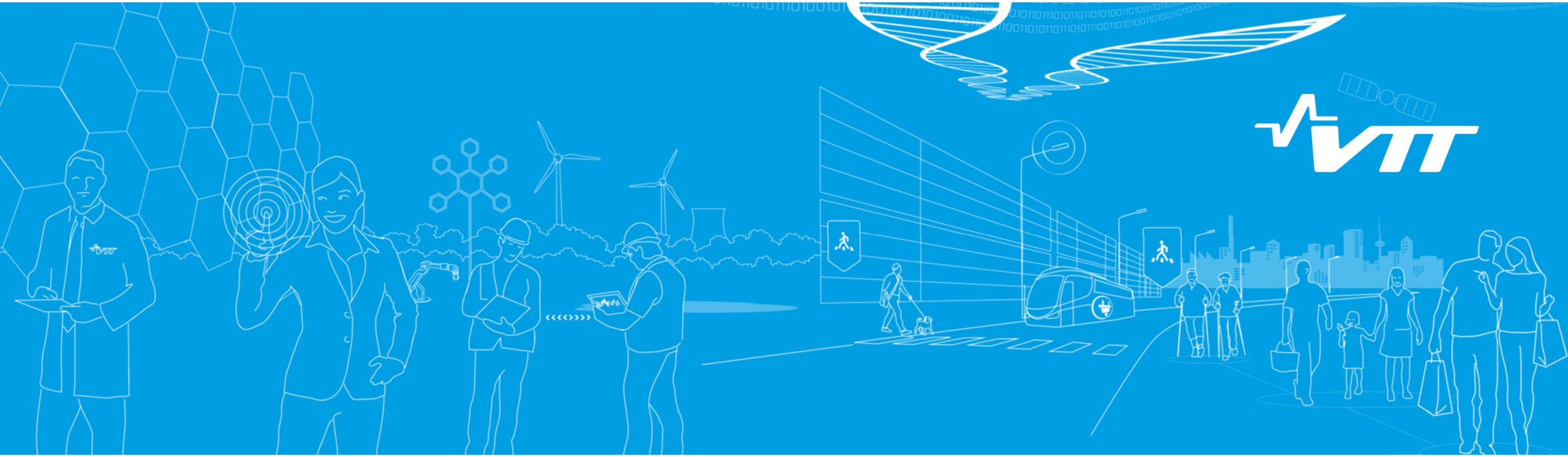

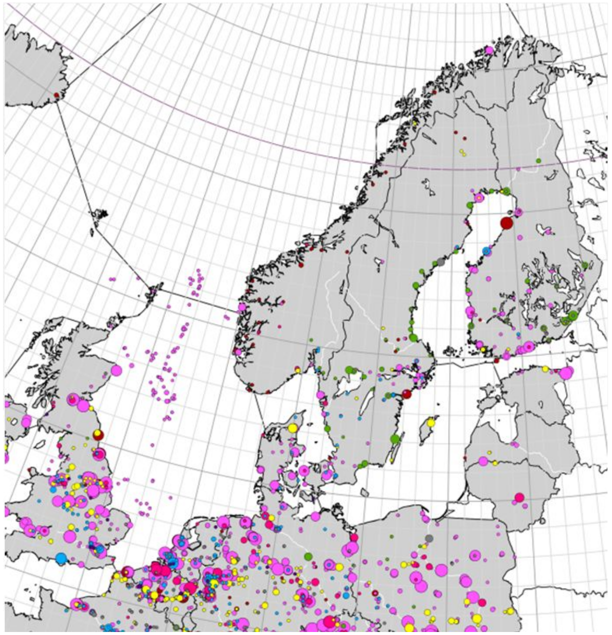

Scenarios and new technologies for a North-European CO_2 transport infrastructure in 2050

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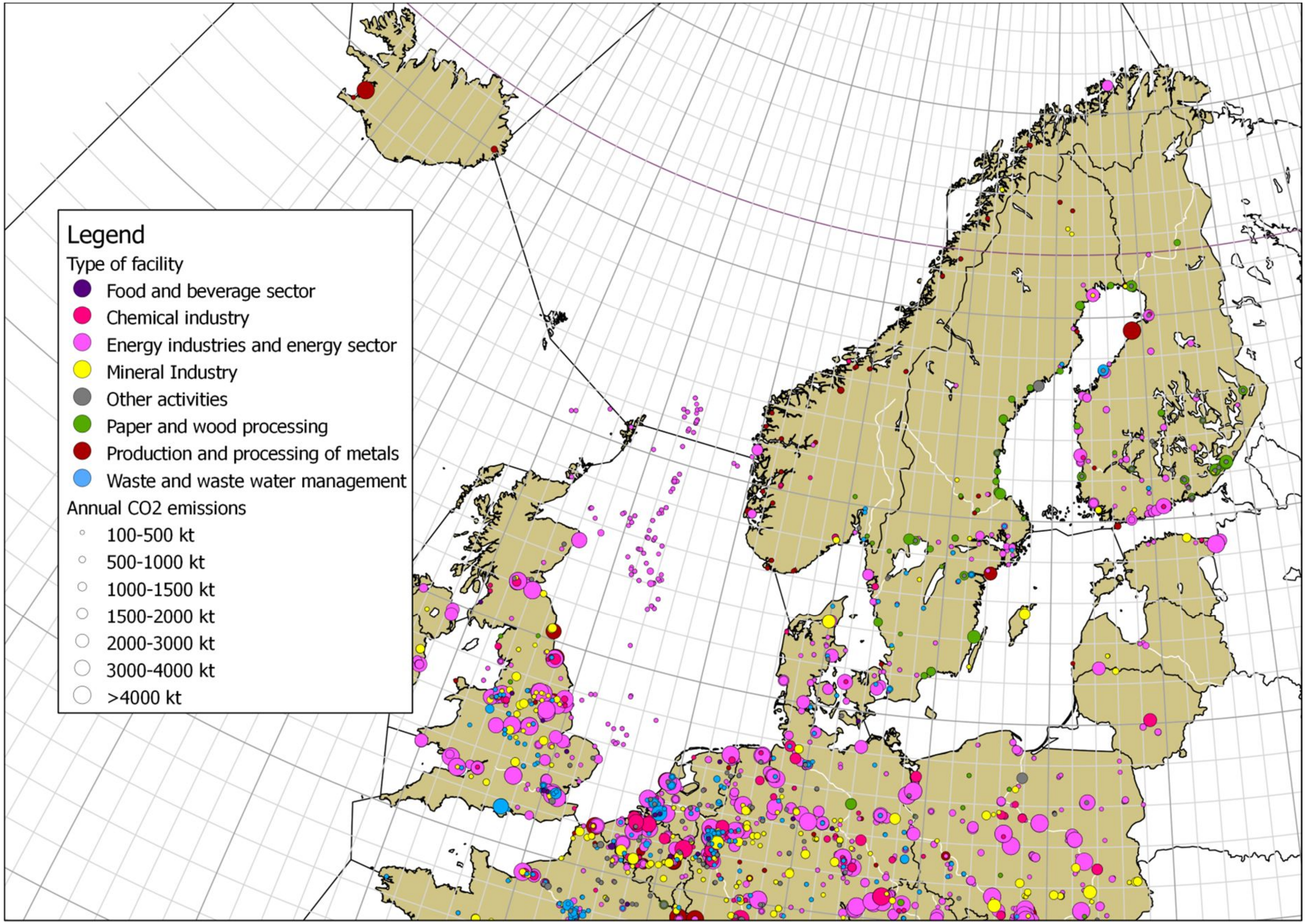
Introduction

- The Finnish Carbon Capture and Storage Program (CCSP, 2011-2015) has assessed transport options and economics from North-European emission sources, with a focus on Finland and the Baltic Sea area.

