



2IMATCH: resilience of hydrogen infrastructure

preliminary results on H₂ transmission pipelines

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Lead PI, Infrastructure/institutions match for resilient & just green electrification (2IMATCH/Strategic Research Council 2023→)



‘Grey zone’ to ‘Mad Max’ scenario

- Currently NATO members are in ‘grey zone’
 - subject to various hybrid operations by Russia
 - In the Russian view, it is in ‘struggle’ over sphere of influence -- markets, natural resources and political influence – against the west; where all measures are in principle possible; in the end, the final solution is war (Lavikainen 2024)
- Hence, some think tanks have warned of how a major war in Europe is possible even before the 2030s
- However, even within ‘grey zone’, and without direct NATO-Russia war, hybrid and/or grey zone operations can cause the following situation:
 - The Baltic Sea becomes unnavigable for commercial purposes due to missile threat and/or drone activity, etc. Verbally expressed threats or refusals to abstain from hostile measures of military nature may in some cases be enough to cause similar outcome
 - Transnational pipelines running e.g. through the Baltic Sea become a military target or are hit ‘accidentally’
 - Onshore pipelines face unidentified sabotage attempts or become ‘accidental targets’ of missiles or drones e.g. in connection to a major military exercise
- In a Mad Max scenario, all of the above + major unconcealed destruction of critical infrastructure and major casualties of both soldiers and civilians

