# Modeling of $LH_2$ loading from onshore storage to a seaborne tanker

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June 7, 2024

Teknologi for et bedre samfunn

# Outline

- SINTEF and SINTEF Energy Research
- Large-scale $LH_2$ transport and loading
- The $LH_2$ Pioneer Project
- Modelling work on $LH_2$ loading operations

# ONE OF EUROPE'S LARGEST INDEPENDENT RESEARCH ORGANISATIONS

| | | | |
|---|---|---|---|
| **4,0 bill**<br>NOK turnover | **2200**<br>employees | **7000**<br>projects | **3200**<br>customers |

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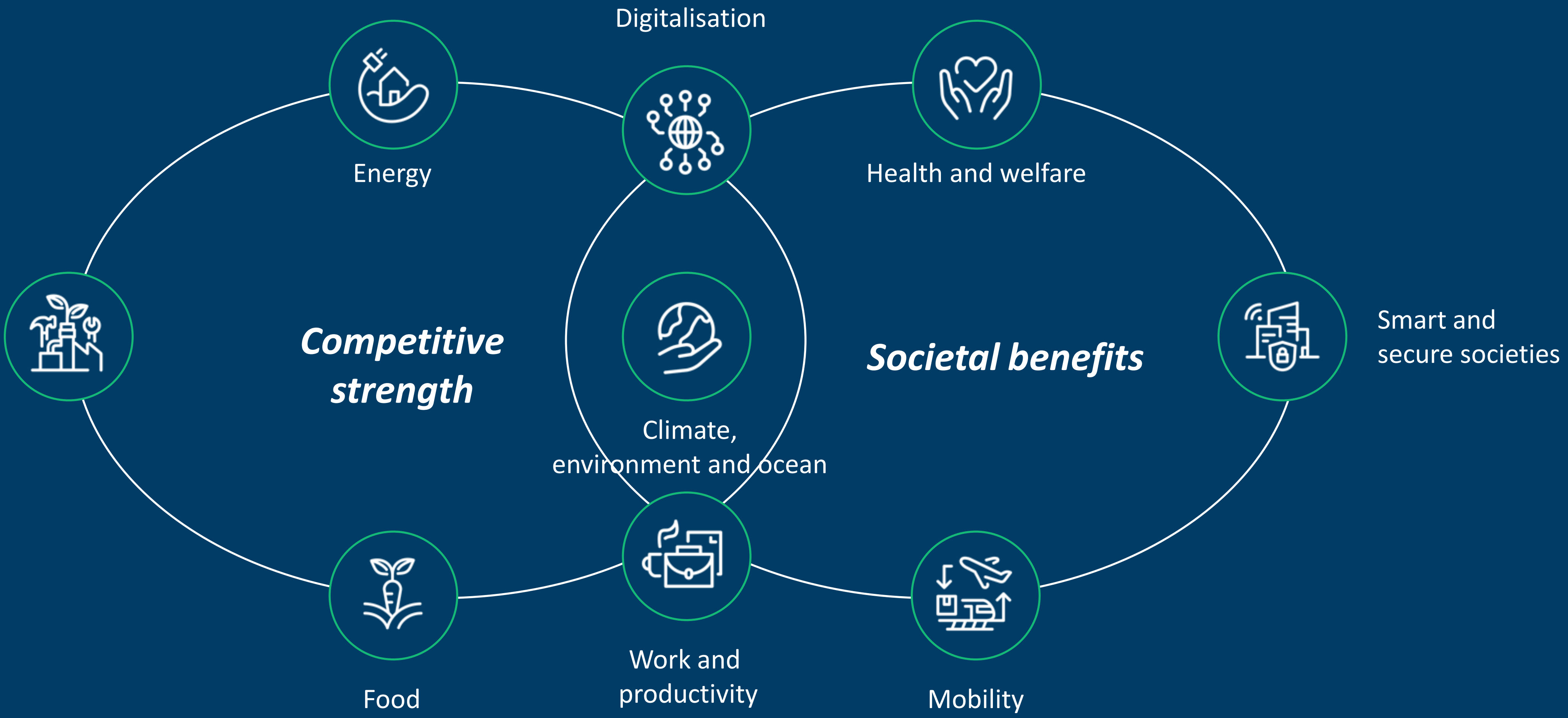
| | | | |
|---|---|---|---|
| INTERNATIONAL<br>**652 mill NOK** | NATIONALITIES<br>**80** | PUBLICATIONS (INCL. DISSEMINATION)<br>**6200** | CUSTOMER SATISFACTION<br>**4,5 / 5** |

1 EUR ≈ 11.5 NOK
**June 2024**

# Vision: Technology for a better society

Contribute to competitiveness and societal benefit by realizing the UN's Sustainable Development Goals



Digitalisation

Energy

Health and welfare

Industry and
construction

***Competitive strength***

***Societal benefits***

Smart and
secure societies

Climate,
environment and ocean

Food

Work and
productivity

Mobility

# OUR GOAL GIVES US IMPORTANT SOCIAL ROLES

**Research and innovation**

Develops new technological solutions and knowledge with our clients

**Laboratories and software**

Develops and runs important research infrastructure

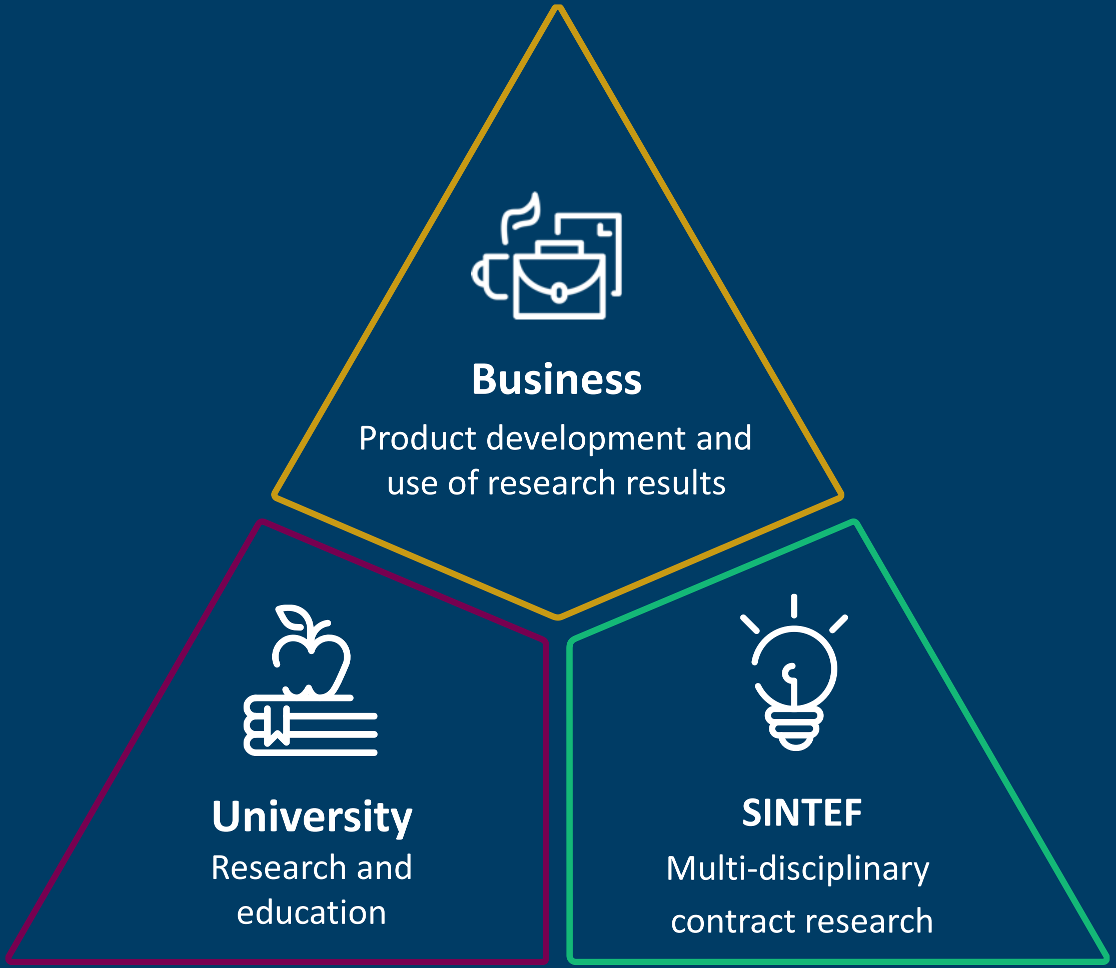
**Commercialisation**

Creates new products and firms

**Thought leadership**

Contributes to debate and politics with advice and knowledge

# Innovation through co-operation and expertise



**Business**

Product development and
use of research results

**University**

Research and
education

**SINTEF**

Multi-disciplinary
contract research

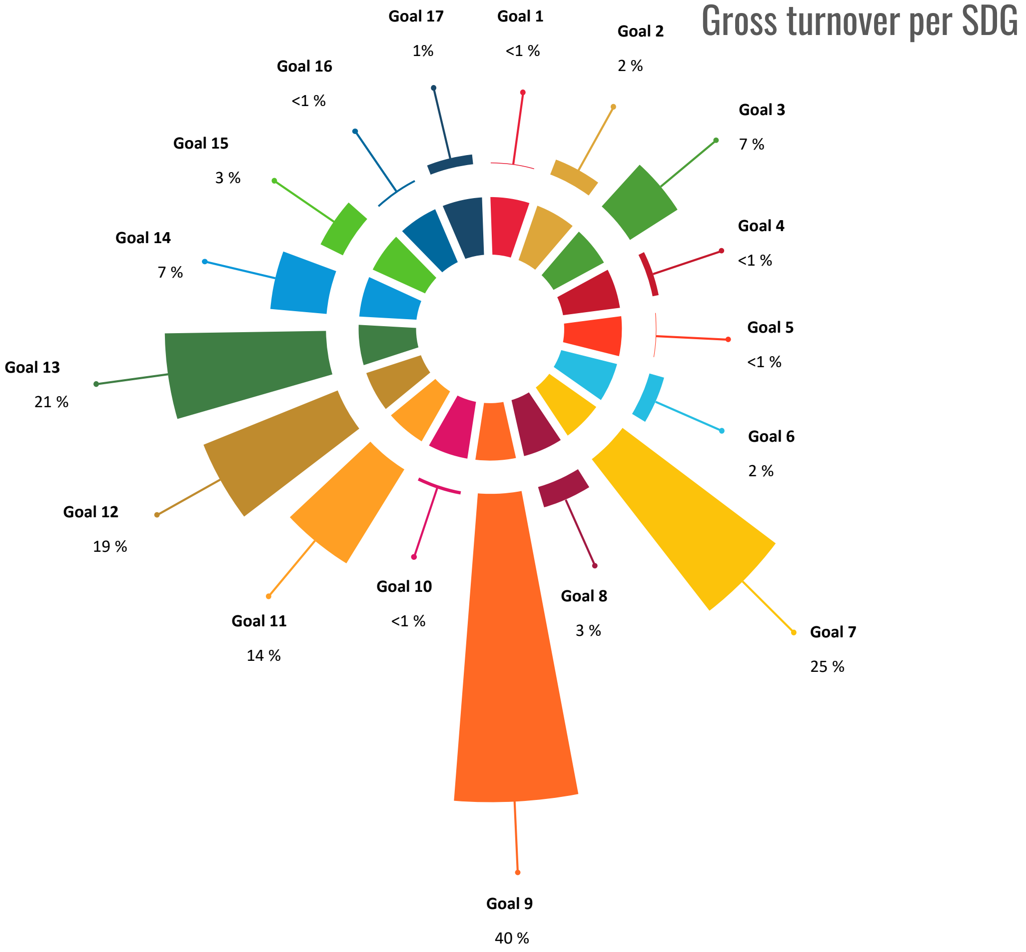
# OUR PROJECTS CONTRIBUTE TO THE SUSTAINABILITY GOALS

The figure illustrates the fact that in 2022 SINTEF had significant activities related to the  SDGs.

SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all

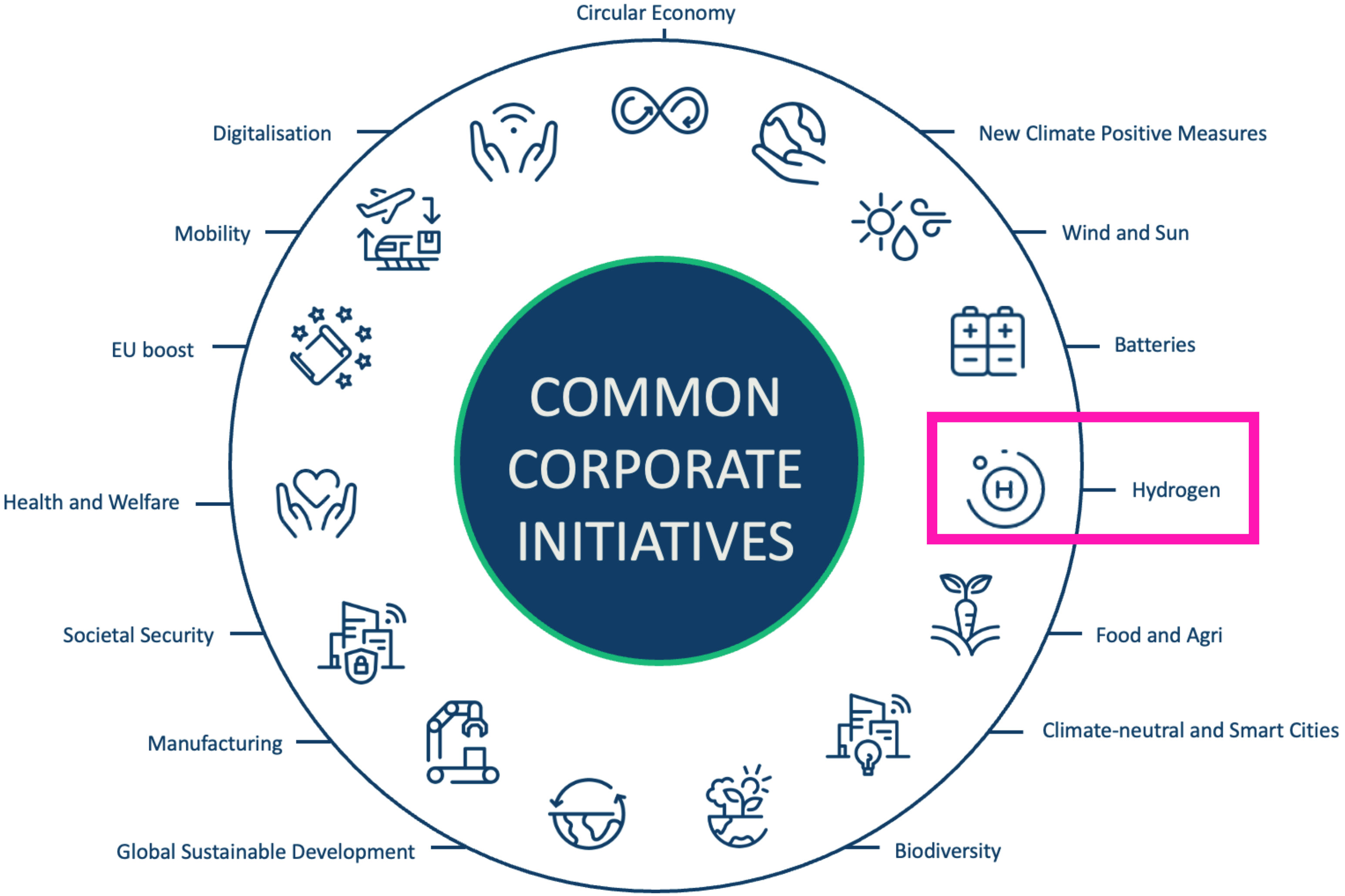
SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Gross turnover per SDG



# Strategic initiatives

- provide multidisciplinary collaboration for complex challenges



# Our organisation with institutes ensures market relevance and academic strength - in One SINTEF

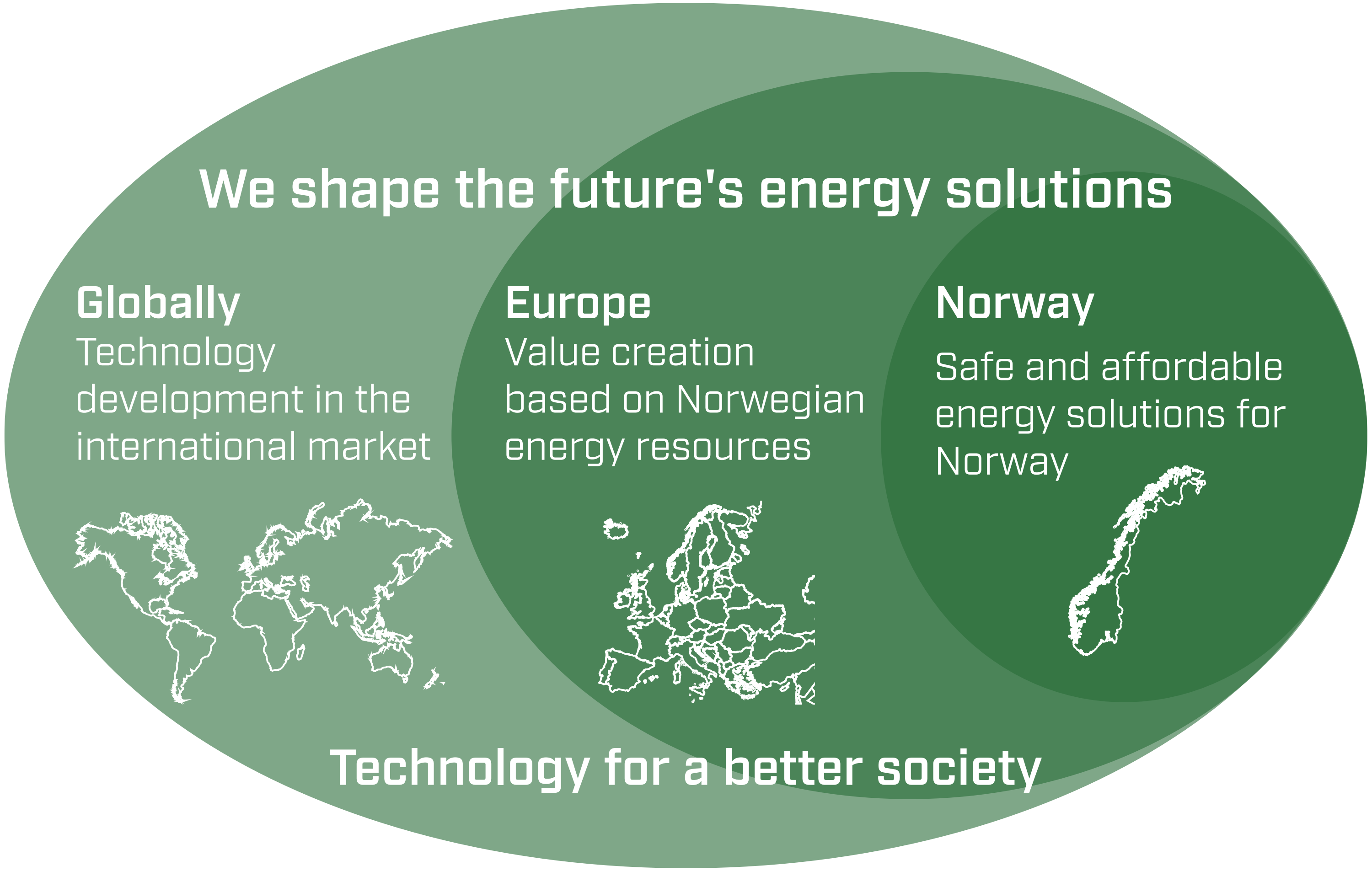
The foundation

**SINTEF**

INSTITUTES

- SINTEF Community
- SINTEF Industry
- SINTEF Digital
- SINTEF Ocean
- SINTEF Energy
- SINTEF Manufacturing

