A future energy chain based on liquefied hydrogen

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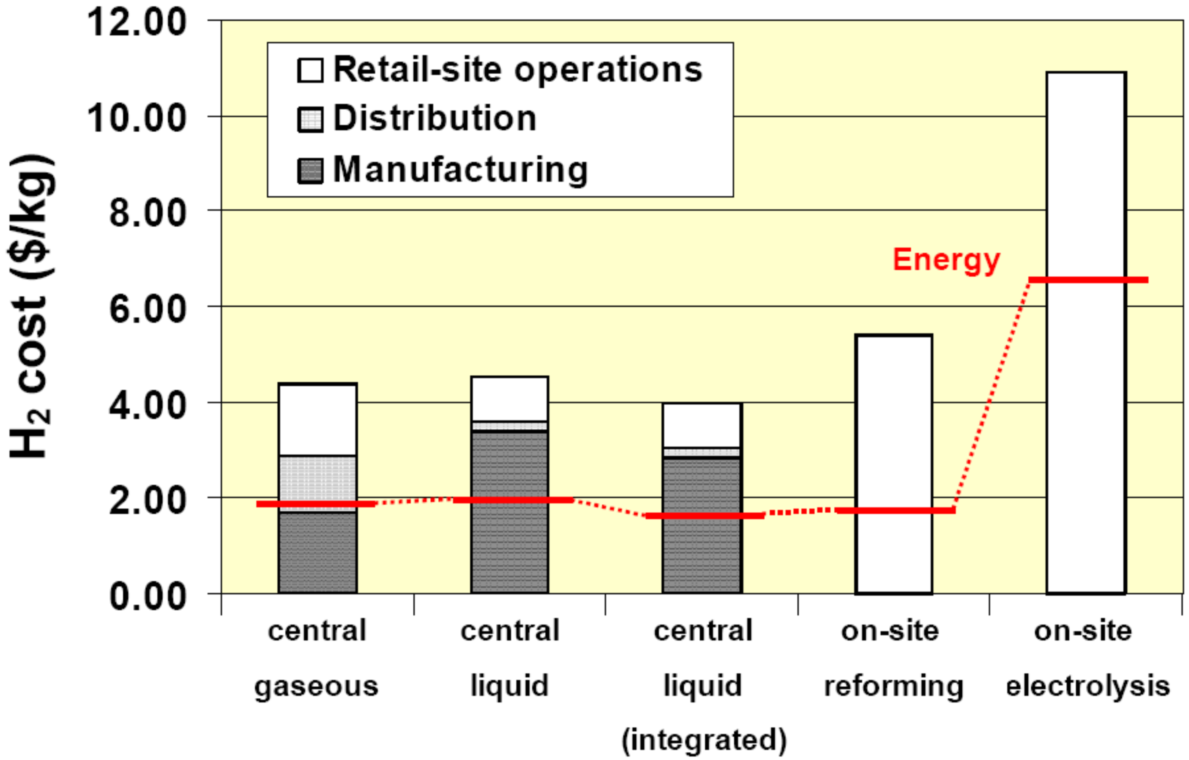
Outline

- Introduction to the role of liquefaction in an energy chain with hydrogen as energy carrier
- Comparison of existing and proposed conceptual hydrogen liquefiers
- Selection of a high-efficiency case for the following tasks:
  - Replacement of original pre-cooling of hydrogen to 75 K with a new pre-cooling cycle based on mixed refrigerant (MR) technology
  - Investigate the consequences of this modification with respect to power consumption and process efficiency
- LH_2 in relation to LNG
- Conclusions and further work

Previous Shell study on hydrogen well-to-wheel [1]

- Early-phase scenario: reforming of methane, CO_2 capture and bulk transportation of hydrogen from production site to retail site
- Liquid hydrogen (LH_2) vs. compressed gaseous hydrogen (CGH_2)



