Large-scale hydrogen transport
Techno-economic assessment of different pathways

Moritz Raab, Ralph-Uwe Dietrich

Jahrestreffen der ProcessNet-Fachgruppe
Energieverfahrenstechnik
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DLR

Agenda

1. Background & Motivation
2. Definition of Business Case
3. Transport pathways
   - LH2
   - LOHC Toluene
4. Results
5. Outlook

1. Background & Motivation

- Availability of RE is unevenly distributed around the globe & most industrial countries are not RE self-sufficient
- New energy import strategies are necessary - Japan in center of research activities for H_2 import
- Numerous studies on how the energy can be transported [1,2] & where it is generated [1,3]

Liquid hydrogen

Project - HESC [4]
Brown Coal based LH_2 is shipped from Victoria, Australia to Kobe, Japan

LOHC system toluene – methyl cyclohexane

Project – AHEAD [5]
MSR based H_2 is shipped as MCH from Brunei to Japan

➢ What are the technical & economical KPI's of the different pathways?

[1] Yoshino 2012
[2] https://www.chiyodacorp.com/
[3] Heuser 2019
[4] https://hydrogenenergysupplychain.com/
[5] https://www.ahead.or.jp/en/

2. Business Case

Goal

- Transparent techno-economic assessment of a large scale **point to point** hydrogen transport
- For the sake of comparability – similar scenario as in study from KHI [2]
- Hydrogen production is excluded from the business case

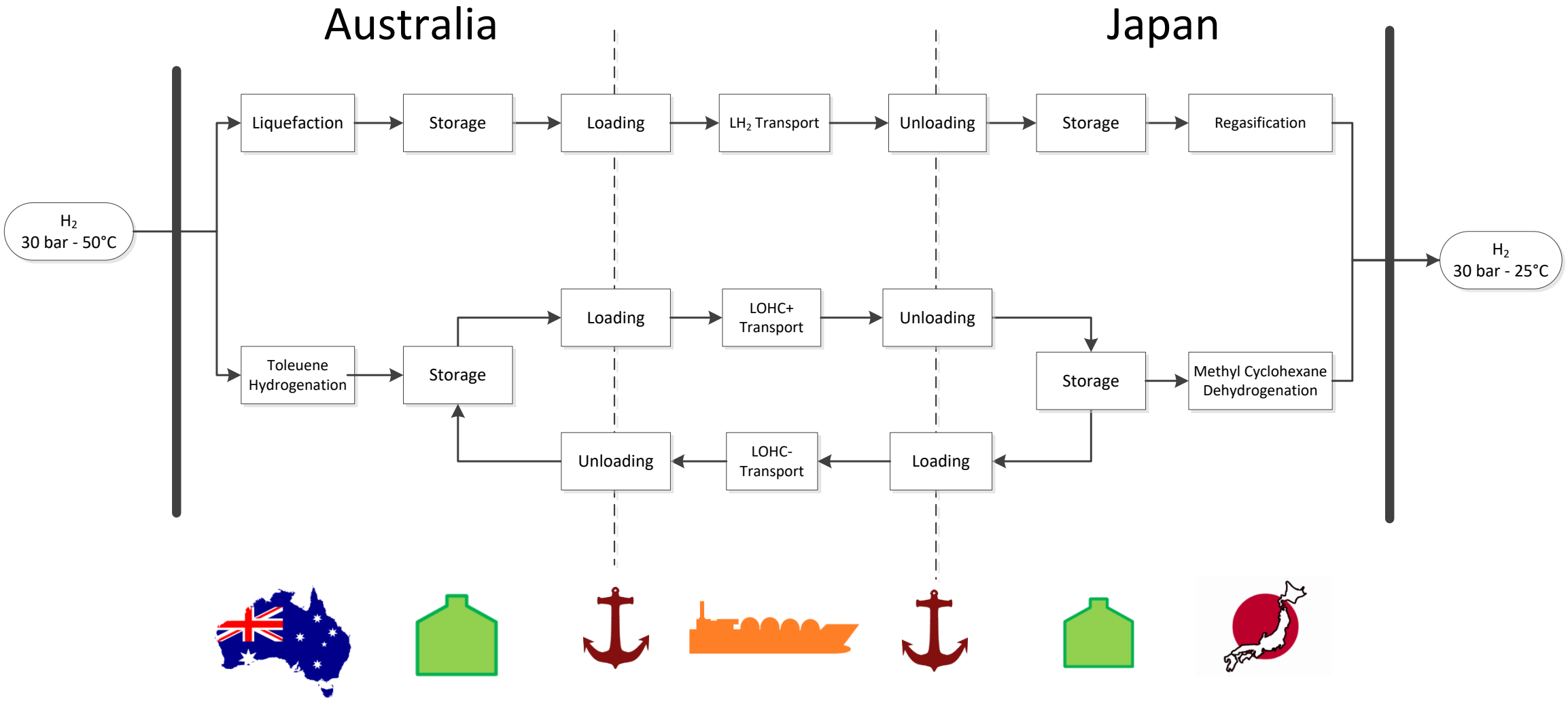
	Unit	Value
H_2 feed	t/a	225’500
H_2 feed	kg/h	28’187.5
Depreciation time	a	20