# Global energy solutions



We shape the future's energy solutions

**Globally**
Technology development in the international market

**Europe**
Value creation based on Norwegian energy resources

**Norway**
Safe and affordable energy solutions for Norway

Technology for a better society

SINTEF

# Research in the ocean space

Marine processing

Digital ocean

Fisheries

Aquaculture

Renewable energy

Sustainable ocean

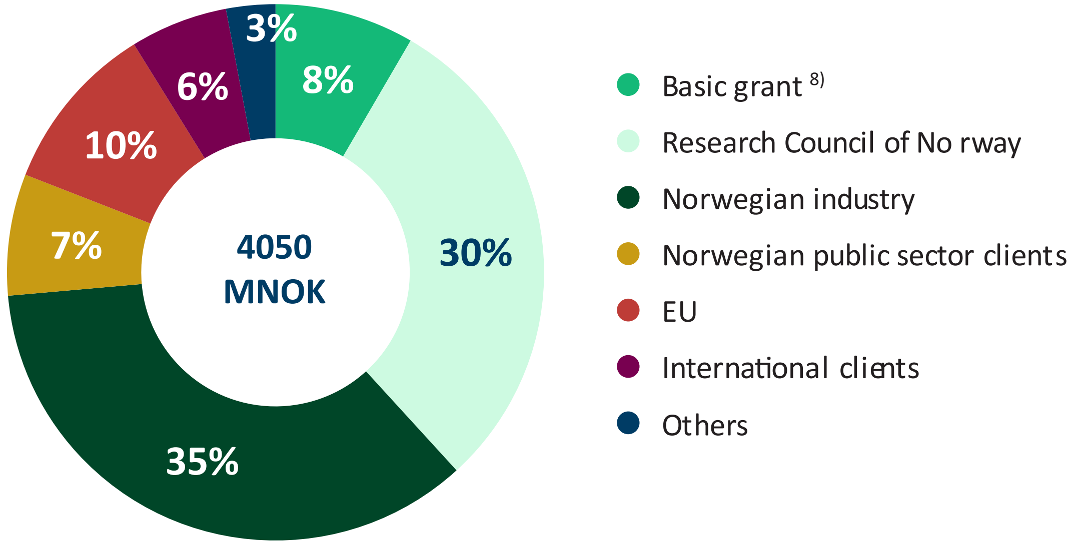
Coastal infrastructure

Maritime transport

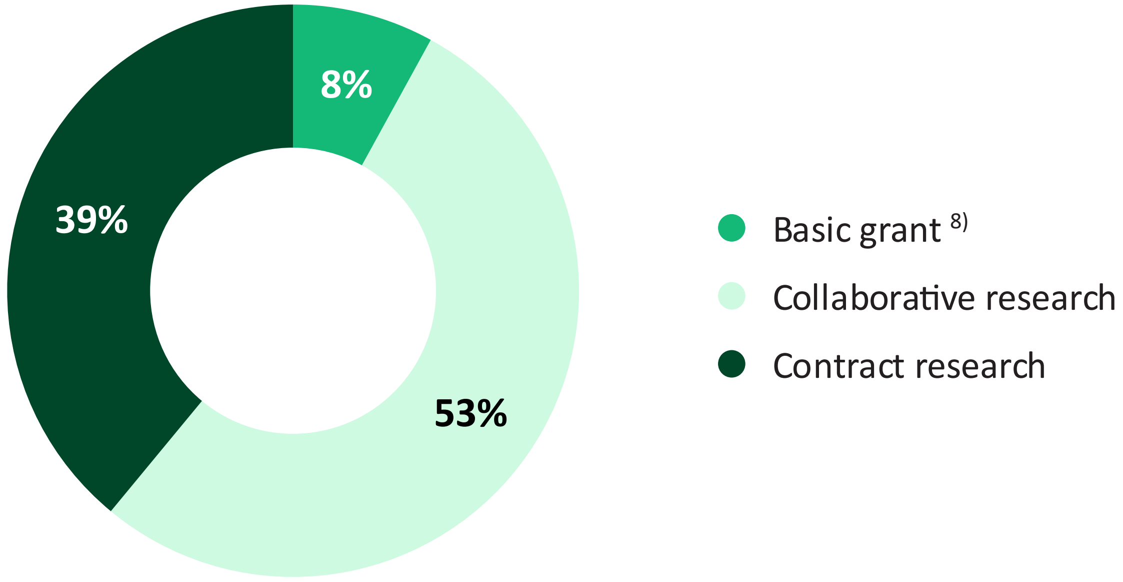
# 92% of income comes from open competitions

- a balanced portofolio of colloborative research and contract research

## Funding sources as a percentage of gross operating income



## Portfolio type



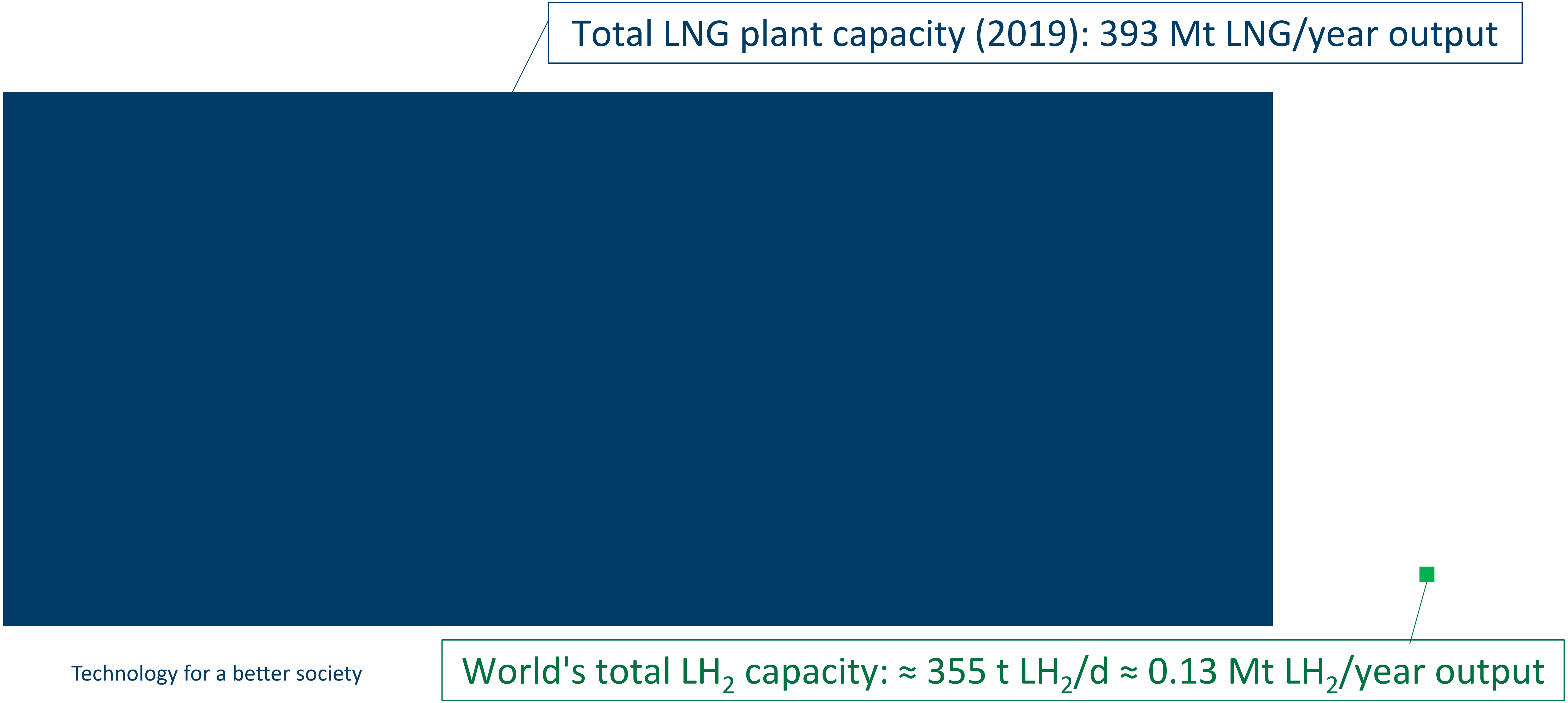
# A WORLD-LEADING RESEARCH INSTITUTE

## -INDEPENDENT AND NON-PROFIT

Technology for a better society

# Some comments about large-scale $LH_2$ transport and transfer

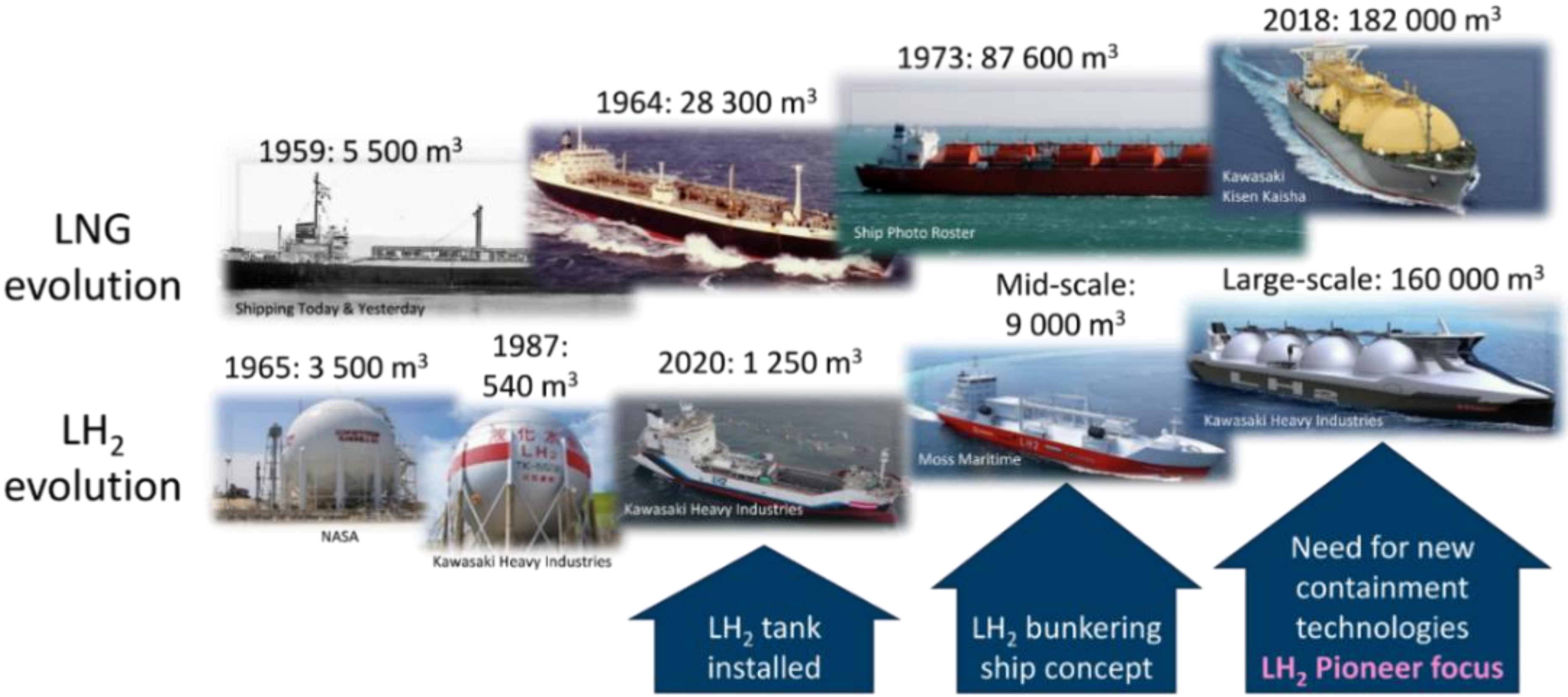
# LNG and $LH_2$ – so far on completely different levels capacity-wise



Total LNG plant capacity (2019): 393 Mt LNG/year output

World's total $LH_2$ capacity: ≈ 355 t $LH_2$/d ≈ 0.13 Mt $LH_2$/year output

# Evolution of LNG and $LH_2$ tanks



LNG evolution

1959: 5 500 m³

Shipping Today & Yesterday

1964: 28 300 m³

1973: 87 600 m³

Ship Photo Roster

2018: 182 000 m³

Kawasaki Kisen Kaisha

$LH_2$ evolution

1965: 3 500 m³

NASA

1987: 540 m³

Kawasaki Heavy Industries

2020: 1 250 m³

Kawasaki Heavy Industries

Mid-scale: 9 000 m³

Moss Maritime

Large-scale: 160 000 m³

Kawasaki Heavy Industries

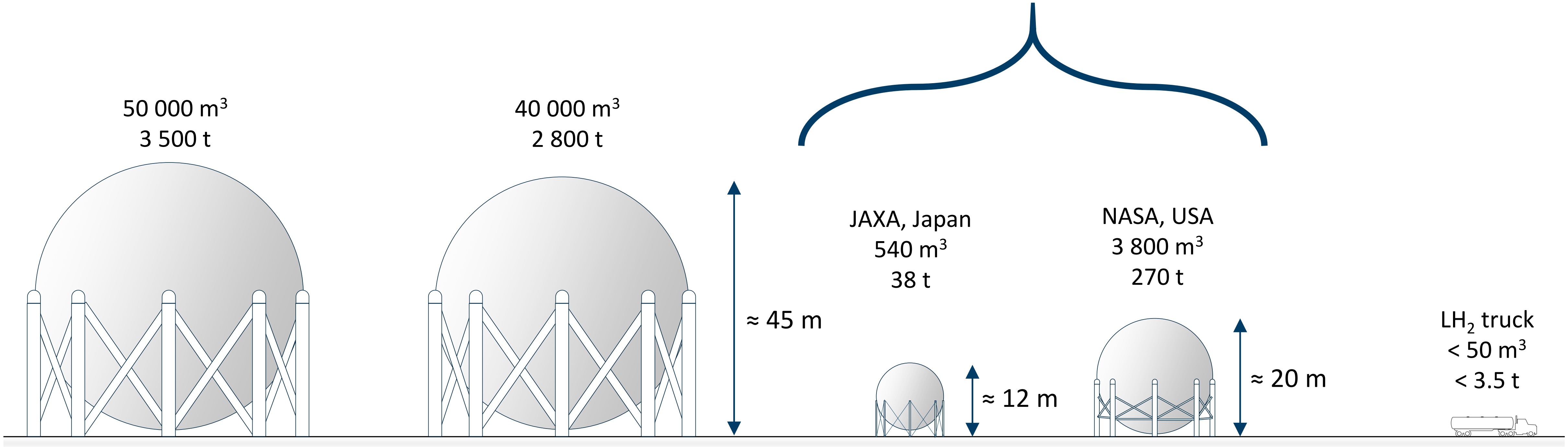
$LH_2$ tank installed

$LH_2$ bunkering ship concept

Need for new containment technologies

**$LH_2$ Pioneer focus**

# Scaling up liquid hydrogen storage



Existing

50 000 m$^3$
3 500 t

40 000 m$^3$
2 800 t

≈ 45 m

JAXA, Japan
540 m$^3$
38 t

≈ 12 m

NASA, USA
3 800 m$^3$
270 t

≈ 20 m

LH$_2$ truck
< 50 m$^3$
< 3.5 t

Image source: https://www.nasa.gov/content/liquid-hydrogen-the-fuel-of-choice-for-space-exploration; Kawasaki Heavy Industries

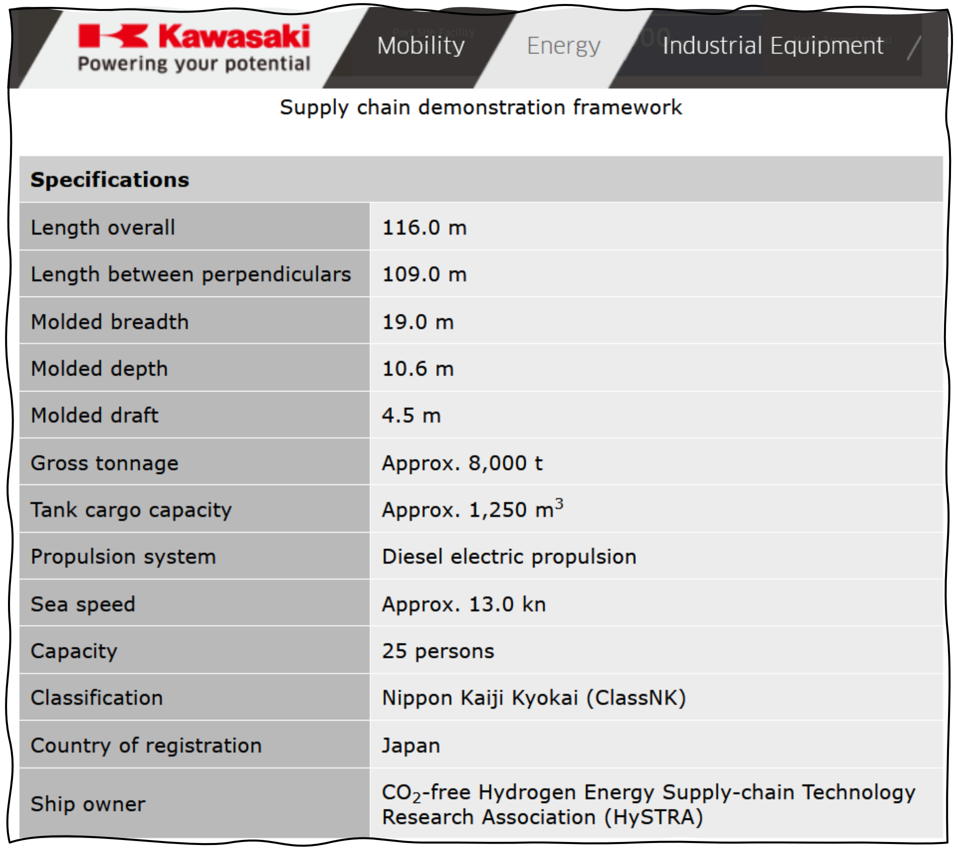
# Examples of current «large-scale» $LH_2$ transfer operations

- The largest and common $LH_2$ transfer operations today are to/from tanker trucks, with capacities typically in the range of 3–4 ton per batch
- Kawasaki Heavy Industries has developed and built terminal for $LH_2$ transfer from ship to shore
  - Double-walled, vacuum-insulated
  - 2 500 $m^3$ $LH_2$ storage tank
- Liquid hydrogen ferry in Norway (MF Hydra, NORLED)
- Aerospacial, e.g., NASA, Florida: Relative $LH_2$-loss during transfer from truck to storage tank is reported to be around 13 % on average. About half of this is caused by precooling of the system
- Developments for using $LH_2$ for air transport.