Assumed specific liquefaction power for LH_2: 10 kWh/kg_{LH2}

Average distribution distance: 75 km

Production volume: 100 tonnes/day

Number of retail sites: 100

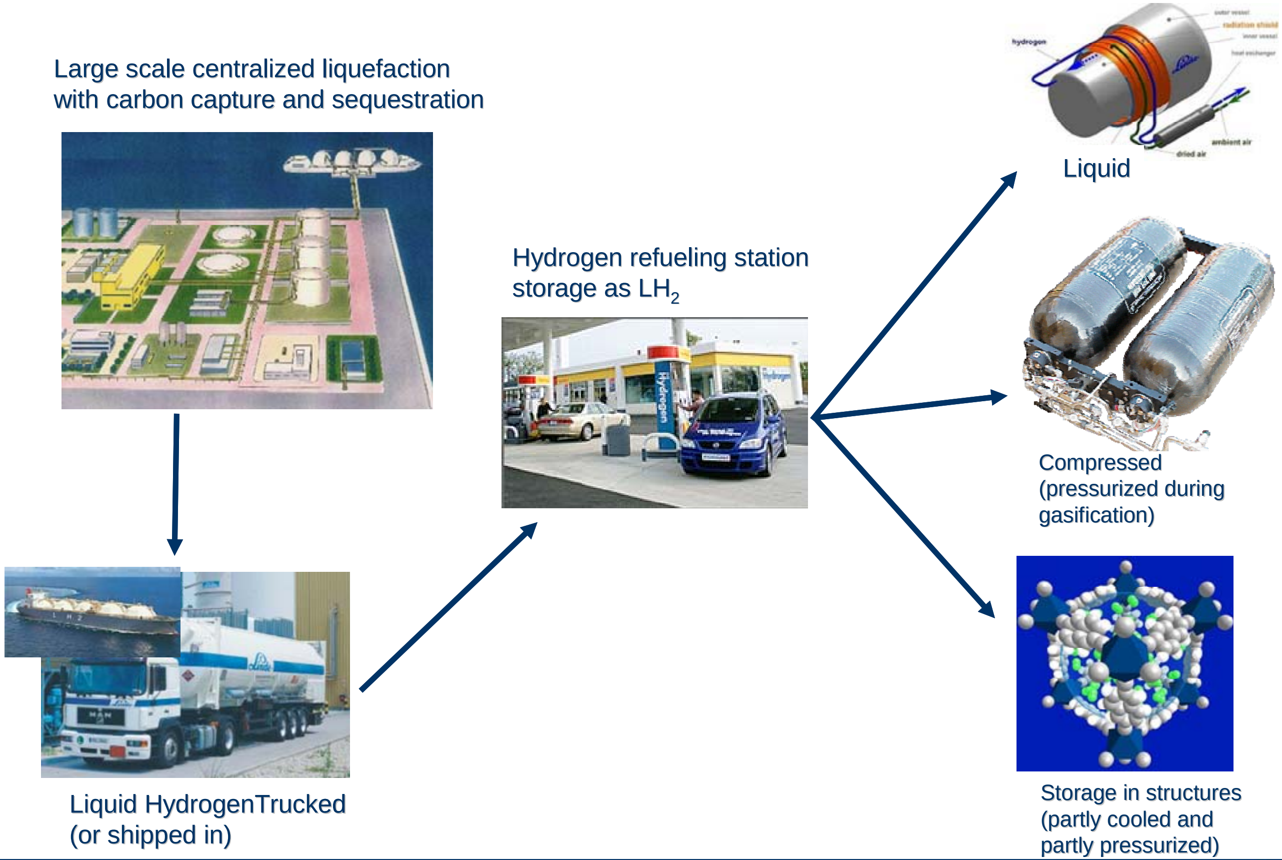
LH_2 transport capacity: 3500 kg/truck

CGH_2 transport capacity: 350 kg/truck

[1]Kramer G.J., Huijsmans J.P.P. and Austgen D.M. *Clean and green hydrogen*. 16th World hydrogen energy conference, 2006

Advantages of LH_2

- Flexibility – With close to equal overall cost, LH_2-based distribution enables delivery of hydrogen in any form with low energy consumption at retail-side filling stations
- CGH_2 does not offer this flexibility without on-site refrigeration