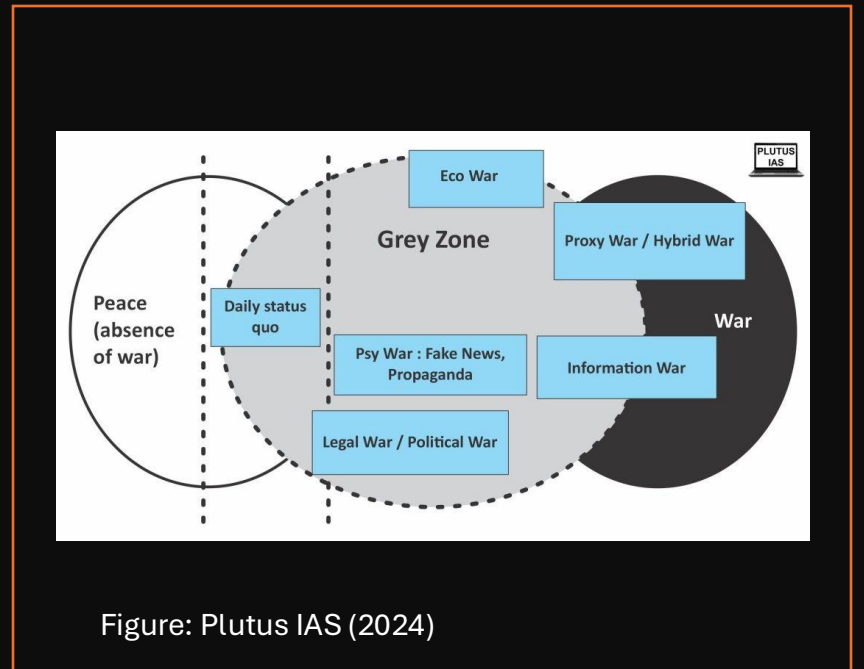
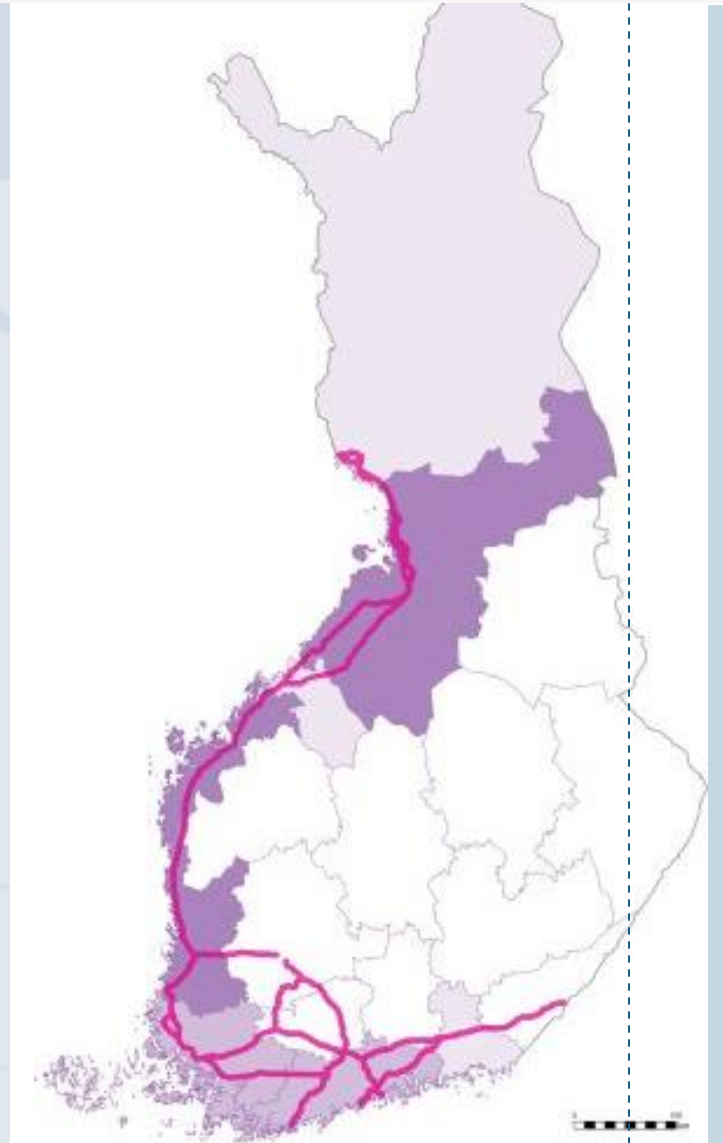
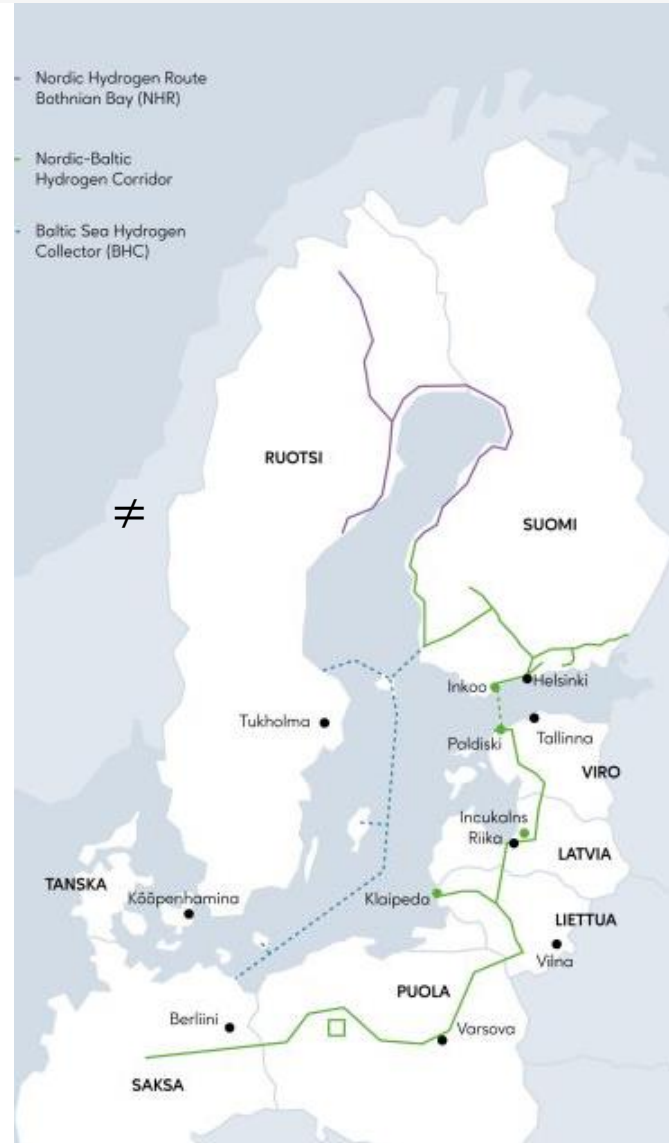