Image source: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery

Kobe $LH_2$ Terminal (Hy touch Kobe)
Image source: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201203_2378

# Marine LH$_2$ Containment & Transport (Kawasaki H.I.)



Supply chain demonstration framework

| Specifications | |
|---|---|
| Length overall | 116.0 m |
| Length between perpendiculars | 109.0 m |
| Molded breadth | 19.0 m |
| Molded depth | 10.6 m |
| Molded draft | 4.5 m |
| Gross tonnage | Approx. 8,000 t |
| Tank cargo capacity | Approx. 1,250 m$^3$ |
| Propulsion system | Diesel electric propulsion |
| Sea speed | Approx. 13.0 kn |
| Capacity | 25 persons |
| Classification | Nippon Kaiji Kyokai (ClassNK) |
| Country of registration | Japan |
| Ship owner | CO$_2$-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA) |

https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

"Suiso Frontier" (Image source: Kawasaki Heavy Industries)

# The hydrogen economy needs effective hydrogen transport solutions

Illustration by Moss Maritime: https://www.mossww.com/gas-technologies/

# $LH_2$ Pioneer Project

# LH$_2$ Pioneer: Ultra-insulated seaborne containment system for global LH$_2$ ship transport

- KSP – Knowledge Building Project
- Project duration: 2021-2025

SINTEF

NTNU

The Research Council of Norway

With funding from
The Research Council of Norway

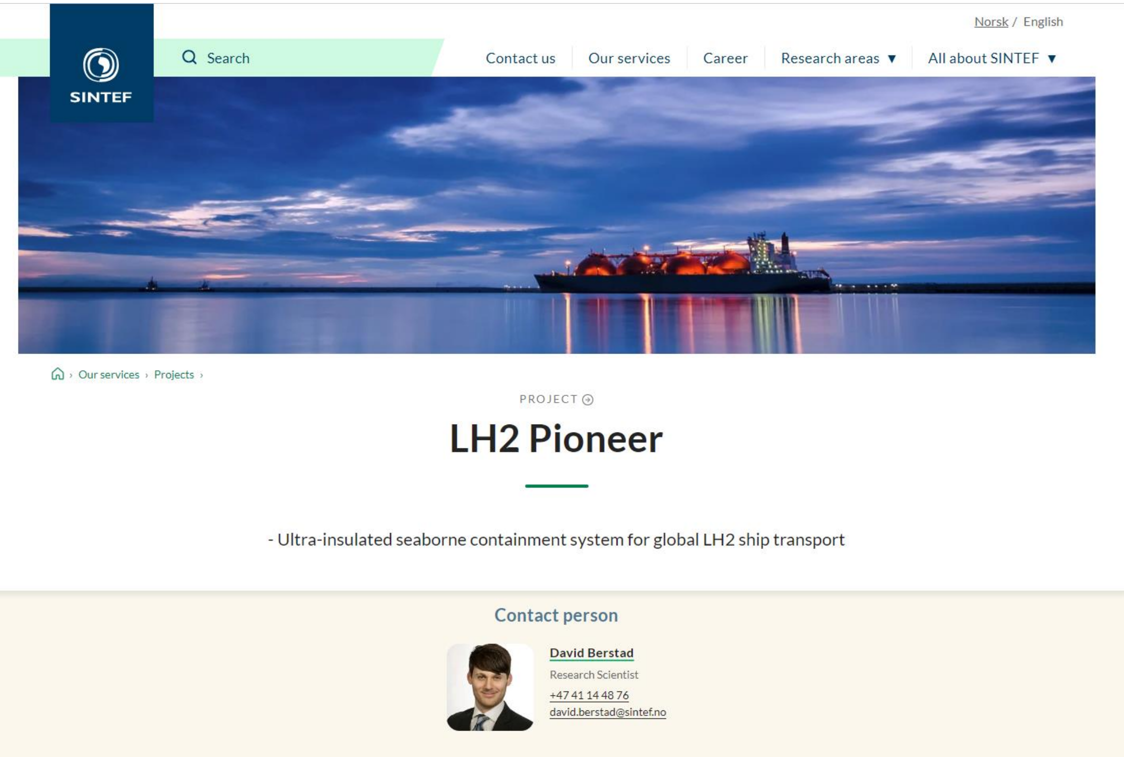
Air Liquide

equinor

mossmaritime

GASSCO

HD KOREA SHIPBUILDING & OFFSHORE ENGINEERING



LH2 Pioneer

- Ultra-insulated seaborne containment system for global LH2 ship transport

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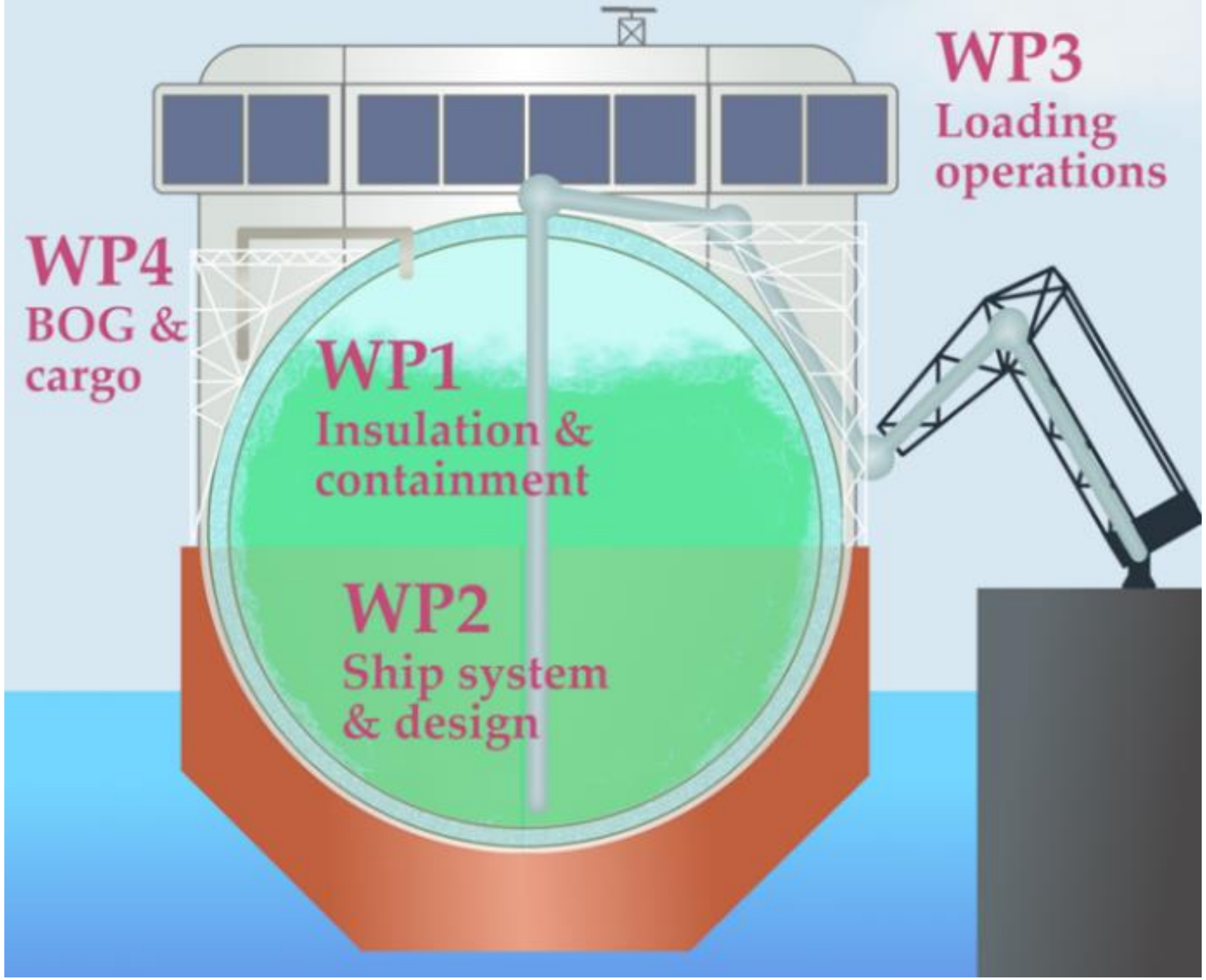
# $LH_2$ Pioneer - Project structure



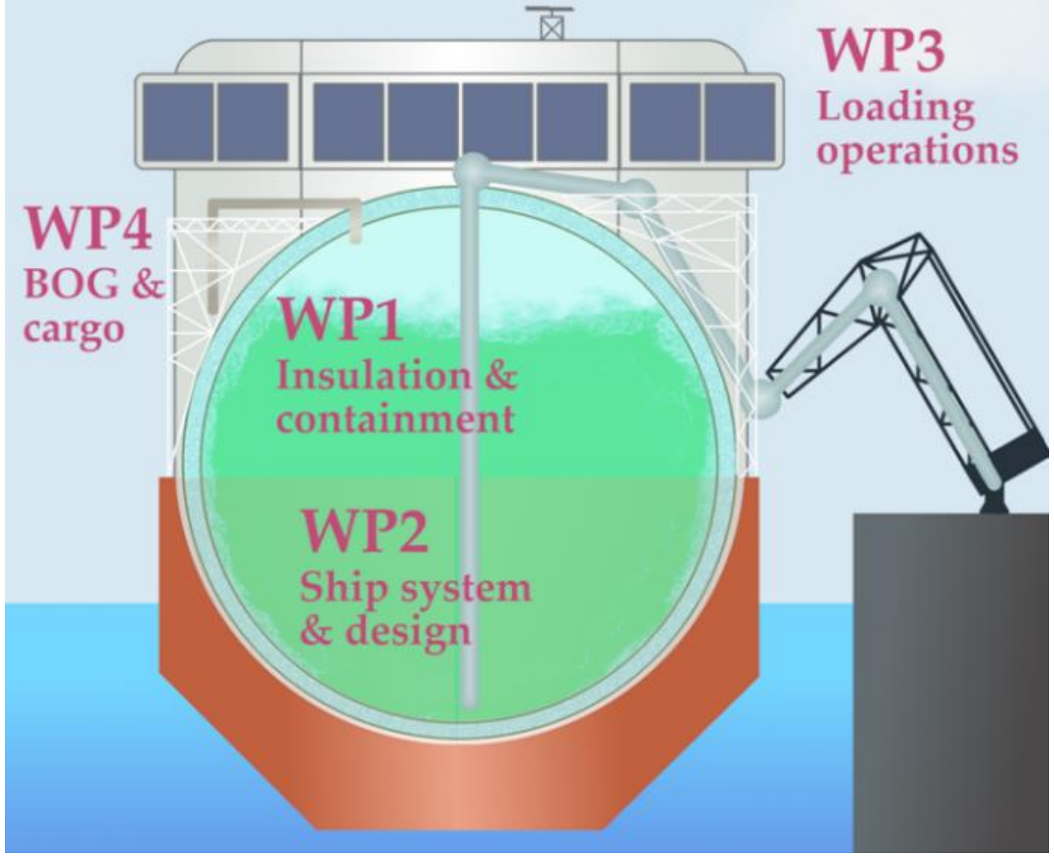
# $LH_2$ Pioneer – Ultra-insulated seaborne containment system for global $LH_2$ ship transport

## Main objective

Develop a feasible conceptual design for the critical components and processes required to enable transport of liquid hydrogen on a similar scale as present-day LNG transport

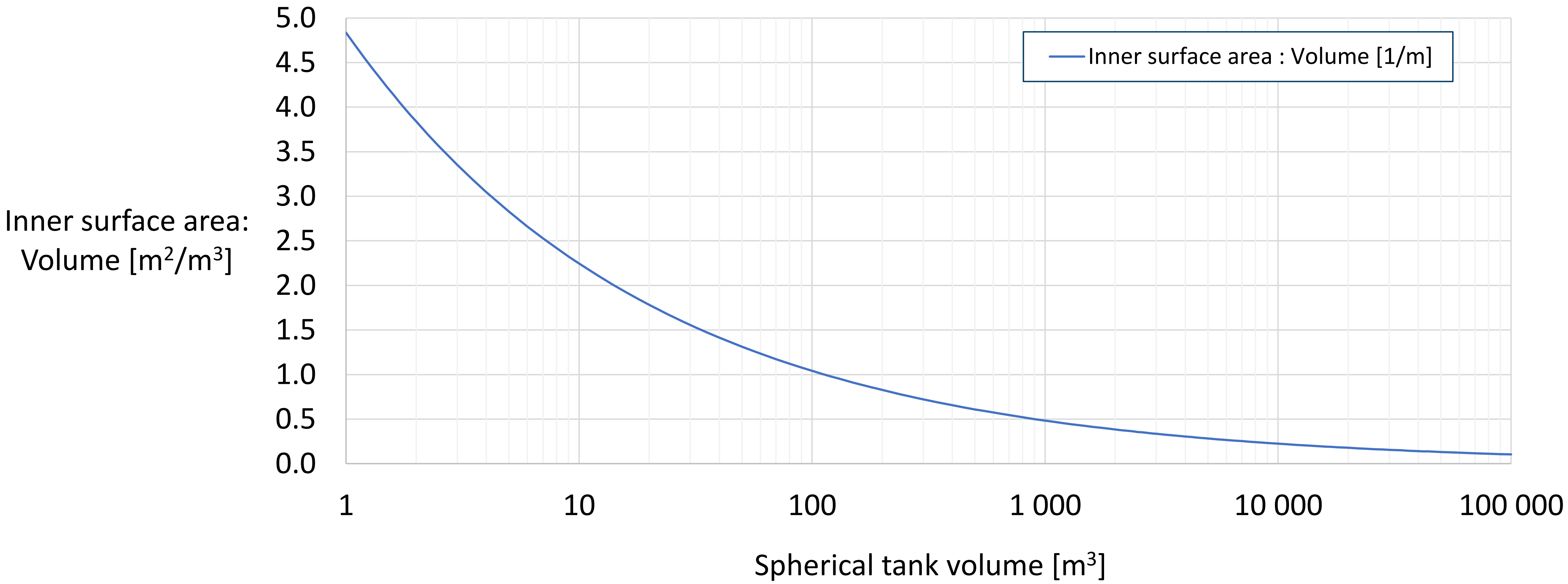
- Develop a pioneering conceptual design for a large and cost-efficient liquid hydrogen containment system with boiloff rates feasible for seaborne transport, targeting 0.1 % / day
- Derive concepts for efficient boiloff handling and reliquefaction processes for LH2 carriers, including the use of boiloff for propulsion and auxiliary power generation
- Determine a conceptual design for a full-scale liquid hydrogen ship loading system