	Unit	Value
Plant availability	h/a	8’000
Sea distance	NM	5’000
Interest rate	%	5

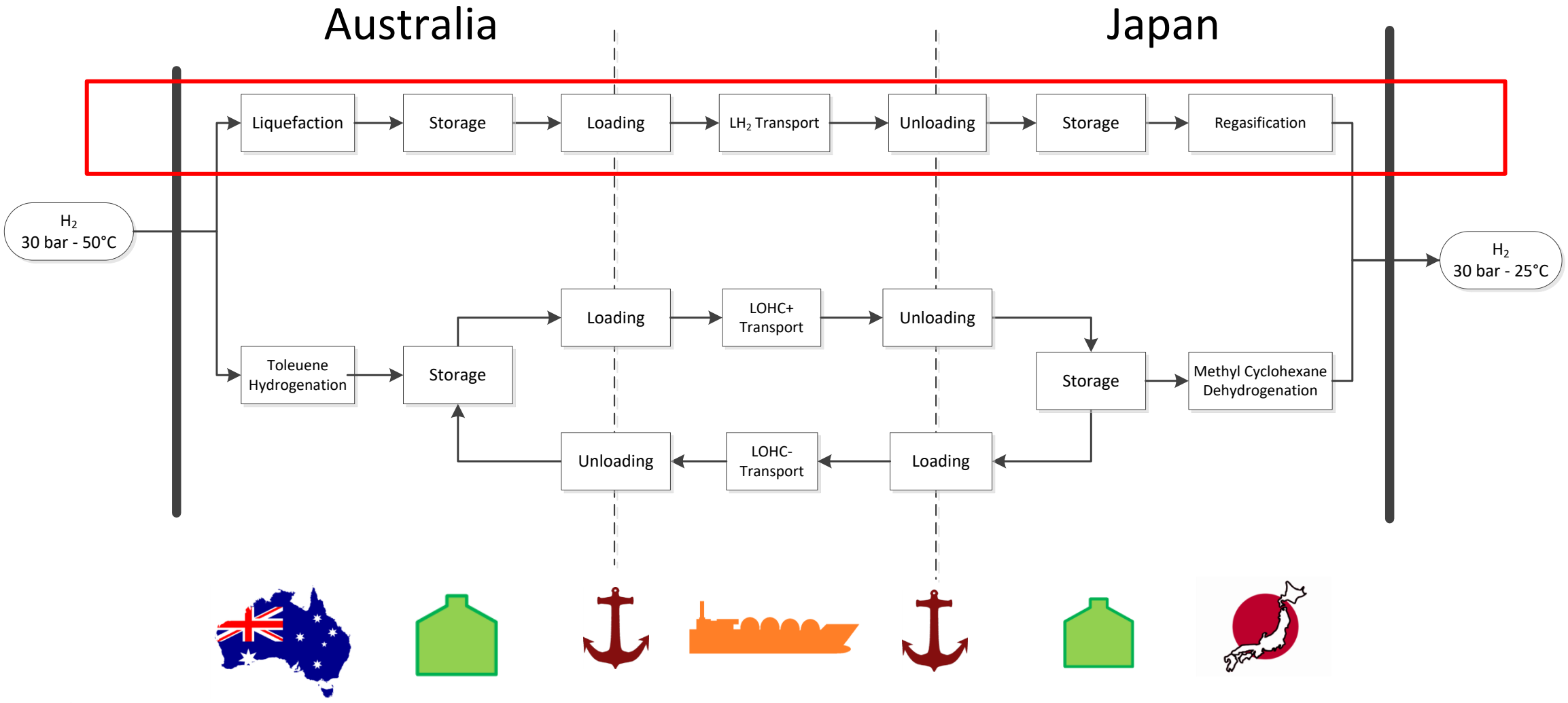
- Methodology based on [6] – except for liquefaction a technical evaluation is performed with Aspen Plus
- Delivered hydrogen meets ISO 14687-2 (FC in road vehicles)