- The goal in the presented work:
  - Quantify the effect of emission source location, transport technology and co-operation between actors on the cost of CO_2 transport in Europe until 2050.
  - Cavern storage technology is currently being investigated as a possible intermediate storage option in CCSP.

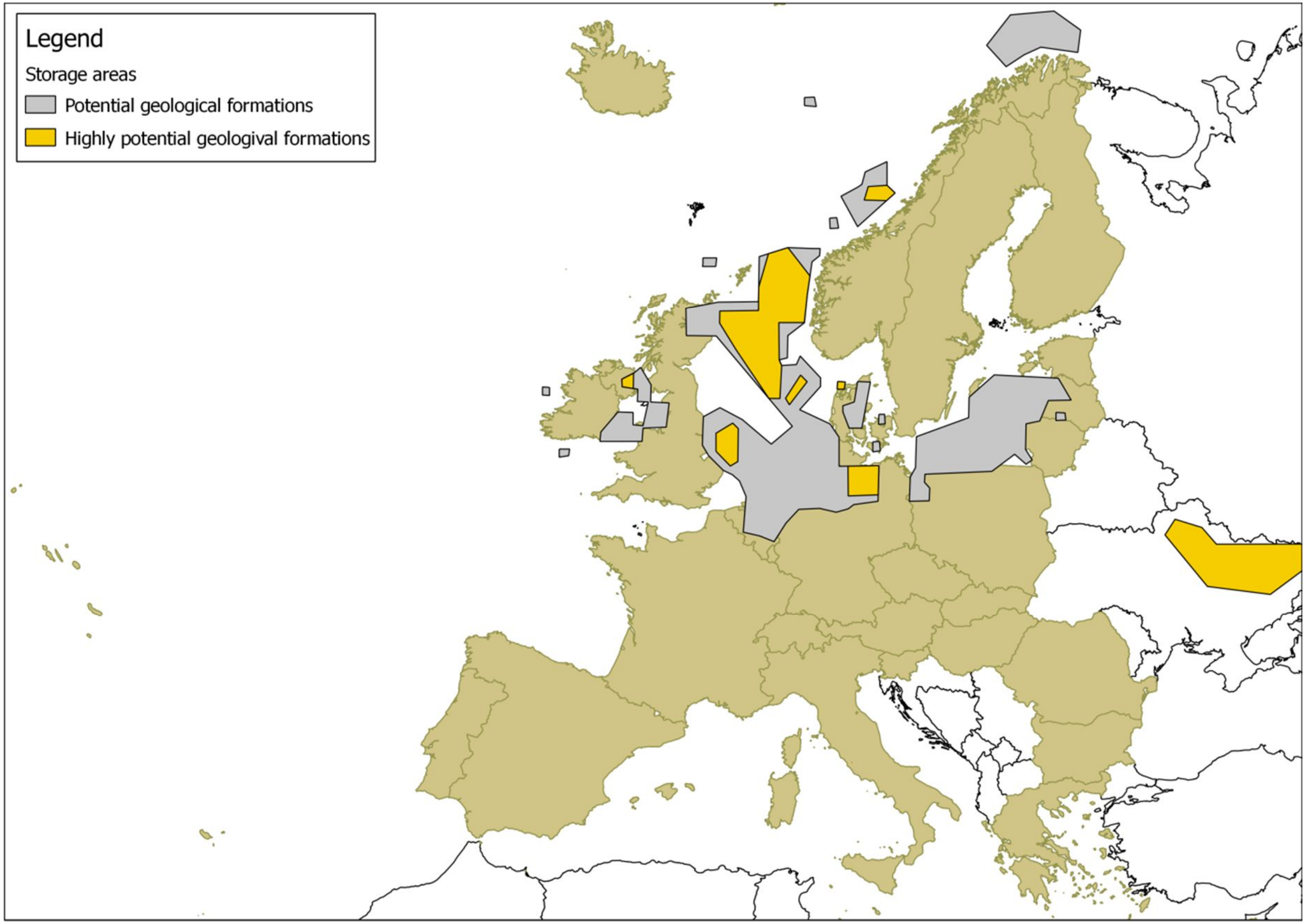
- How does our work differ from published infrastructure studies?
  - The past studies generally apply source-to-sink matching route optimization models to arrive at the most cost-efficient CO_2 transport networks.
  - In our approach, a set of pre-defined scenarios are used instead of a system optimization model to generate the CO_2 transport networks in 2050 and the associated transport costs.

The North-European CO_2 emission sources



(Data from EEA,2012)

