Latest Global Trend in Liquid Hydrogen Production

HYPER Closing Seminar

Lutz Decker

Brussels, December 10, 2019

Making our world more productive

Agenda

1. The Rise of Liquid Hydrogen
2. The Economy of Scale
3. A Roadmap to Clean Energy
4. Recent Initiatives asking for Larger H_2 Capacities
5. Linde's Hydrogen Value Chain for H_2 Mobility

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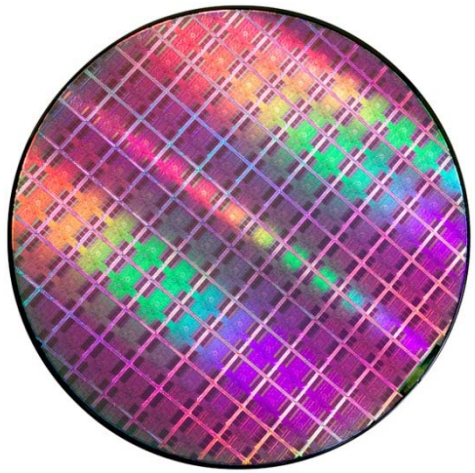
The Rise of Liquid Hydrogen
From Rocket Fuel to H_2 Mobility

Rocket Fuel

Driver	energy density
Demand	stagnating
Plant sizes	up to 20+ tpd

Conventional
e.g. Semiconductor Industry



Driver	purity, distribution
Demand	slight increase
Plant sizes	up to 5 tpd

Clean Energy and H_2 Mobility

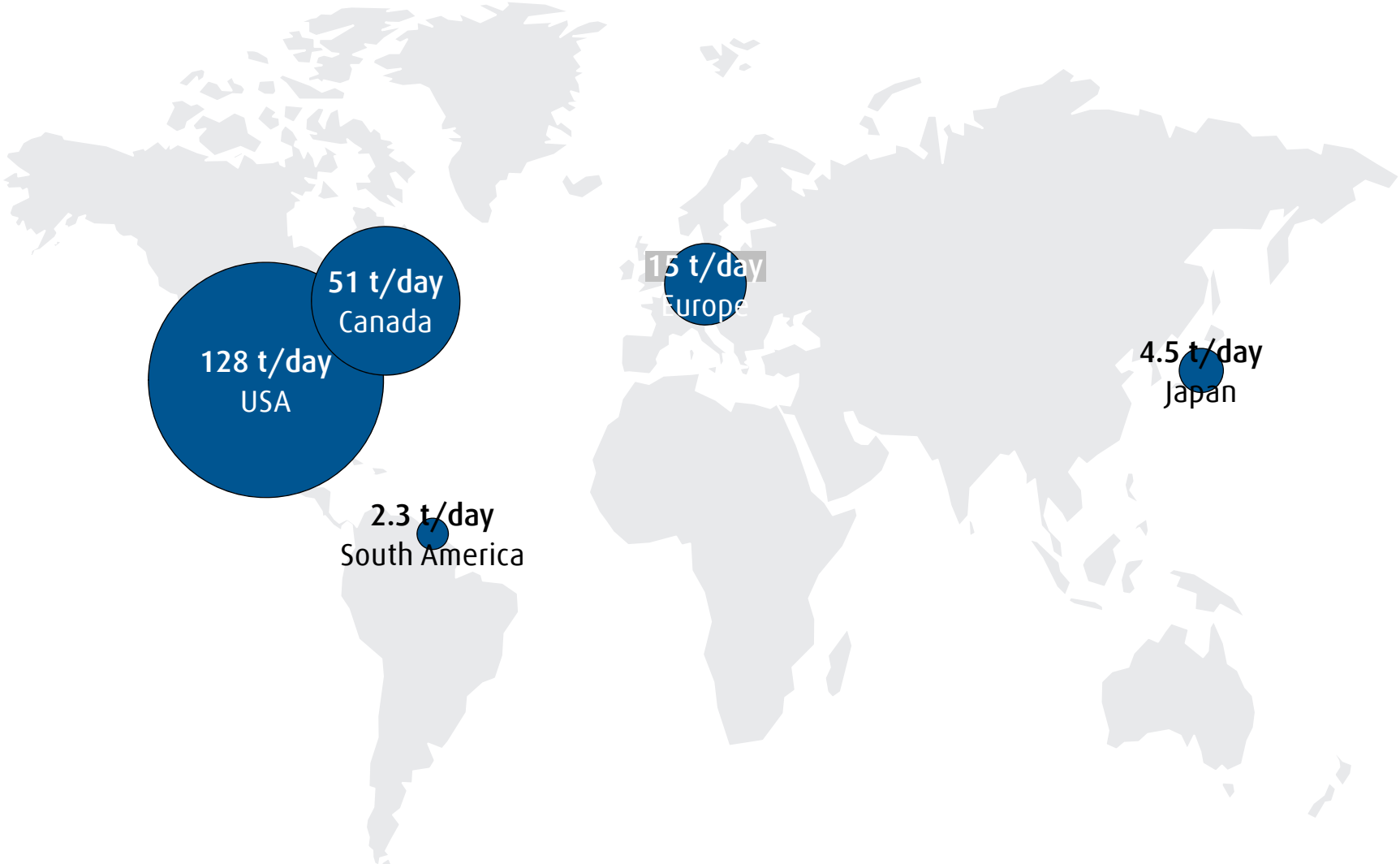
Driver	distribution
Demand	potential boost
Plant sizes	20 to 50+ tpd

