Comparison of system variants for hydrogen production from offshore wind power

Short study

APRIL 2022

The study compares system variants for hydrogen production from offshore wind power, with regard to implementation time, costs and environmental impact

INITIAL SITUATION

- The AquaVentus initiative aims to support the achievement of **Germany's energy and climate targets** with CO_2-neutral hydrogen production
- The vision is to provide **10 gigawatts of electrolyser capacity powered by offshore wind energy, by 2035**
- With this capacity, an **offshore production of up to 1 million tonnes of green hydrogen** is intended
- The hydrogen is planned to be transported to shore with a **pipeline system**
- The project is to be implemented in the **German exclusive economic zone (EEZ)** in the North Sea

Key Question:

Is offshore hydrogen production and transport via pipeline the **time-efficient, cost-efficient and environmentally friendly** system option?

OBJECTIVES

- **Different stylised technical setups** for hydrogen production and transport shall be compared in a short study, regarding the following criteria:
  - **Implementation time**
  - **Investment and operating costs**
  - **Environmental impact**
- With these objectives, the following system variants were analysed using a greenfield approach[1)]:

Submarine Cable with Onshore Hydrogen Production

Offshore Hydrogen Production with Pipeline Transport

Offshore Hydrogen Production with Ship Transport

1) Assuming full new build of all systems without consideration of potential synergies and conflicts with existing facilities

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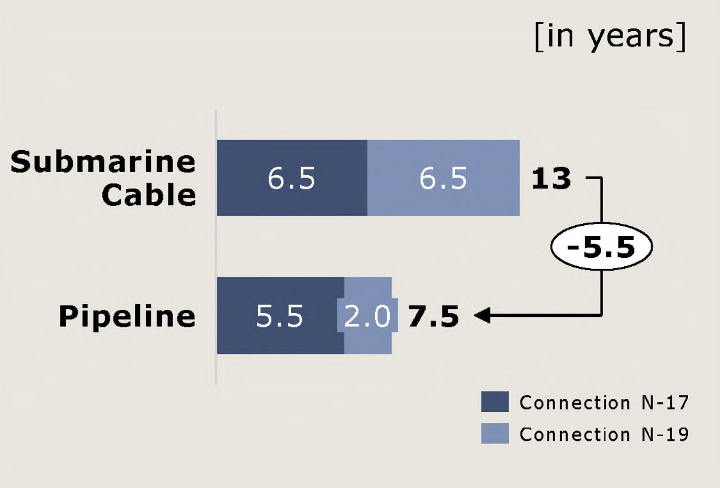
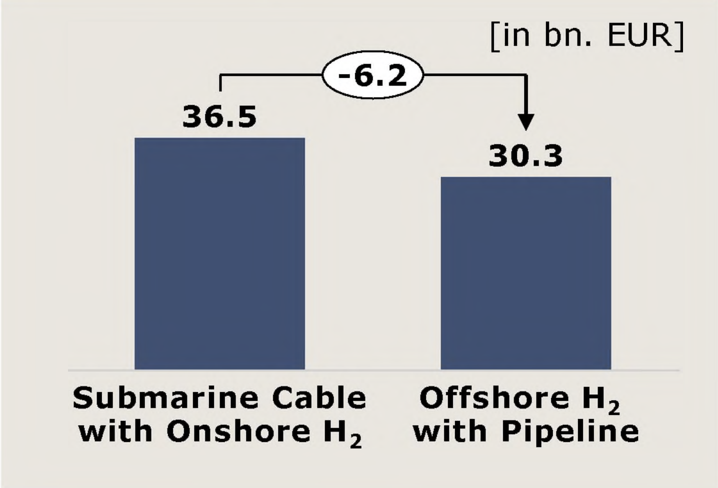
Offshore Hydrogen Production with Pipeline Transport emerges as time-efficient, cost-efficient and most environmentally compatible option of the studied variants