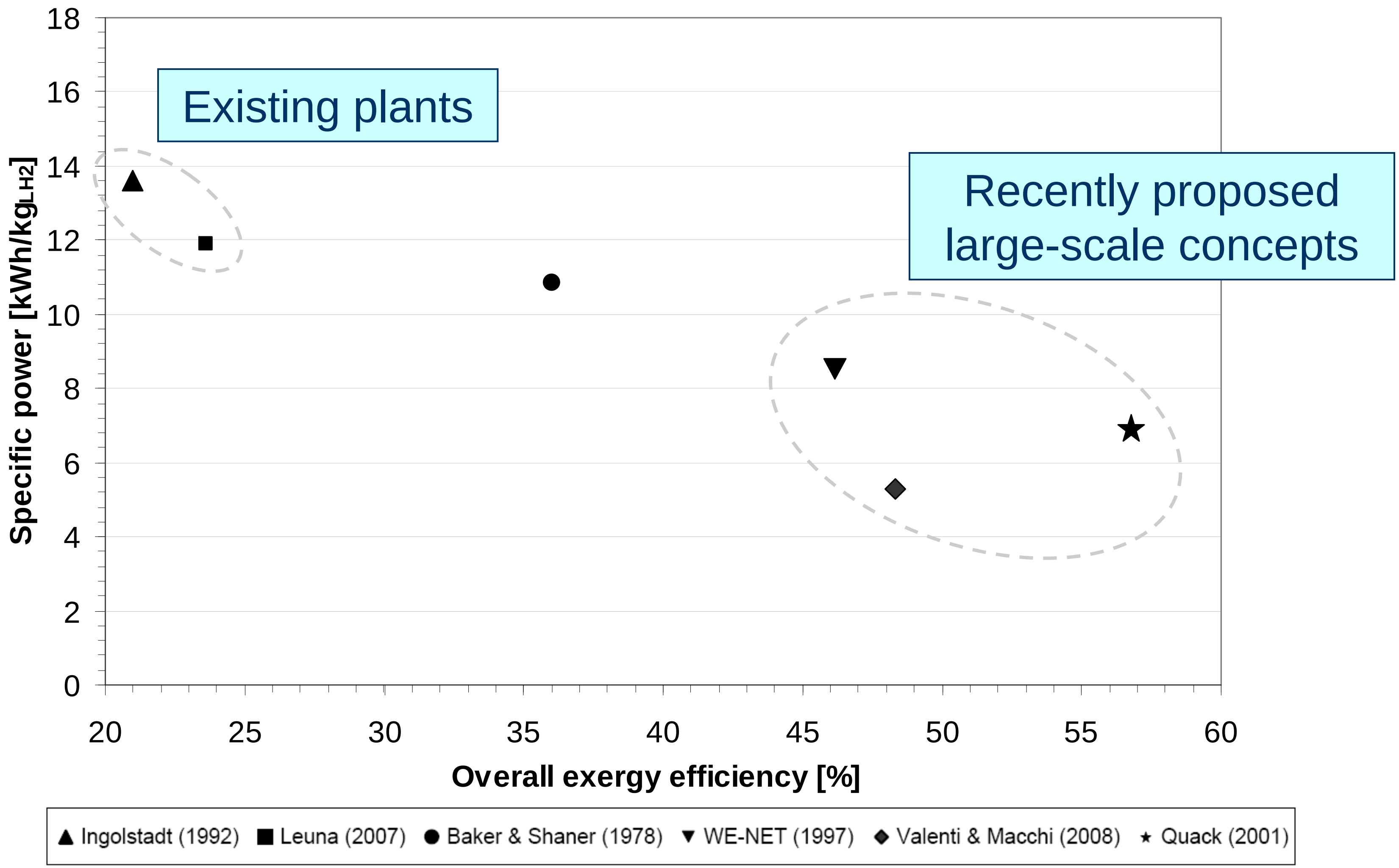
Transition from current LH_2 production

	Existing liquefiers	Envisioned future liquefiers
Market	LH_2 for specific industrial purposes	LH_2 as an energy commodity
Plant capacity	4.4 tonnes/day (Ingolstadt, 1992)[1] 5.0 tonnes/day (Leuna, 2007)[2]	Significant scale-up in capacity (50–100 tonnes/day or more)
Specific liquefaction power consumption	13.6 kWh/kg (Ingolstadt)[1] 11.9 kWh/kg (Leuna)[2] (10 kWh/kg used in Shell study)	Considerably lower due to higher emphasis on energy efficiency, scaling-up advantages and shifted cost structure
Operation	Flexible operation (Leuna: 40–100% load range)	Large base-load plants with high efficiency at full load

[1]Bracha M. et al. *Large-scale hydrogen liquefaction in Germany*. Int J Hydrogen Energy 19(1):53–59, 1994

[2]Bracha M. and Decker L. *Grosstechnische Wasserstoffverflüssigung in Leuna*. Deutsche Kälte-Klima-Tagung, 2008

Efficiency of hydrogen liquefiers



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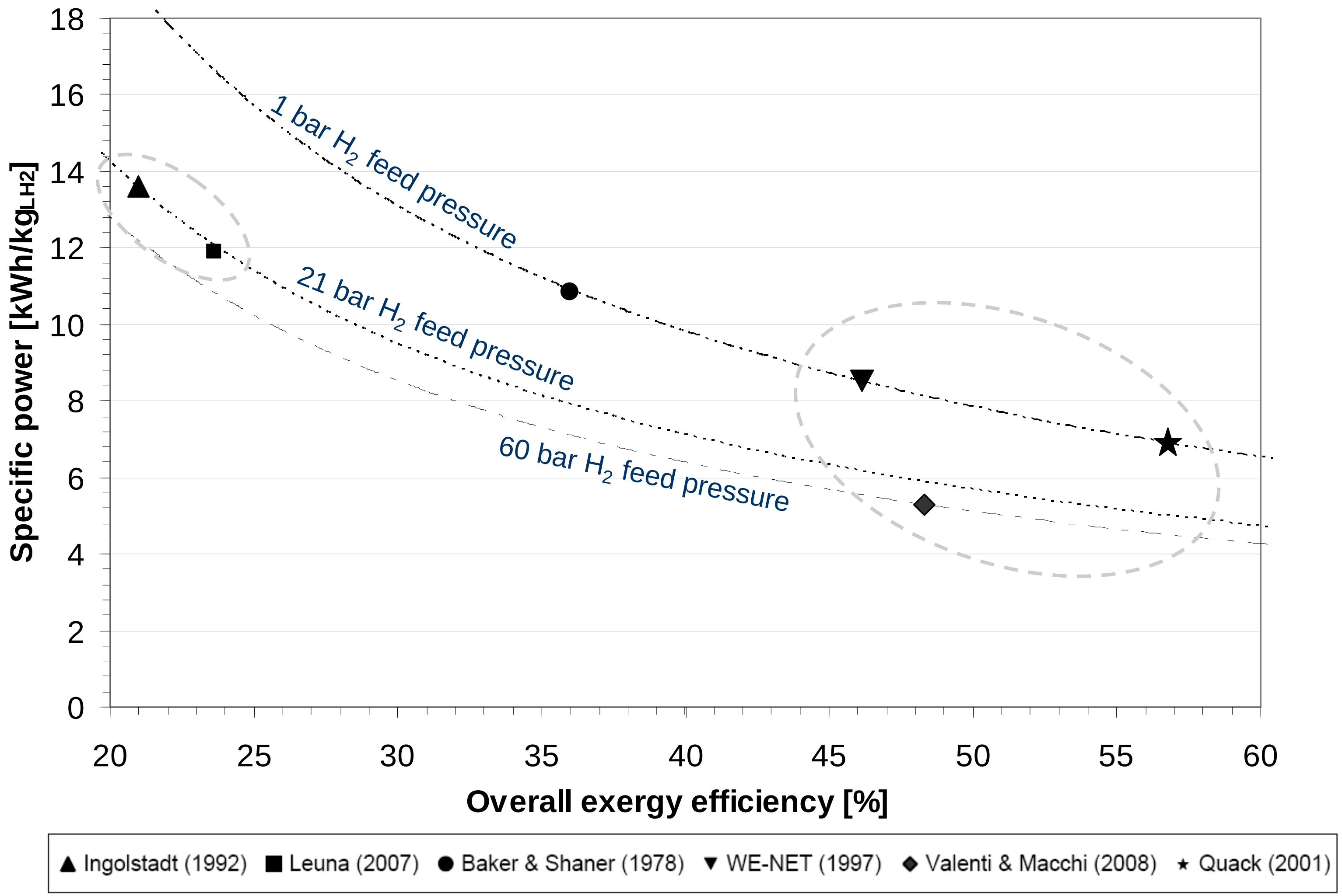