The Rise of Liquid Hydrogen

LH_2 Liquefaction Capacities until 1980

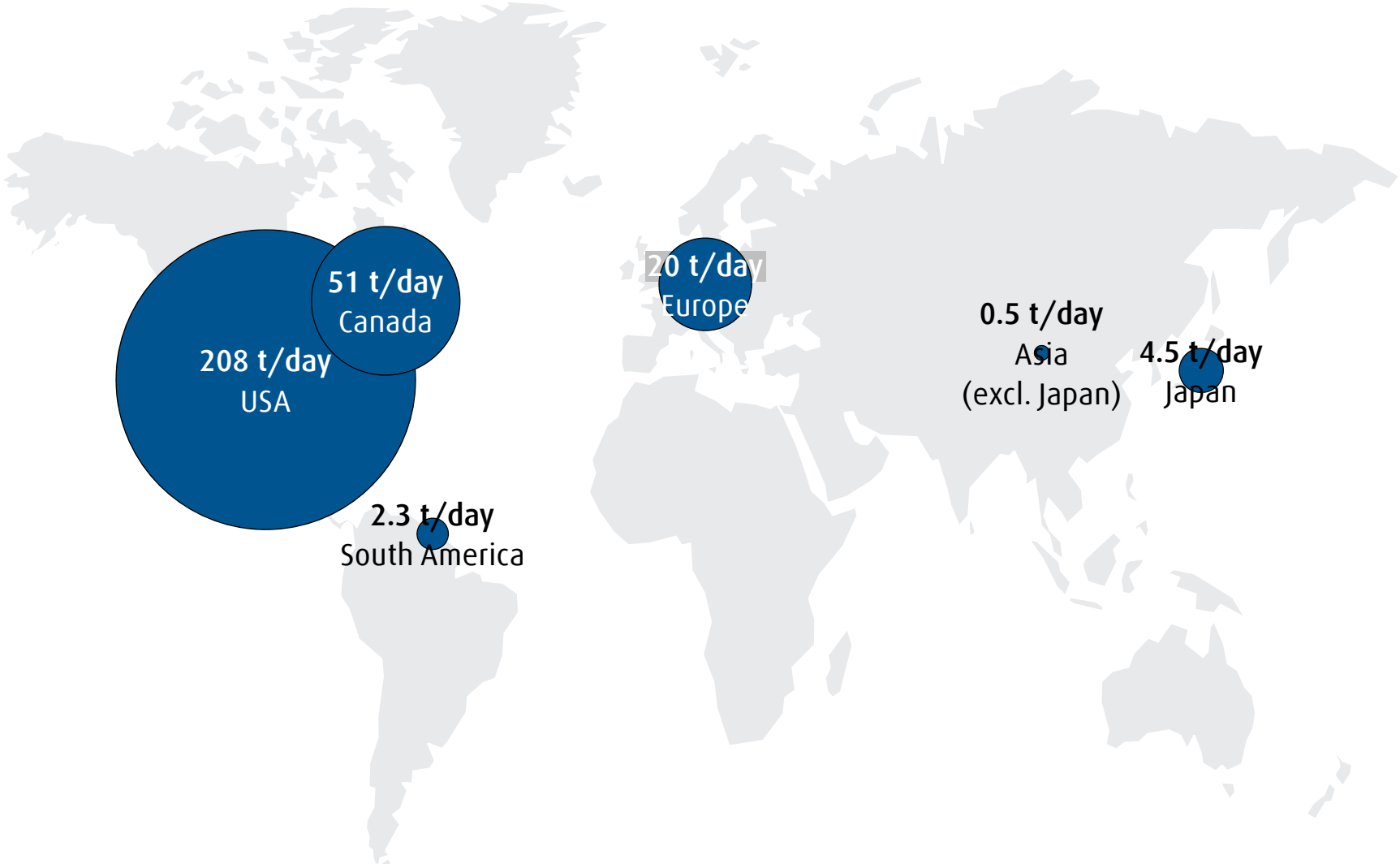
The Rise of Liquid Hydrogen

LH_2 Liquefaction Capacities until 1990



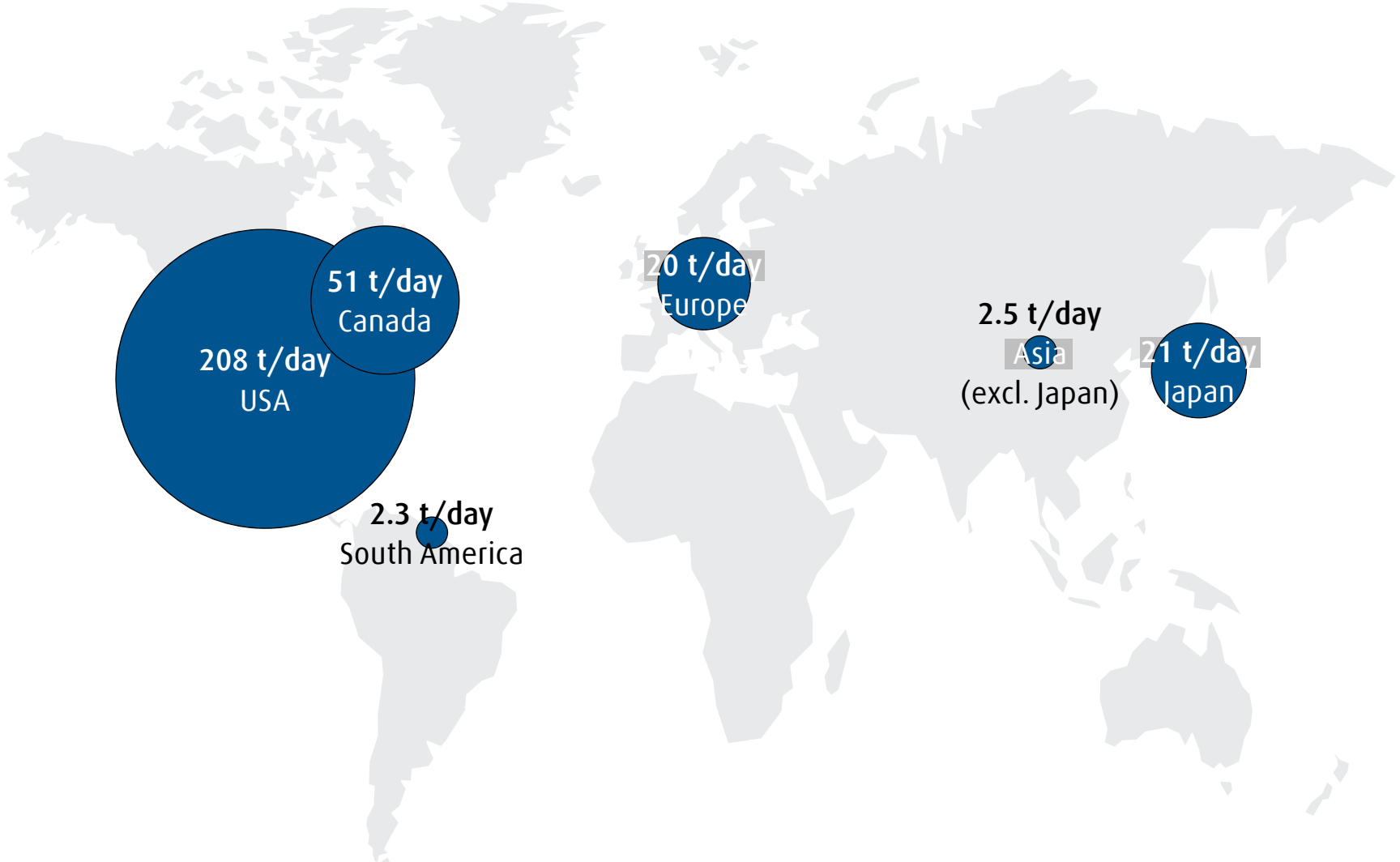
The Rise of Liquid Hydrogen

LH_2 Liquefaction Capacities until 2000



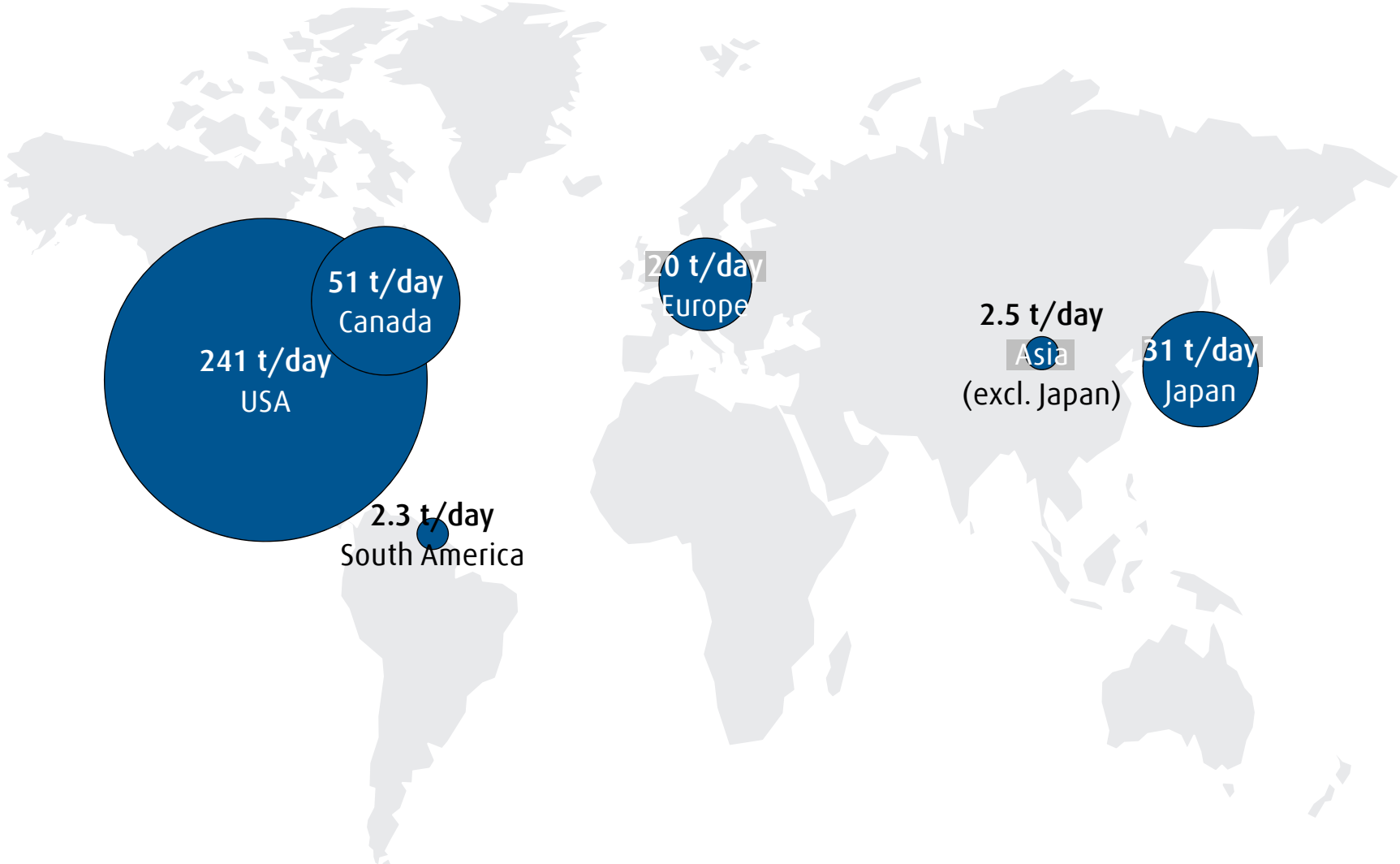
The Rise of Liquid Hydrogen

LH_2 Liquefaction Capacities until 2010



The Rise of Liquid Hydrogen

LH_2 Liquefaction Capacities today



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The Economy of Scale
Limited Data on Efficiency

Published data on existing plants