Figure: Plutus IAS (2024)

The risks of H₂ transmission pipeline compared to CH₄ remain uncertain

(Froeling et al. 2021)

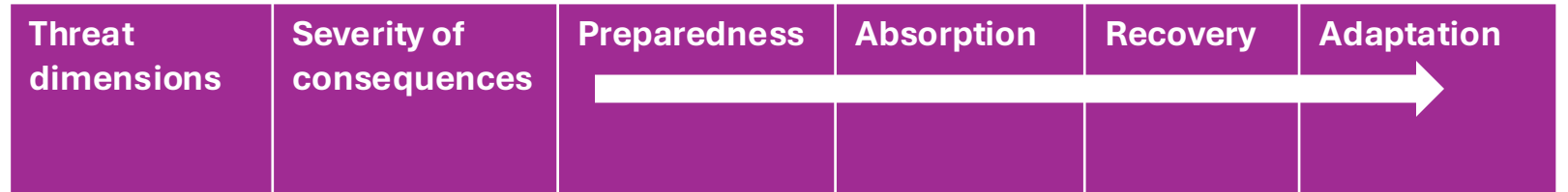
- For CH₄ transmission pipelines, the main failure mechanisms in the EU are corrosion, external interference, mechanical defects, ground movement (trucks, etc.)
- H₂ is not CH₄ in terms of physical & chemical properties
- H₂ ignites easier than CH₄
- Pipeline may puncture easier due to likely higher operational pressure (Ruiz-Tagle & Groth 2024)
- H₂ disperses also faster, with lower flame dimensions and thermal radiation levels
- Individual Risk (IR) combines failure frequency, ignition probability and lethality
- 36" diameter H₂ pipeline has overall lower IR level than NG, including lethality, yet it has higher ignition risk
- 16" H₂ pipeline has high IR in the pipeline's vicinity
- Significant lethality impact up to 350m from the pipeline, or up to 600m for short pipes; for 100% protection of trunk line with no protection protocols, 1000m; while for low pressure pipes, 200m (Jo & Ahn 2006); CH₄, 600m



Method for scoping: resilience matrix



- Scopus AI search for a rough mapping of the scholarly state-of-the-art on the resilience of hydrogen pipelines
- Identification of key publications (which are few) to extract interdisciplinary information
- Filling in the 2IMATCH resilience matrix, in several iterations
- Current iteration 1.0, for SMR and H₂ transmission pipeline...
- Expert consultancy to validate the matrix