[2] Yoshino 2012
[6] Albrecht 2017

2. Business Case



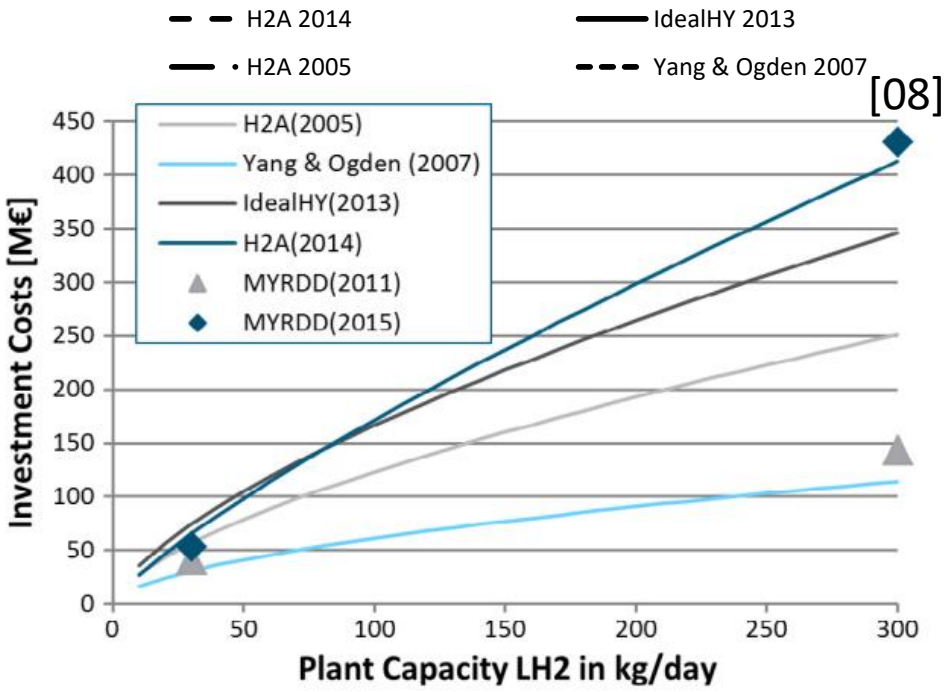
2. Business Case



3. Pathways – LH2

Liquefaction

- 3 liquefaction trains - capacity of 225.5 tons per day (tpd)
- worldwide capacity in 2009 @ **355** tpd [7]
- Costs assumed based on [8]
- FCI of 330 Mio. € per train
- Conservative SEC of 7 kWh/kg – lower published [9]



[7] Krasae-in 2010
[8] Reuß 2017
[9] Cardella 2017

3. Pathways – LH2

Storage

- No large-scale H_2 tanks built so far - LNG storage as reference
- Tanks: 3 x 100’000 m³ in Australia & 3 x 90’000 m³ in Japan Cost from [10]

Harbor

- Required infrastructure
  - Jetty
  - Flare
  - Loading/Unloading line
- Costs from [11]

[10] Michael Baker 2013
[11] Roger Smith 2017

[2]

3. Pathways – LH2

LH2 Carrier

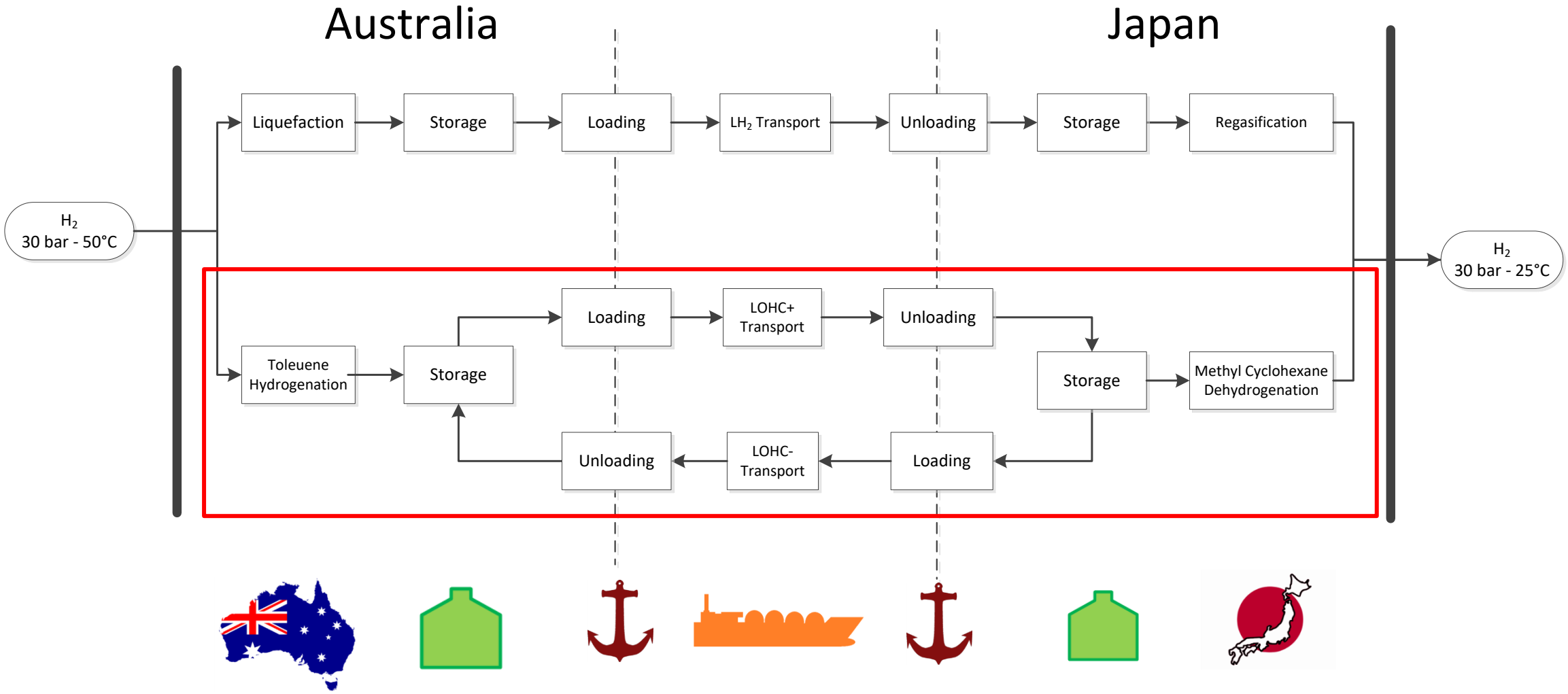
- Technical data based on [2] - 160’000 m³ capacity
- LNG carrier used as reference for costs [12]
- Boil-off is used for propulsion - OPEX for manpower, supply, maintenance and insurance