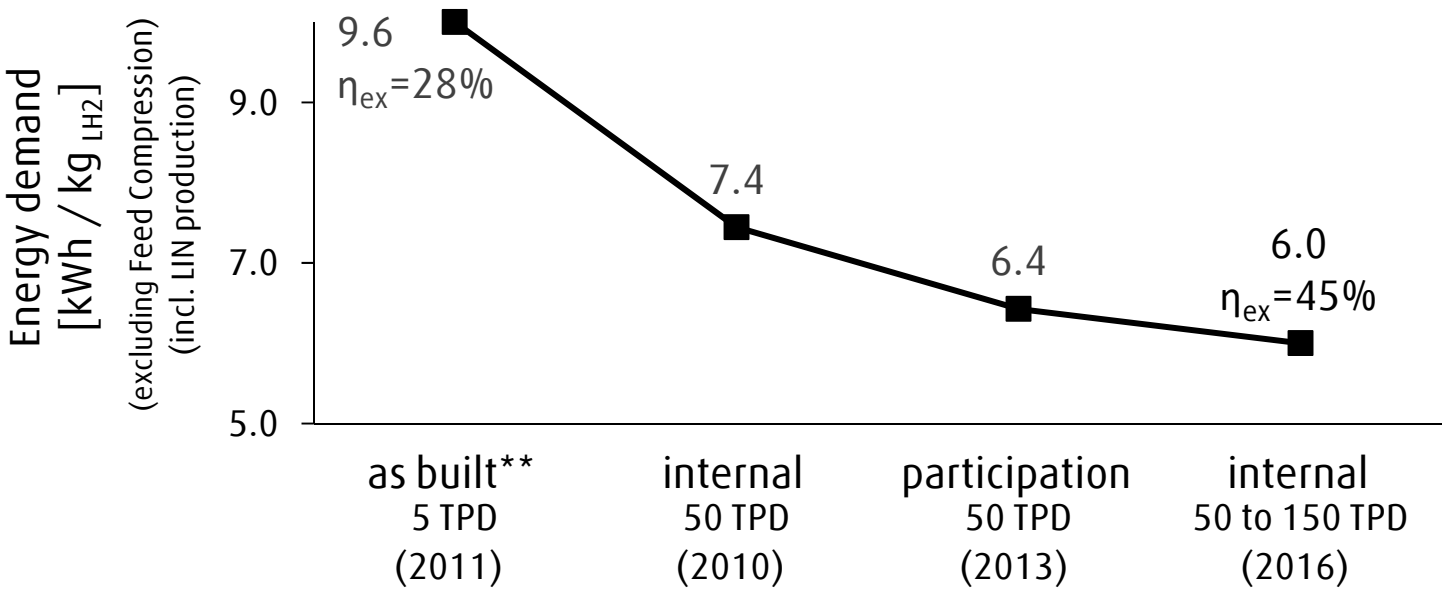
location	TPD tonnes per day		specific energy consumption feed compression excluded	supplier
Ingolstadt/D	4.5	(1992)	12.0 kWh/kg_{LH2}	Linde
Leuna/D	5.3	(2007)	10.3 kWh/kg_{LH2}	Linde
USA	5.4 to 32.0		15 to 12.5 kWh/kg_{LH2}*[1]	Praxair

* boundary conditions not stated

[1] Drnevich, R., Hydrogen Delivery - Liquefaction & Compression, in Praxair, Strategic Initiatives for Hydrogen Delivery Workshop, May 7. 2003.

The Economy of Scale
Limited Data on Efficiency

Linde R&D



** improved design

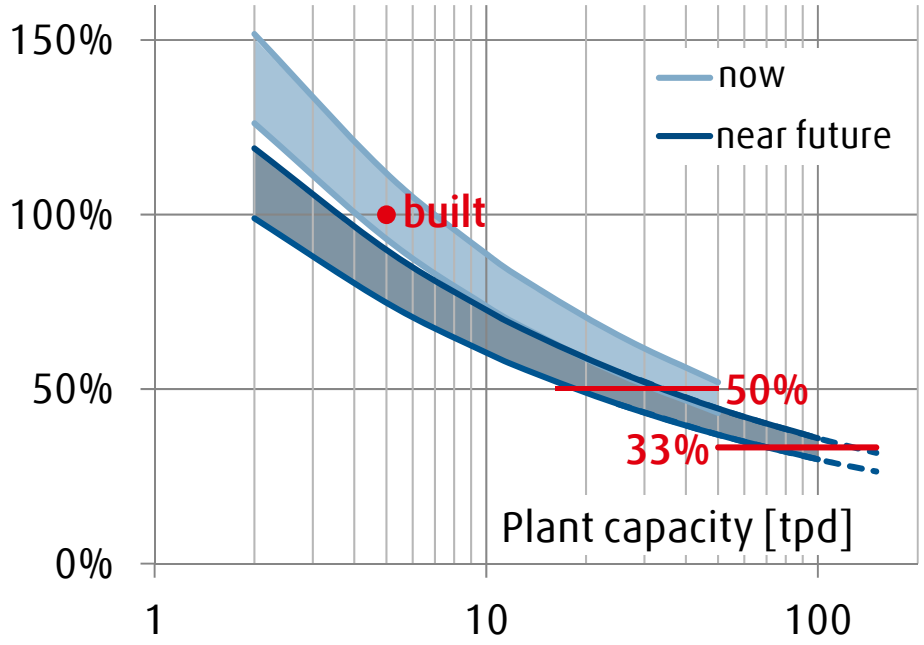
The Economy of Scale
Specific Liquefaction Cost