Implementation time



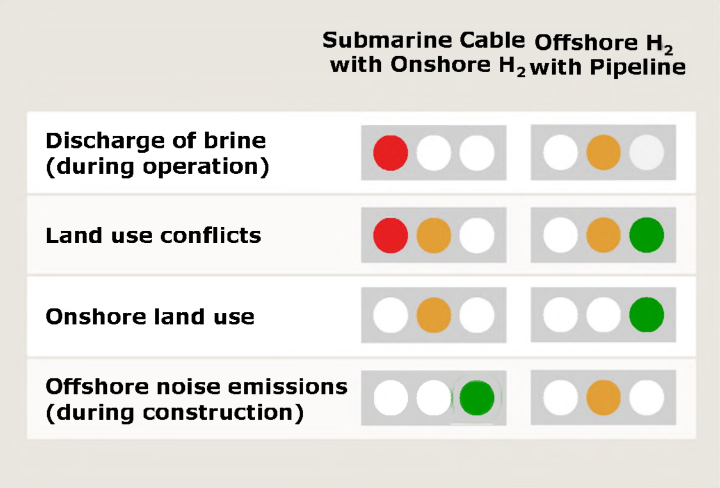
- The **cable** system is on the **critical path** for the onshore H_2 set-up and **misses the 10 GW target by 2035**
- The **pipeline** can be **completed on time,** with the H_2 platform installation determining the overall project duration
- The capacities for **ship transport cannot be implemented before 2035**

Investment costs



- Investment costs for **power cable** with onshore H_2 are **approx. at 36.5 bn EUR[1)]**
- The investment costs for offshore H_2 with **pipeline transport** are **approx. at 30.3 n EUR[1)]**
- The optimal dimensioning for H_2 ship transport is yet unknown, comparatively lower CAPEX but higher OPEX to be expected

Environmental impact



- The possibility to obtain a permit for the discharge of brine near the coast for the onshore system **appears doubtful**
- The onshore system bears a risk of **severe conflicts of interest regarding land use,** with local residents and associations
- Pile-driving for the offshore system requires **noise protection measures** for marine mammals

1) Excluding investment costs for offshore wind generation

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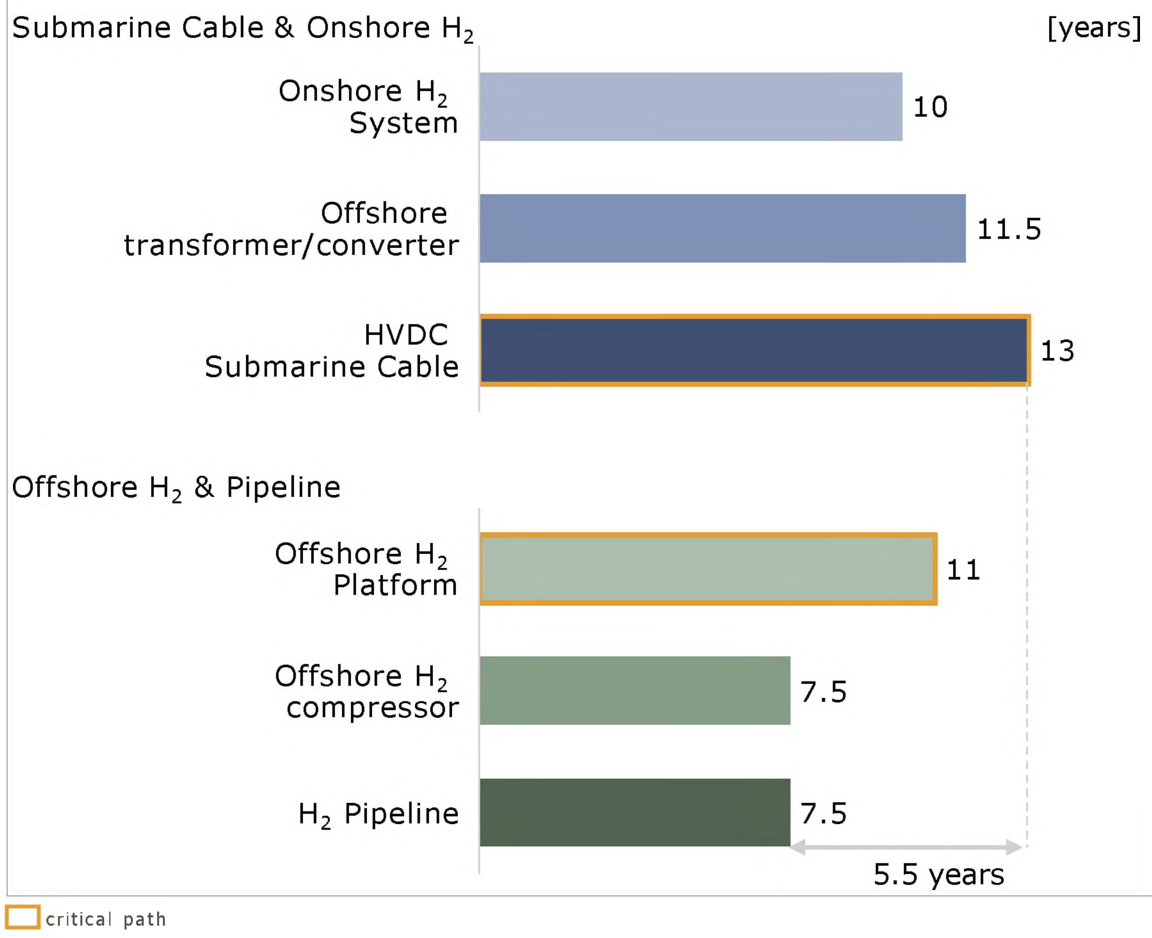
The H_2 pipeline system is expected to be commissionable 5.5 years earlier than the HVDC cable system

