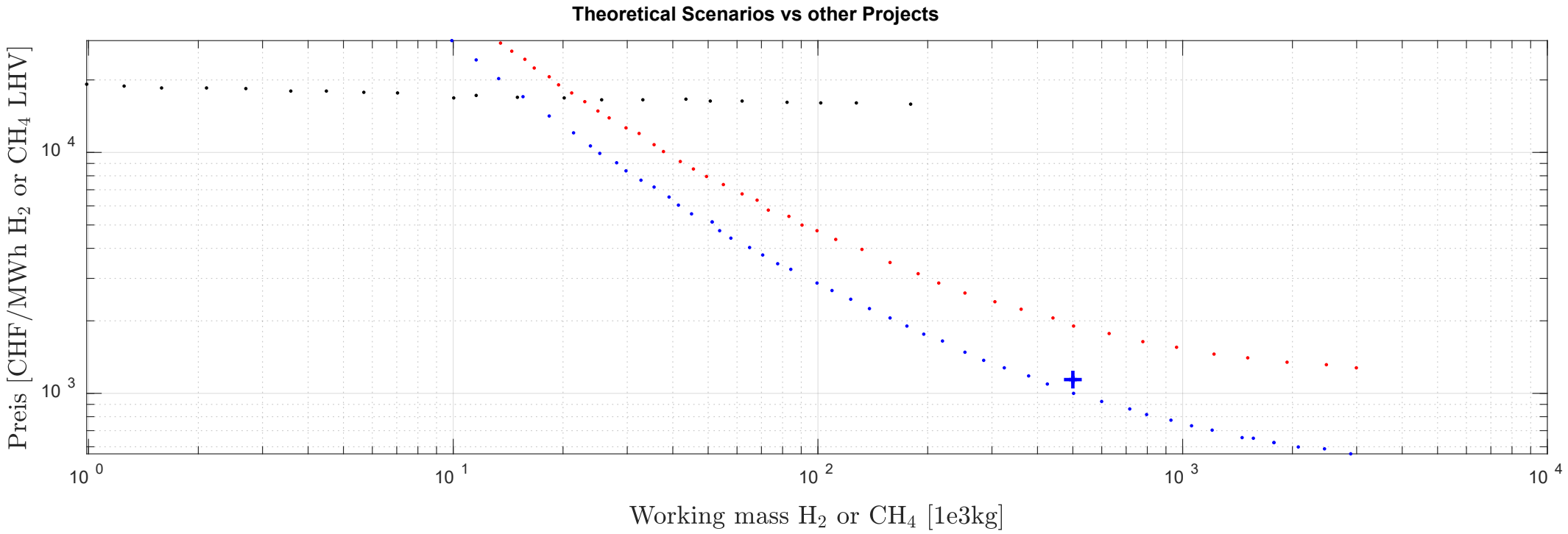


After: Papdias D (2021). Bulk storage of hydrogen, International journal o f hydrogen energy