Total expenditure (TOTEX) = capital expenditure (CAPEX) + operational expenditure (OPEX)

General boundary conditions

- turnkey w/o land
- 20 years depreciation
- 0.05 €/kWh
- feed compression excluded

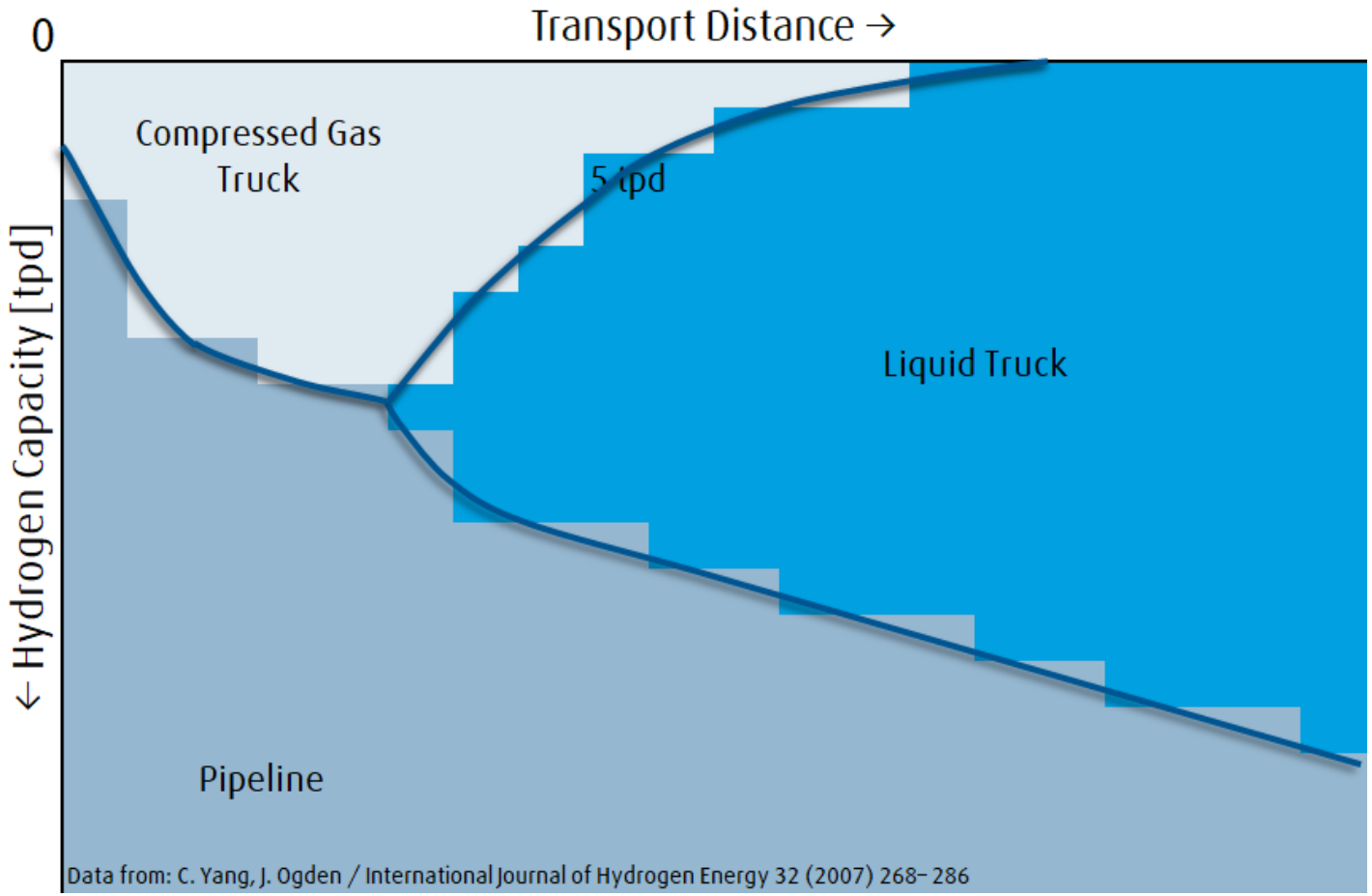
Specific liquefaction cost



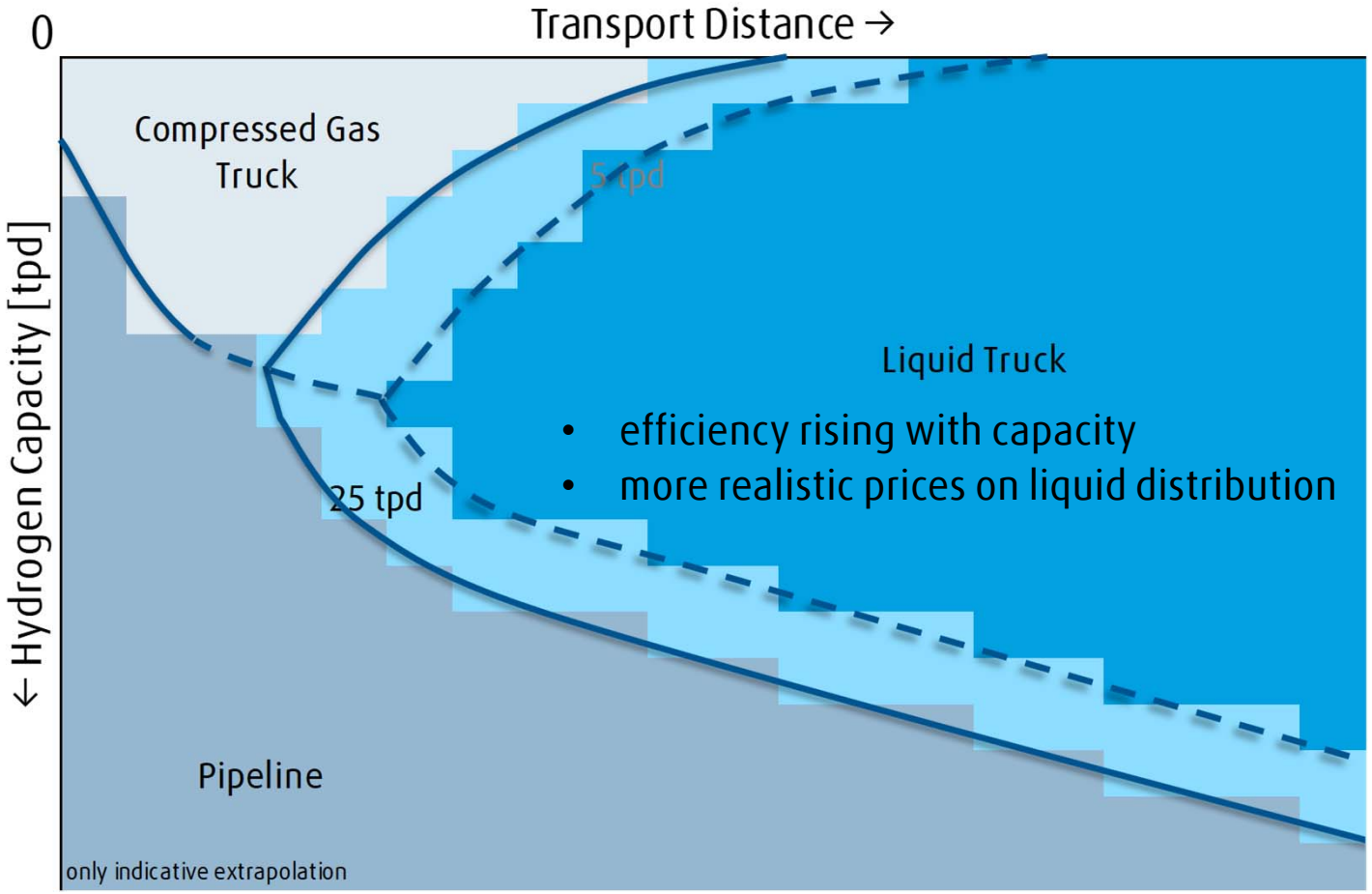
Medium term future

- within 5 years from project start
- modification of proven technology

The Economy of Scale
Optimum Distribution Concept – Yang & Ogden



The Economy of Scale
Optimum Distribution Concept



The Economy of Scale
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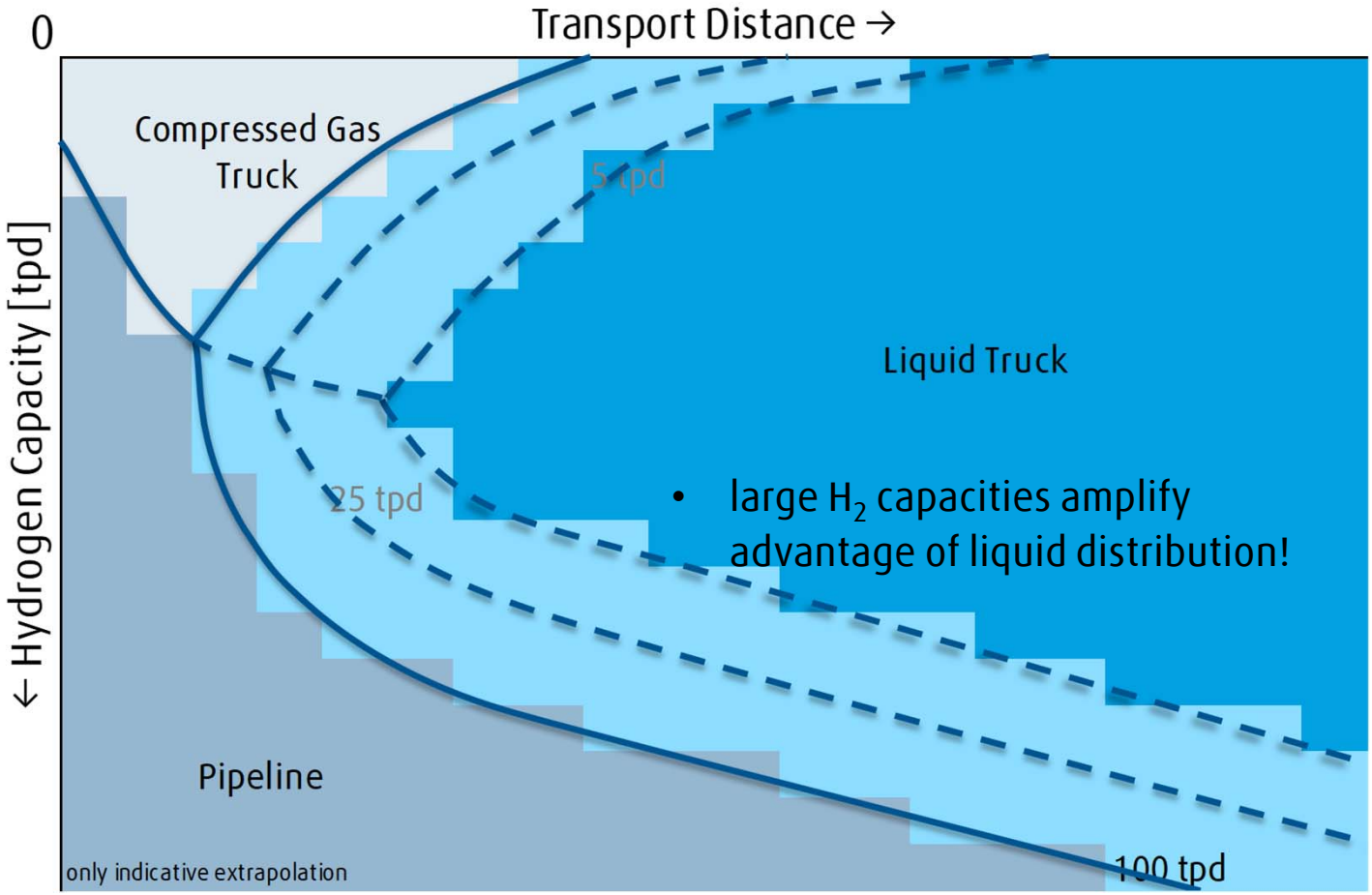