COMPARISON OF IMPLEMENTATION TIMES



SUMMARY

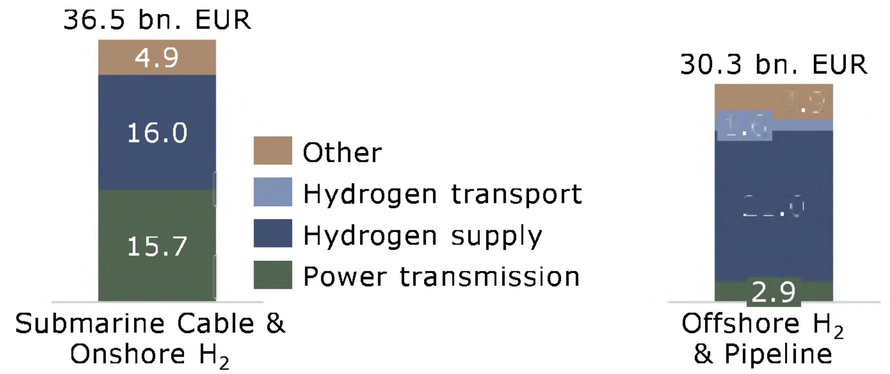
- The implementation time analysis reveals significant time advantage for Offshore Hydrogen with Pipeline compared to Submarine Cable with Onshore Hydrogen
- For the pipeline variant, the full transport capacity is already available after 7.5 years while the submarine cable variant is completed five and a half years later, i.e. about 13 years after the start of the project, narrowly missing the 10 GW expansion target by 2035
- The critical path of the pipeline variant is determined by the construction of the offshore H_2 platforms while the construction of the submarine cables determines the overall time requirement for the submarine cable variant

KEY ASSUMPTIONS

- New construction without influences or limitations from existing systems, e.g. pipelines in the area under consideration
- Parallel, synchronised planning & approval of the entire system and the components without project plan changes
- H_2 systems, offshore transformer/converters and compressors are produced and installed in parallel
- Transport systems are produced and installed sequentially

Investment costs for Offshore H_2 with Pipeline are 6.2 bn. EUR (17%) lower than for Submarine Cable with Onshore H_2

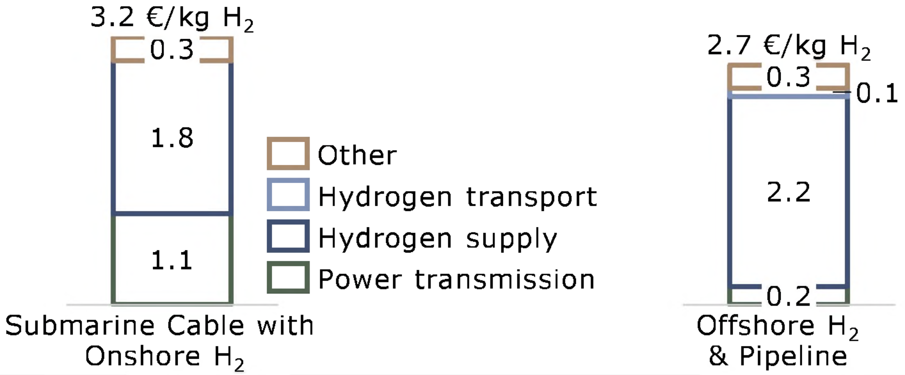
ASSESSMENT OF TOTAL SYSTEM COSTS[1)]