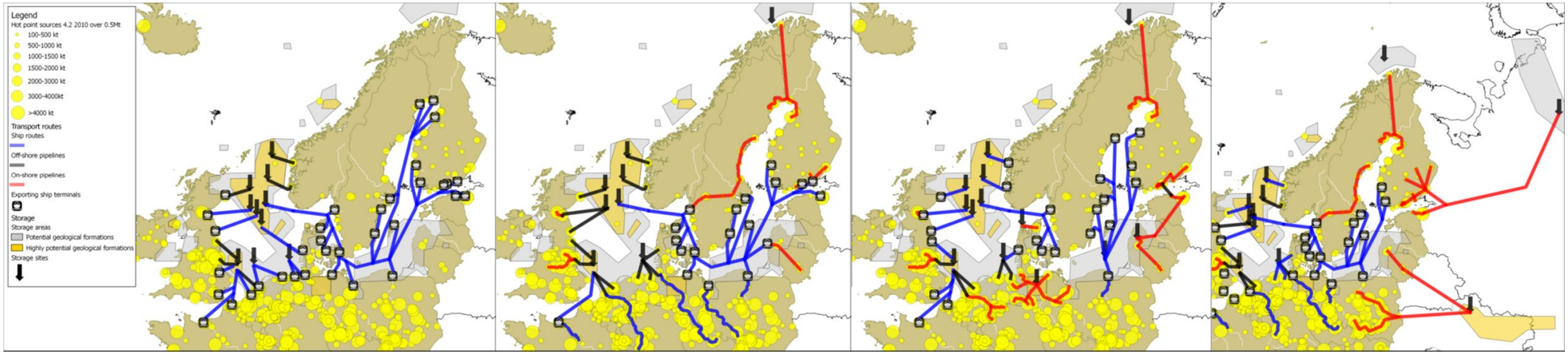
Storage possibilities in North-Europe



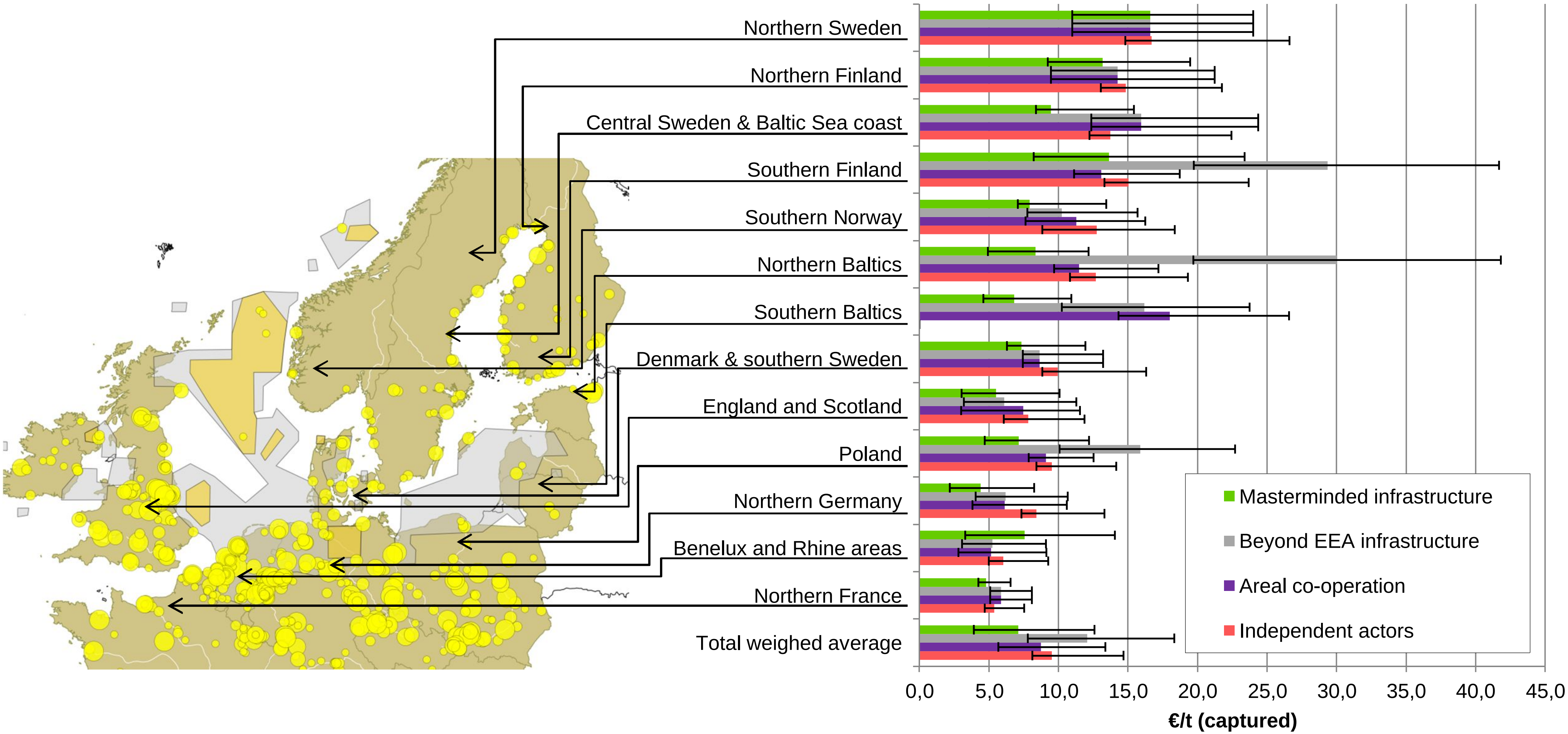
The four transport scenarios at a glance

Scenario	Defining character	Trunklines	Shared ship terminals	Storage
Independent actors	Less co-operation	No	No	Off-shore
Areal co-operation	Co-operation	Yes	Yes	Off-shore, Off-shore pipelines preferred
Beyond EEA infrastructure	Storage outside EEA allowed	Yes	Yes	On-Shore, Off-shore (EEA)
Masterminded infrastructure	High system efficiency	Yes	Yes	On & Off-Shore

Independent actors Areal co-operation Masterminded inf. Beyond EEA inf.



Scenario results



First conclusions: Modes of transport (1/2)

- The results indicate that ship transportation would often be the best transport option from the Baltic Sea region to final storage sites at the North Sea.

- Heavily industrialized areas around North Sea would benefit from a shared pipeline infrastructure.
  - Pipeline transport costs are sensitive to the distance, and can become high for isolated capture facilities far upstream from a main trunkline.
  - Open questions on how costs should be allocated between the users of a shared pipeline network.

- Joint transport infrastructure in the “Areal co-operation” scenario resulted in ~8% cost reduction compared to “independent actors” scenario where, only the largest point sources invest in CCS.
  - The cost reduction was ~25% in the “masterminded infrastructure” scenario.

First conclusions: Geological storage options (2/2)

- Use of the on-shore storage potential in Latvia and Germany would reduce transport cost levels.
  - Interesting trunkline options for Finland and the Baltics.
  - The resulting pipeline collection network from the German industries would seem one of the most economic CO_2 transport networks in the North Europe.

- If the storage potential in the southern Baltic Sea could be used, ship transport cost from the surrounding coasts would be reduced.
  - Possible barrier: Article 2 of the CCS directive limits the geological storage of CO_2 to within the EU and European Economic Area (EEA).

Intermediate storage of CO_2 underground

- Ship transport of CO_2 requires intermediate storage facilities acting as a buffer on the interface between ship transportation and capture plant or pipeline transportation.
  - Cylindrical steel tanks are the most commonly studied intermediate storage option.
  - An alternative option is to use underground storage facilities in rock caverns.

- Potential benefits from rock cavern intermediate storages:
  - Less space above ground compared to conventional tanks.
  - Economy of scale when the transported amount of CO_2 at the hub become high.

- Suitable bedrock conditions can be found in Northern Baltic Sea region.

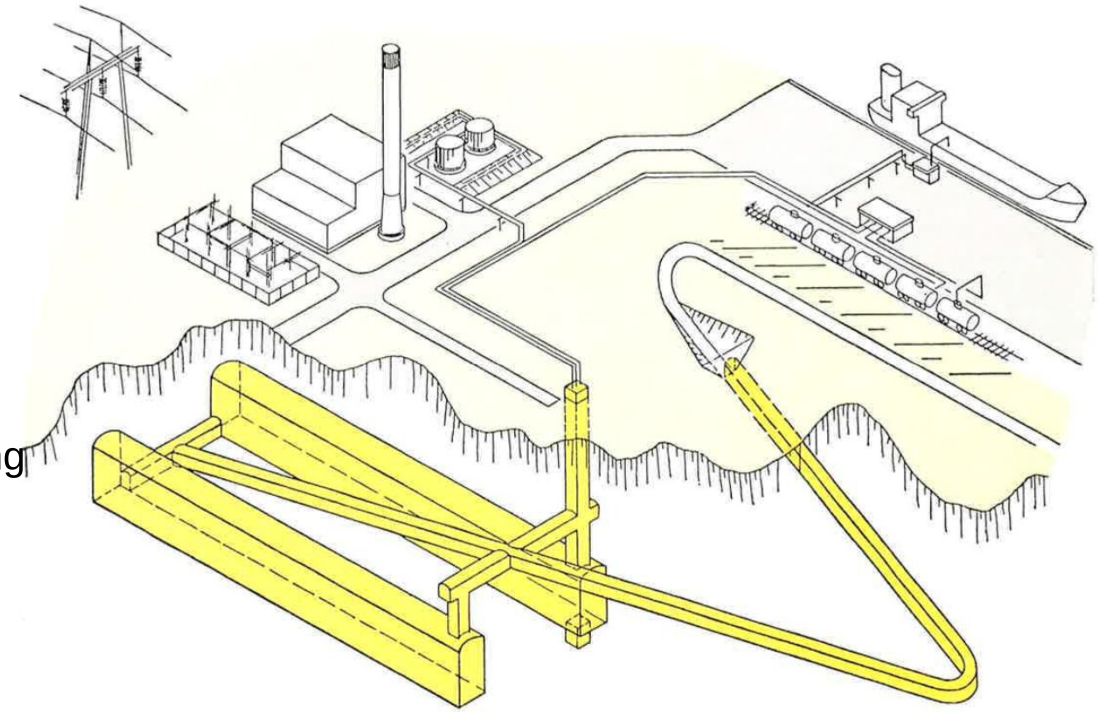
Case assessment of an underground storage unit of 50 000 m^3

- Temperature of -42 °C and pressure of 14 bar.