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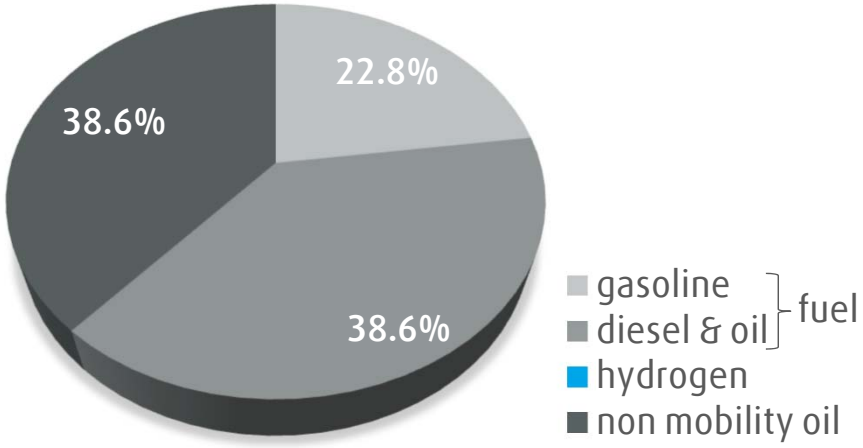
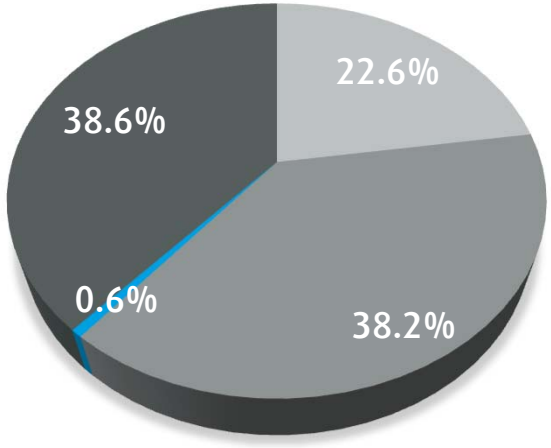
A Roadmap to Clean Energy
Starting with 1% Market Share of Mobility Fuel

Mobility fuel market: 6.6 billion USD/day
USA / EU / Japan / ROK / China (2014)



Assumptions: diesel & oil: ~ 50% of oil
Fuel: gasoline + diesel & oil
4 USD/gal average

1% of fuel market: H_2: 24 billion USD/year
USA / EU / Japan / ROK / China



Assumption: 1% of fuel equivalent price

Source: The U.S. Energy Information Administration, TheGlobalEconomy.com

Replacing 1% of today's fuel consumption by hydrogen is a big deal.