SHORT SUMMARY

- The calculated total system costs and the resulting costs for delivered hydrogen are lowest for offshore H_2 with pipeline
- The total system costs are around six billion euros lower than those of onshore H_2 with submarine cables
- The transport system cost (not including hydrogen production cost) per kilogram of hydrogen delivered to the Startnetz H_2 is EUR 2.7/kg H_2, EUR 0.5/kg H_2 less than for onshore H_2 with submarine cables
- Due to uncertainties and missing data points, a cost calculation for the option of H_2 transport by ship could not be substantiated sufficiently at the present time and was omitted

ASSESSMENT OF SPECIFIC SYSTEM COSTS[1)]



KEY ASSUMPTIONS

- The analysis uses 2021 as reference year for costs of system components, total system costs and current prices
- The analysis of the hydrogen supply costs uses the Levelised Cost of Energy (LCOE) approach
- System costs cover energy transport only and do not include offshore wind generation
- Potential future cost degressions are not included, would decrease total system cost and cost per kg of delivered H_2

1) Excluding investment costs for offshore wind generation

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From an environmental perspective, Offshore H_2 with Pipeline is preferrable to Submarine Cable with Onshore H_2

ENVIRONMENTAL IMPACT - CONSTRUCTION

Impact Factor	Submarine Cable with Onshore H_2	Offshore H_2 with Pipeline
Noise emissions offshore	green	amber
Temporary land use	amber	green
Land use conflicts	red / amber	amber / green
Disposal of hazardous materials	green	amber
Geological risks	green	green
ESG & supply chain risk	amber	green

SHORT SUMMARY

- From an environmental perspective, Offshore H_2 with Pipeline is more compatible with underlying ecological requirements
- For Onshore H_2, the risk of conflicts of interest with local communities over land use is significant during planning and permitting – delays in project development and lawsuits against the project need to be expected
- The discharge of brine into the waddensea area is unlikely to be permitted

ENVIRONMENTAL IMPACT - OPERATION

Impact Factor	Submarine Cable with Onshore H_2	Offshore H_2 with Pipeline
Permanent land use	amber	green
Disposal of hazardous materials	green	amber
Water extraction and brine discharge	red	amber

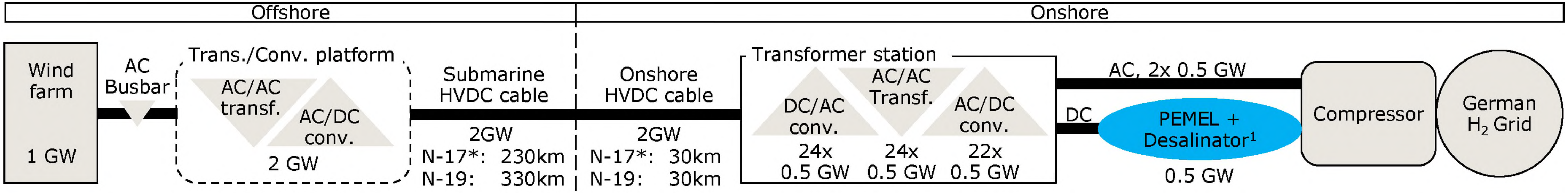
KEY ASSUMPTIONS

- Technical options for the re-use and recycling of brine onshore are limited and currently not economically feasible

Content

Transport system comparison between pipeline, ship and cable uses joint component scheme between common electricity input and H_2 outlet (1/3)