More information: https://www.sintef.no/en/projects/2021/lh2-pioneer/

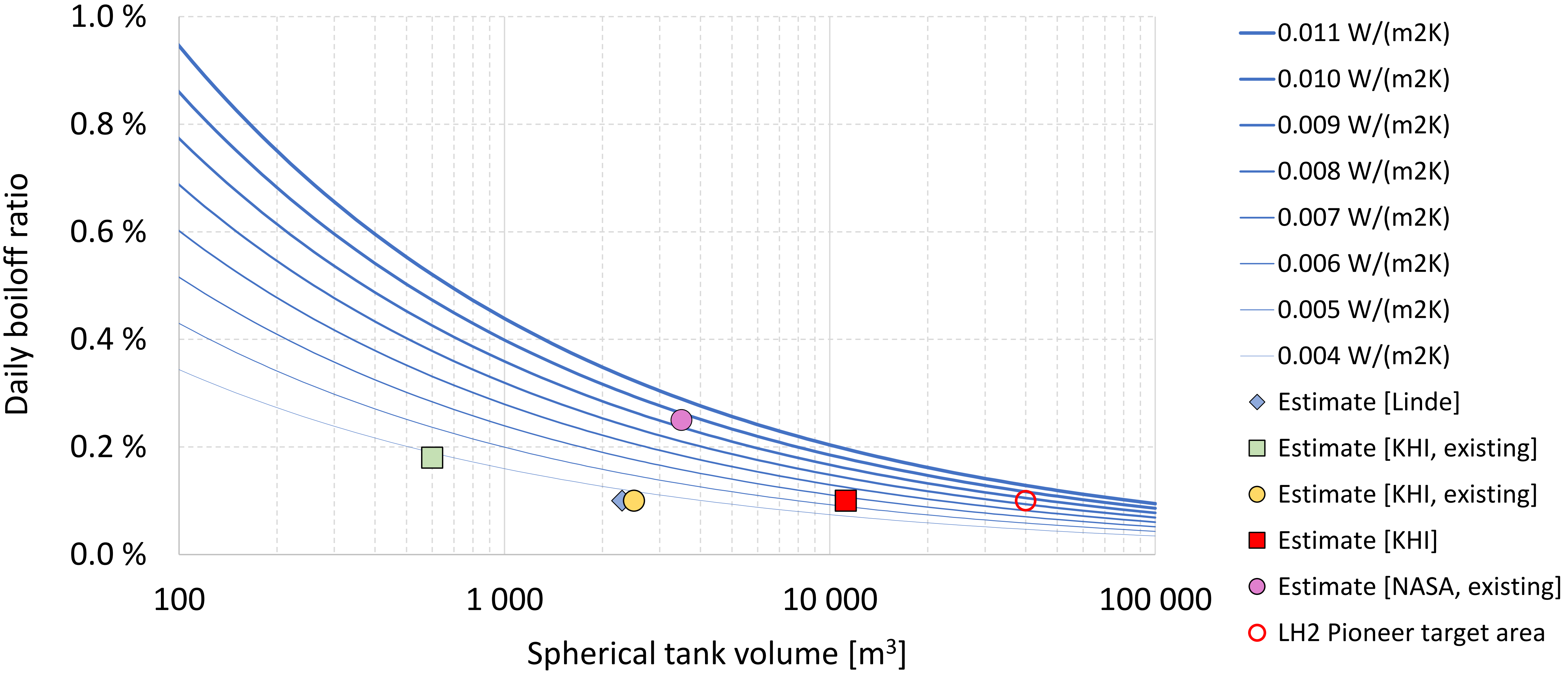


# Scaling up liquid hydrogen storage – Does it facilitate or impede performance?

## Area-to-volume ratio for spherical tanks

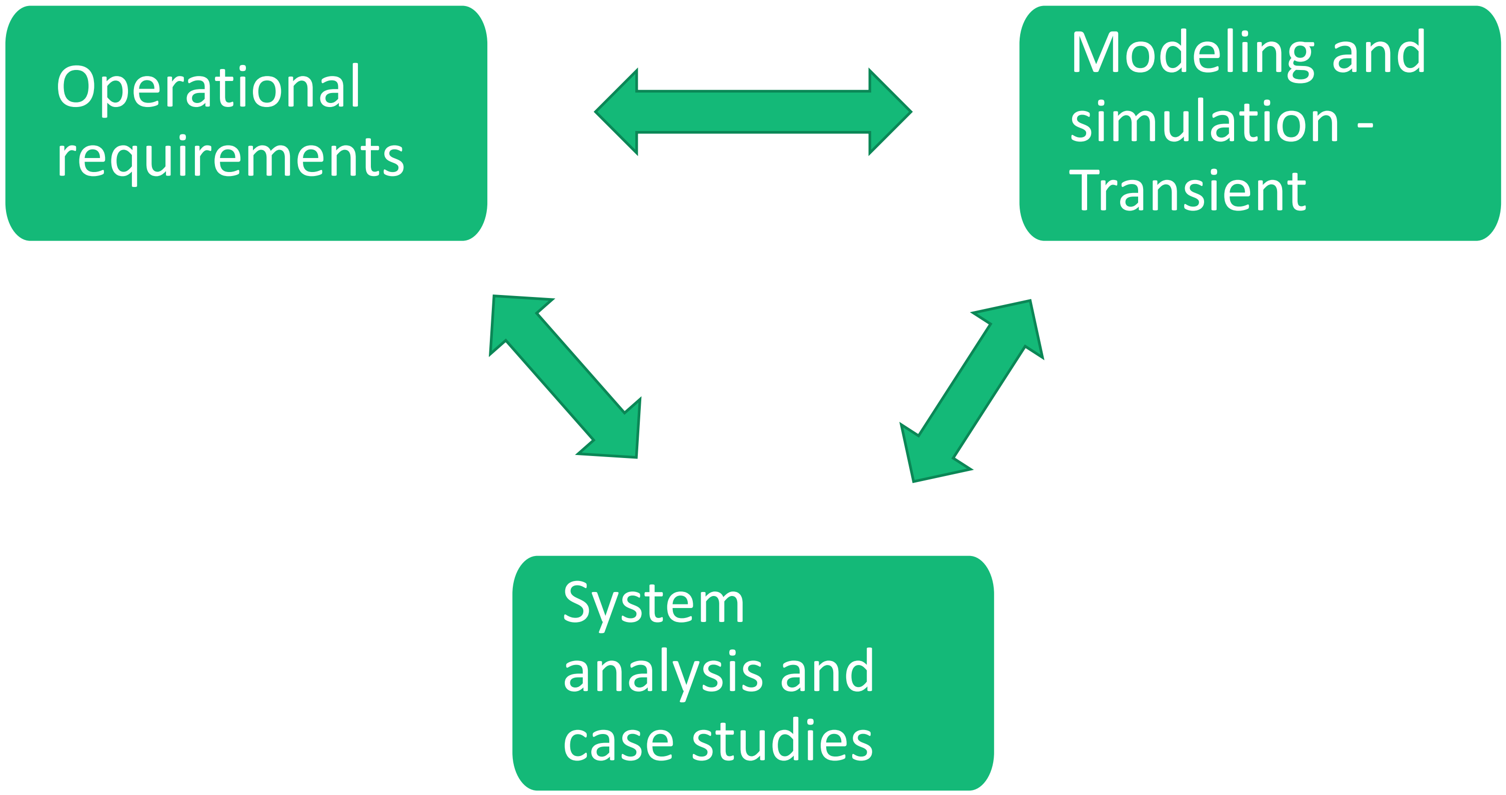


# Estimates based on existing and conceptual tank systems



Berstad et al. (2021) Liquid hydrogen as prospective energy carrier: A brief review and discussion of underlying assumptions applied in value chain analysis. Renewable and Sustainable Energy Reviews

# WP3 Loading operations



Operational requirements

Modeling and simulation - Transient

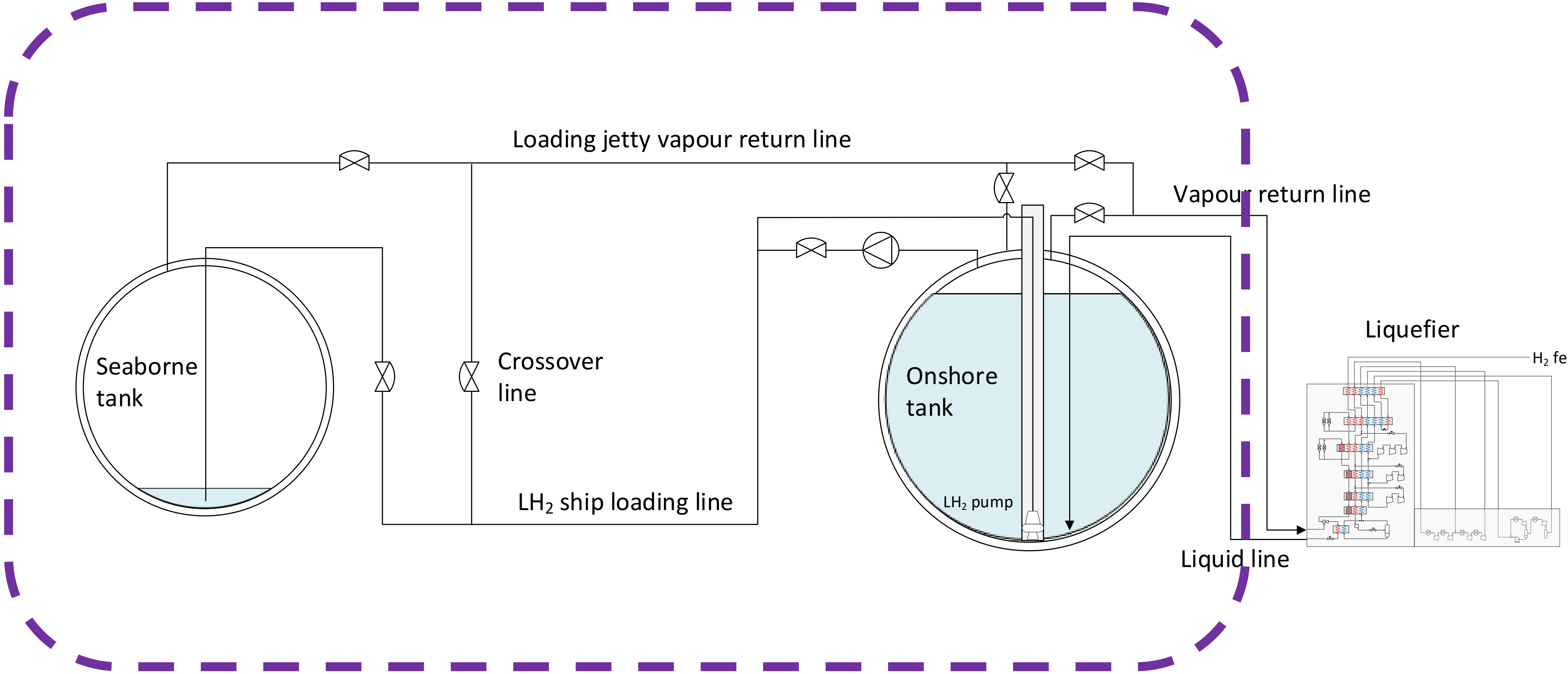
System analysis and case studies

# $LH_2$ Pioneer Project – the loading system

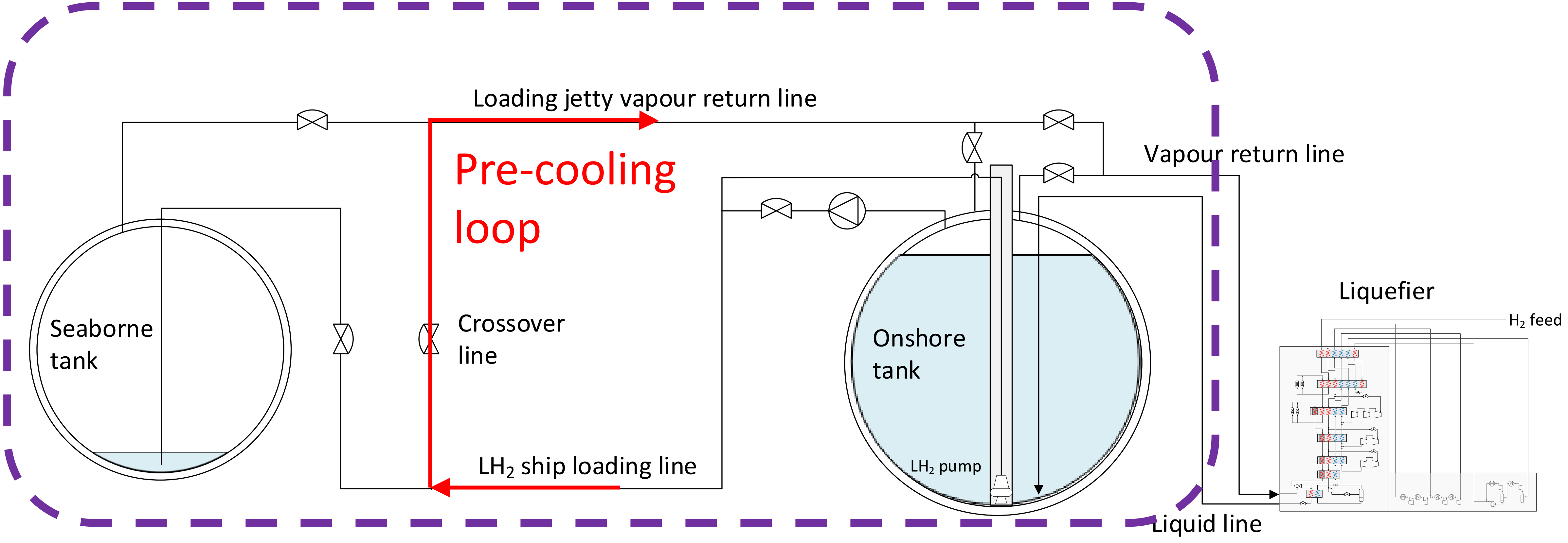
# Outlook: requirements for a large-scale $LH_2$ loading system

- Generally: large-scale requirements are larger than for any state-of-the-art or pilot systems made so far
- Energy flux: Expected to be typically 20–30 GW at rated capacity to cater to full-scale tankers
  - 150' – 200 000 $m^3$ cargo capacity
- Adequate pre-cooling procedures/techniques
  - The best option can vary depending on location
  - Potentially very different options between an export terminal and import terminal
- Low overall $LH_2$ "boil-off losses" for the full $LH_2$ loading cycle