Regasification

- LNG reference - On shore terminal is used - no usage of “precious cold”
- 2 HX system - 1st ORV with seawater - 2nd closed loop with water
- Costs taken from [13]

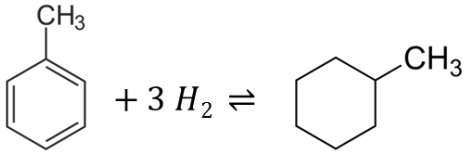
[02] Yoshino 2012
[12] 2018 World LNG report
[13] Peters 2002

2. Business Case



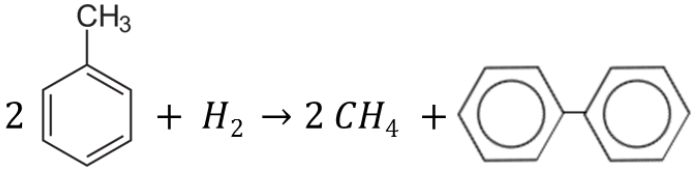
3. Pathways – LOHC Toluene

Hydrogenation



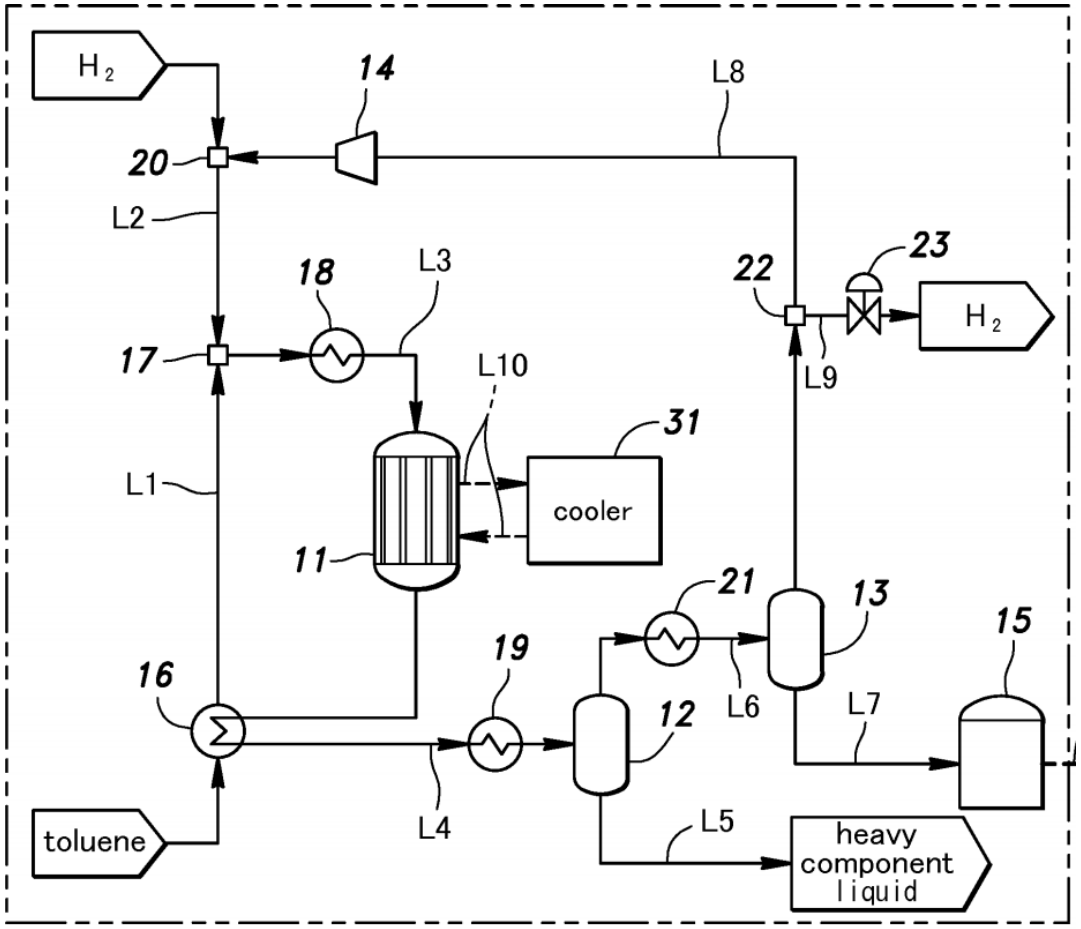
$$+ 3\,H_2 \rightleftharpoons \qquad \Delta H^0 = -205\,\frac{\mathrm{kJ}}{\mathrm{mol_{Tol}}}$$