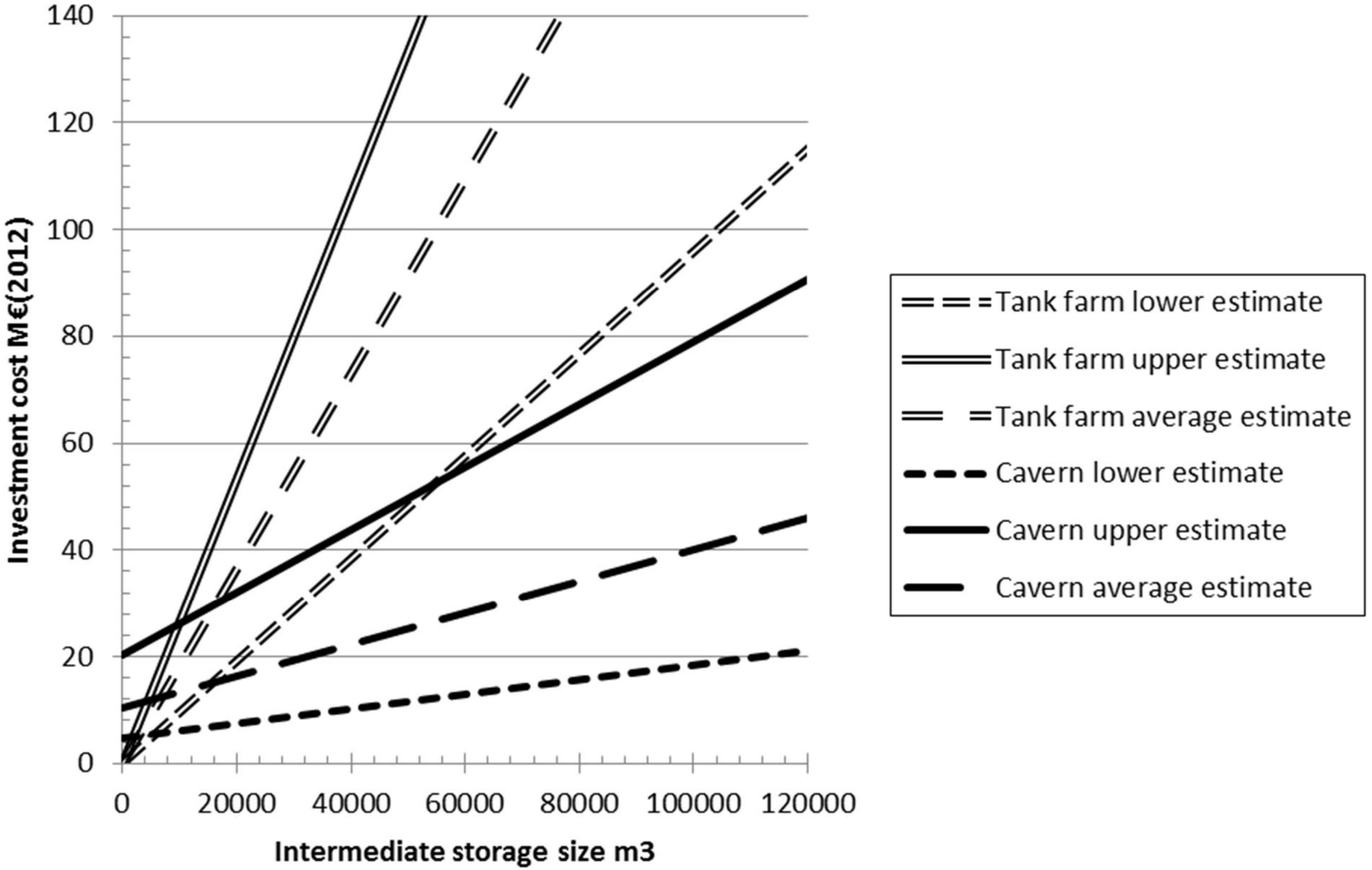
- Volume of the storage is 50 000 m^3, consisting of two parallel caverns (A = 500 m^2, L = 50 m) and an access tunnel.

- Construction time of the underground storage would be about 2.5 - 3 years.
  - Includes planning and site investigation processes
  - Initial cooling of the storage will take 5 - 7 months with the CO_2 fed into the storage.

- Total construction cost 14 M€
  - Annual heat losses 23 000 €/year (assuming 40 €/MWh electriciy price)



Comparison of investment cost estimates for cavern and tank farm intermediate CO_2 storages

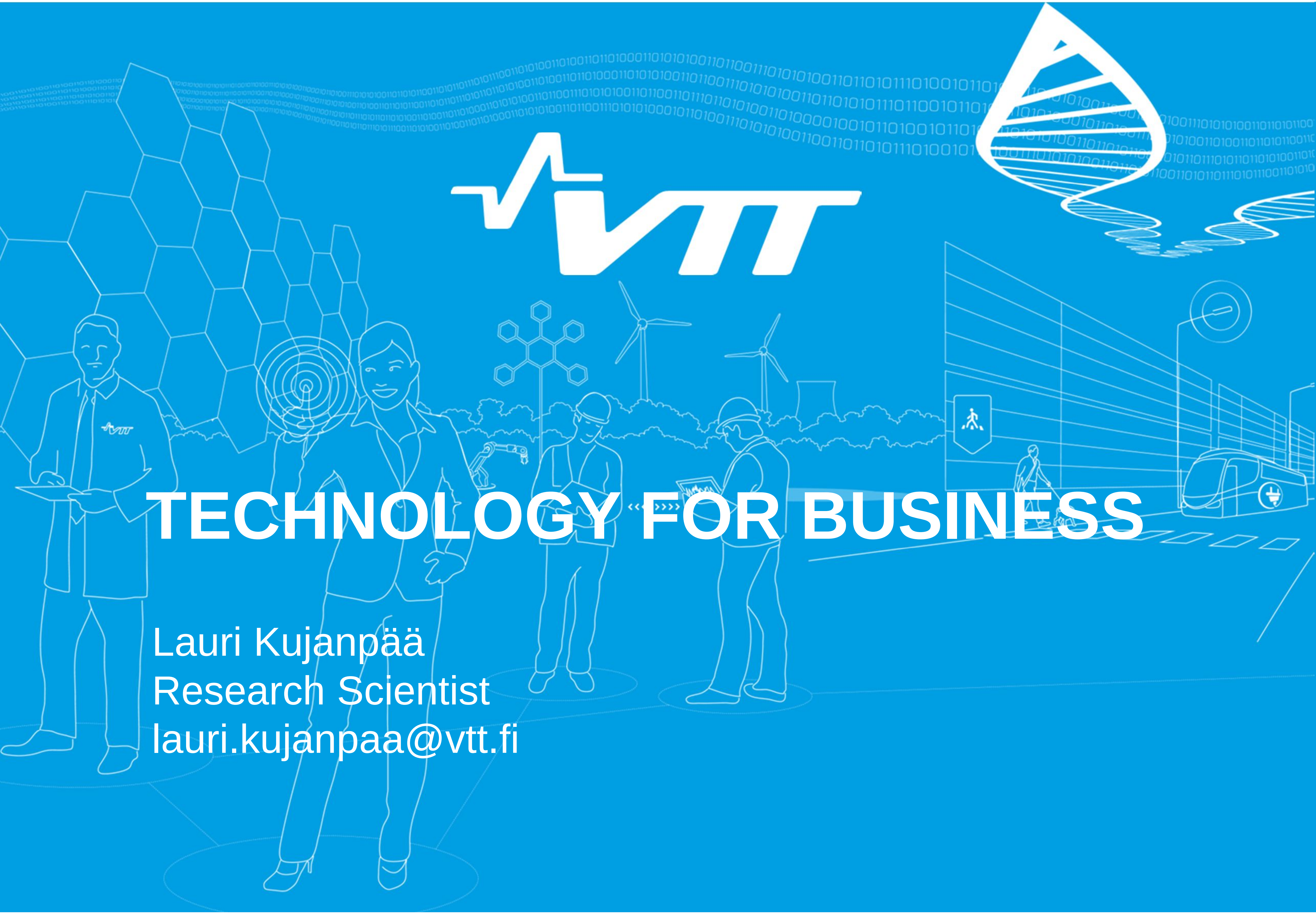


Final conclusions & next steps

- Underground refrigerated caverns could provide an alternative technology for intermediate storage of CO_2.
  - The preliminary results indicate that an underground storage unit of 50 000 m^3 or larger would have a significantly smaller investment cost than a similarly-sized steel tank storage complex.