Sites: Evaluation

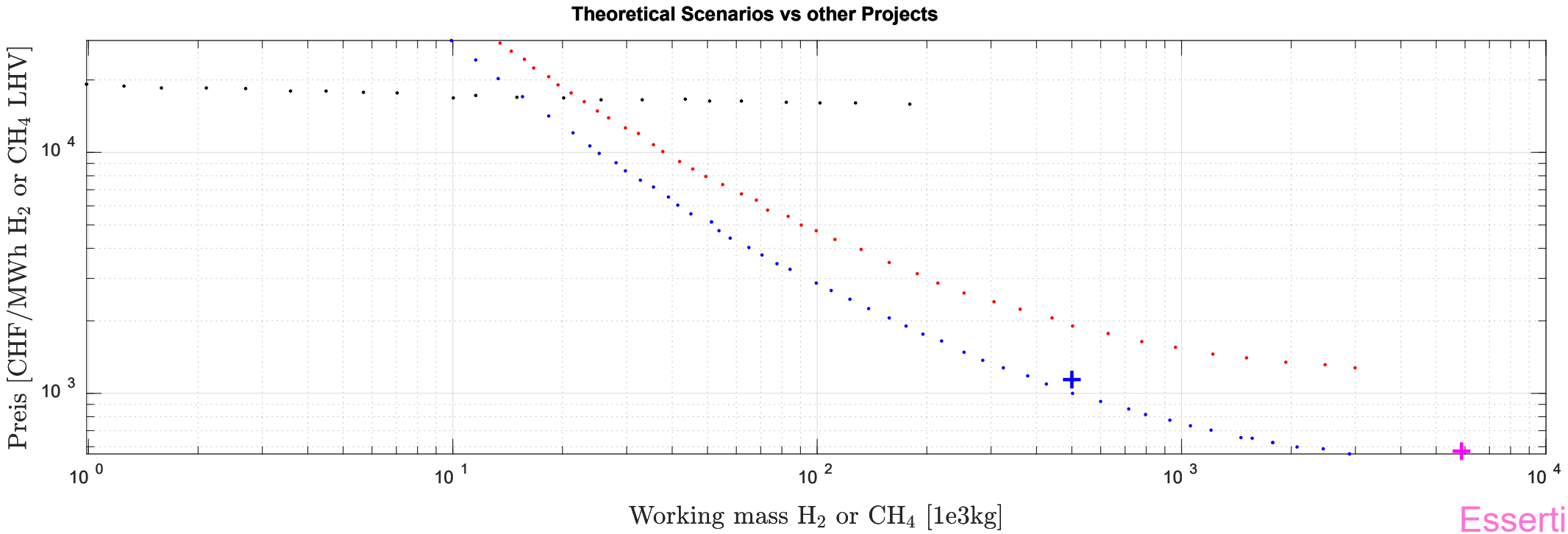


Sites: Evaluation



- Pipe storage
- LRC
- Salt cavern (SC)
  + Ref. SC. @1220m depth

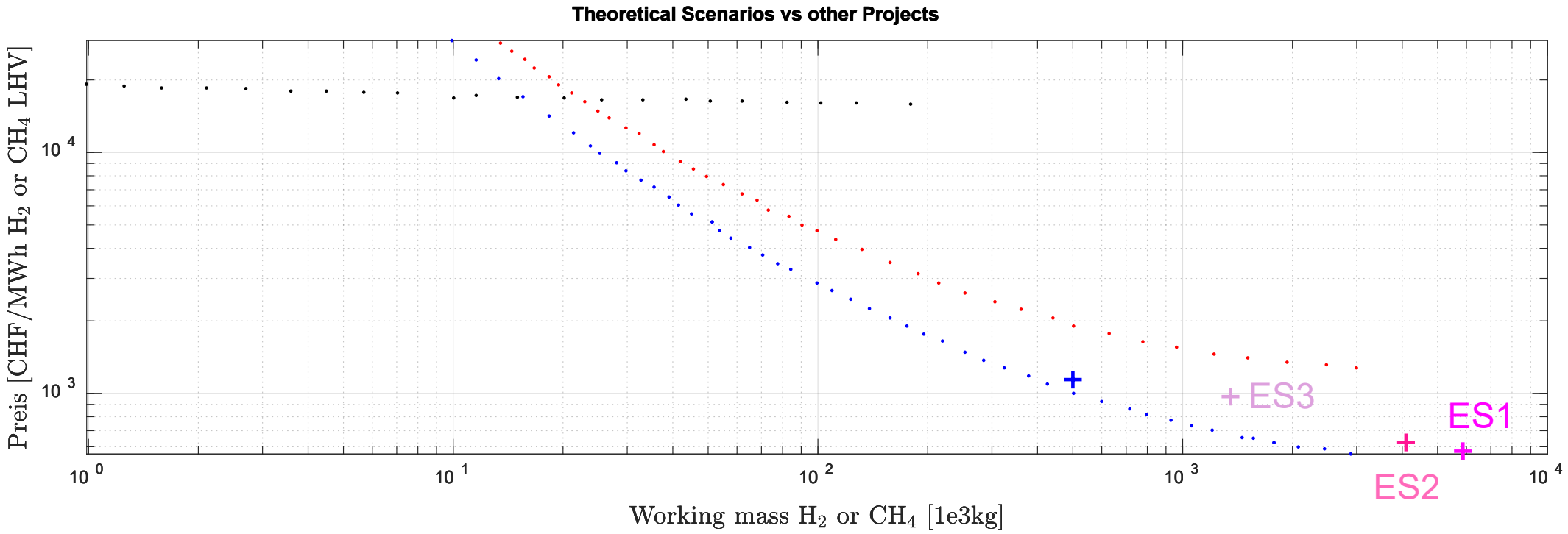
Sites: Evaluation



Essertine S1

- Pipe storage
- LRC
- Salt cavern (SC)
  + Ref. SC. @1220m depth

Sites: Evaluation



Pipe storage