A Roadmap to Clean Energy
Back-to-Base Fleets as Market Access

Key numbers on H_2 consumption

Vehicle	H_2 cons. rate [tpd]	Fuel type H_2	Units served by liquefier 5 tpd	25 tpd
car (California)	0.0008	compressed gas	6 000	30 000
bus / truck	0.03	compressed gas	167	835
train	0.25	compressed gas liquid	20	100
Inland navigation, ferries	0.4-1.5	liquid	4	20
coastal ship	2	liquid	2.5	12.5
cruiser ship	10	liquid	0.5	2.5

Back-to-base fleets reduce initial investment in infrastructure.

Few large scale consumers trigger the price level for small scale!

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Recent Initiatives asking for Larger H_2 Capacities
Ferries in Norway and France / Trucks in Switzerland

13 May 2019

FLAGSHIPS project to deploy two hydrogen vessels

The European innovation project FLAGSHIPS has been awarded 5 Million Euros from the EU to support deploying two commercially operated zero-emission hydrogen fuel cell vessels in France and Norway…

https://www.norled.no/en/news/as-part-of-norleds-green-venture-we-are-pleased-to-be-part-of-an-exciting-eu-project-that-can-give-us-more-hydrogen-powered-ferries/

19 September 2018

Hyundai and H2 Energy to launch world's first fleet of Fuel Cell Truck

Hyundai Motor, in cooperation with H2 Energy, to provide 1,000 fuel cell electric trucks to Swiss commercial vehicle market, beginning 2019 through to 2023…

https://www.hyundai.news/eu/brand/hyundai-motor-and-h2-energy-will-bring-the-worlds-first-fleet-of-fuel-cell-electric-truck-into-commercial-operation/

1,600 FC trucks until 2025

Recent Initiatives asking for Larger H_2 Capacities
Trains in Germany

16 Sep 2018

World premiere: Alstom's hydrogen trains enter passenger service in Lower Saxony

It was a world premiere being celebrated ...

... 2021, when Alstom will deliver a further 14 Coradia iLint trains ...

https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower

21 May 2019

RMV's subsidiary fahma orders the world's largest fleet of fuel cell trains from Alstom

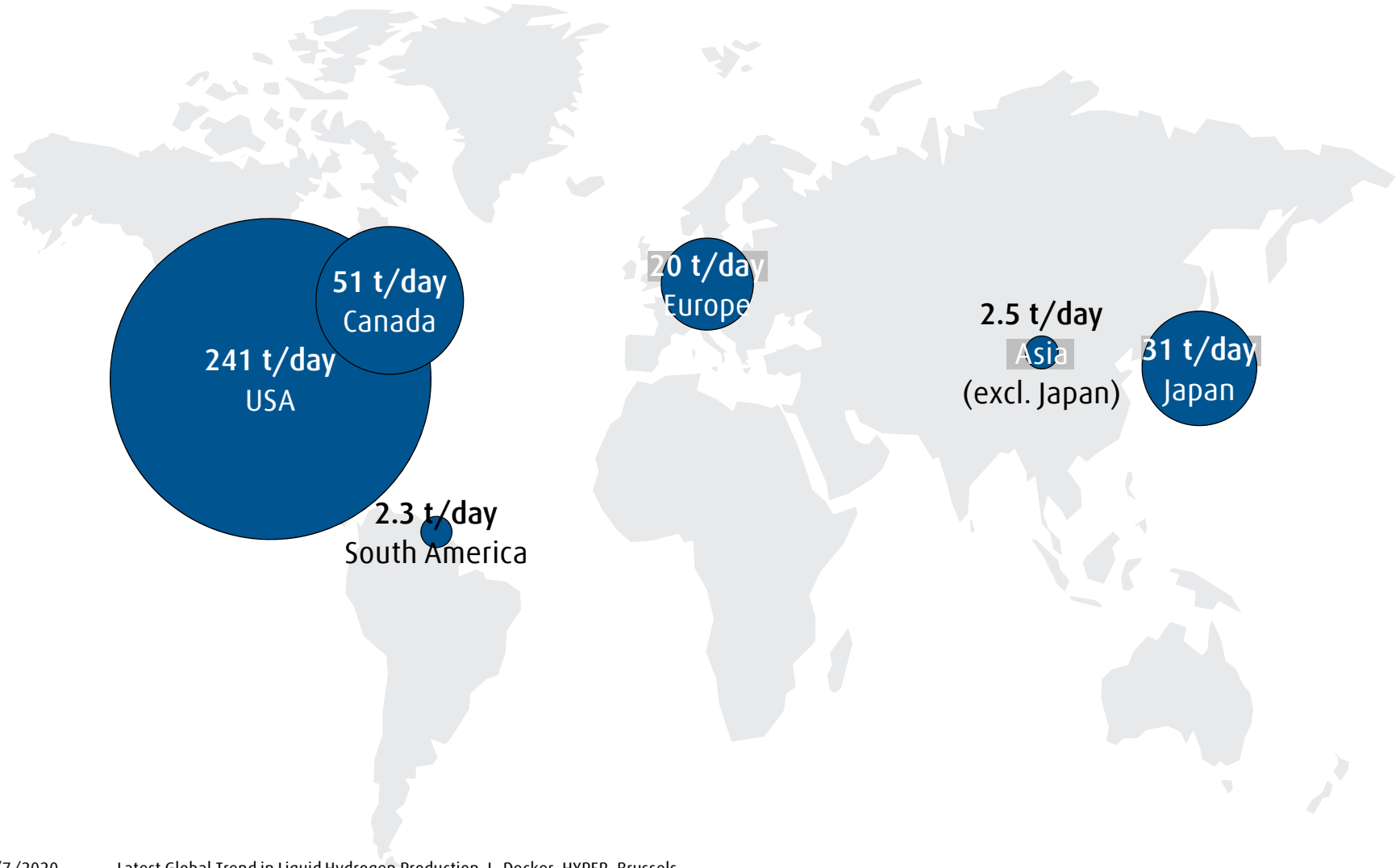
- A contract worth around €500 million
- ...