- Process design from Chiyoda [14]
- 3 hydrogenation trains - reaction kinetics from [15]
- Side reaction leading to Biphenyl forming



- Column for benzene-stripping is added to process
- FCI estimated with [13] and [17]

[14]



[14] Patent by Chiyoda - PCT/JP2015/000400
[15] Saeys 2005
[13] Peters 2002
[17] Woods 2007

3. Pathways – LOHC Toluene

Storage

- More tank volume required - for both toluene and methyl cyclohexane
- Tanks: 4 x 150’000 m³ in Australia & 4 x 150’000 m³ in Japan.
- Costs from 100’000 m³ tank are up-scaled [18]

Harbor

- Similar harbor infrastructure as in LH2 pathway

[18] Viva Energy 2017

3. Pathways – LOHC Toluene

LOHC carrier

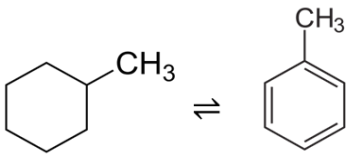
- Suezmax oil tanker used as reference [19] - capacity between 160’000 – 200’000 m³
- Costs of 65 Mio. $ are considered [20] with adaption for capacity and reactor
- Dehydrogenation is used for propulsion - OPEX for manpower, supply, maintenance and insurance

[19]

[19] Shipyard Brodosplit - Donat 447
[20] Compass Report 2020

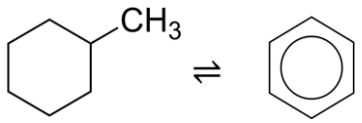
3. Pathways – LOHC Toluene

Dehydrogenation



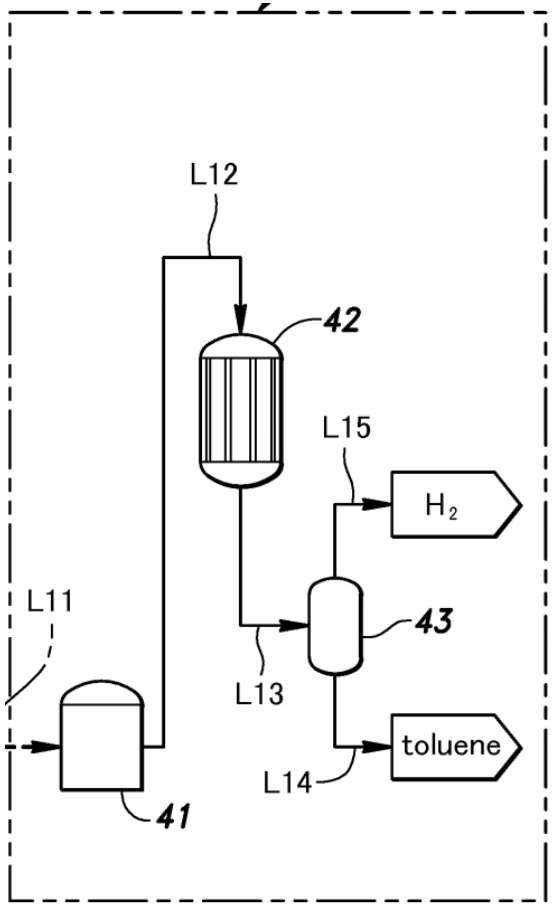
$$\rightleftharpoons \quad + 3\,H_2 \quad \Delta H^0 = +205\,\frac{\mathrm{kJ}}{\mathrm{mol_{MCH}}}$$