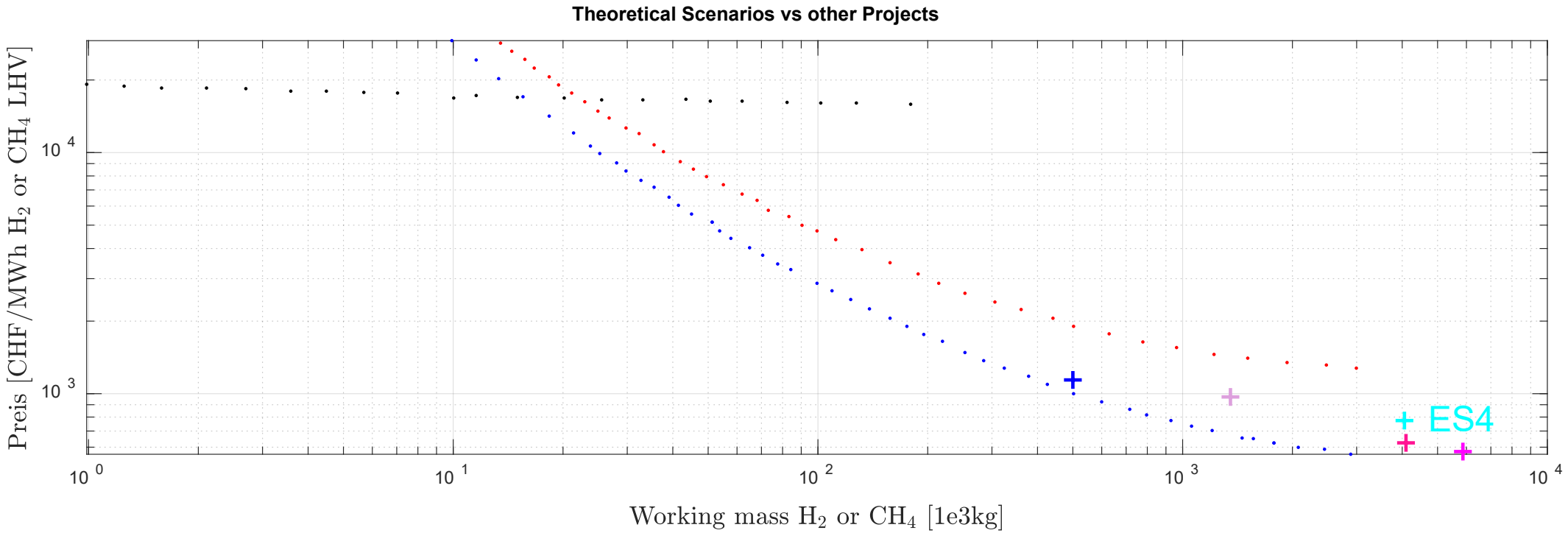
LRC

Salt cavern (SC)

+ Ref. SC. @1220m depth

+ Essertine (ES1)

Sites: Evaluation



Pipe storage

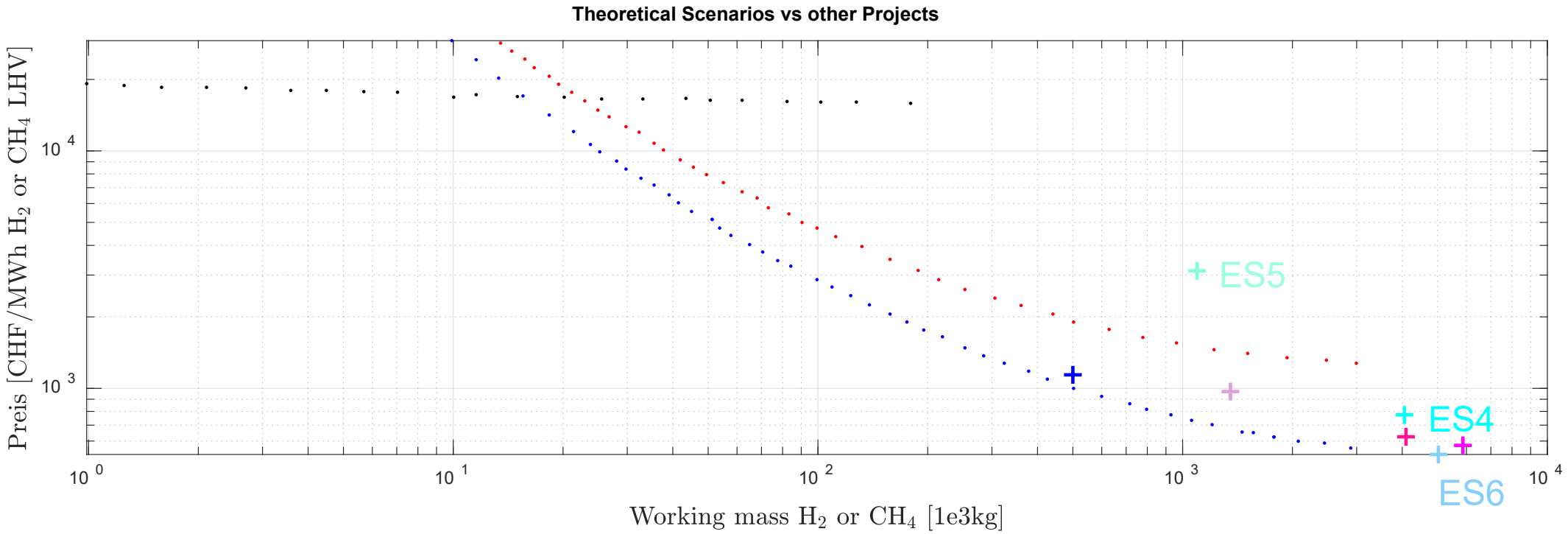
LRC

Salt cavern (SC)

+ Ref. SC. @1220m depth

+ Essertine (ES1, ES2, ES3)

Sites: Evaluation



Pipe storage

LRC

Salt cavern (SC)