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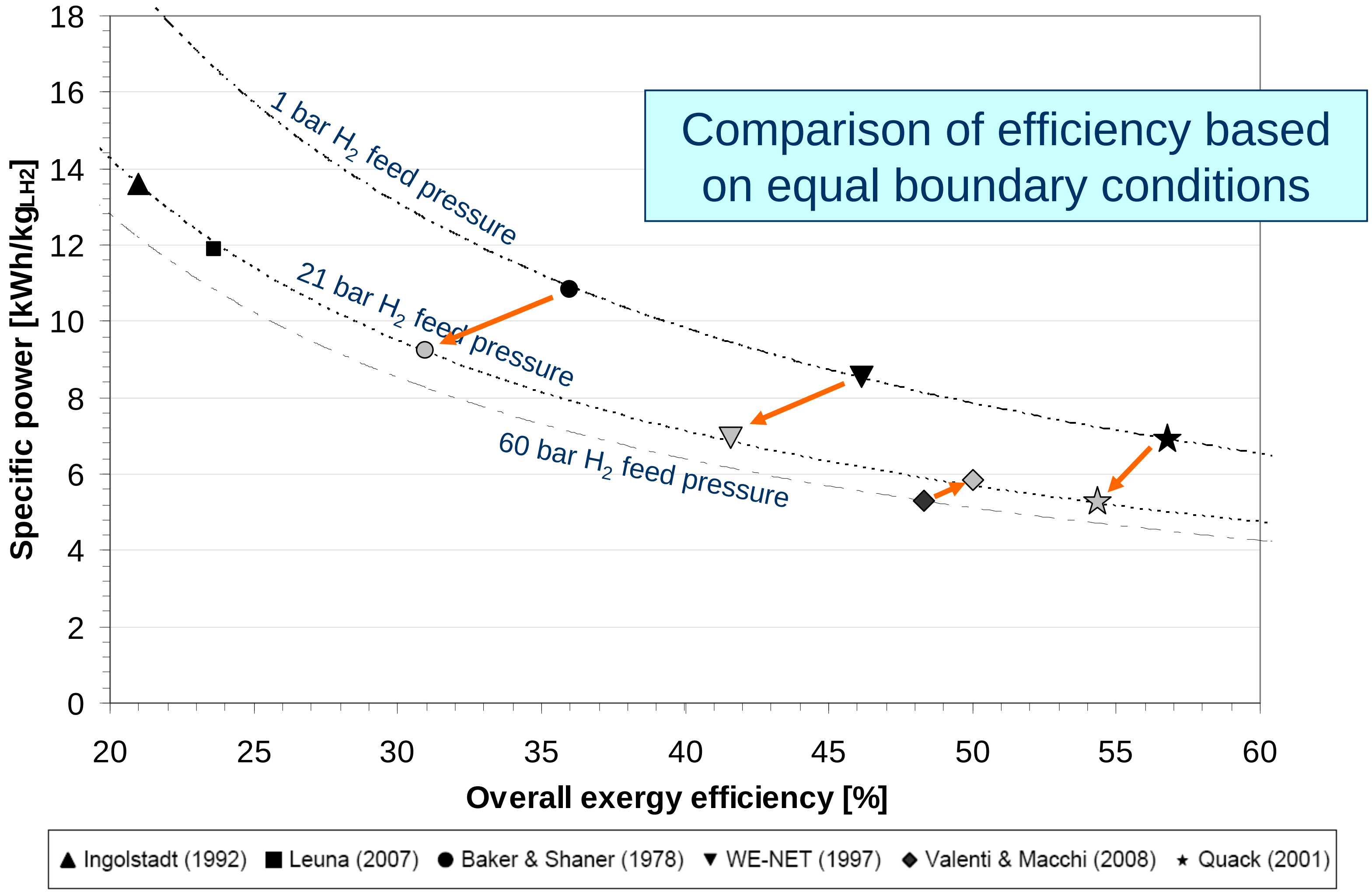