- In EU, legal barriers still remain for ship transport of CO_2 for purposes of CCS.
  - Notably, Monitoring and reporting regulation under the EU-ETS for ship transport is yet missing.

- Work on the non-technical barriers for CCS continue in the CCSP, along with work on the underground storage technologies.



TECHNOLOGY FOR BUSINESS

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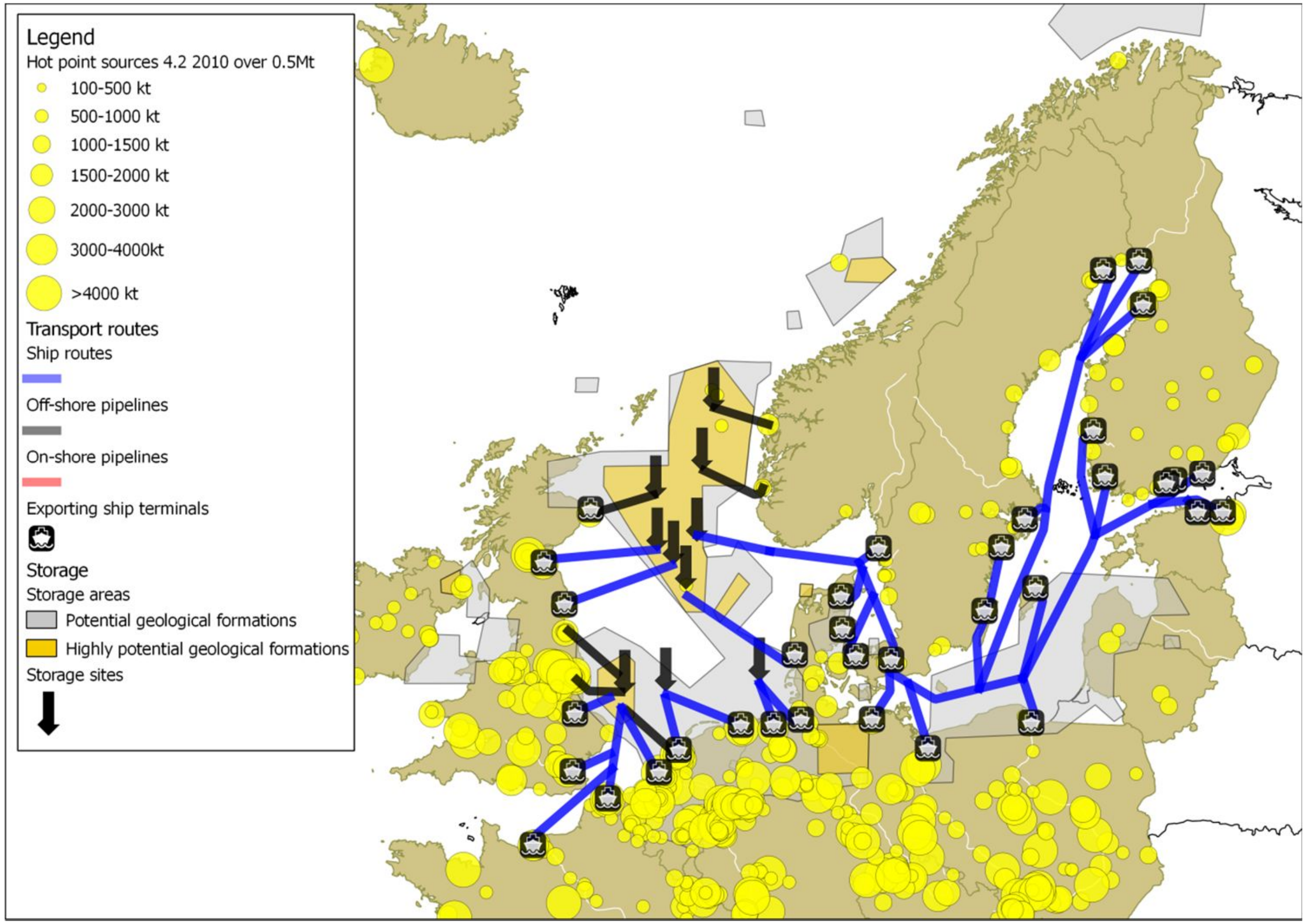
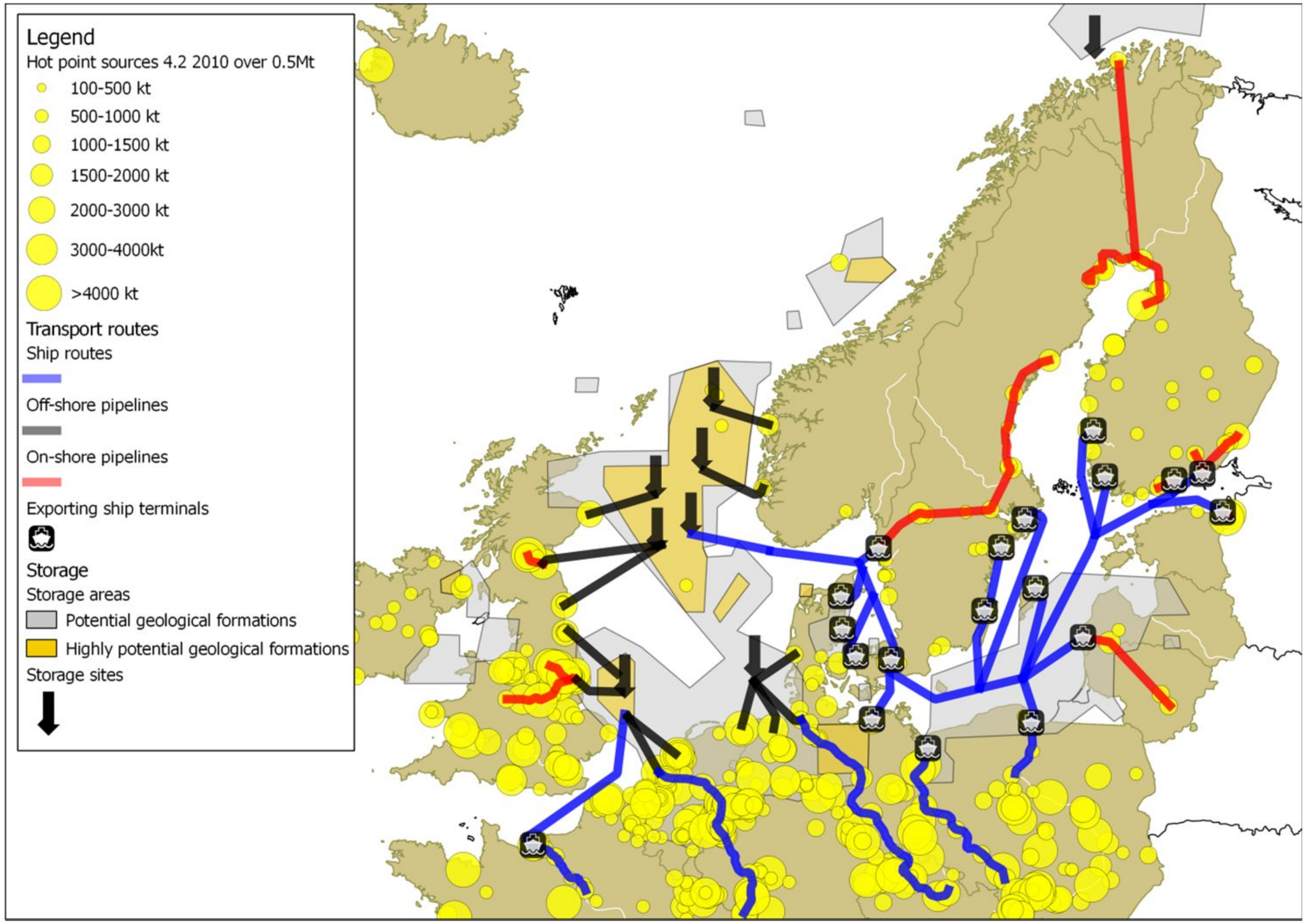
Independent actors