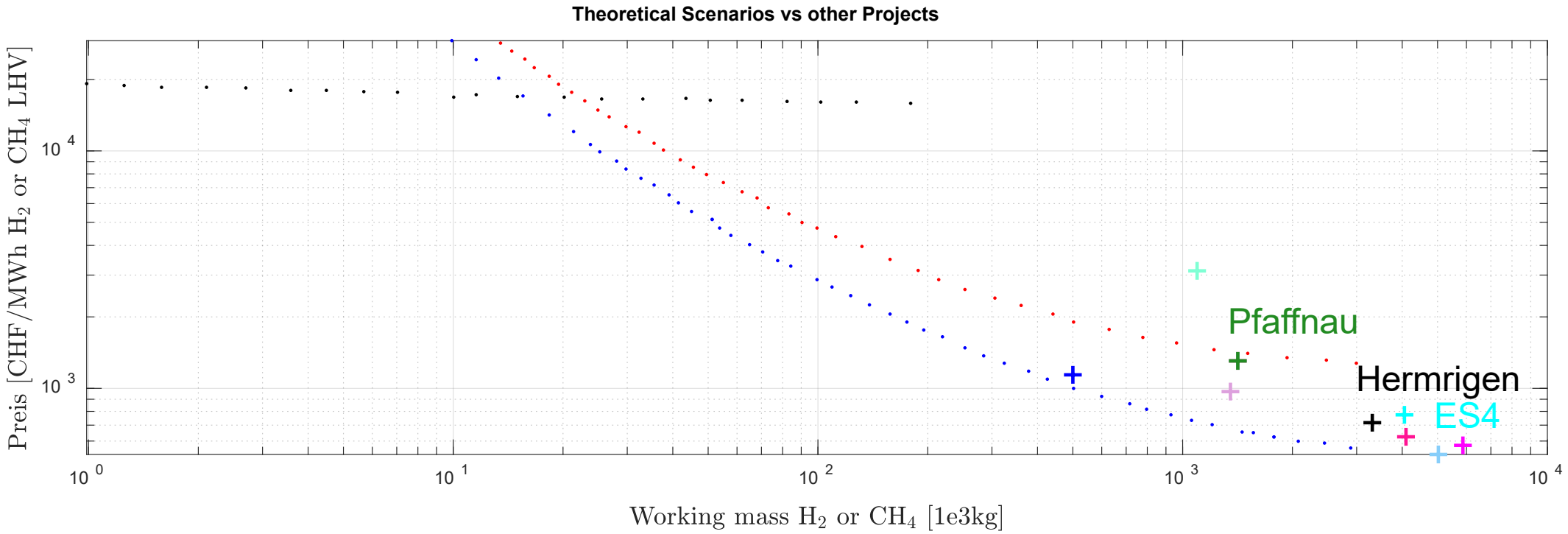
+ Ref. SC. @1220m depth

+ Essertine (ES1, ES2, ES3)

+ ES4

Source or Reference: APA citation style

Sites: Evaluation



Pipe storage

LRC

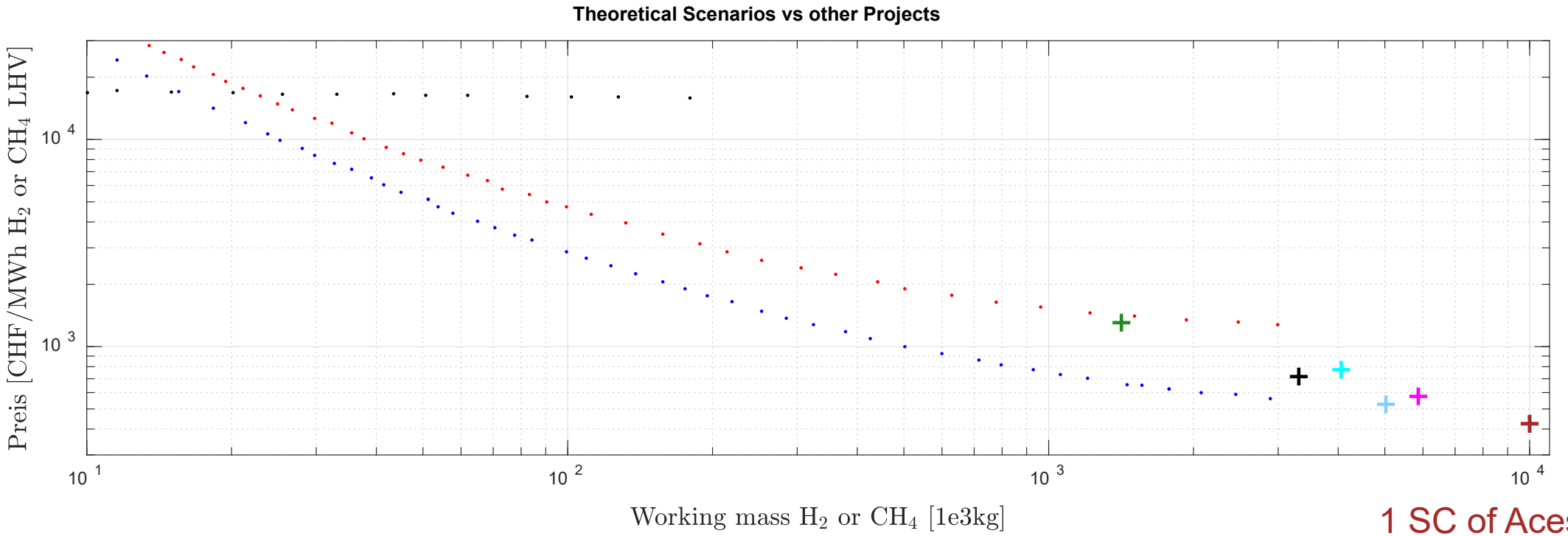
Salt cavern (SC)