- Process design from [14] - reaction kinetics from [21]
- Side chain scission leads to benzene forming



$$\rightleftharpoons \quad + 2\,H_2 + CH_4$$

- Large amount of heat at 350°C is required - source can be
  - Hydrogen
  - Electricity
  - ➢ <u>Natural gas</u>



[14] Patent by Chiyoda - PCT/JP2015/000400
[21] Kurosaki 2018

3. Pathways – LOHC Toluene

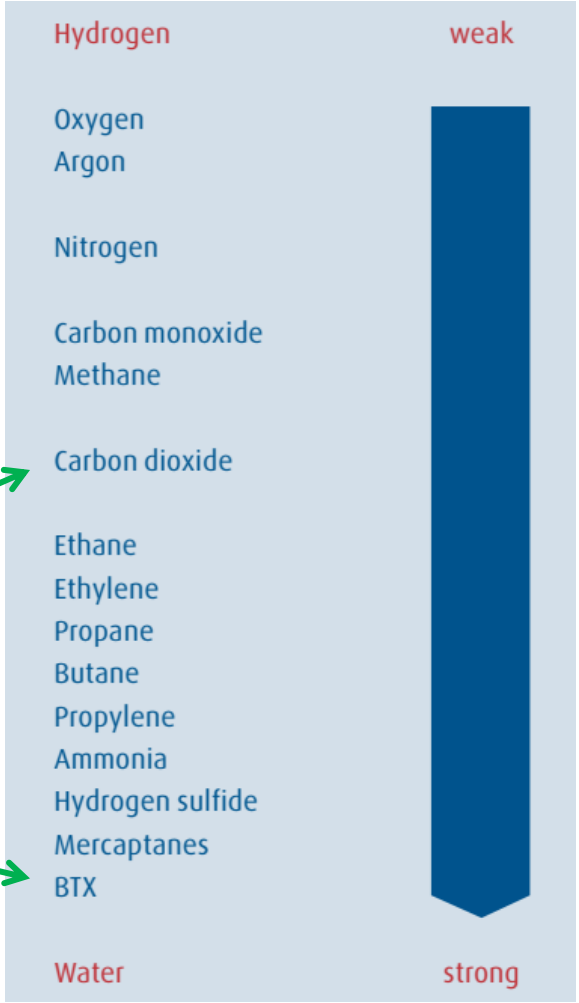
ISO 14687-2 [26]

- Purification to ≥99.97% required for ISO 14687-2 [26]
- Max. HC content 2 ppm_v (except CH_4)

Purification with PSA

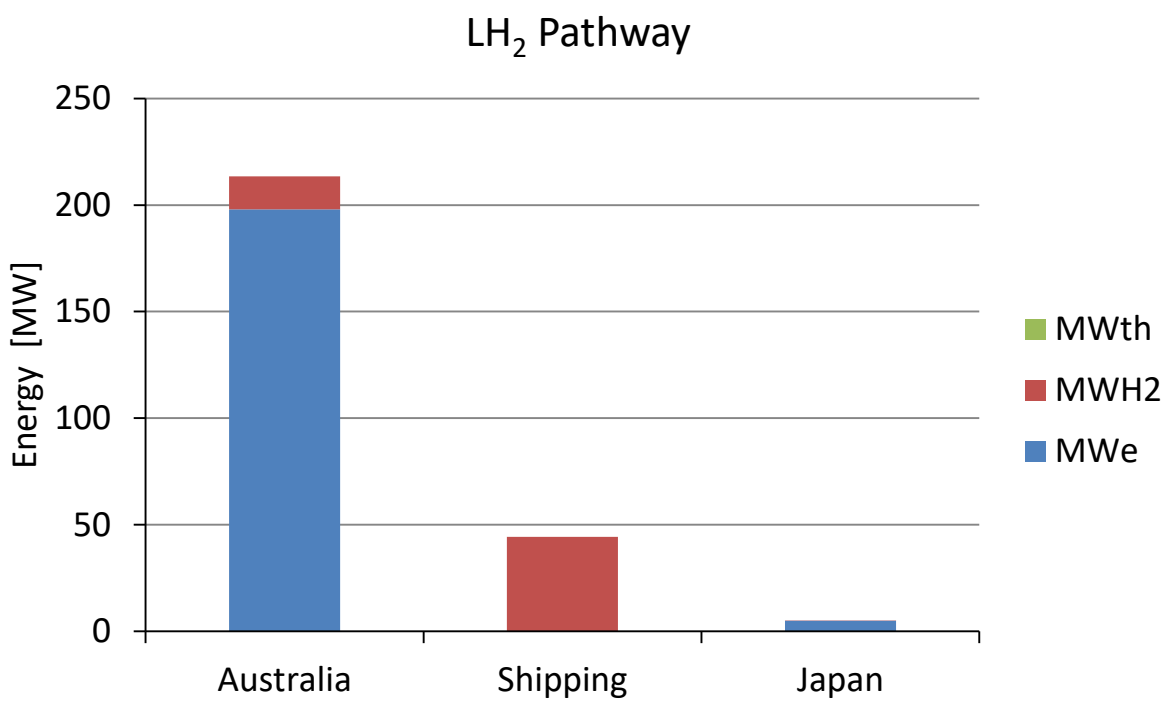
- 93% H_2 recovery with CO_2 as main pollutant feasible [27]
- Tendency to adsorb depends on molecular structure [28]
- PSA with high recovery rate of **95%**