- No shared storages in cavities
- No on-shore trunklines – less export hubs, more ship terminals
- Higher terminal costs – only shorter transport distances are feasible
- Off-shore terminals for unloading – higher number on lower life-expectancy off-shore storage areas



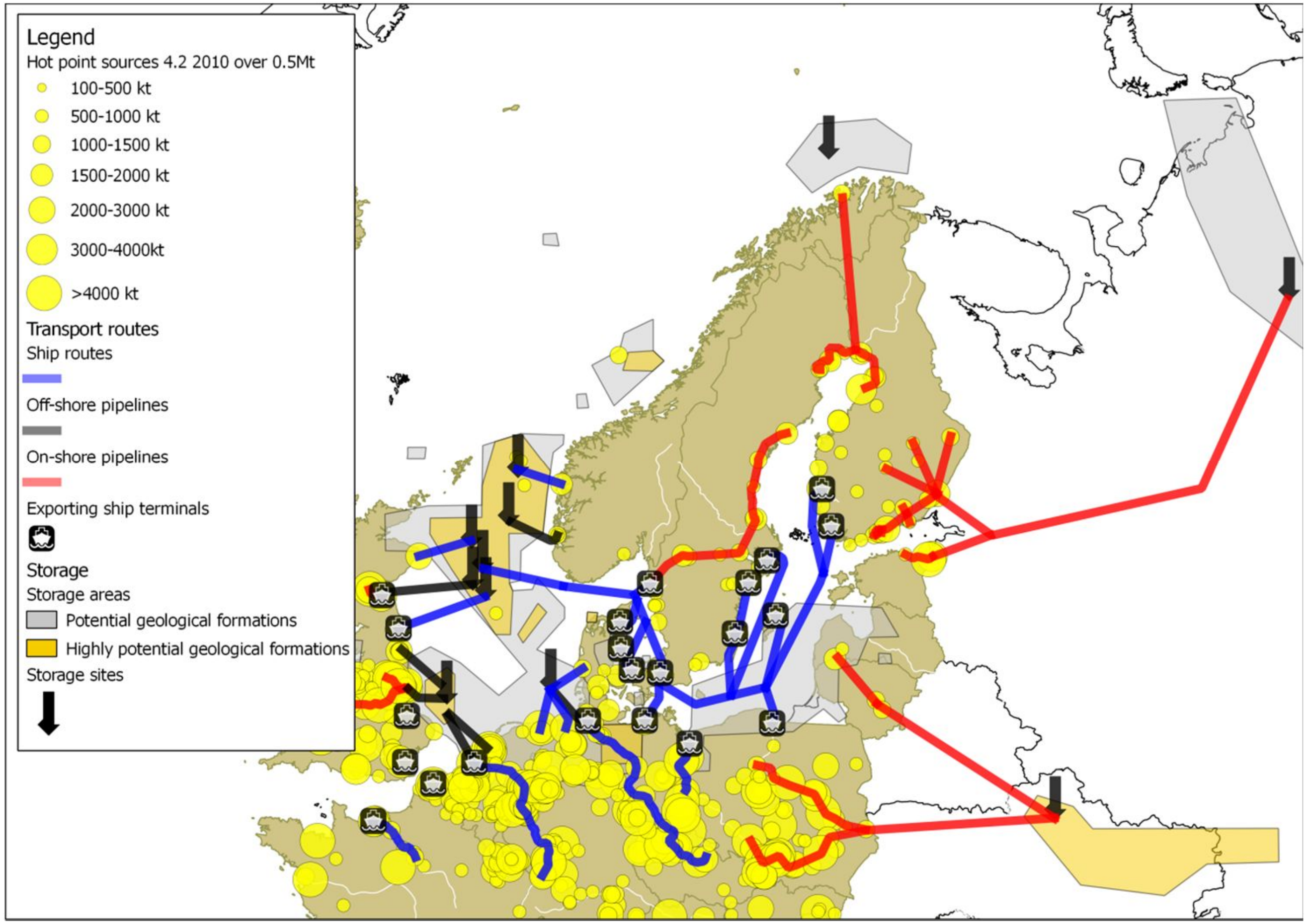
Areal co-operation

- On-shore storage remains limited due to public rejection of private led sequestration projects
- Trunklines to exporting terminals
- Shared exporting terminals with high capacity and cost-efficient intermediate storages in rock cavities
- Off-shore pipelines to long life-expectancy sequestration sites