+ Ref. SC. @1220m depth

+ Essertine (ES1, ES2, ES3)

+ ES4, ES5, ES6

Sites: Evaluation

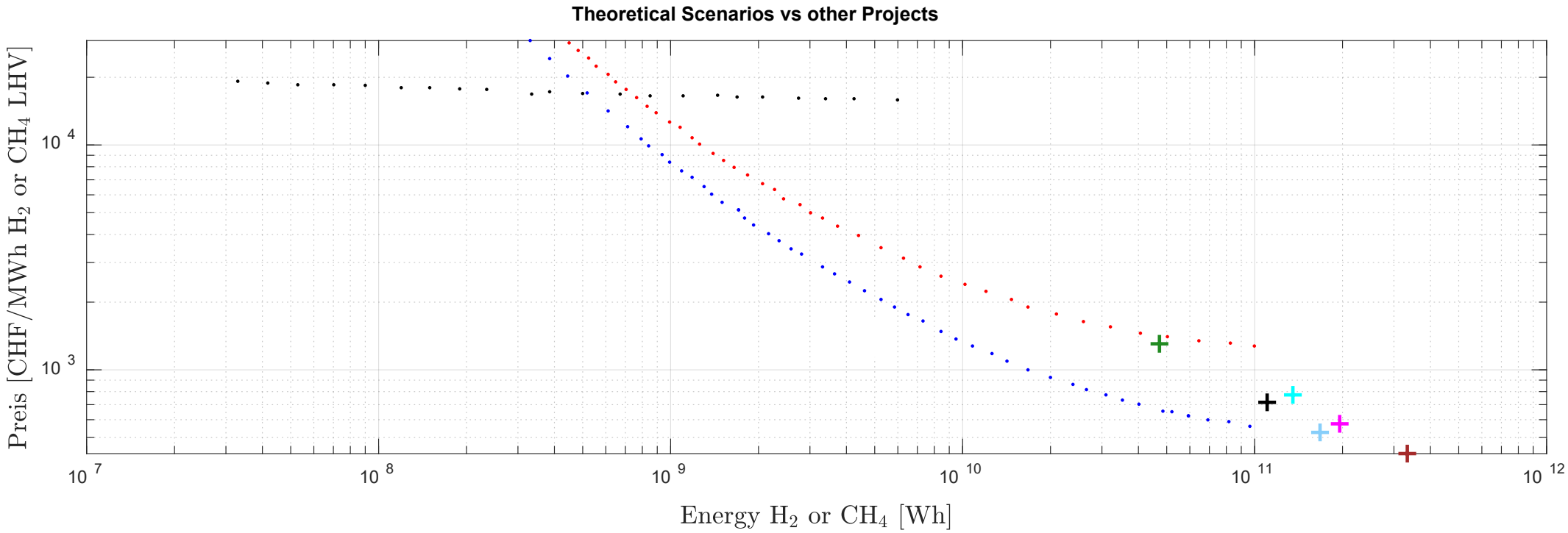


1 SC of AcesDelta

- Pipe storage
- LRC
- Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau

Sites: Evaluation

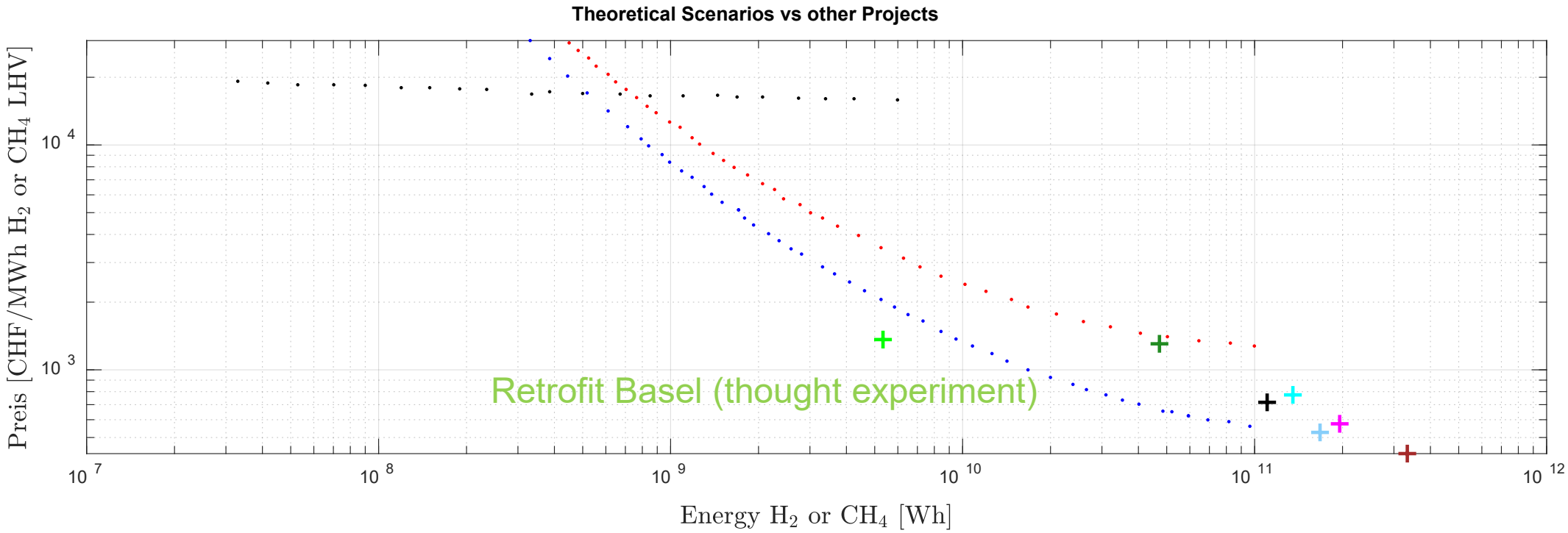