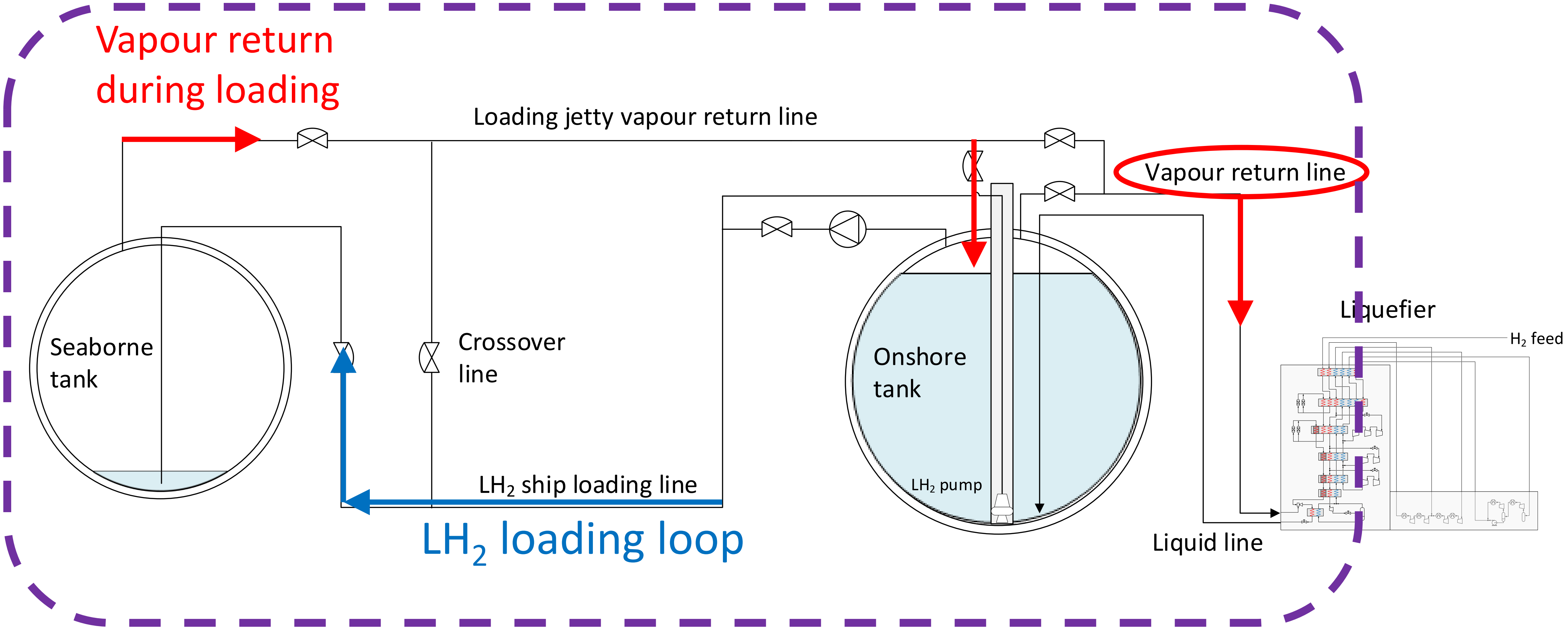
# $LH_2$ loading system



# $LH_2$ loading system



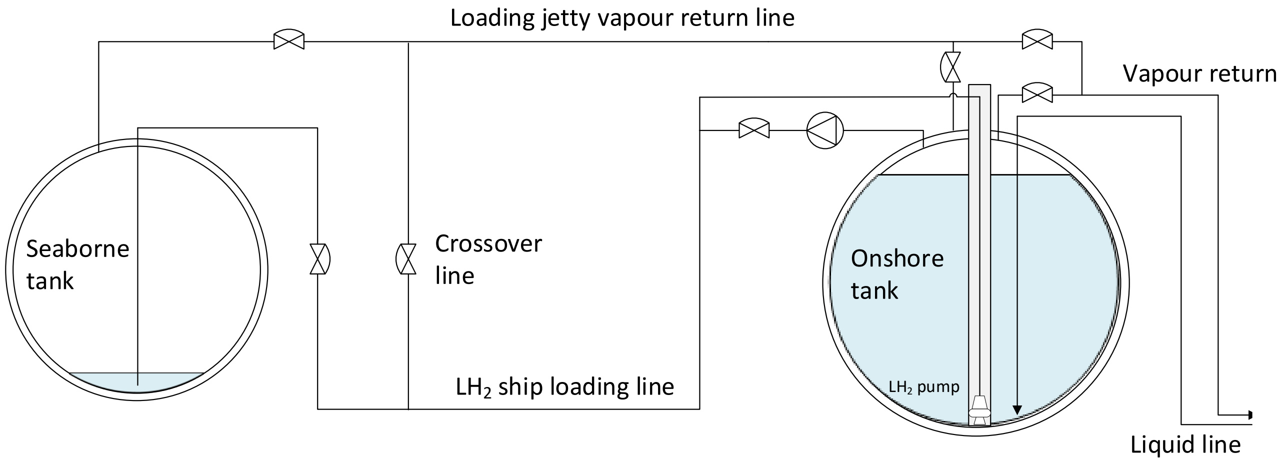
# $LH_2$ loading system



Vapour return during loading

$LH_2$ loading loop

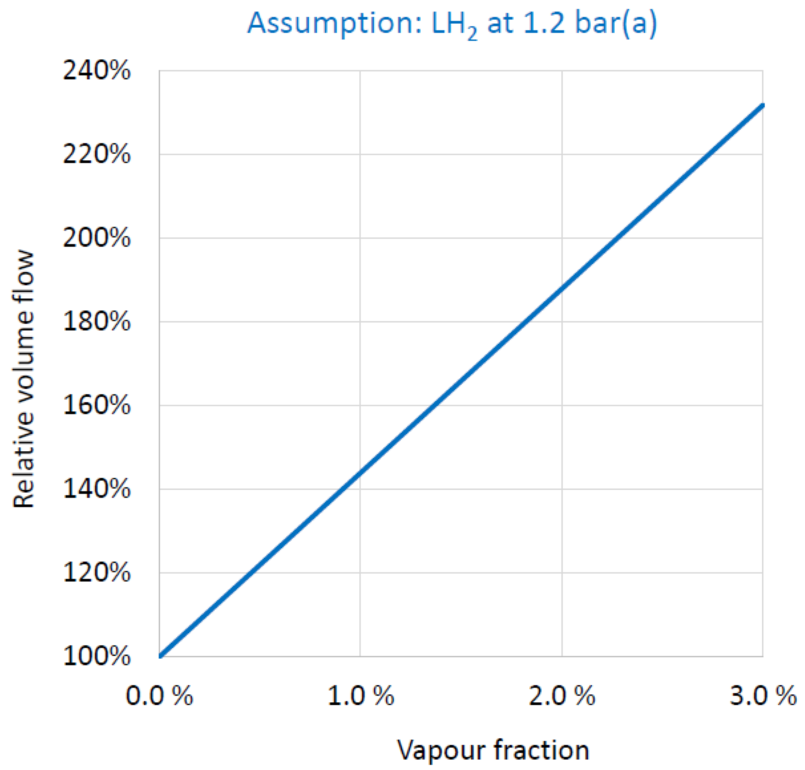
# $LH_2$ loading system



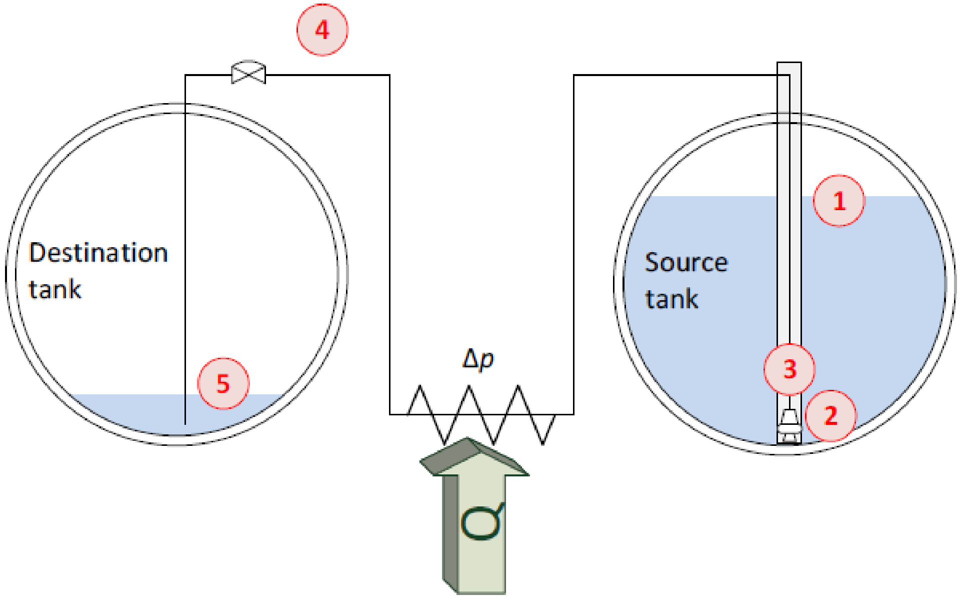
| Component | Parameter | Value | Unit |
|---|---|---|---|
| Seaborne tank | Capacity | 50 000 | $m^3$ |
| Seaborne tank | Heat ingress | 50 000 | W |
| Seaborne tank | Pressure | 1.105 | bar |
| Onshore tank | Capacity | 50 000 | $m^3$ |
| Onshore tank | Pressure | 1.105 | bar |
| Onshore tank | Heat ingress | 50 000 | W |
| $LH_2$ pipeline | Inner diameter | 0.3 | m |
| $LH_2$ pipeline | Length | 500 | m |
| $LH_2$ pipeline | Insulation | 0.07 | m |
| Vapor $H_2$ pipeline | Length | 500 | m |

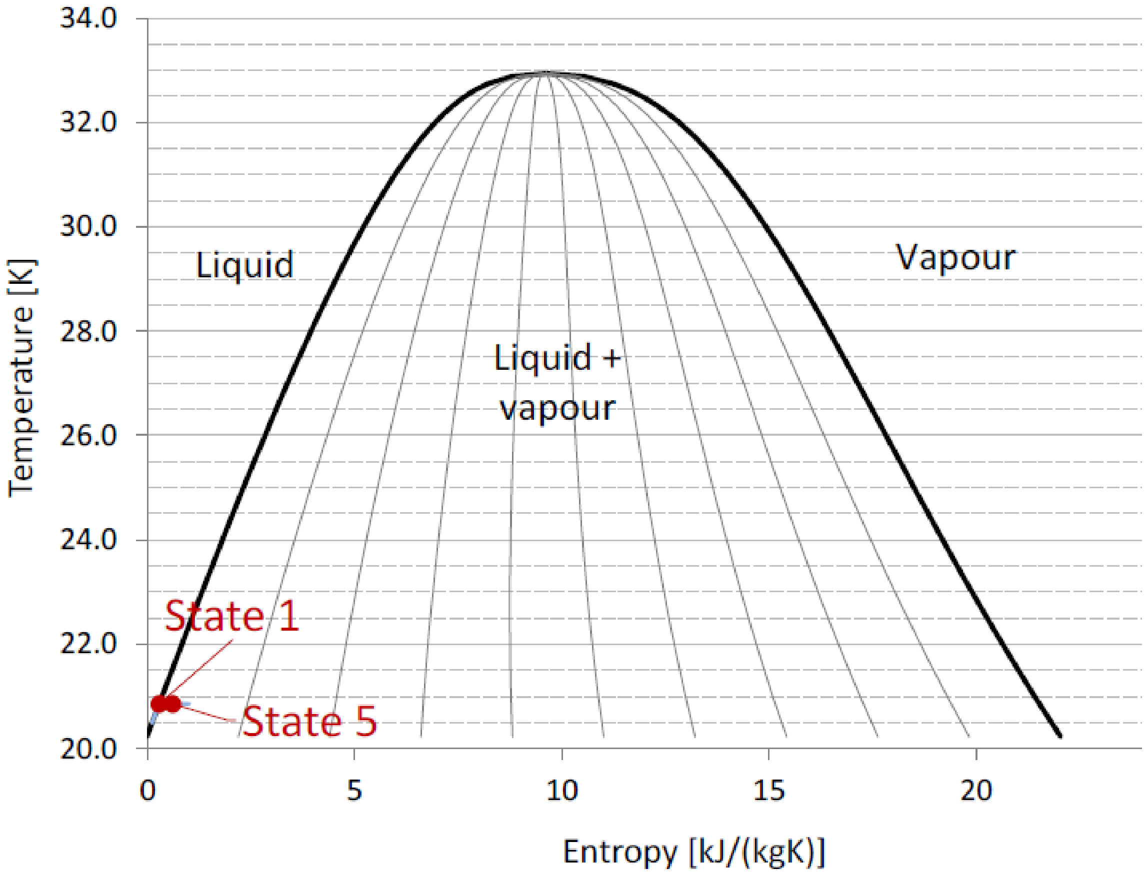
# Thermodynamic analysis

- Specific volume increases rapidly with vapour fraction
- The occurrence of two-phase in the transfer line can therefore lead to escalating pressure gradients and low capacity
- The liquid should be kept in a subcooled liquid state during transfer
- This can be enabled by pumping the liquid upstream of the liquid transfer line
    - Presumably by submerged pumps located on the bottom of the LH2 tanks

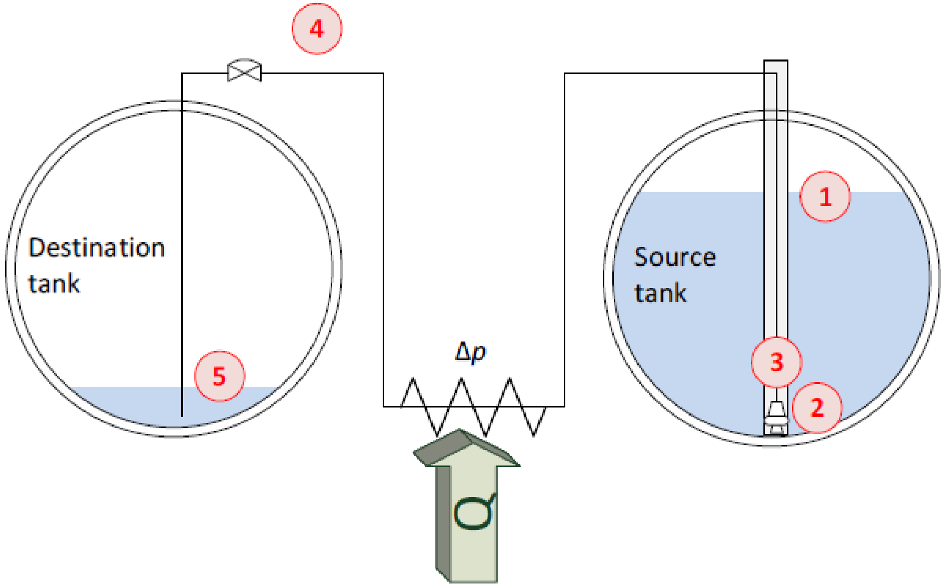


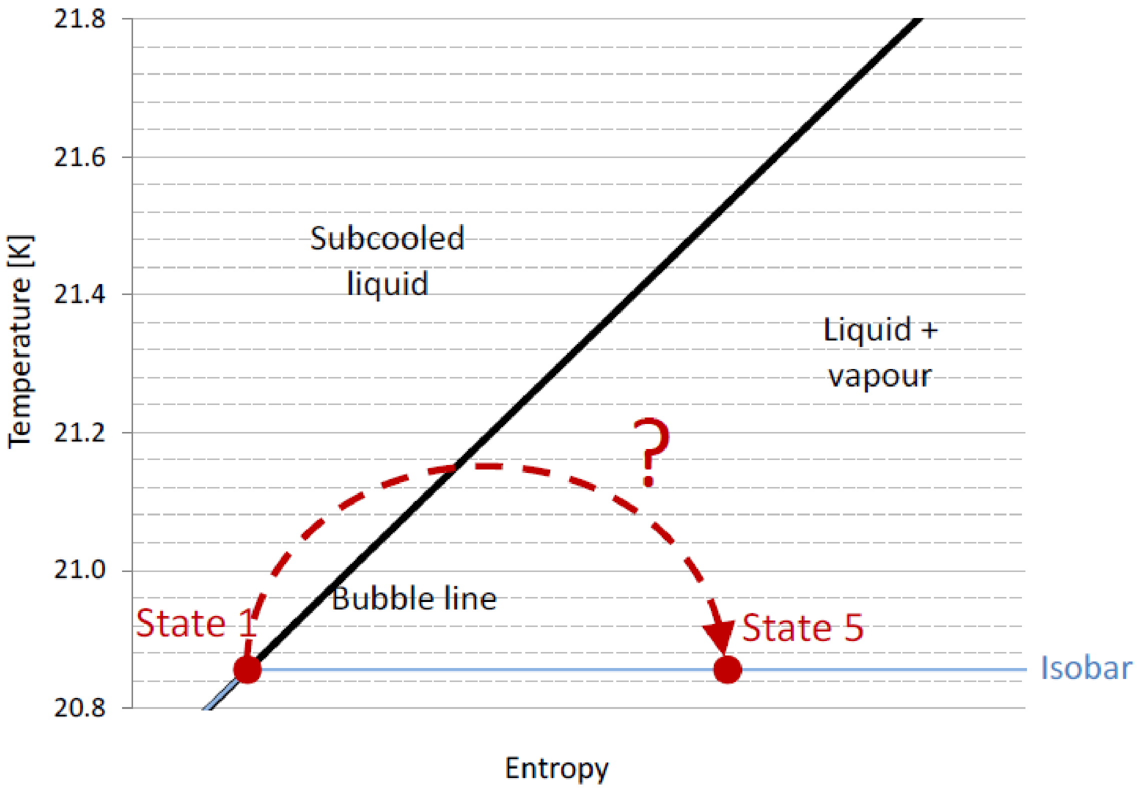
# State points along the $LH_2$ transfer line





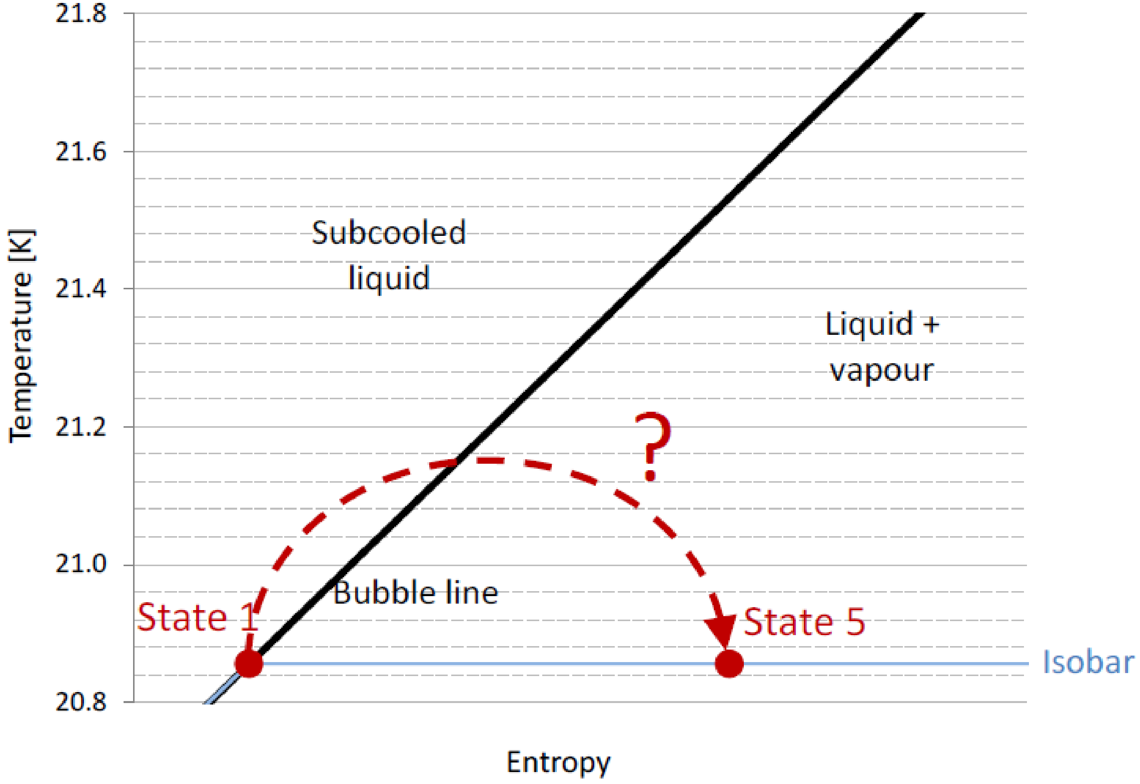
# State points along the LH$_2$ transfer line





# Drivers for evaporation along the $LH_2$ transfer line

- The amount of vapour generated is proportional to the entropy increase through the transfer process
- A "loss-free"/reversible transfer would give State 5 ≈ State 1
  - No friction or heat ingress
  - Not possible in practice



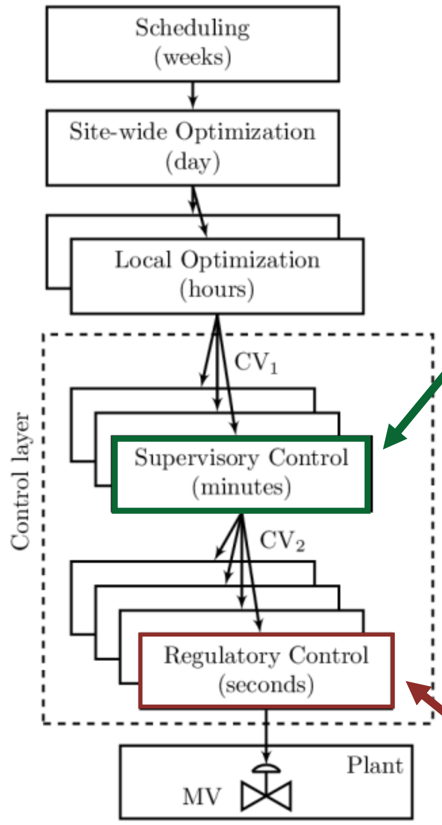
# Some observations from the thermodynamic analysis

- Each sub-process contribution to evaporation "losses" is proportional to its entropy generation
- The evaporation is not necessarily visible/detectable where it occurs, but the contribution can be quantified when analysed thermodynamically
- Pump efficiency is a major factor and element of uncertainty, and dissipation/inefficiency in the pump is a major cause for entropy generation
- Pressure losses due to hydraulic resistance seem to be generally more prominent than heat leak, when using typical values
- Additional heat losses are probable, but the impact will still be limited relative to dissipation and throttling
- High pump efficiency and low hydraulic resistance seems more of a concern to mitigate, in comparison with heat losses
- Heat ingress is still a major contributor e.g. during cooldown of the transfer lines.