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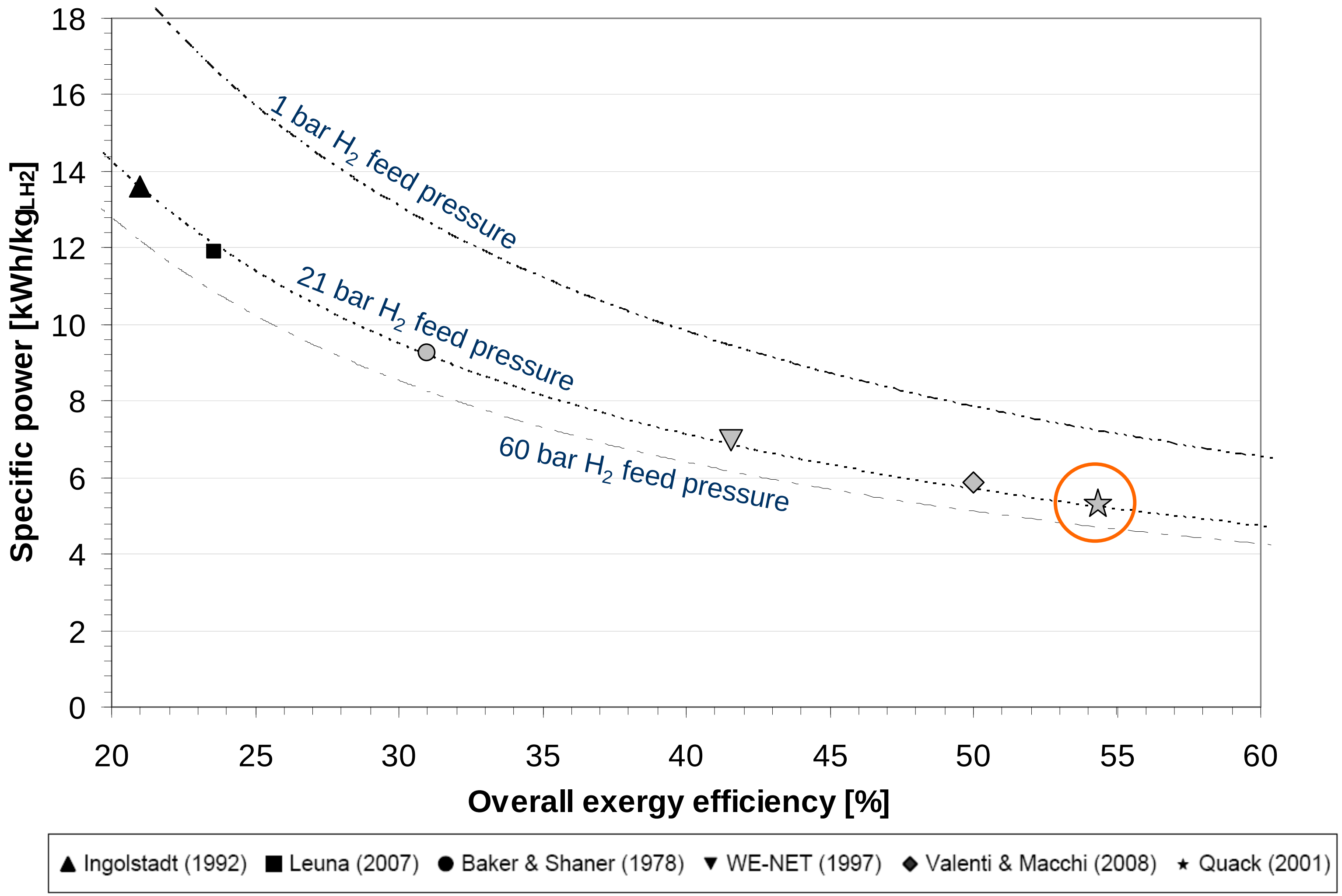

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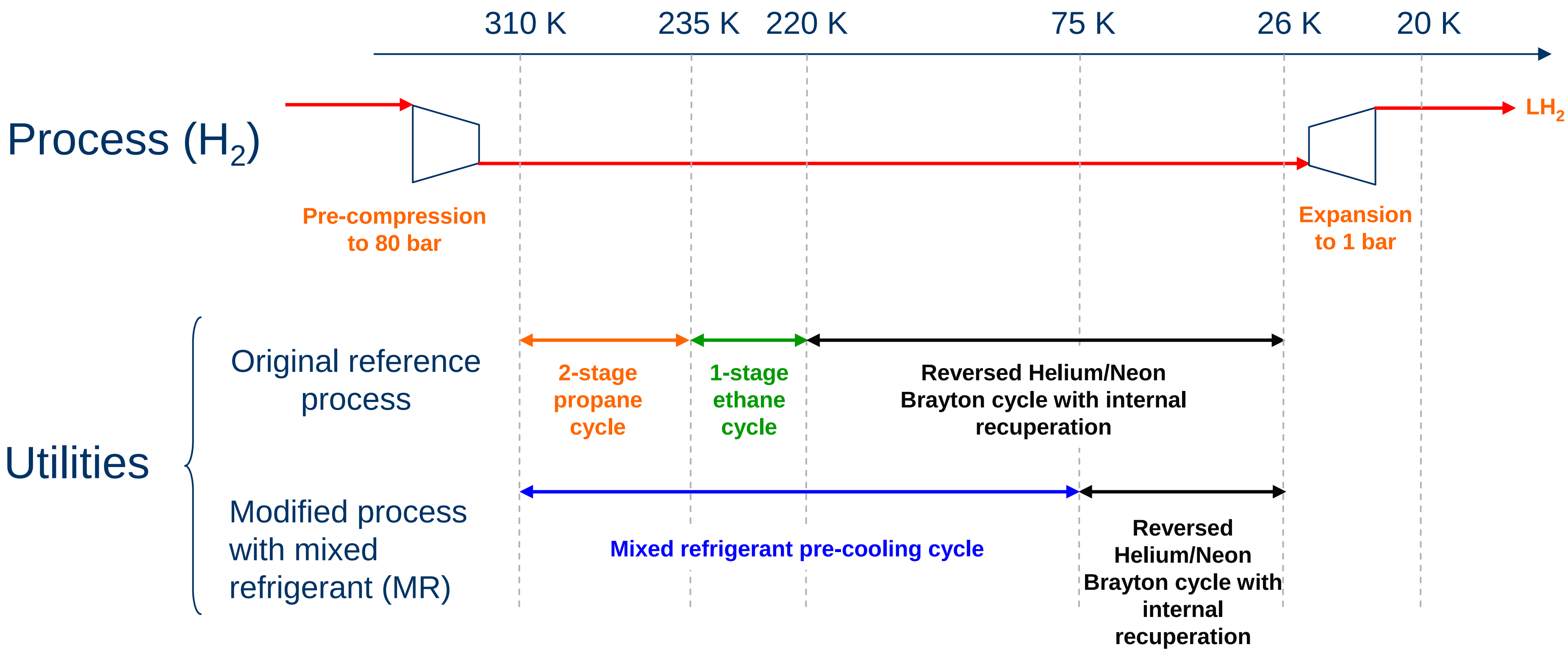
Selecting a reference case for our work