SUBMARINE CABLE WITH ONSHORE ELECTROLYSIS

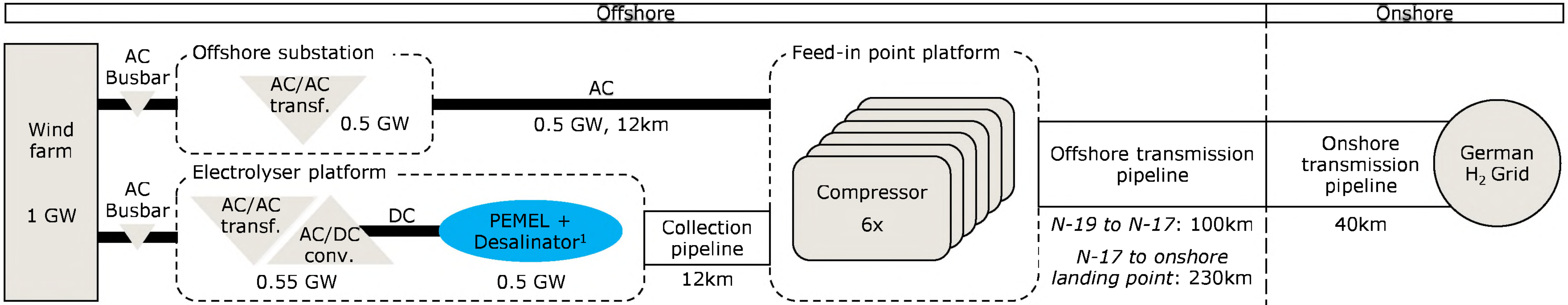


N-17*	6x Wind farm	3x Trans./Conv. platforms	3x Submarine HVDC cable	6x Onshore HVDC cable	1x Transformer station	20x PEMEL + desalinator[1]	12x Compressor	1x H_2 grid connection
N-19	6x Wind farm	3x Trans./Conv. platforms	3x Submarine HVDC cable					

N-17* = All N-17 fields + N-18.3 and N-20.1 | [1]Just in time desalination is assumed

Transport system comparison between pipeline, ship and cable uses joint component scheme between common electricity input and H_2 outlet (2/3)

OFFSHORE ELECTROLYSIS WITH PIPELINE TRANSPORT

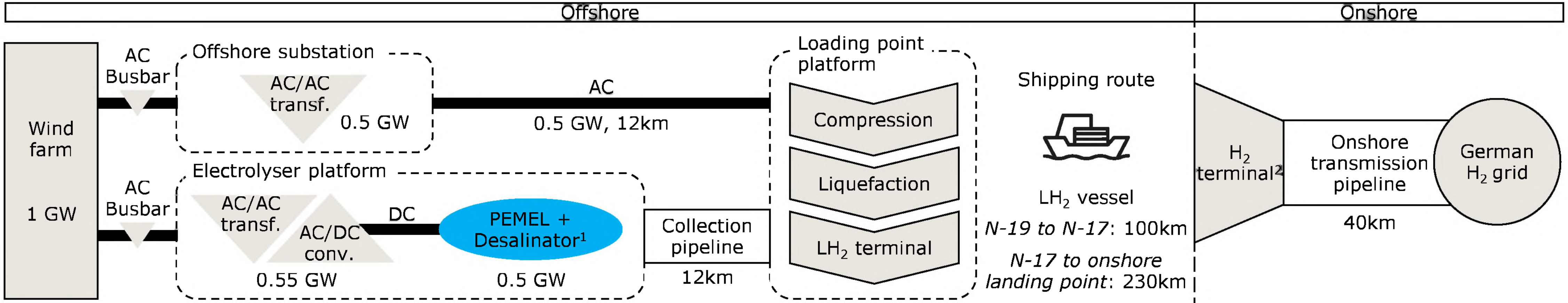


N-17*	6x Wind farm	1x Offshore substation 10x Electrolyser platform	1x AC power line 10x collection pipeline	1x Feed-in point platform	1x Offshore transmission pipeline	1x Onshore transmission pipeline	1x H_2 grid connection
N-19	6x Wind farm	1x Offshore substation 10x Electrolyser platform	1x AC power line 10x collection pipeline	1x Feed-in point platform			

N-17* = All N-17 fields + N-18.3 and N-20.1 | [1]Just in time desalination is assumed

Transport system comparison between pipeline, ship and cable uses joint component scheme between common electricity input and H_2 outlet (3/3)