RMV's subsidiary fahma issued a tender for 27 fuel cell trains throughout Europe...

https://www.alstom.com/press-releases-news/2019/5/rmvs-subsidiary-fahma-orders-worlds-largest-fleet-fuel-cell-trains

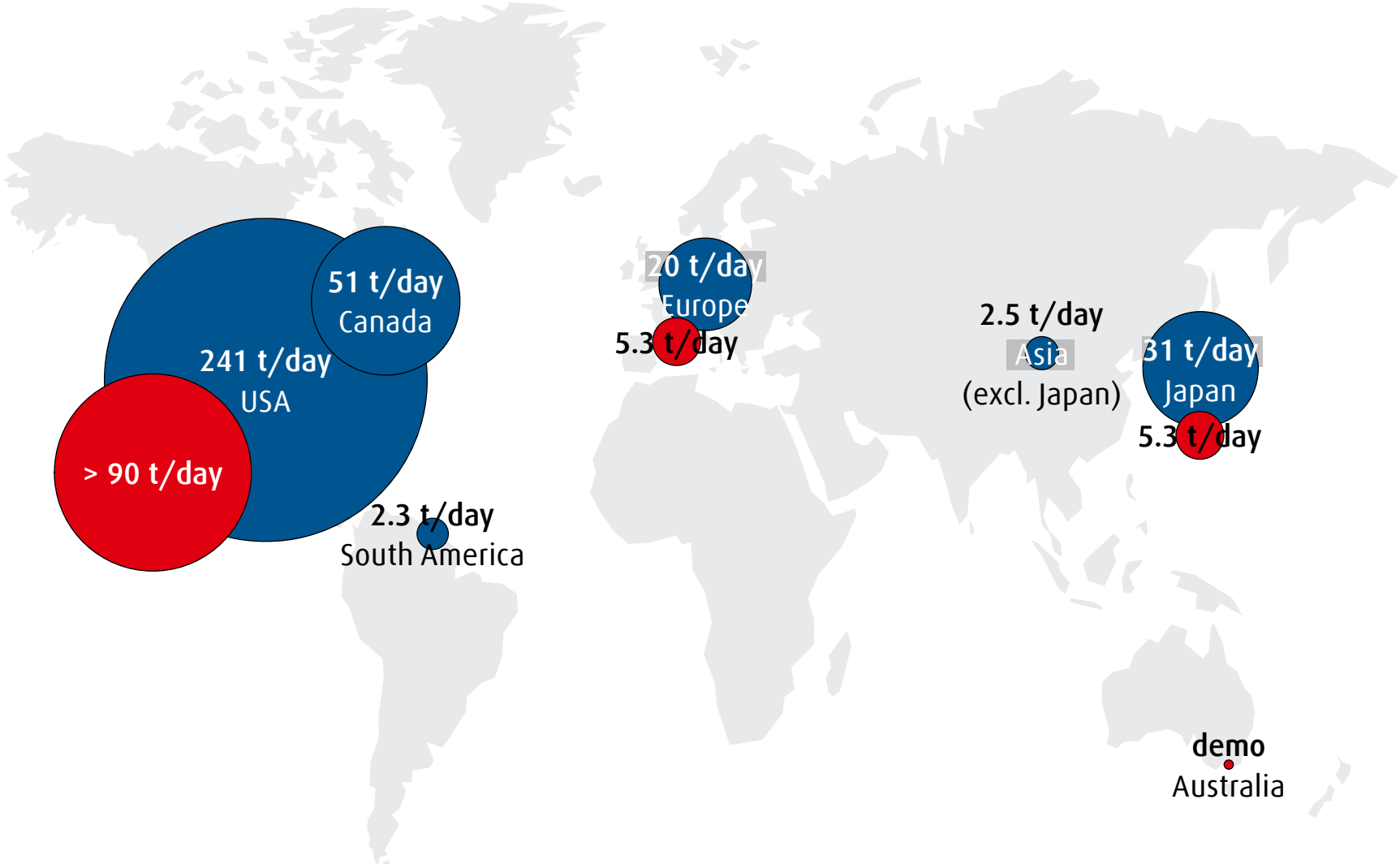
Recent Initiatives asking for Larger H_2 Capacities

LH_2 Liquefaction Capacities today



Recent Initiatives asking for Larger H_2 Capacities

LH_2 Liquefaction Capacities planned for 2021



A Roadmap to Clean Energy

Starting with 1% Market Share of Mobility Fuel

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176’000 t/day

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17’600 t/day

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Starting with 1% Market Share of Mobility Fuel

1% market share for H_2 in mobility fuel
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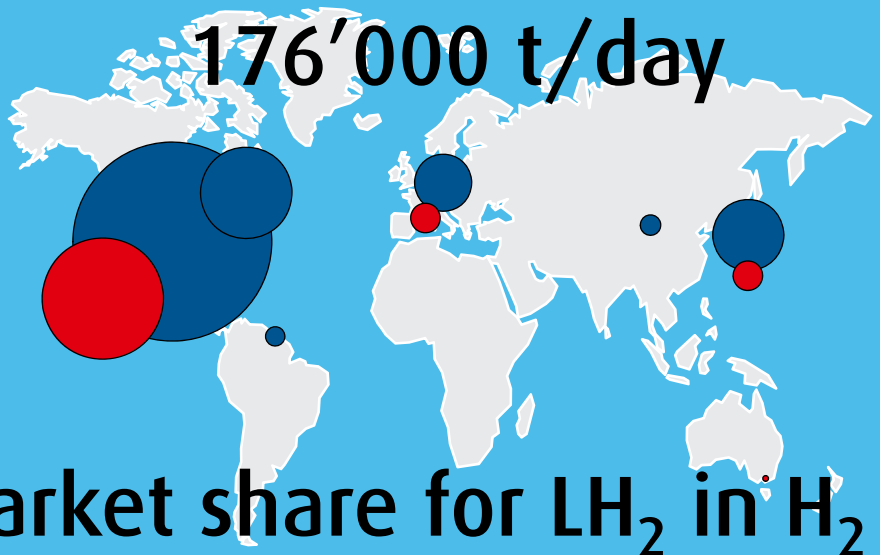
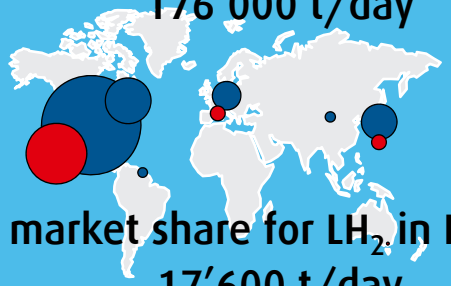