Pipe storage
LRC
Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau

+ 1 SC of AcesDelta

Sites: Evaluation

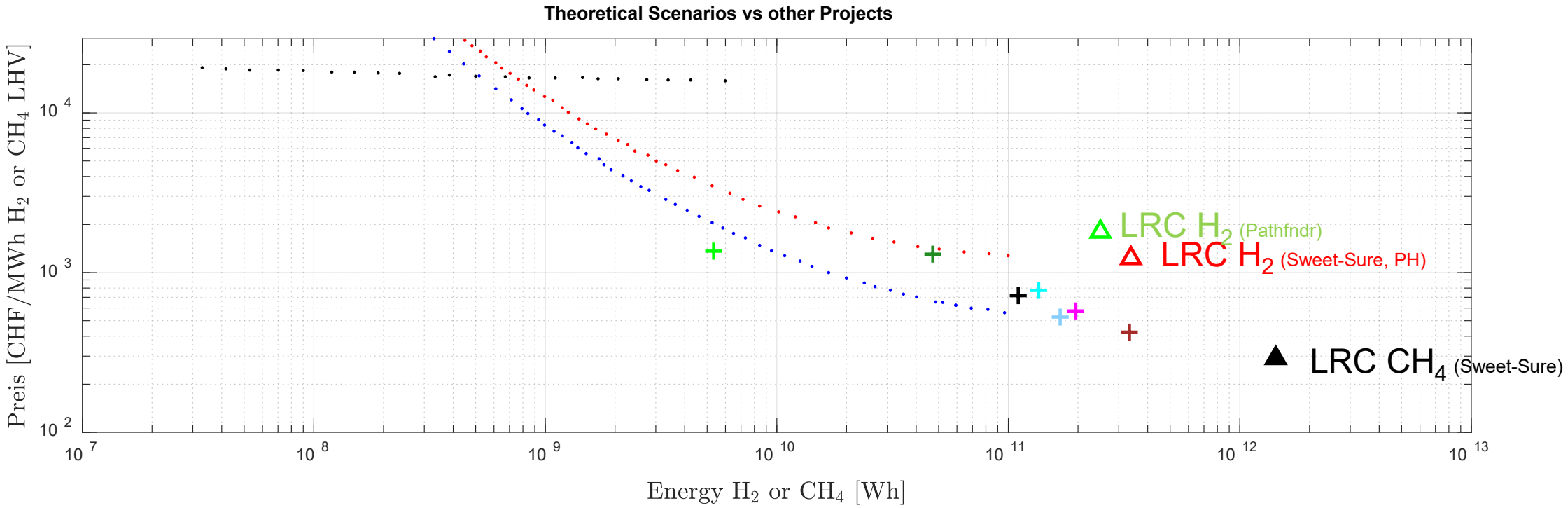


Pipe storage
LRC
Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau
+ Retrofit Basel (thought experiment)