OFFSHORE ELECTROLYSIS WITH SHIP TRANSPORT

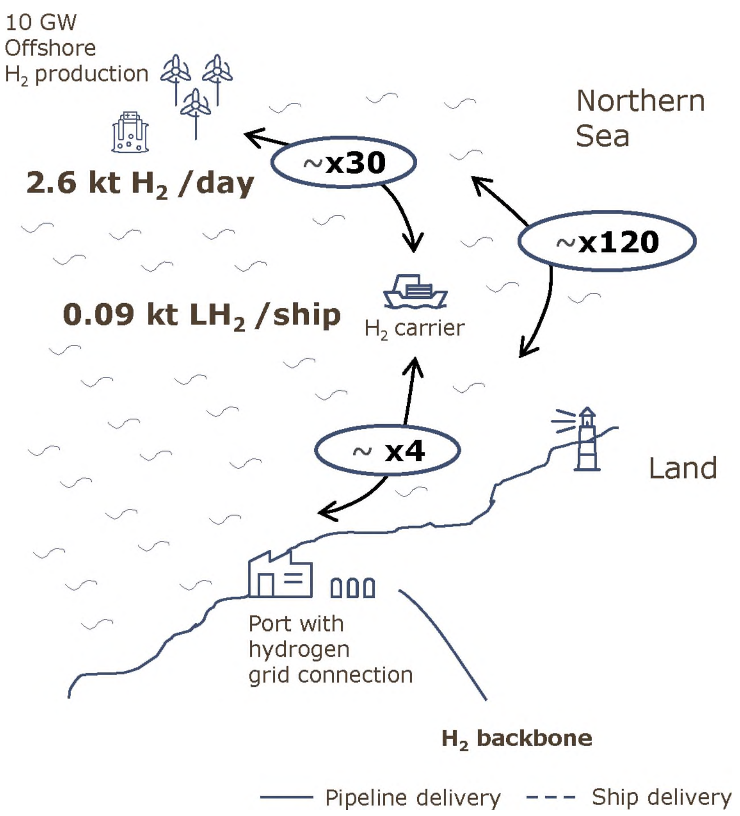


N-17*	6x Wind farm	1x Offshore substation 10x Electrolyser platform	1x AC power line 10x Collection pipeline	1x Loading point platform	100x LH_2 vessels	1x H_2 terminal[2]	1x Onshore transmission pipeline	1x H_2 grid connection
N-19	6x Wind farm	1x Offshore substation 10x Electrolyser platform	1x AC power line 10x Collection pipeline	1x Loading point platform				

N-17* = All N-17 fields + N-18.3 and N-20.1 | [1]Just in time desalination is assumed | [2]incl. regasification and compression units

With current technology[1)], continuous shuttling of H_2 from 10 GW offshore wind would require a fleet of more than 100 specialised transport vessels

STYLISED OFFSHORE H_2 WITH SHIP TRANSPORT[1)2)]



COMMENTS

- 10 GW electolysis output results in 0.94 Mt of hydrogen production annually and 2.6 kt of hydrogen per day
- World‘s first liquid hydrogen carrier ship Suiso Frontier is capable of transporting 89 t of liquid hydrogen
- Appr. 30 LH_2 tanker ships of this specification would be needed to accomodate one single daily production output
- Total fleet needs to ensure a continous stream of vessels that load, sail inbound, unload and sail outbound at all times requiring around four times as many ships as needed for one daily production output

- Ship transport is not analysed in further detail, as it is considered unsuitable for the AquaVentus project
  - Significant insecurity regarding future load volume and resulting fleet size requirement
  - Additional insecurities from production bottlenecks in shipyards and potential resistance by the BSH (Federal Maritime and Hydrographic Agency) against additional traffic in the German bight and in proximity to wind parks

1) Only one prototype Liquid H_2 tanker currently in operation globally, load capacity 1.250 m^3 LH_2
2) Assumptions: vessel speed in German bight: 15 knots / 28 km/h; Sailing time inbound/outbound: appr. 15 hours per leg, loading/unloading time: 1 day per vessel

Content

1. Technical Setup
2. **Comparison of Implementation Times**
3. Comparison of Investment and Operating Costs
4. Comparison of Environmental Compatibility

Due to significant demand for high voltage cables, project may be impacted by production capacity bottlenecks that would lead to long delivery times