Physical

Informational

Cognitive

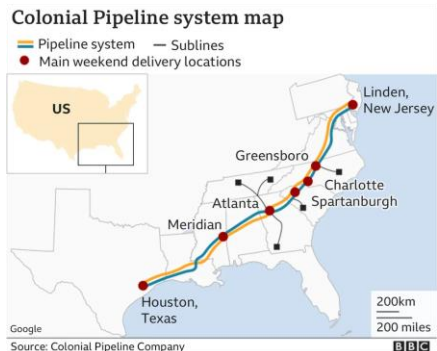
Social

Physical threats → preparedness

Threat type	Risk severity & type	Planning & preparedness measures
Gas leakage	Low risk for supply security & safety	Testing of critical points, monitoring devices
Lack of access of service personnel to pipeline or its parts	Low risk for supply security & safety	Standards for inspection, service & maintenance personnel
Interrupted gas supply	High risk for security of supply	Alternative producers & suppliers
Sabotage, terrorist strike or other kinetic threat (e.g. bomb, rocket, missile, drone attack)	High risk of ignition, explosion, fireball & thermal radiation; overpressure less a risk	Underground siting; fencing; sensors, cameras, fibreoptic cables to monitor the security zone; pipe reinforcements (e.g. carbon); spare part storage; management of excavation activity in the zone; no horizontal drilling; concrete reinforced coating for service buildings; protection equipment for personnel
Accidents (excavation works near underground pipes, heavy transport operation, airplane crash)	High risk of ignition, explosion, fireball & thermal radiation; overpressure less a risk	
Flooding	Medium risk of leakage, ignition, explosion, etc.	Bulwark structures outside of pipe, made of clay
Storms	Medium risk of leakage, ignition, explosion, etc.	Avoid combined electric cable and pipeline
Earthquakes	Medium risk of leakage, ignition, explosion, etc.	Pre-estimation in pipeline siting & routing
Lack of critical personnel	Medium risk of low risk for supply security & safety	Education, training, horizontal communication

Information-based threats → preparedness

Threat type	Risk severity & type	Planning & preparedness measures
Information gaps on the system	Medium risk for supply security & safety	RDI measures to establish e.g., to what extent H ₂ systems differ from CH ₄
Misguided or incorrect information on the system's state (measurement, modelling, IT)	Medium risk for supply security & safety	Standards for inspection, service & data management protocols; adequate staffing; personnel training
Ambiguities in the use of systems (unclear roles between IT, AI & supervising/operating personnel)	Medium risk for supply security & safety	Organizational & procedural planning; personnel training
Viruses, hacking & other cyberattacks	High (?) risk for supply security & safety	Cybersecurity measures; personnel training
Espionage and spy recruitment	High risk for supply security & safety	Counterintelligence; personnel training



Testimony in the US Congress after the Colonial pipeline was hacked by allegedly Russia-based ransomware group, in 2021 and 5M USD ransom paid



Cognitive threats → preparedness

Threat type	Risk severity & type	Planning & preparedness measures
Individual level cognitive vulnerabilities (e.g. information leak, collusion, infiltration of hostile actors/terrorists into systems)	High risk for supply security & safety	Organizational & procedural planning; counterintelligence; personnel training
Operator is influenced, pressured or blackmailed by hostile actors	High risk for supply security & safety	Counterintelligence; personnel training
Insufficient expertise (e.g. inexperience vis-à-vis H ₂ based gases & systems, undeveloped standards)	Medium risk for supply security & safety	RDI measures to establish e.g., to what extent H ₂ systems differ from NG; standardization of operational practices
Varying attitudes vis-à-vis risks & situational picture (e.g. cost minimization as the single goal, low sanctions for causing risks, undeveloped H ₂ safety culture)	High risk for supply security & safety	Personnel training; interdisciplinary security analysis including but not limited to safety assessment; standardization of operational practices; situational picture analysis including geopolitics



Social threats → preparedness

Threat type	Risk severity & type	Planning & preparedness measures
Information flow is disrupted	Low risk for supply security & safety	Data management planning
Unclear responsibilities	Low risk for supply security & safety	Organizational & procedural planning
Actors fail to fulfil their duties	Low risk for supply security & safety	Organizational & procedural planning; inspection; control over business ownership & subsidiaries
Disinformation dissemination (e.g. social media campaigns or rumours leading to panic)	Low risk for supply security & safety	Counterintelligence; personnel training

Hydrogen 'guerilla' decentralised scenario

- Not only large, also small & decentralised
- When a large transmission pipeline is non-operational for weeks/months
- No economies of scale but more targets, not all of which can be hit
- Mobile, on-wheels & container size solutions
- Operationality during crisis & war-time

Photos: IMI (2024), Siemens Gamesa (2021), USA DoE (2024)