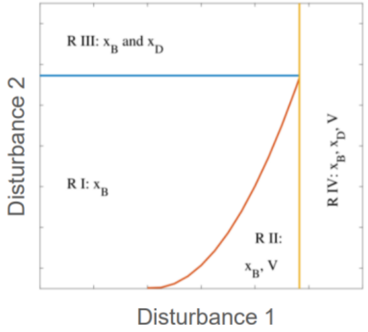
# Design vs Operation

- **Degrees of freedom (DOF) for design:**
  - Layout of the process → process configuration/topology
  - Design of equipment → capacities

- **Degrees of freedom (DOF) for operation:**
  - Equipment and process configuration are selected
    - What we can manipulate while we are operating the plant
  - Depend on which control layer we are focusing on
  - The control structure will affect:
    - Steady-state → economics
    - Dynamic behavior → stable process



Keeps operation in the active constraint region



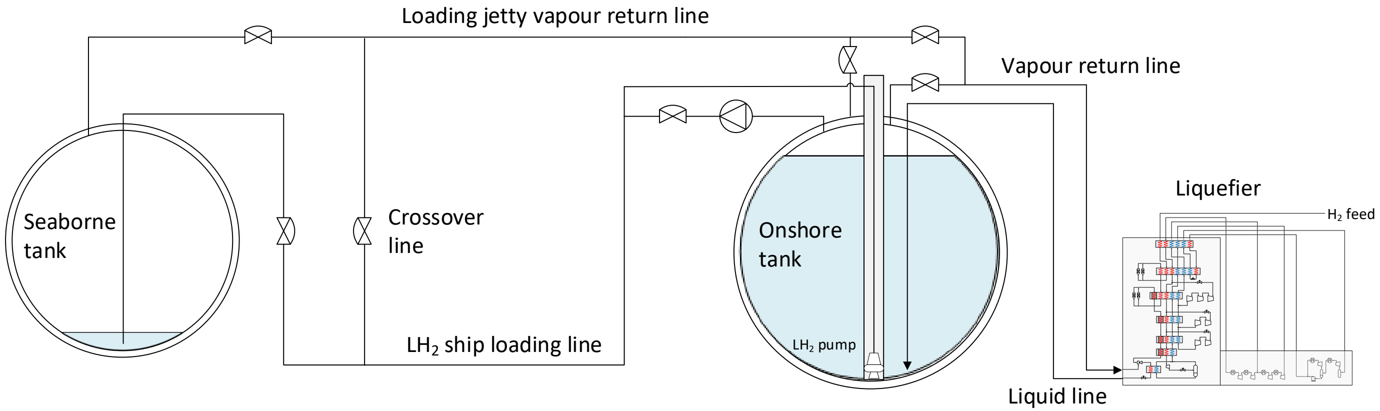
Stabilizing control layer

S. Skogestad, ``Control structure design for complete chemical plants'', Computers and Chemical Engineering, 28 (1-2), 219-234 (2004)
Jacobsen and Skogestad "Active constraint regions for optimal operation of chemical processes". Industrial & Engineering Chemistry Research. (2011)

# Degrees of freedom *for design* in the $LH_2$ loading system

- Tanks
  - Objective: Improve understanding for BOG handling/effect of evaporation during loading
    - Total capacity
    - Heat ingress

- Transfer system
  - Objective: Optimize transfer operations
    - wrt time, pressure losses, energy
  - DOF for design we can analyze:
    - Pipelines: diameter, insulation material, insulation thickness, layout, fittings
    - Pump: efficiency/capacity
    - Valves: size



# Analysis of dynamic behavior and *operation*

Need to identify:

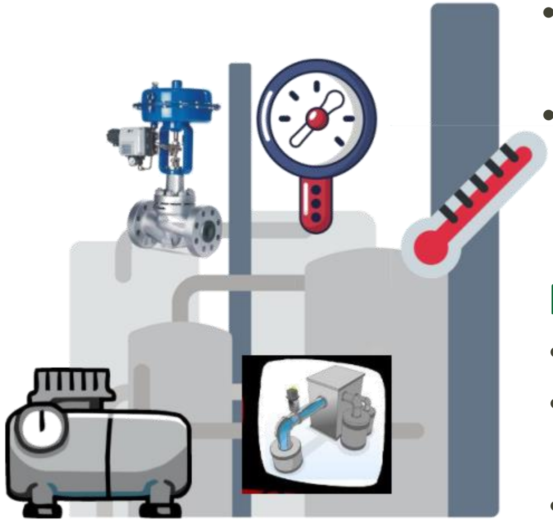
- Controlled variables (CV)
- Manipulated variables (MV)
- Disturbances (DV)
- Constraints
- Throughput manipulator (TPM)

## Constraints

- What limits your operation
- e.g., design, thermodynamics (max/min temperature, pressure, flowrate, level, etc.)

## Disturbance variables (DV):

- Type of input
- What you cannot choose/manipulate
- e.g., ambient temperature, desired production, upstream operation



## Controlled variables (CV):

- "Output"
- Can be measurements or calculations
- What you want to keep at a certain set point
- e.g., temperature, pressure

## Manipulated variables (MV):

- "Input"
- What you can "directly" choose/manipulate
- e.g., valve opening, rotational speed

## Throughput manipulator (TPM)

- DOF that affects the network flow and is not determined by the control of individual units

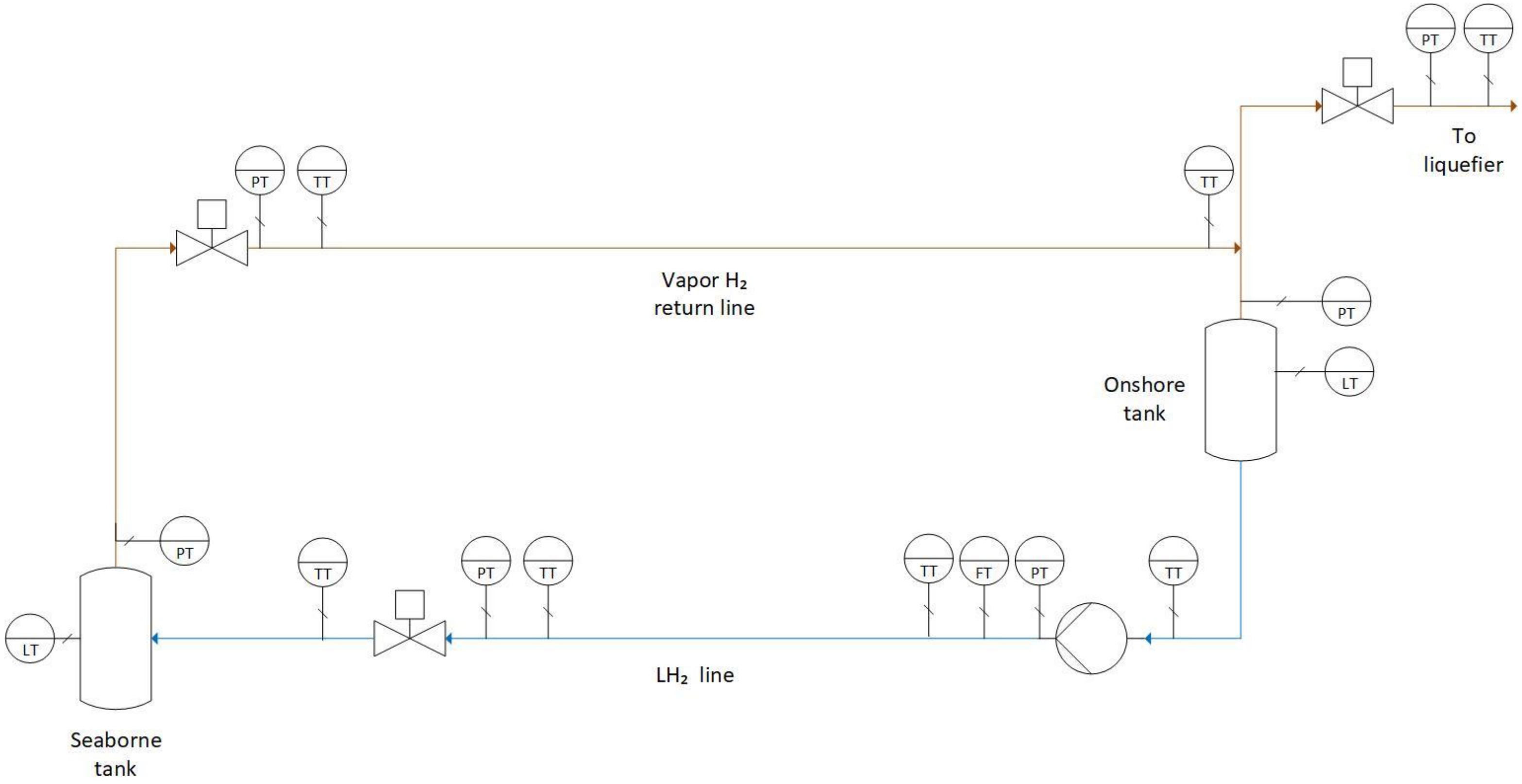
# *Operation* of the $LH_2$ loading system

**Operational objective:**

- To transfer $LH_2$ from the onshore tank to the seaborne tank

**Constraints:**

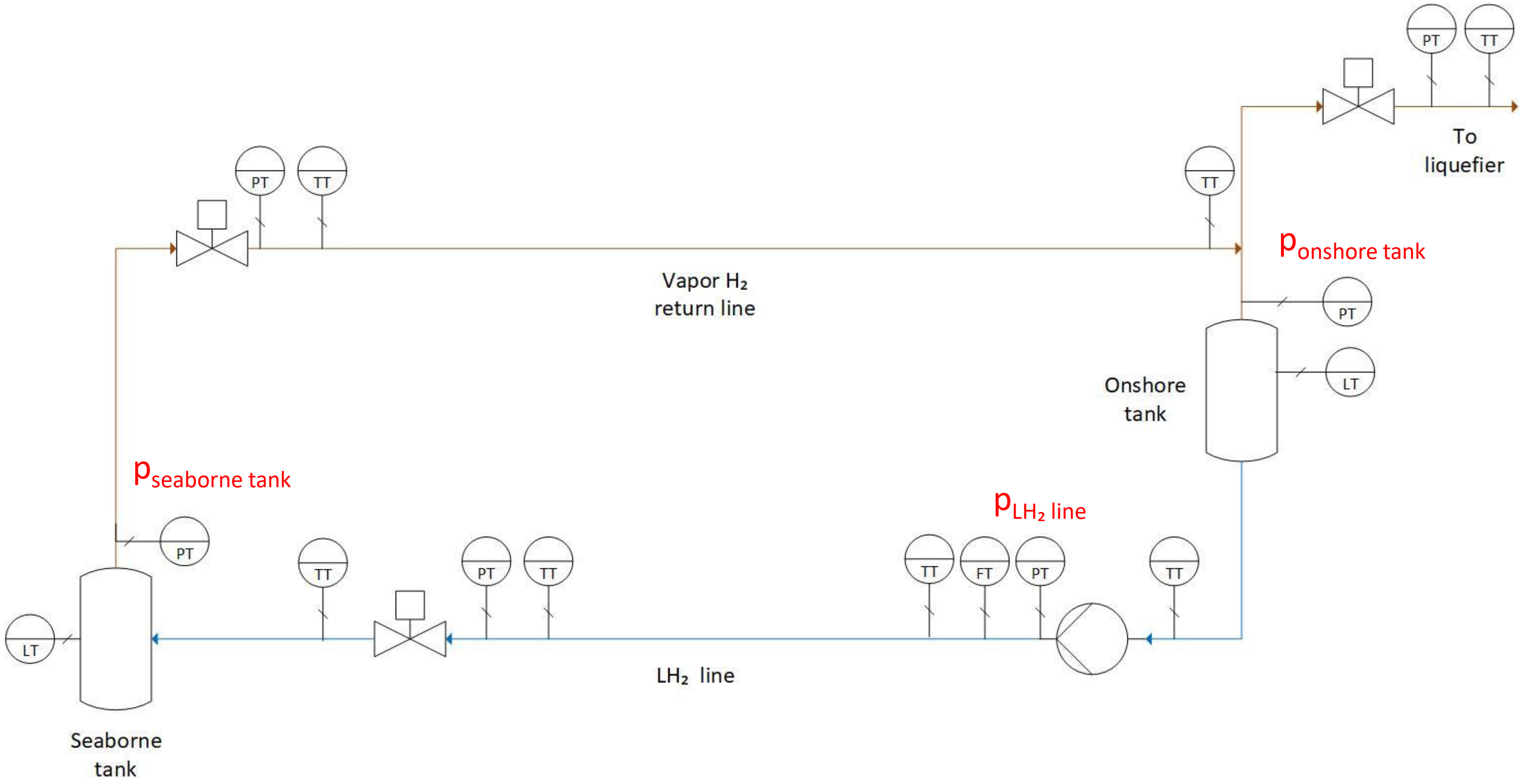
- Design capacities
- Maximum flowrate in $LH_2$ line
- Thermodynamics:
  - Keep liquid phase in $LH_2$ line
- Fluid-dynamics:
  - Pressure differences that allow transfer



# *Operation* of the $LH_2$ loading system

## Controlled variables (CV):

- $p_{\text{seaborne tank}}$
- $p_{\text{onshore tank}}$
- $(p_{LH_2\text{ line}})$
- May define others…



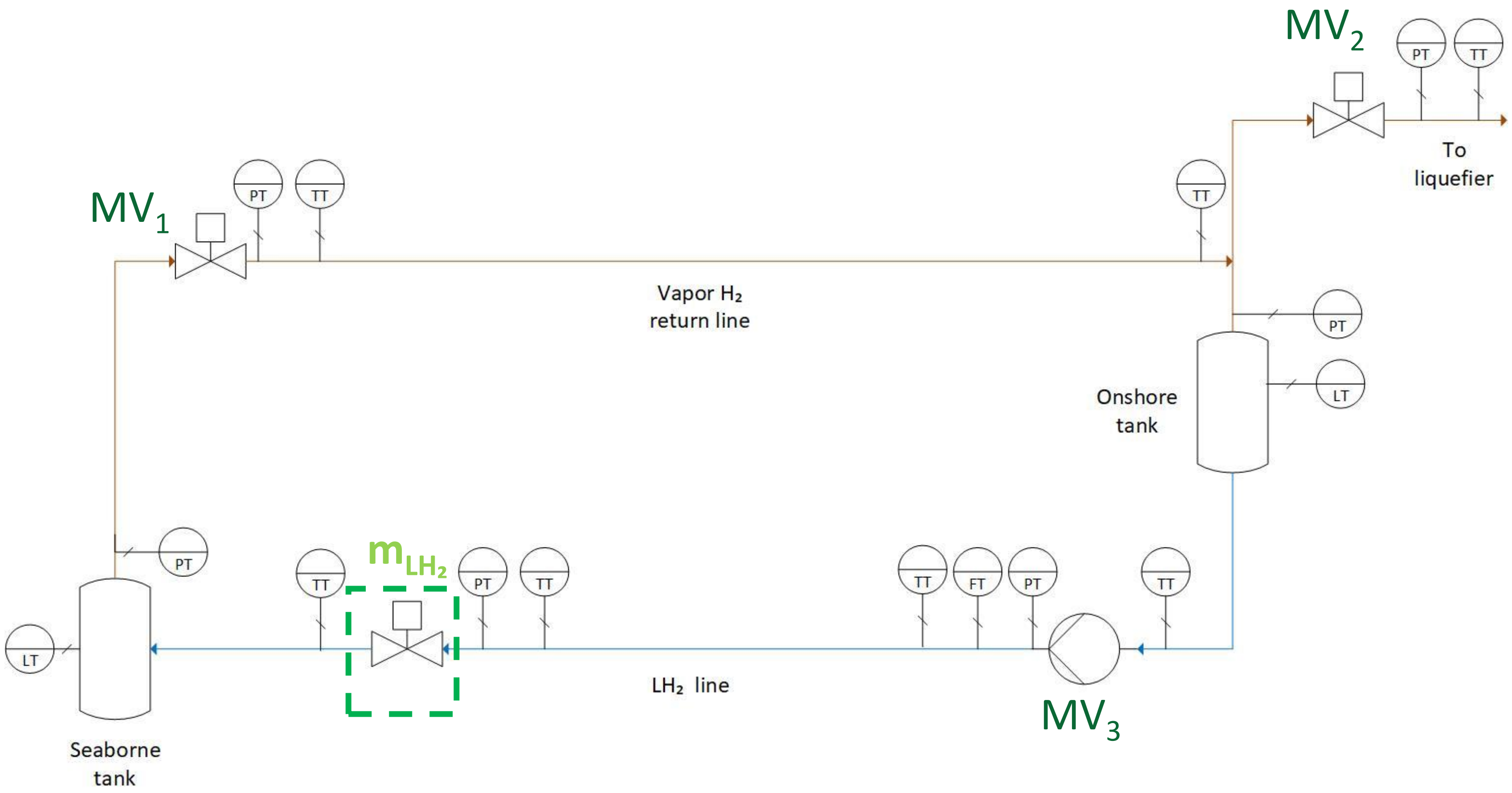
# *Operation* of the $LH_2$ loading system