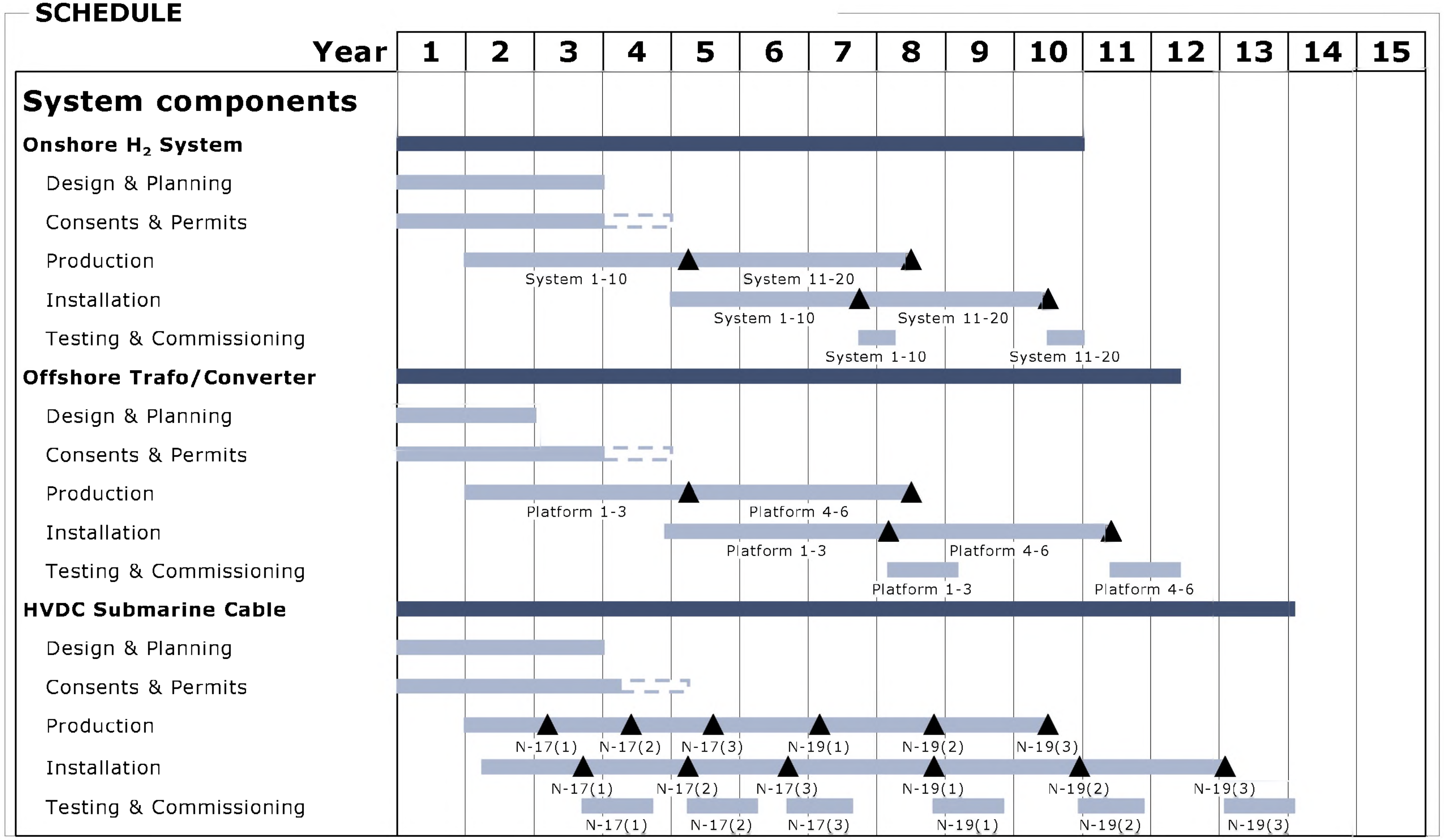
TECHNICAL AND SUPPLY CHAIN READINESS – SUBMARINE CABLE WITH ONSHORE H_2

System Components	Technology Readiness	Supply Chain Readiness	Availability of Resources	Comments
Onshore H_2 System	7	Orange	Orange	– Challenges deriving from system configuration and seawater treatment and feedback
Onshore transformer/converter	9	Green	Orange	– Possible bottlenecks due to competition with other major submarine cable projects
Onshore desalinator	8	Orange	Orange	– Additional H_2 device specifications successfully tested – High development potential and high demand expected
Onshore electrolyser	9	Green	Orange	– Supply chains are established – Supply bottlenecks already observed today
Onshore H_2 compressor	9	Green	Orange	– Already in operation in many ways – Bottlenecks along the supply chain due to H_2 ramp-up
Offshore trafo/converter	9	Green	Orange	– Increasing number of projects in the offshore environment – Oligopolistic market structures among suppliers
HVDC submarine cable	9	Green	Red	– High resource requirements, complex manufacturing and existing increase in demand leads to capacity bottlenecks

Green: No risks or delays expected | Orange: Moderate risks or delays expected | Red: High risks or delays expected

TRL Level: 5 – Proof of function in simulated environment, 6 – Demonstration in simulated environment, 7 – Demonstration of prototype(-system) in operational environment, 8 – Qualified system with proof of function in operational environment, 9 – Qualified system with proof of successful operation

Sequential procurement, manufacture and installation of HVDC cable systems would lead to a failure to reach 2035 capacity targets