- The concept by Prof. Quack[1] (2001) is the most efficient concept published – we have therefore based our work on this concept and using it as reference process
- Changed assumptions of the reference process to be more conservative than in original configuration:
  - For pre-cooling to 220 K, the original 3-stage propane cycle is replaced with 2-stage propane + single-stage ethane refrigeration cycles
  - Assumed 21 bar feed pressure instead of 1 bar
  - Inter-cooler temperature in compressor trains: 310 K
  - Implemented pressure drop in all heat exchangers and inter-coolers
  - Minimum temperature approach (MTA) in heat exchangers:
    - Above 235 K: MTA = 3 K
    - Below 235 K: MTA = 2 K
- Liquefaction capacity: 86 tonnes/day (~ 1 kg/s)
- Resulting exergy efficiency: 45.7%

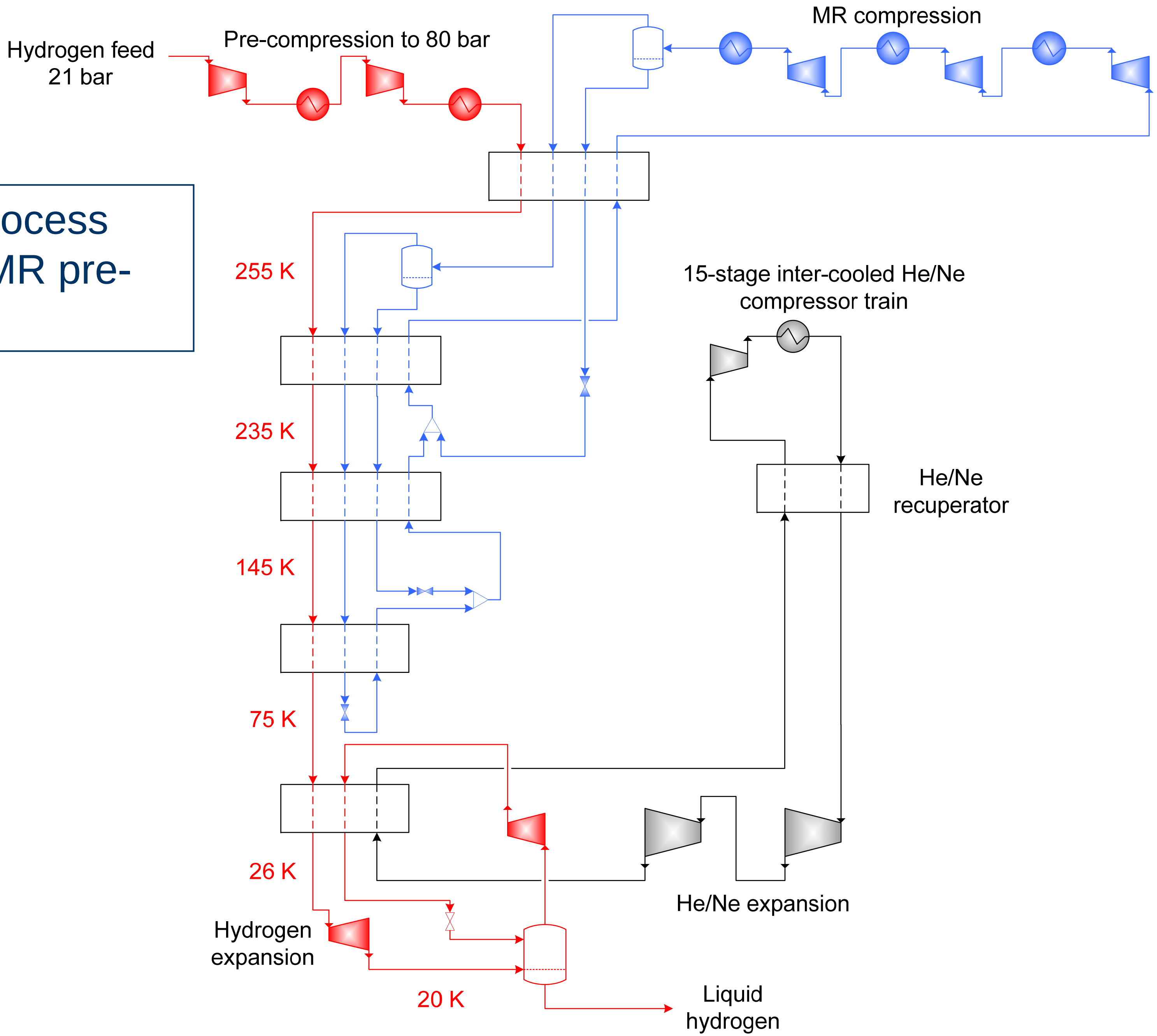
[1]**Quack H. *Conceptual design of a high efficiency large capacity hydrogen liquefier*. Advances in Cryogenic Engineering 47:255–263, 2001**