**Degrees of freedom for stabilization:**

- $MV_1$
- $MV_2$
- $(MV_3)$

**Throughput manipulator**

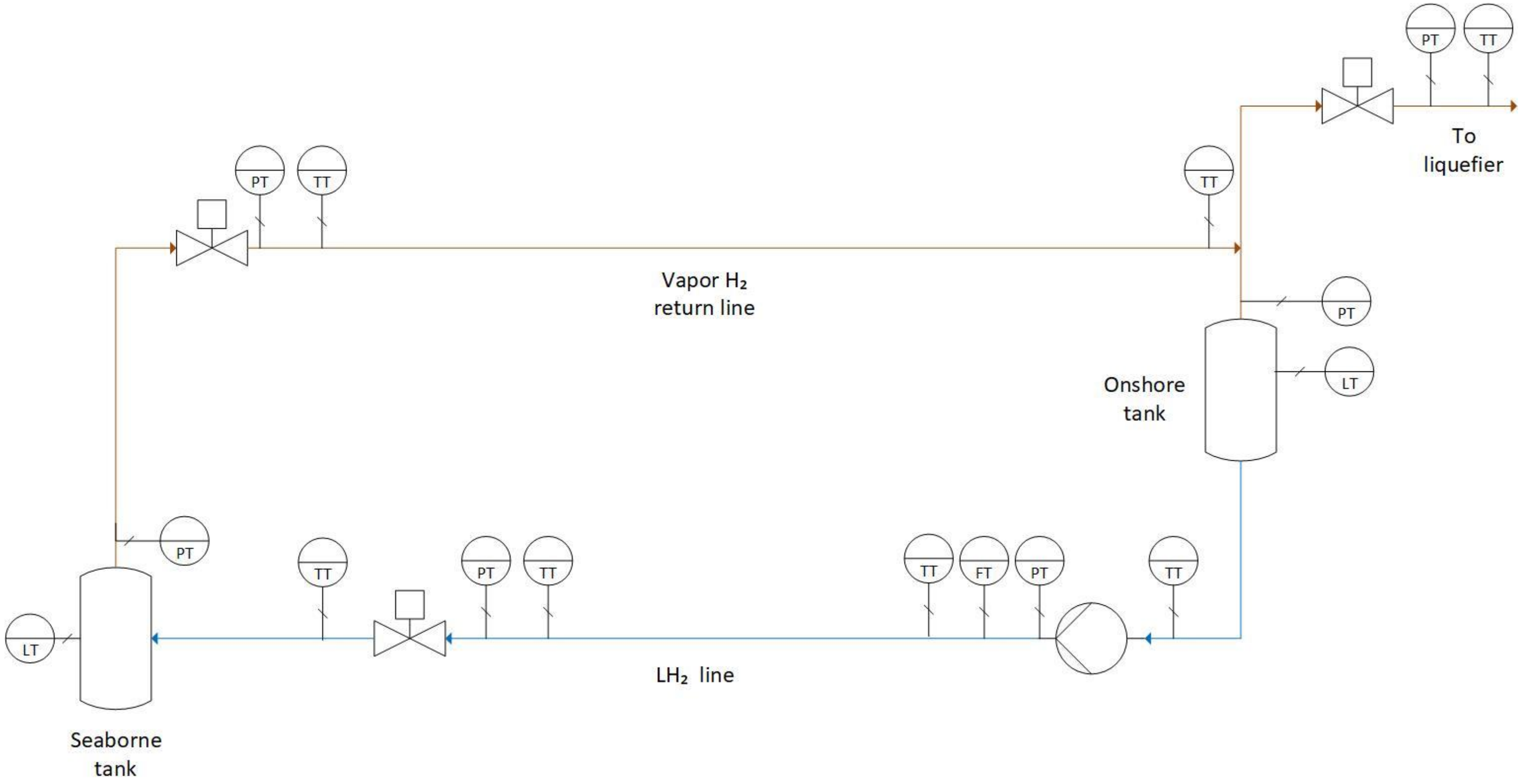
- $m_{LH_2}$



# *Operation* of the $LH_2$ loading system

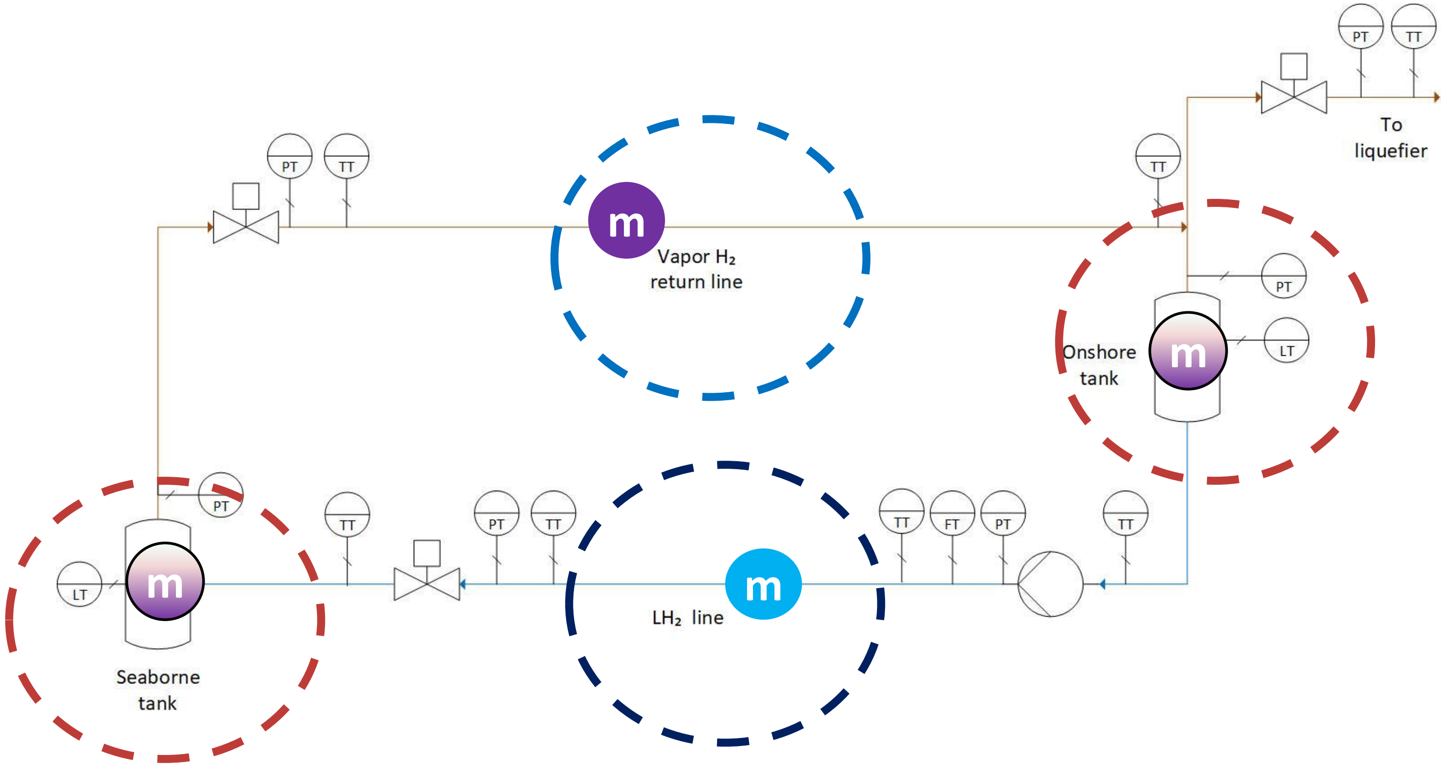
**Loading procedure:**

- mooring,
- connection,
- flushing,
- precooling,
- ramp-up,
- "steady-state" transfer,
- ramp-down,
- etc.



# We want consistency in the inventory

- Consistency.
  - An inventory control system is consistent if it can achieve acceptable inventory regulation for any part of the process, including the individual units and the overall plant.
- Inventory



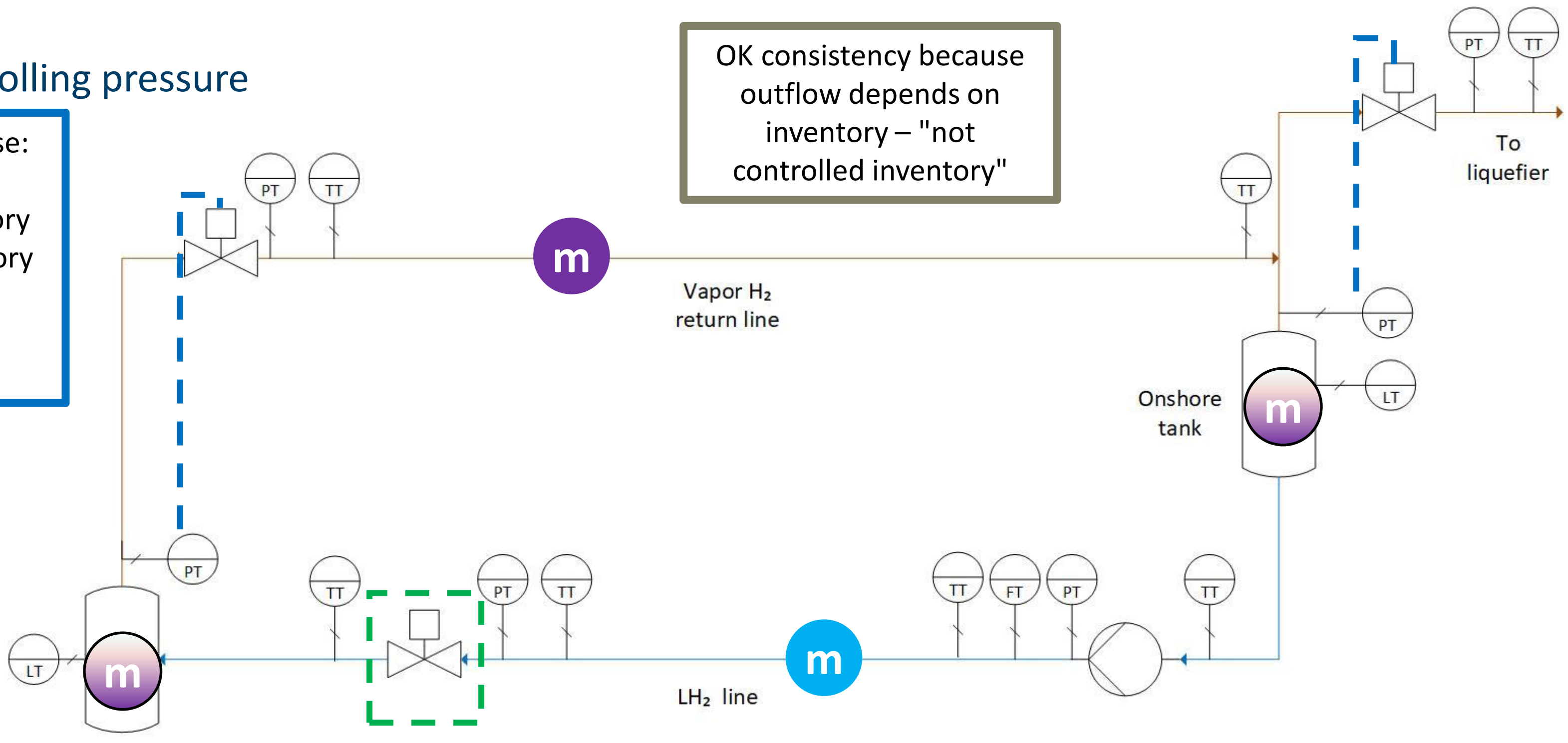
Aske and Skogestad. "Consistent Inventory Control". Ind. Eng. Chem. Res. 2009, 48, 10892–10902

# Some guidelines for a consistent control structure

- We want both "local consistency" and "global consistency"
  - Local consistency:
    - only local/close loops (short time delays)
    - the control inventory of the unit depends on loops around the unit, i.e., its inflows or outflows:
      - local inventory regulation
      - At least one flow in or out of any part of the process (unit) depends on the inventory inside that part of the process (unit)
- Pressure controllers:
  - Pressure and inventory dependency: strong for liquids
  - Pressure regulation = inventory regulation
- Flow controllers:
  - Fix a flow in every recycle loop
  - Cannot be used for inventory control because flow is not a measure of inventory
- For systems with several phases, the inventory of each phase of any part of the process must be regulated by its in- or outflows or by phase transition
- In closed systems, leave one uncontrolled inventory

Aske and Skogestad. "Consistent Inventory Control". Ind. Eng. Chem. Res. 2009, 48, 10892–10902

# Checking consistency



Valve controlling pressure

OK consistency because:
- Vapor outflow depends on inventory – controlled inventory
- Liquid inventory depends on phase transition

Assumption: maximum liquid trasferred will not exceed tank capacity

OK consistency because outflow depends on inventory – "not controlled inventory"

Valve controlling pressure

OK consistency because:
- Vapor outflow depends on inventory – controlled inventory
- Liquid inventory depends on phase transition

If inlet to tank was producing liquid, there would not be local consistency for the liquid phase!

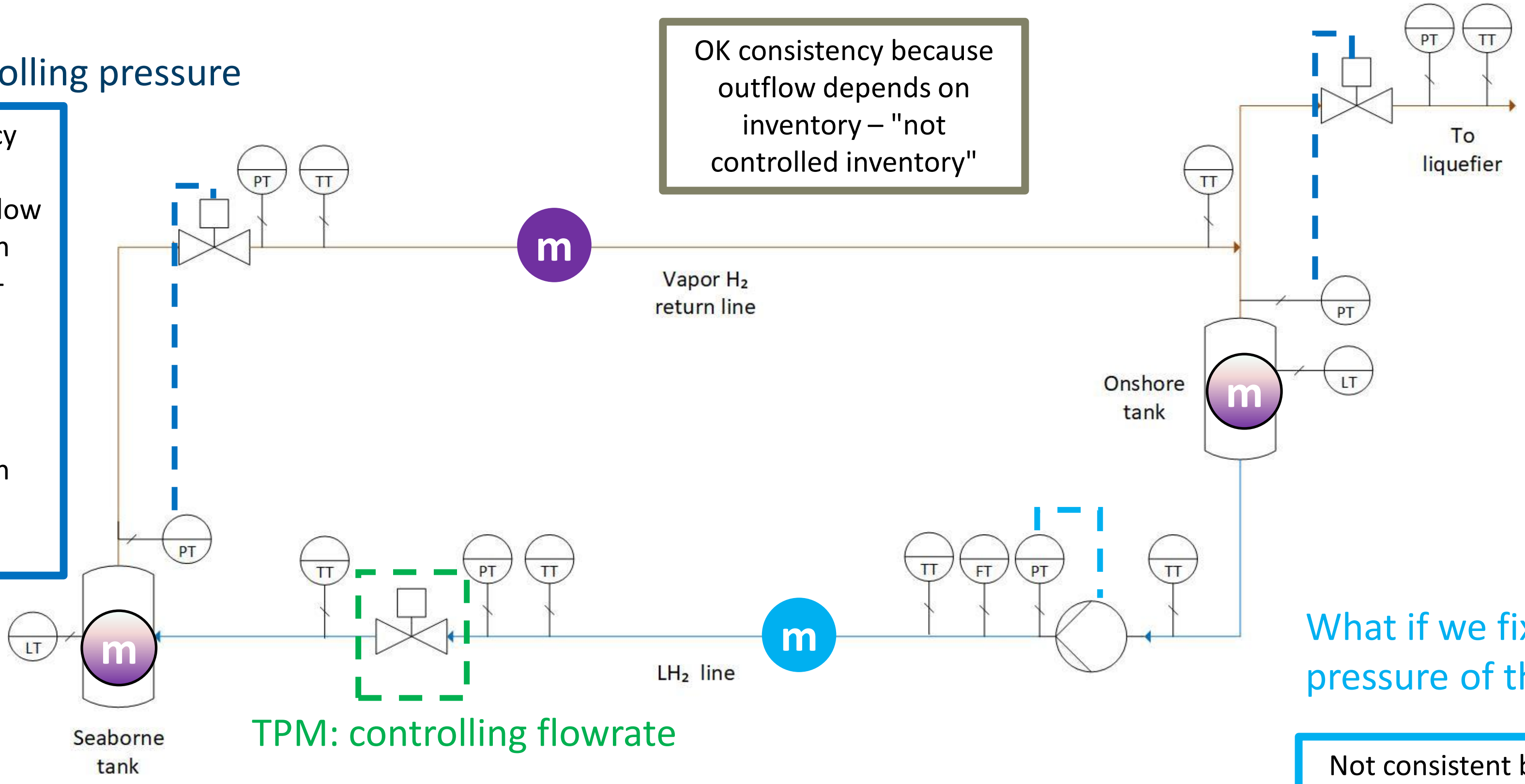
TPM: controlling flowrate

TPM: throughput manipulator

# Checking consistency

Valve controlling pressure

OK consistency because:
- Vapor outflow depends on inventory – controlled inventory
- Liquid inventory depends on phase transition



OK consistency because outflow depends on inventory – "not controlled inventory"

Valve controlling pressure

OK consistency because:
- Vapor outflow depends on inventory – controlled inventory
- Liquid inventory depends on phase transition

TPM: controlling flowrate

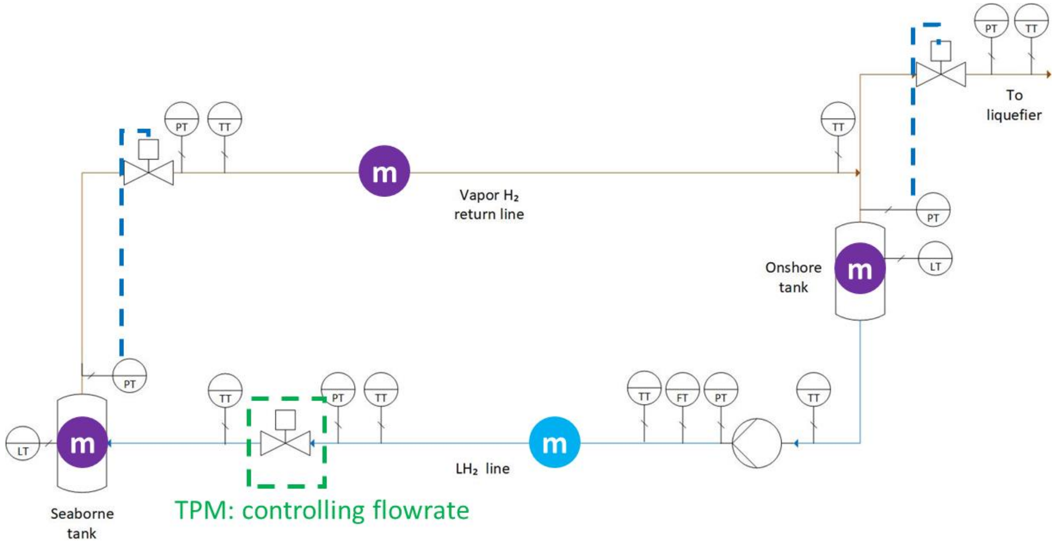
What if we fix the delivery pressure of the pump?