+ 1 SC of AcesDelta

Sites: Evaluation

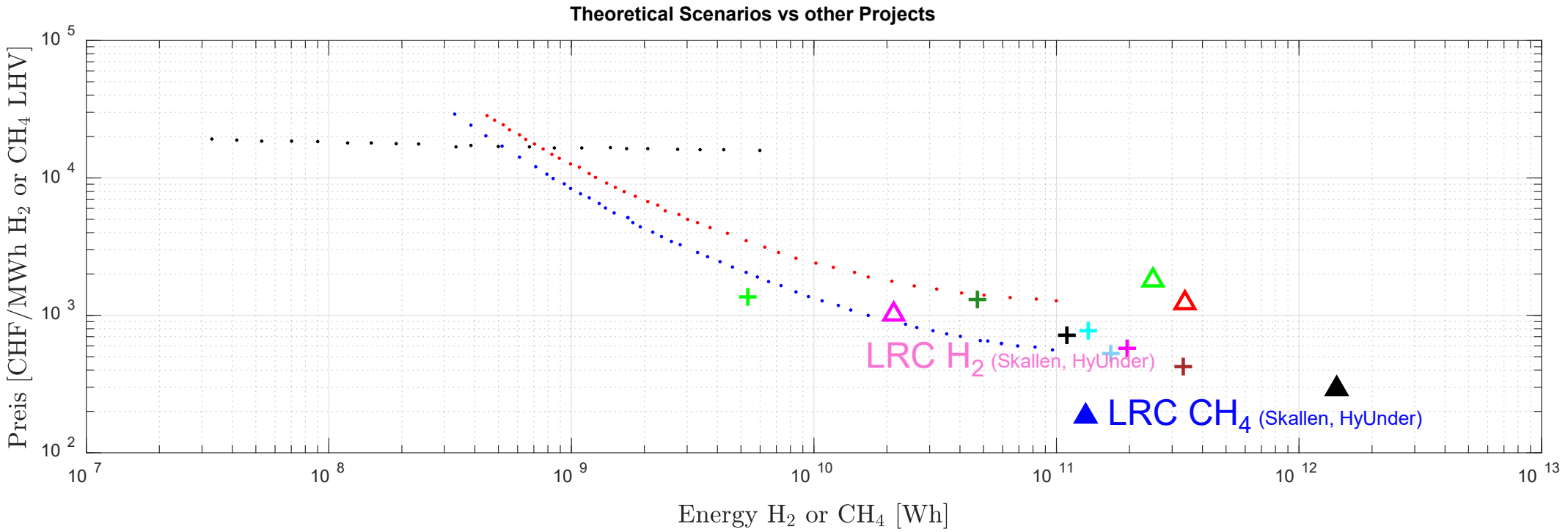


Pipe storage
LRC
Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau
+ Retrofit Basel (thought experiment)

+ 1 SC of AcesDelta

Sites: Evaluation

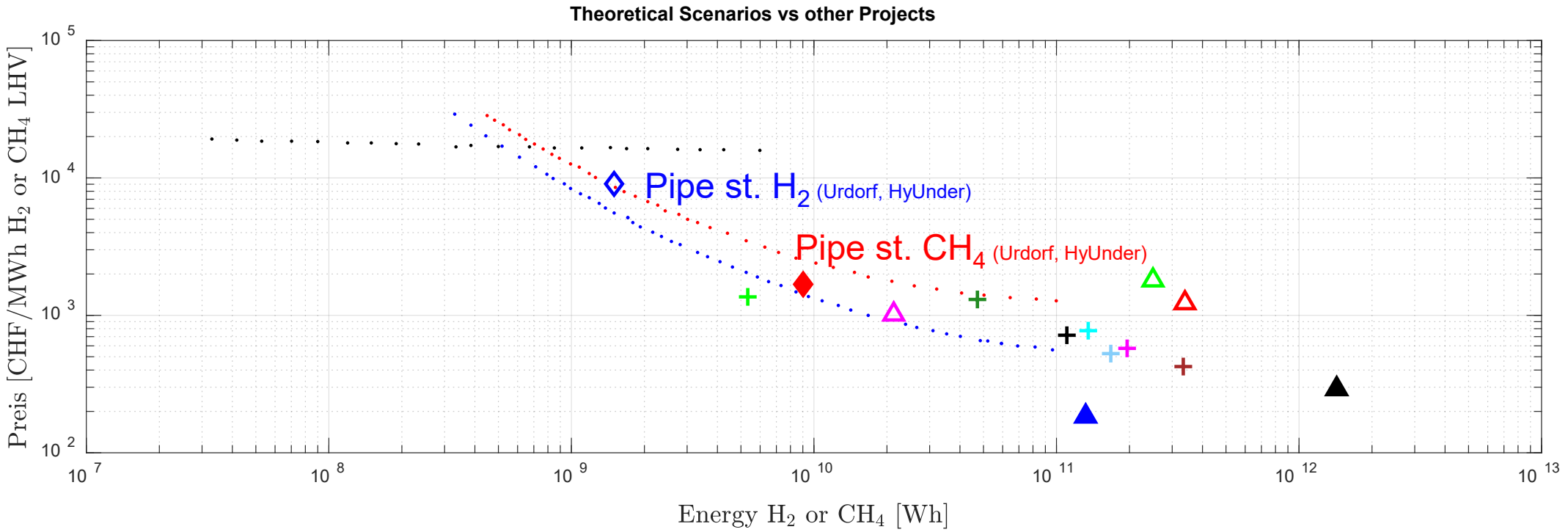


Pipe storage
LRC
Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau
+ Retrofit Basel (thought experiment)

+ 1 SC of AcesDelta
Δ LRC H_2 (Pathfndr)
Δ LRC H_2 (Sweet-Sure, PH)
Δ LRC CH_4 (Sweet-Sure)

Sites: Evaluation



Pipe storage
LRC
Salt cavern (SC)

+ Essertine (ES1)
+ ES4, ES6
+ Hermrigen
+ Pfaffnau
+ Basel (thought experiment)

Δ LRC H_2 (Pathfndr)
Δ LRC H_2 (Sweet-Sure, PH)
▲ LRC CH_4 (Sweet-Sure)
▲ LRC CH_4 (Skallen, HyUnder)
Δ LRC H_2 (Skallen, HyUnder)