Implementing mixed refrigerant pre-cooling in the reference case

Utilities in the different temperature intervals



Liquefaction process modified with MR pre-cooling



Power figures and overall results

	Reference case	Modified MR case with J-T expansions	Modified MR case with liquid expanders
	Electric power [MW]	Electric power [MW]	Electric power [MW]
He/Ne compression	23,139	14,867	14,869
H2 feed compression	2,401	2,401	2,401
Propane-ethane/MR compression	0,732	7,392	6,330
H2 flash-gas compression	0,043	0,043	0,043
Total compression power	**26,315**	**24,703**	**23,643**
He/Ne expansion	3,443	1,271	1,271
H2 liquid expansion	0,086	0,086	0,086
MR expansion	0	0	0,085
Total expansion power	**3,529**	**1,357**	**1,442**
Net power consumption	**22,786**	**23,346**	**22,201**
Specific power consumption [kWh/kg]	**6,33**	**6,49**	**6,17**
Exergy efficiency	**45,7 %**	**44,6 %**	**46,9 %**

- Replacement of J-T valves with rotating liquid expanders (85% isentropic efficiency):
  - Reduces MR HP/LP ratio from 22.4 to 12.4
  - Reduces MR compression power by 17%

LH_2 related to LNG

- Lower heating value:
  - LNG: ~13.6 kWh/kg (~49 MJ/kg)
  - LH_2: 33.4 kWh/kg (120 MJ/kg)
- Reversible liquefaction power (specific):
  - LNG: 0.11 kWh/kg (Snøhvit gas, Hammerfest conditions)
  - LH_2: 2.89 kWh/kg (21 bar feed pressure, 300 K ambient temperature)
- The Snøhvit LNG plant:
  - Specific design power consumption: 0.23 kWh/kg[1]
  - Exergy efficiency: ~48%
- The best-performance LH2 process with MR pre-cooling:
  - Specific design power consumption: 6.17 kWh/kg
  - Exergy efficiency: ~47%

[1]**Heiersted R.S., Lillesund S., Nordhasli S., Owren G. and Tangvik K. *The Snohvit Design Reflects A Sustainable Environmental Strategy*. Conference paper, LNG-14, Quatar, 2004.**