10% market share for LH_2 in H_2 mobility
17’600 t/day

A Roadmap to Clean Energy

Starting with 1% Market Share of Mobility Fuel

1% market share for H_2 in mobility fuel
176’000 t/day



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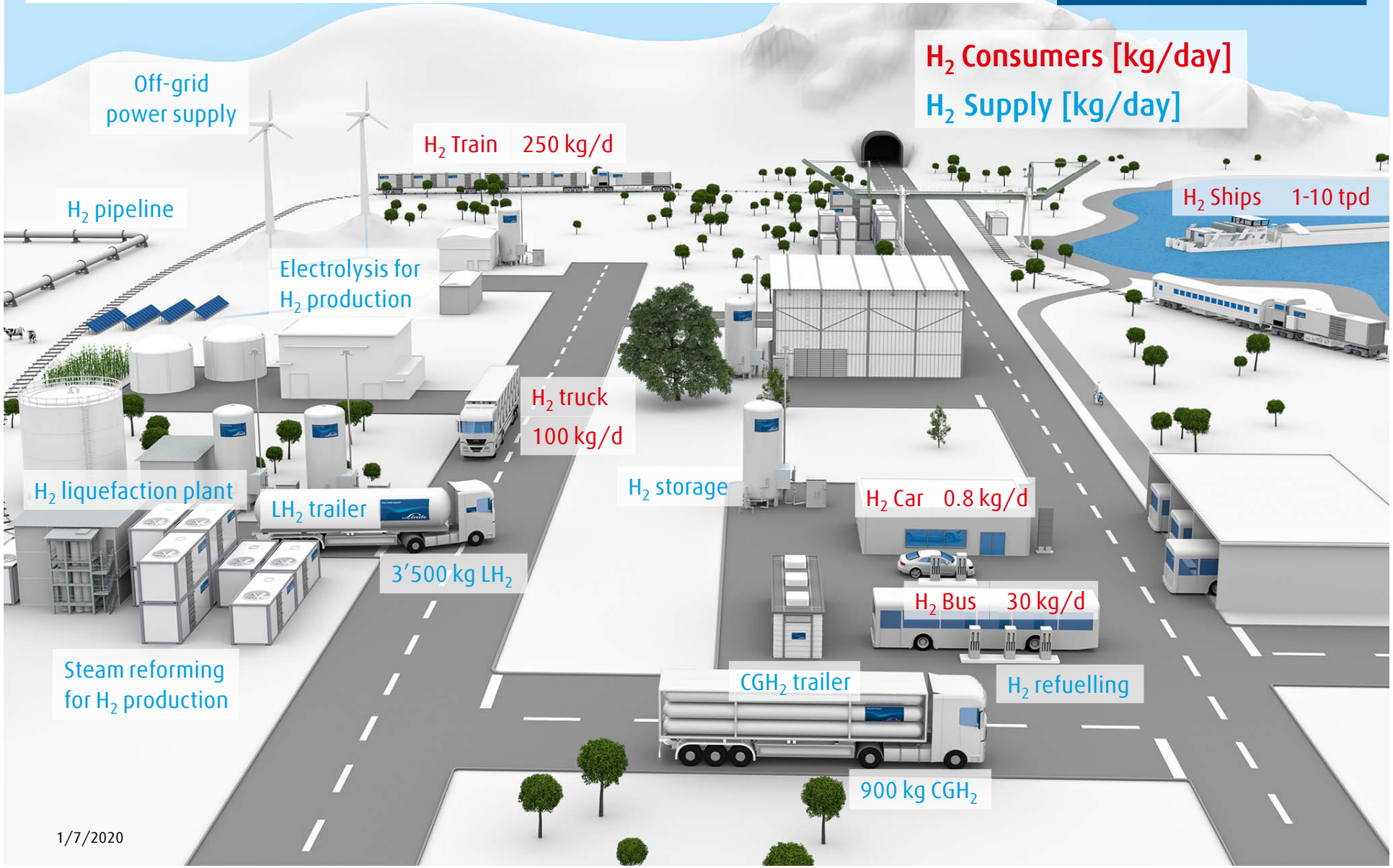
Linde's Hydrogen Value Chain for H_2 Mobility

Supply and Consumer



1/7/2020

Linde's Hydrogen Value Chain for H_2 Mobility

Linde Covers the Full Value Chain!

Production

Conventional
(e.g. SMR)

Renewable
(e.g. electrolysis)

Onsite electrolysis

Distribution & Storage

LH_2
liquid hydrogen

CGH_2
Compressed
gaseous hydrogen

Liquefaction

H_2 Fueling Stations

Cryopump

Ionic compressor

Boil-off mgmt.
system

Dispenser

Infrastructure & Vehicles

Out of one hand
Reliable
operations of H_2
supply and
fuelling
equipment to a
range of mobility
applications

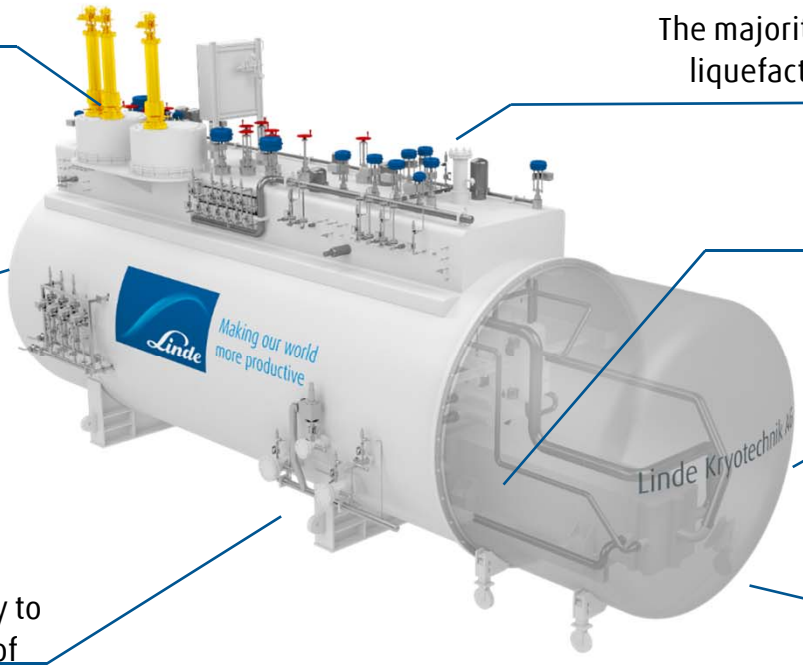
Linde's hydrogen liquefaction
The core competence - technology

Innovative technology of unique dynamic gas bearing turbine

Lowest total cost of ownership concepts for different ranges

Small	<1 tpd	(He cycle)
Medium	~5 tpd	(H_2 cycle)
Large	>30 tpd	(H_2 cycle)

Complete inhouse cold box assembly to ensure high quality and full control of delivery time



Proven track record:
The majority of the world's installed hydrogen liquefaction plants have been built by Linde

Inhouse produced PFHX for highest quality and long lifetime

Full EPC capability
LH2 solution provider

Ready for the future
Concepts with record efficiencies for plants up to 100 tpd available

Linde's hydrogen liquefaction

Proven track of hydrogen liquefaction projects

On-stream until 1999

location	capacity [tpd]	on-stream
USA	20	1962
USA	16	1981
Japan	1	1986
USA	16	1988
Canada	16	1989
Germany	5	1992 (†)
USA	30	1995
China	<1	1995
USA	30	1997

On-stream from 2000 on

location	capacity [tpd]	on-stream
Japan	<1	2003
India	1	2005
Japan	5	2006
Japan	5	2006
Germany	5	2007
Japan	5	2008
Japan	5	2011
Japan	5	2017
Japan	5	2019
Germany	5	2021
USA	30	2021

Note: Due to non-disclosure agreements, the reference list is not complete.

Summary

- For the supply of hydrogen mobility programs, a significant increase in hydrogen production is expected, e. g. based growing demand for fuel cells
- Gaseous supply is often more economical at small scale <200 kg/day and local consumption
- Large volumes of hydrogen, in particular distribution on long distance and high power consumption in clean mobility is preferably done with liquid hydrogen
- The transition to clean mobility asks for huge production capacities of hydrogen
- The technology of hydrogen liquefaction is well established and improves with economy of scale

Linde's capabilities:

- Linde has broad experience for gaseous as well as liquid hydrogen.

(commuting train Alstom) driven from hydrogen generated by electrolysis coming from wind power.

Thank you for your attention

Linde Kryotechnik AG
Lutz Decker
Tel +41 52 304 05 26
lutz.decker@linde-kryotechnik.ch
www.linde-kryotechnik.ch

Making our world more productive