Not consistent because then neither inflow nor outflow of the the $LH_2$ line depends on its inventory

TPM: throughput manipulator

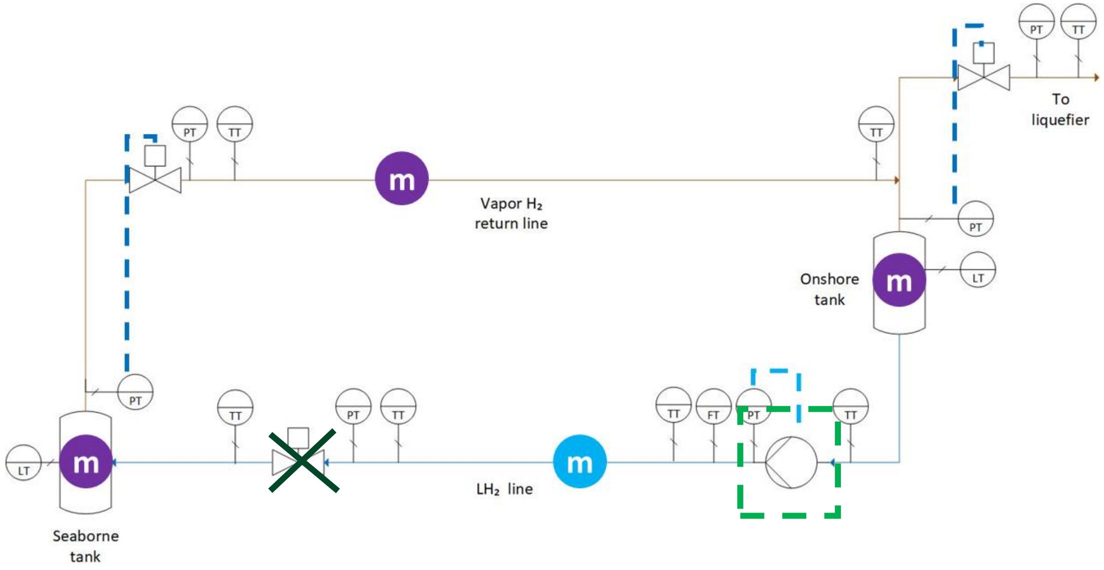
# Alternatives for controlling loading

- Use $LH_2$ flowrate as TPM
- Pump not controlling pressure/defining flow to $LH_2$ line



TPM: controlling flowrate

- Use pump as TPM
- Pump defining flow to $LH_2$ line



TPM: throughput manipulator

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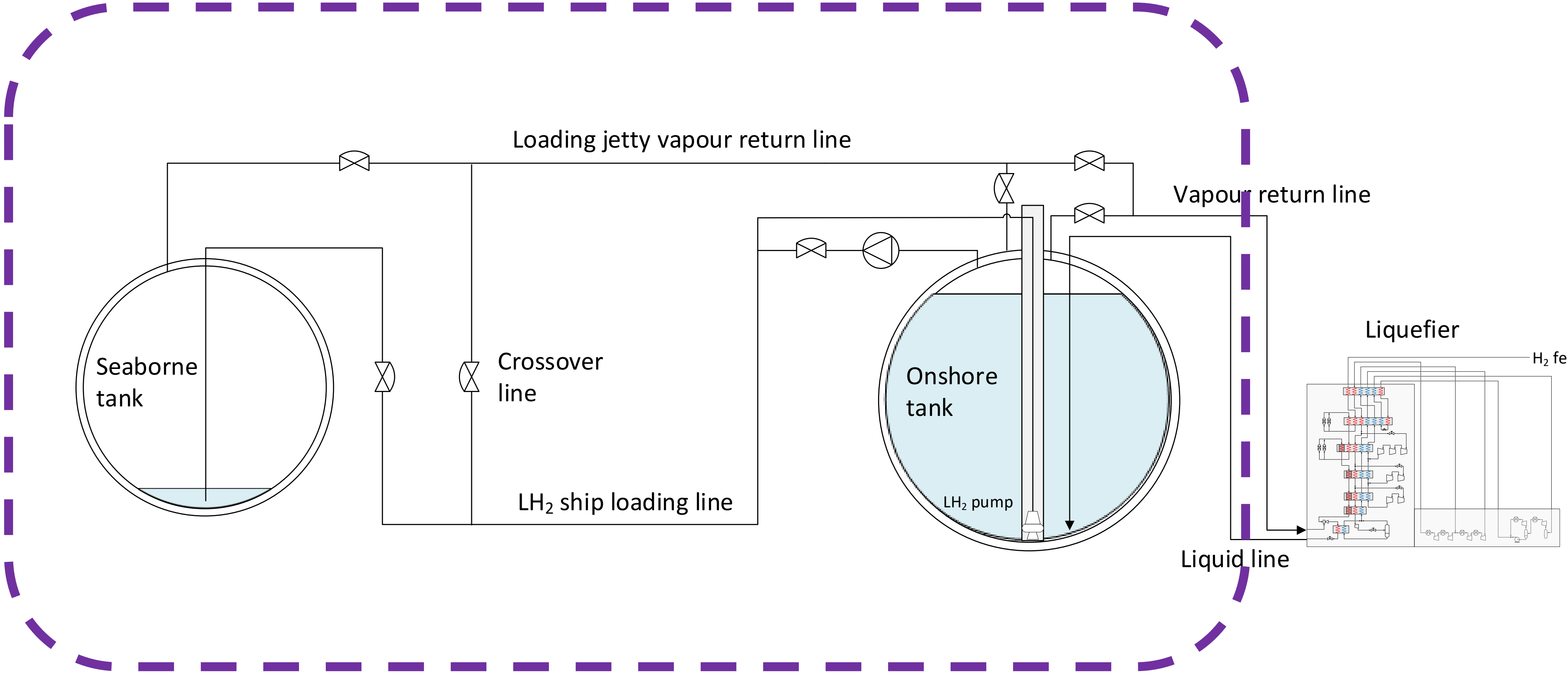
# $LH_2$ Pioneer Project – dynamic model for the loading system

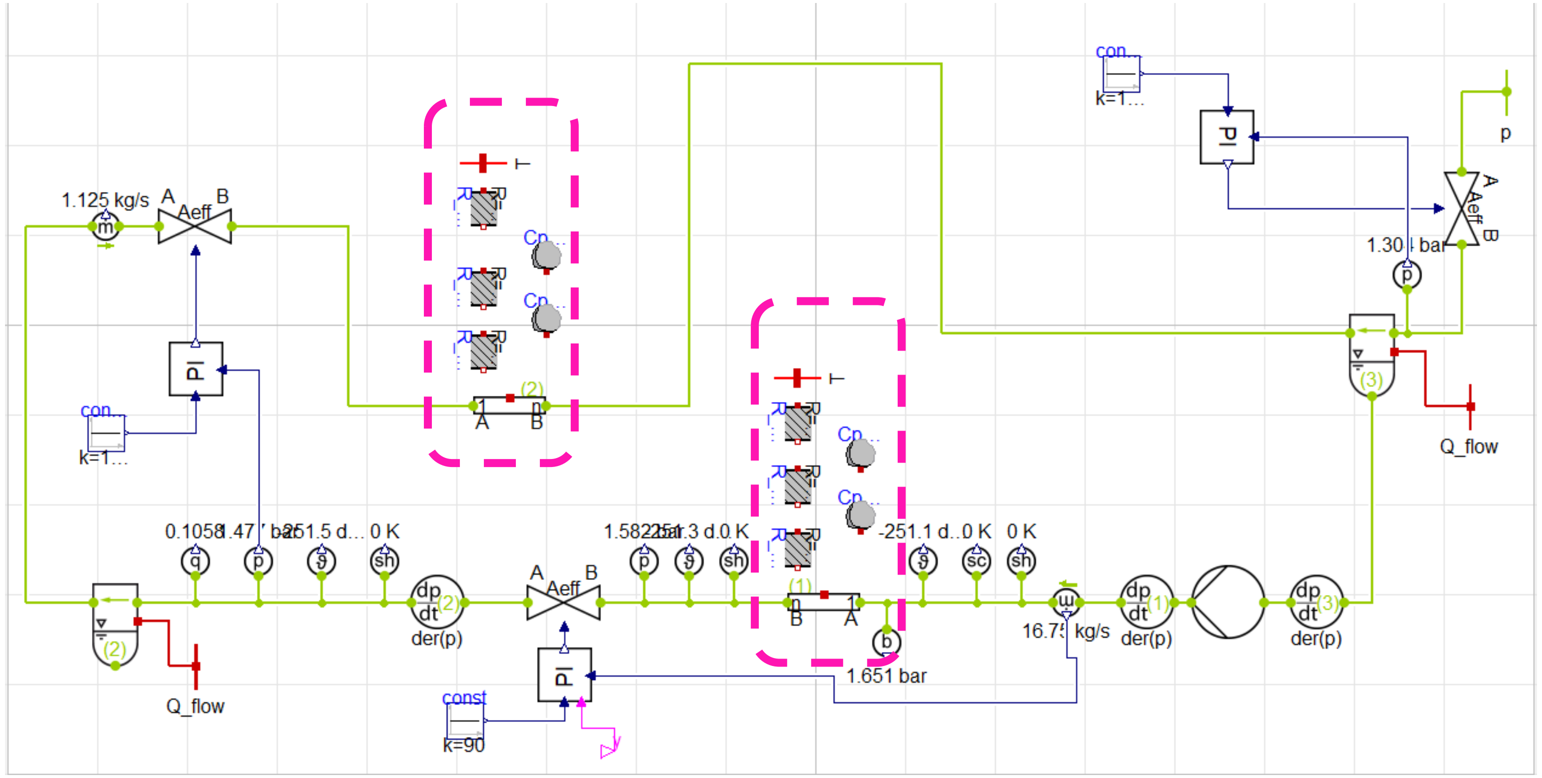
# Tools for the dynamic model

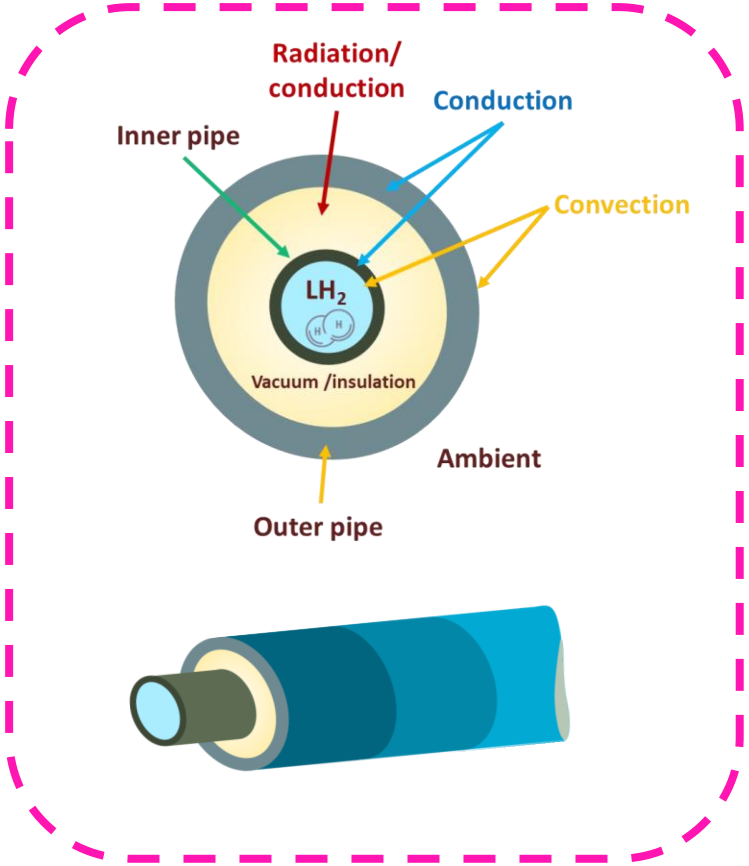
- Modelica: "physical modeling language"
  - "High-fidelity" simulation that incorporates
    - Thermodynamics
    - Heat transfer mechanisms
    - Geometry
  - Modeling and simulation environment: Dymola
- TIL:
  - Model library for thermal components and systems
- TIL Media:
  - Model library for efficient calculation of thermophysical properties
  - Using REFPROP (here, 100% para-hydrogen)

# $LH_2$ loading system

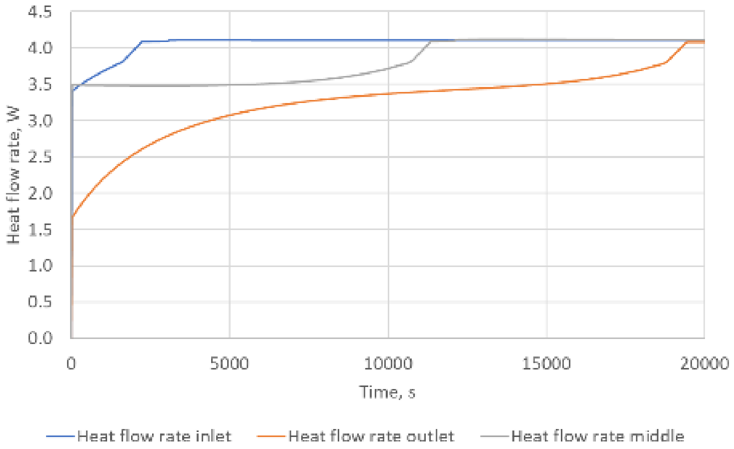


# $LH_2$ loading system

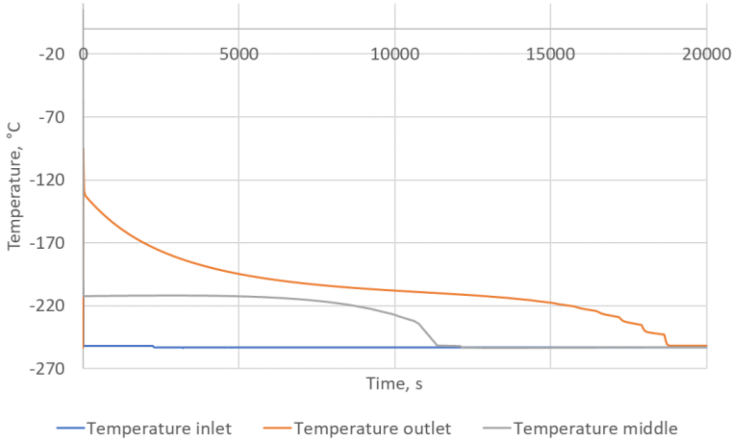




# Simulations results during priming (cooling and filling with $LH_2$)



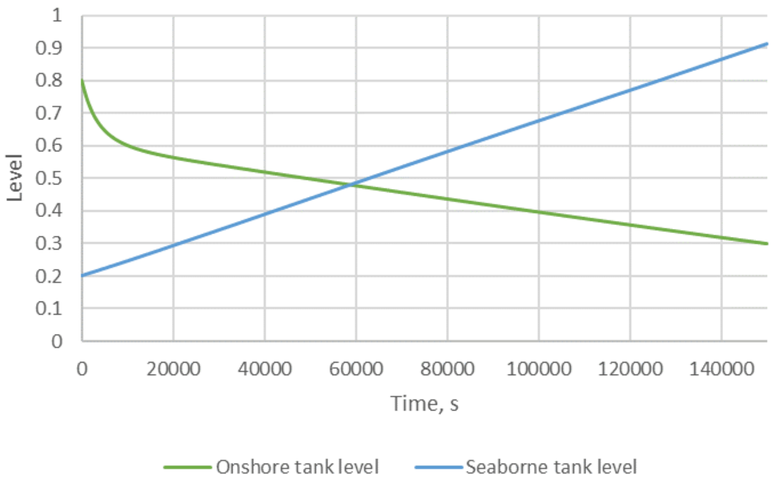
Heat ingress per segment



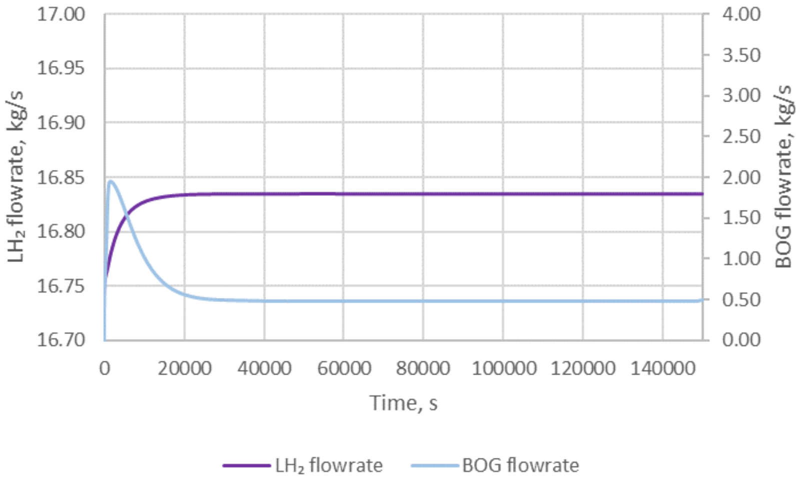
Temperature in pipeline

Initially, the pipeline is filled with hydrogen in vapour state (vapor quality =1) and the ambient temperature is 15°C.

# Simulation results during loading



a) Level of onshore and seaborne tanks



b) $LH_2$ and BOG flowrate

# Final comments

- Large-scale $LH_2$ transfer – possible in the future, first steps being taken
- Consistency analysis:
  - understanding the dynamic behavior of the system and developing the control system
  - understanding the implications and limitations of possible alternatives for loading
- Identification of degrees of freedom for operation and regulatory control layer for the transfer system → steady-state transfer
- Improved understanding of the dynamic behavior of large-scale $LH_2$ transfer operation of $LH_2$ between tanks
- **Important assumptions: Lack of data and experience upscaling components**

# Acknowledgements

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