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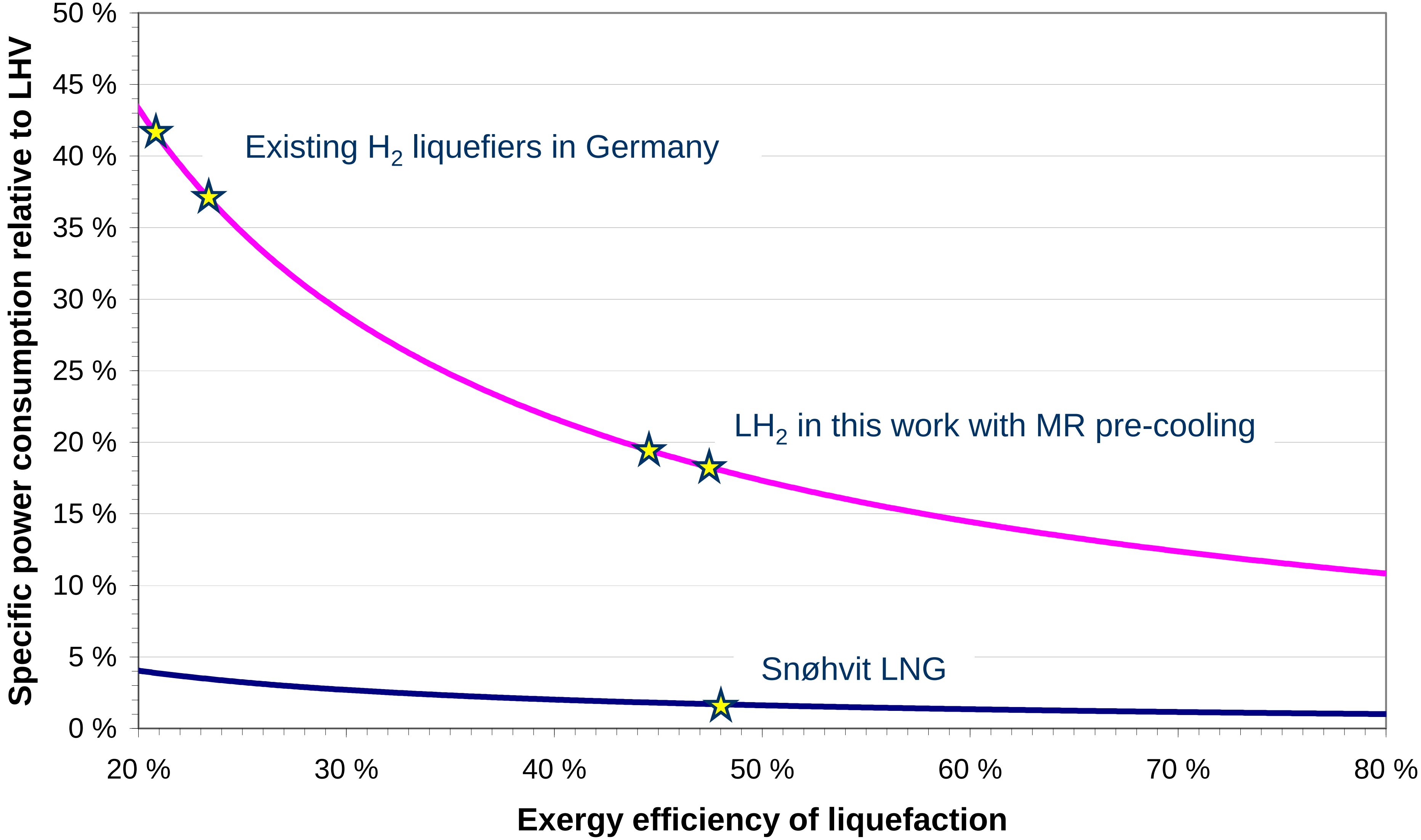
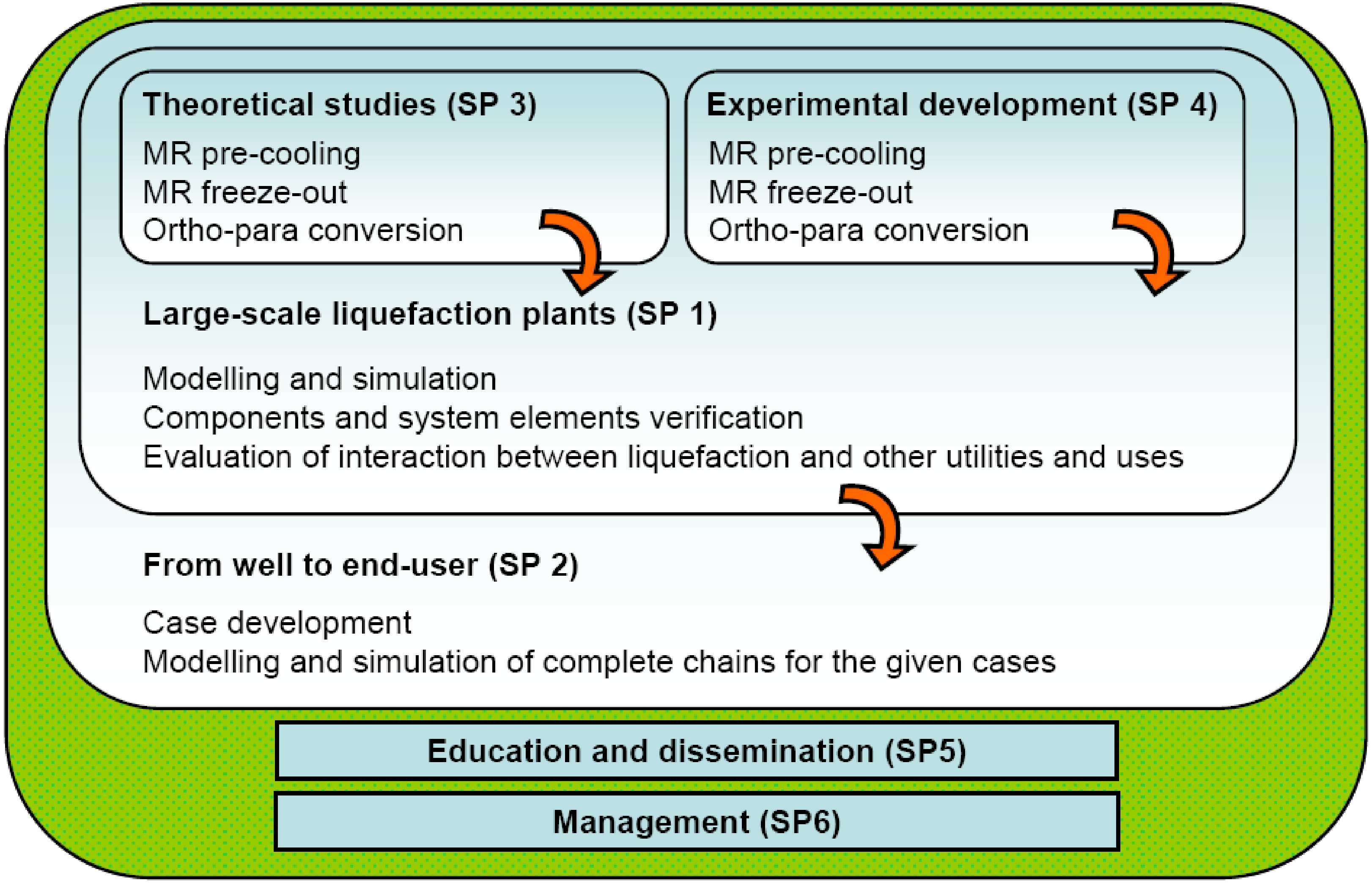


Conclusion

- The LH_2 processes employing MR pre-cooling show a specific power consumption of 6.17–6.49 kWh/kg and exergy efficiency of 44.6–46.9%
- 40–50% reduction of power consumption, down from 12 to 6–7 kWh/kg, will represent a radical improvement within large-scale hydrogen liquefaction and contribute to further enhancement of the competitiveness of LH_2 as energy carrier in an hydrogen-based energy chain
- As for LNG, MR pre-cooling may play an important role in the efforts towards efficient large-scale liquefaction processes
- High exergy efficiency is desired and may be obtainable for large-scale liquefiers with energy optimisation, extensive process integration and high-efficiency compressors and expanders

Further work: continuation project proposal



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