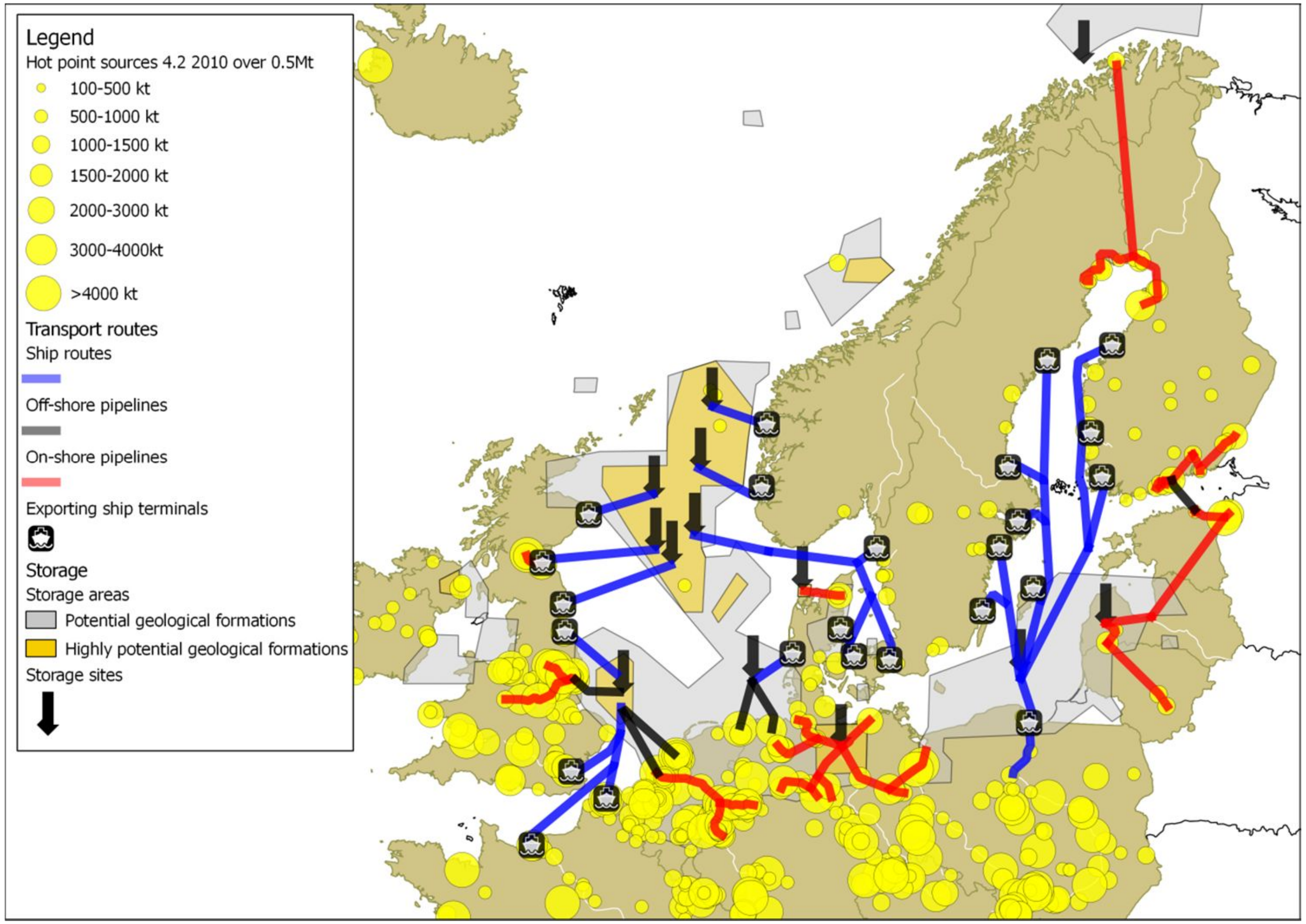
Beyond EEA infrastructure

- On-shore storage remains limited in Europe due to public rejection of private-led sequestration projects
- Trunklines to exporting terminals
- Shared exporting terminals with high capacity and cost efficient intermediate storages in rock cavities
- Off-shore pipelines to long life-expectancy sequestration sites



Masterminded infrastructure

- High level of state involvement – high potential on-shore storage areas available
- Trunklines to exporting terminals when feasible
- Shared exporting terminals with high capacity and cost efficient intermediate storages in rock cavities
- Off-shore sequestration sites accessed by either ships or pipelines



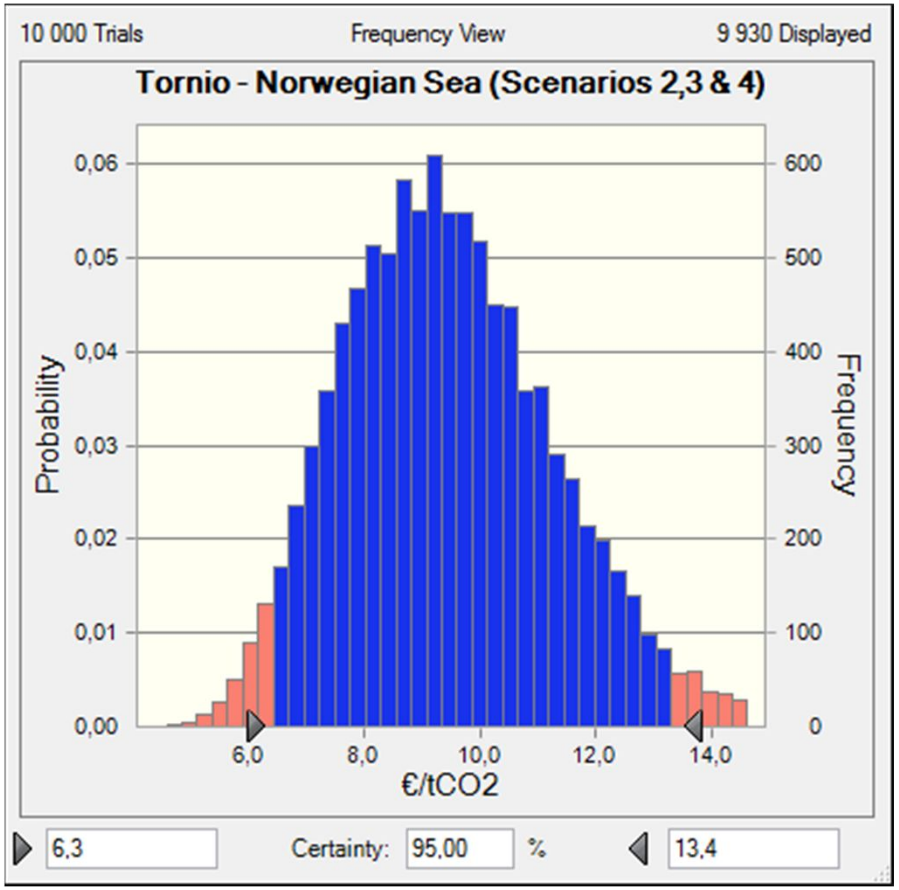
Construction and cooling costs of the case underground CO_2 storage facility

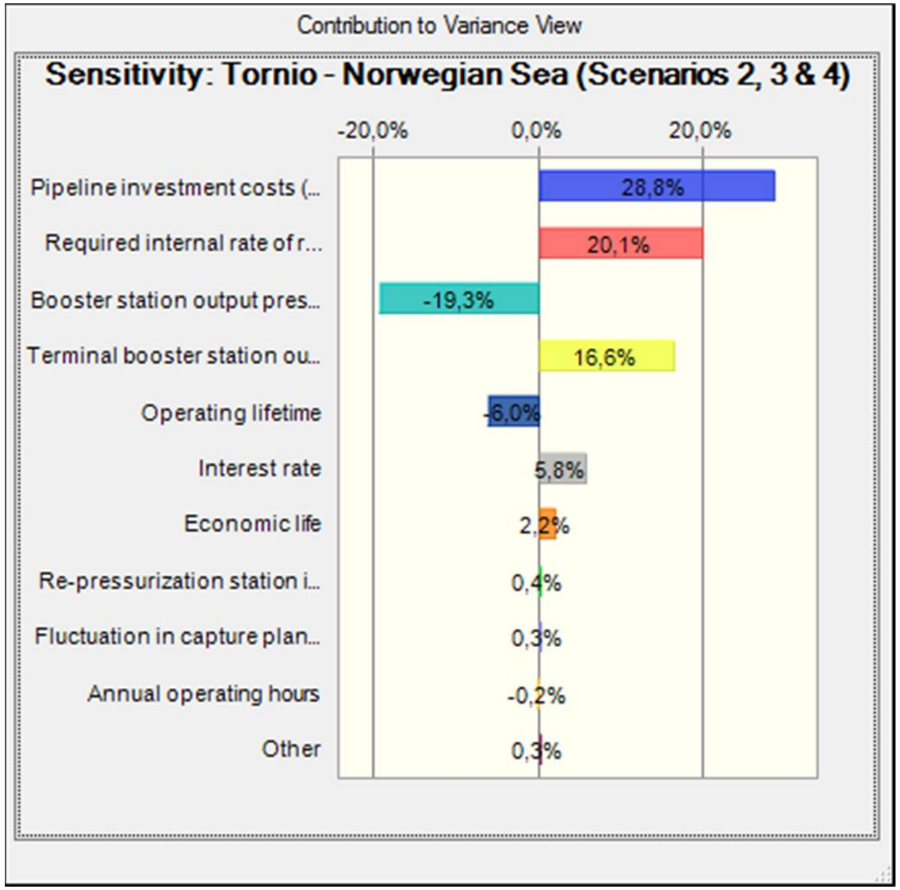
<u>Construction:</u>	
Investigations, design, project start up & management	1 650 000 €
Excavation of storage (blasting, bolting, shotcreting), drilling of shaft	7 763 000 €
Concrete works in storage space	250 000 €
Groundwater control & underground operational equipment	1 430 000 €
Reservations for uncertainty	2 920 000 €
Total construction cost estimate of storage	**14 M€**