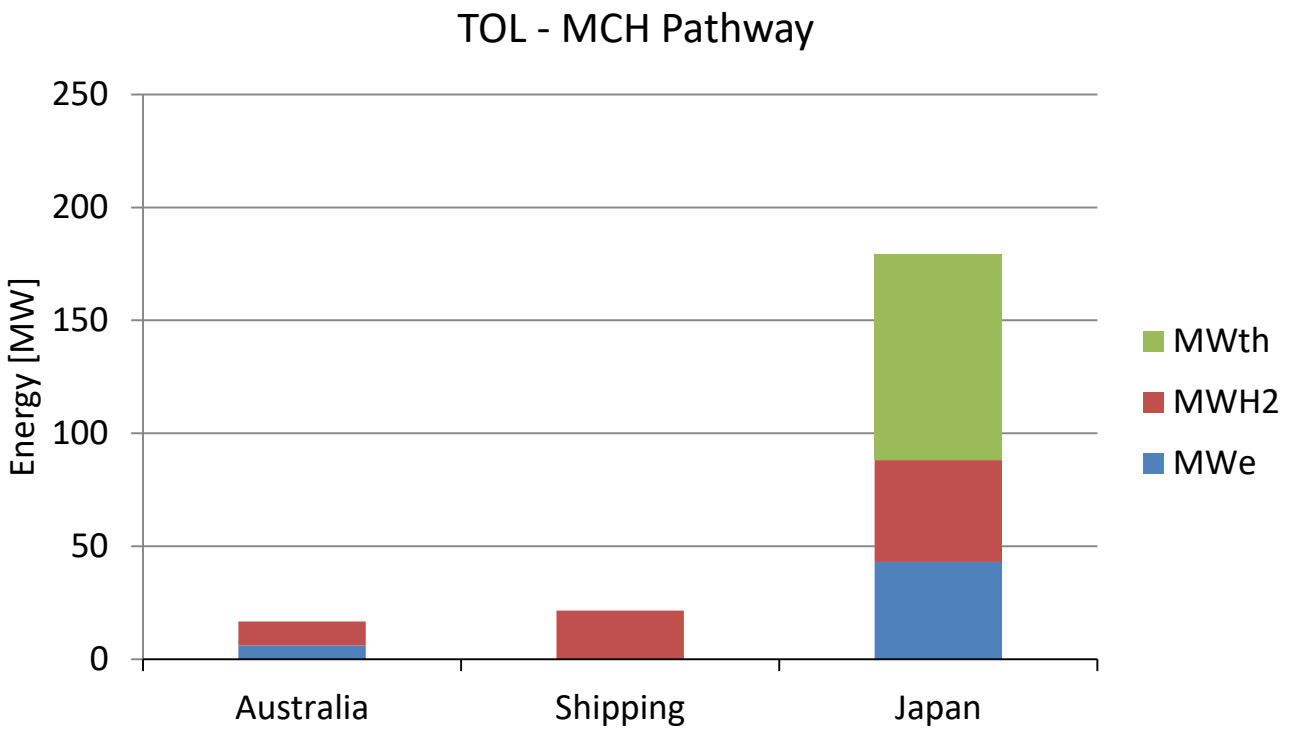
[28]



[26] Bulgarin 2020
[27] Luberti 2013
[28] Linde PSA

4. Results – Energy





- Energetic perspective – LH2 pathway favorable since energy demand is at location of energy excess

P [MW]	EL - 50 kWh/kg	Feed	Output
LH2	1‘409	940	880
TOL	1‘409	940	862

4. Results - Costs

NPC - €/kg	Australia	Shipping	Japan	Sum	Yield
LH2	1.86	0.16	0.29	2.31	93.6%
TOL	0.65	0.08	0.97	1.70	90.1%