Summary

- **General - on studies and salt caverns**
- Potential studies should consider filling factor (interlayers, quality of salt)
- Salt caverns are an established and cheap technology for bulk storage of energy
- Some Salt caverns are operated since the 70ties
- Due to the creep of salt, salt caverns have for certain an end-of-life date
- With increasing temperature creep of salt increases exponentially

- **Switzerland**
- A lot of resources went already into the search for geological storage
- To make decisions, geological data is required, which is often private
- To build salt caverns in Switzerland the limiting parameters must be extended
- Advancement in the salt cavern, building in less favorable environments possible
- Essertine would be a high-risk project

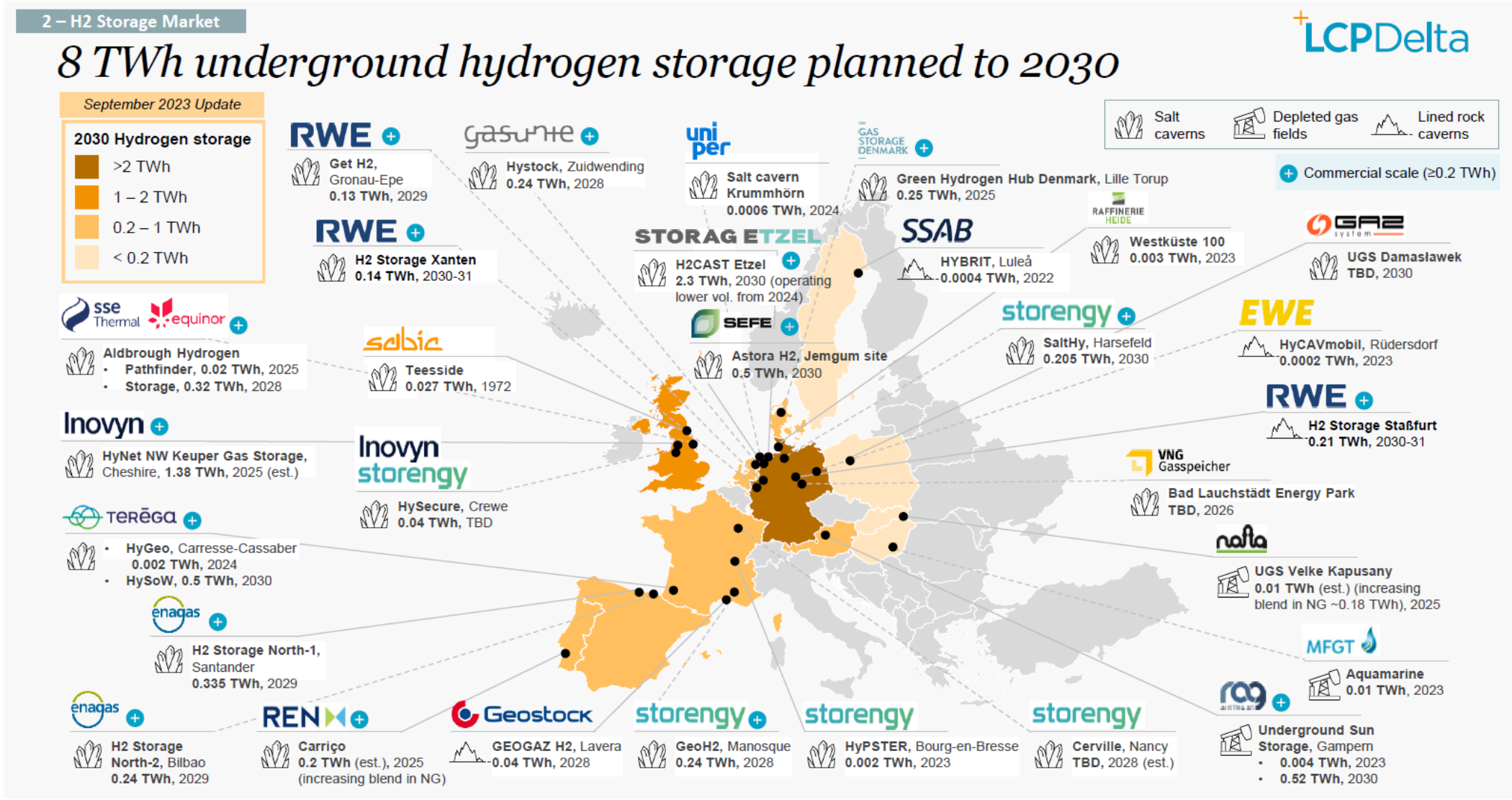
Outlook

- Finalize report on salt cavern assessment
- Assessment on seasonal storage

Source or Reference: APA citation style

Outlook

Source or Reference: APA citation style



Martinez N, (2024) LONG-DURATION ENERGY STORAGE , NetZero Week

sweet swiss energy research for the energy transition

PATHFNDR

Dr. Pascal Häfliger
Pascal.haeflige@psi.ch
PSI
Fuel Cell Systems and Diagnostics Group

PATHFNDR: www.sweet-pathfndr.ch

ETH zürich Empa PAUL SCHERRER INSTITUT PSI zhaw HOCHSCHULE LUZERN UNIVERSITÉ DE GENÈVE EPFL TU Delft