<u>Cooling:</u>	
Initial cooling (First year)	15 000 €
Operational cooling of store (heat losses)	23 000 €/y
CO_2 - cooling/charge (50 000 m^3)	23 000 €/charge
(Assumed cooling energy price 40 €/MWh, Cooling by electricity sourced compressors, COP = 2.5	

On the uncertainty of the transport costs:

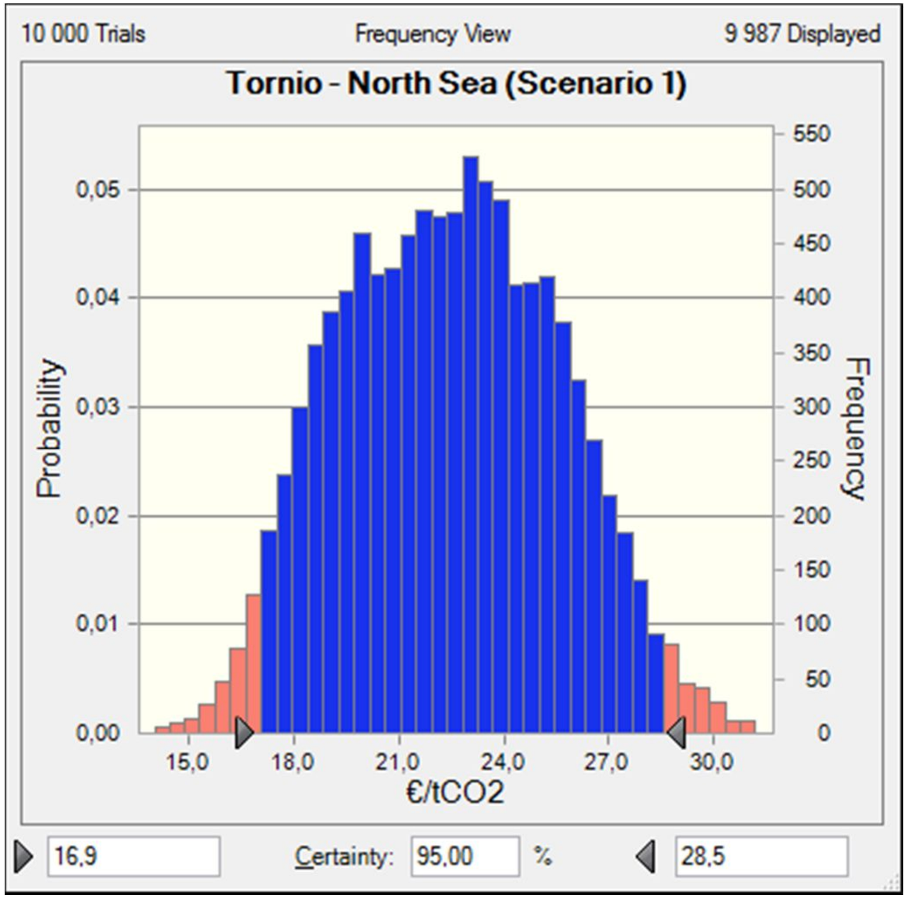
- Based on transport cost sensitivity analysis (to be published), the variance of pipeline transport cost are sensitive to an expected variation in the investment costs and the design pressure in the pipeline.

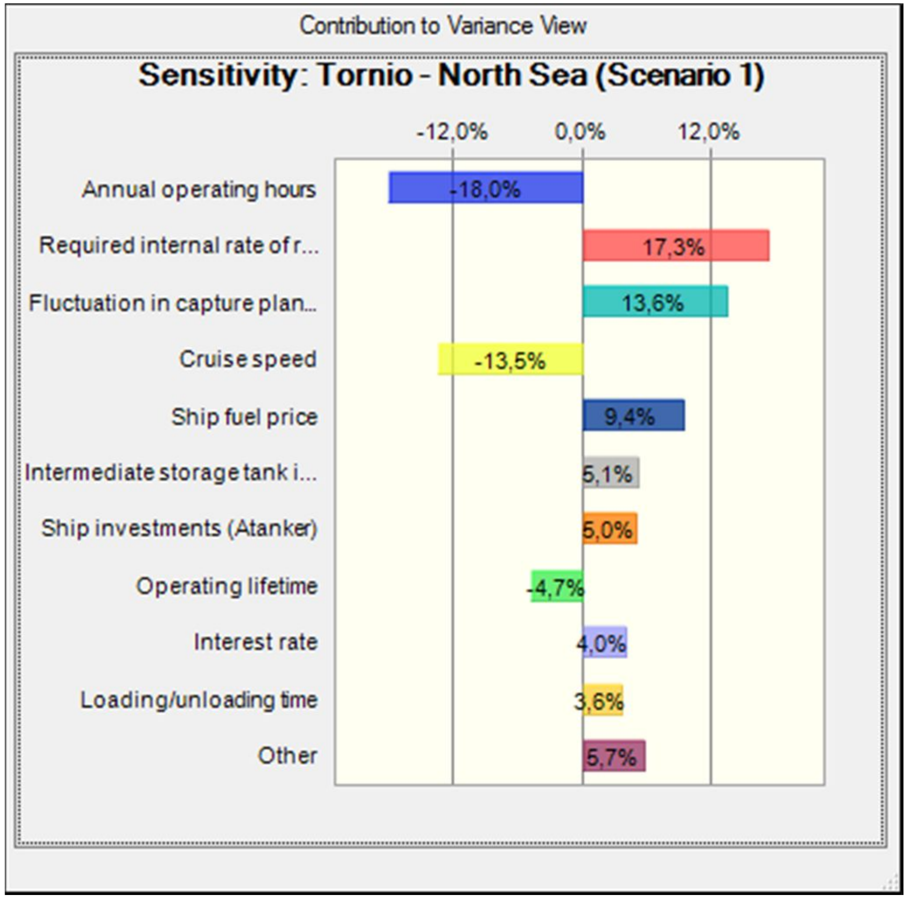




On the uncertainty of the transport costs:

- Ship transport cost variance seems sensitive to changes from the design operation and to cruise speed and fuel price.
  - Costs can also be sensitive to changes in Intermediate storage investment





Scope of the transport cost model

Capture & liquefaction
- Not included

Intermediate storage & loading
- Storage tanks / cavern space
- Loading equipment
- Harbour costs not included

Shipping
- 10 – 50 kt capacity per ship
- Low sulphur fuel oil

Unloading
- Off-shore equipment

Injection & geological storage
- Not included

Capture & initial pressurization
- Not included

Access to trunkline
- Pipeline and all transport costs allocated to capture plant operator
- Pressure boosted to 110 bar upon arrival at trunkline

Trunkline segments
- All costs divided between “clients” on a given segment, based on transported amount of CO_2

Repressurization at the destination
- Output pressure 150 bar

Injection & geological storage
- Not included