- Assuming H_2 feed costs of 5 €/kg
- Applied method has accuracy of ± 30% → both pathways are equal
- FCI for LH2 pathway significant higher

FCI Mio. €	Australia	Shipping	Japan	Sum
LH2	1’380	325	397	2‘102
TOL	471	110	655	1‘236

5. Conclusion and Outlook

Conclusion

- Techno-economic assessment has been extended to large-scale hydrogen transport
- From energetic point of view LH2 pathway is favorable for given scenario
- Economic differences between LH2 and TOL/MCH regarding NPC are not significant

Outlook

- Higher precision of LH2 liquefaction costs – improvement of confidence
- LOHC system H00-DBT as a highly promising candidate since no PSA is required [26] [27]
  - ➢ Adaption of the business case – decentralized supply for H_2 “gas” stations

[26] Bulgarin 2020
[27] Raab 2020 – to be published

Thank you for your attention

Moritz.raab@dlr.de
Ralph-Uwe.Dietrich@dlr.de

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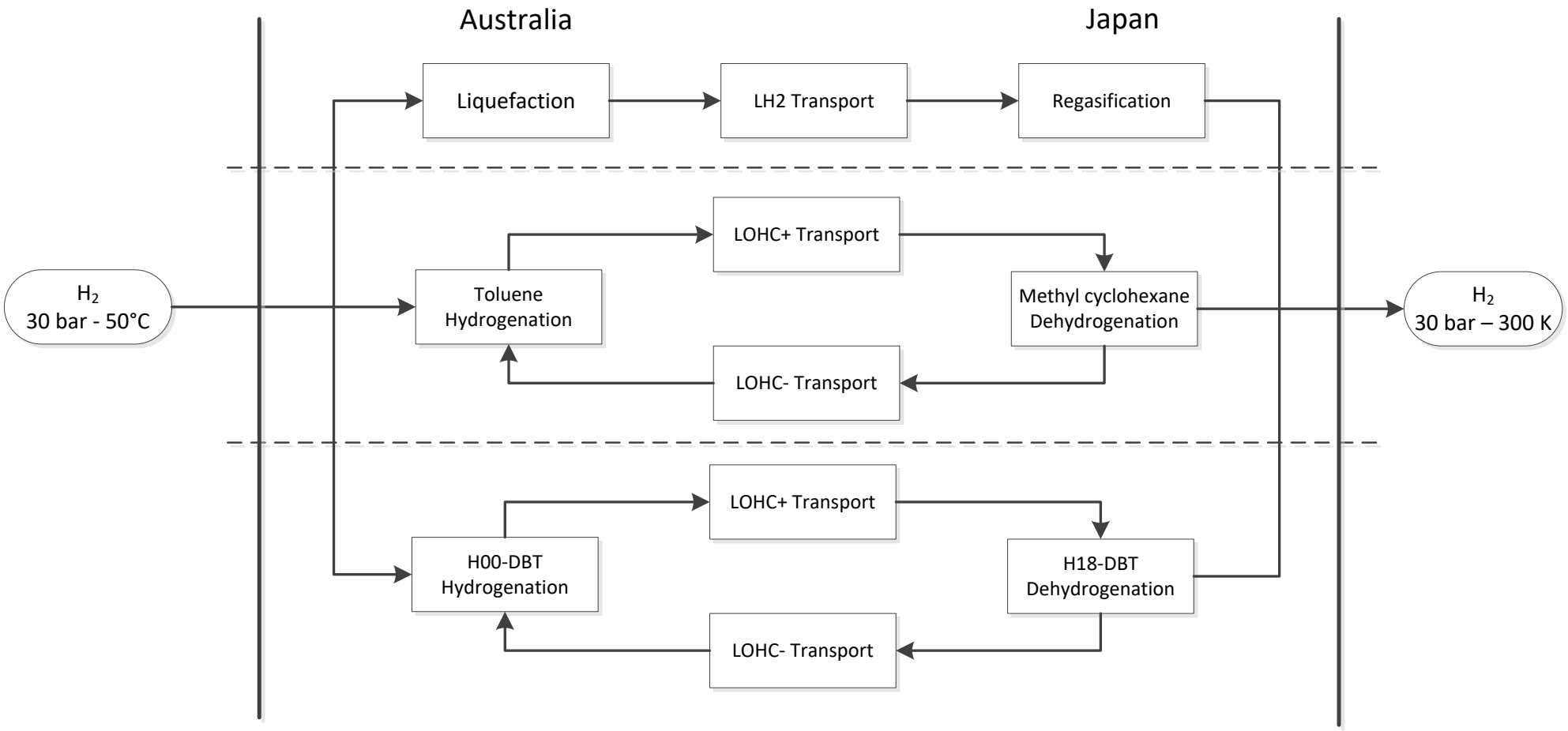
2. Business Case