COMMENTS

- 10 onshore H_2 systems have to be manufactured and installed in parallel to reach 10 GW by 2035
- 3 offshore transformers/converters need to be manufactured and installed in parallel
- The 10 GW system is assumed to be managed by one consortium – planning to commissioning is synchronised along all components
- Relevant political support and no interim project plan changes are assumed as given
- Under these assumptions, even if the project is launched in 2023, it is finalised by 2036 only and misses the 2035 target

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Configuration and construction of offshore H_2 platforms with different components may hold new maritime risks – no significant risks expected for pipelines

TECHNICAL AND SUPPLY CHAIN READINESS – OFFSHORE H_2 WITH PIPELINE

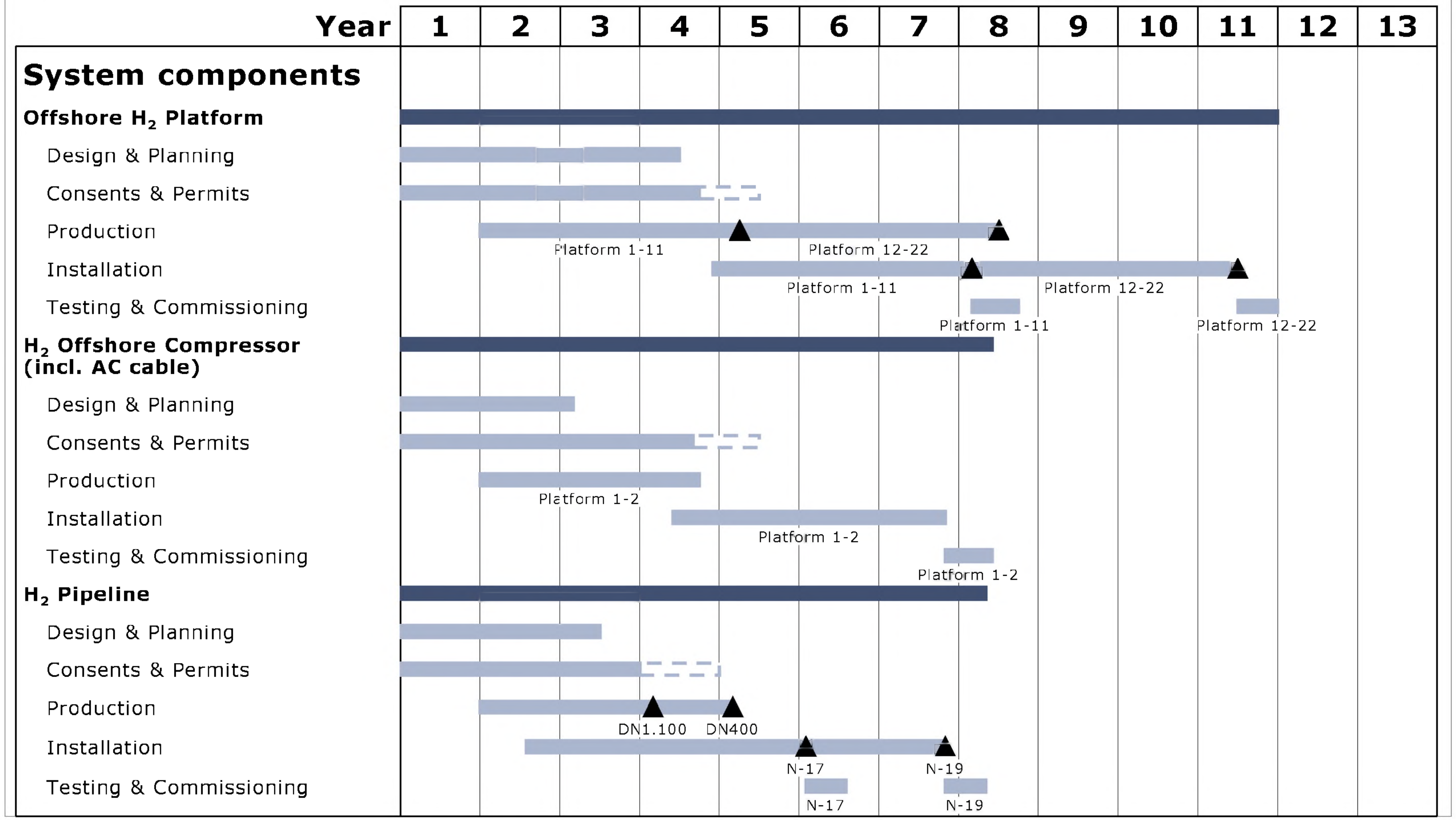
System Components	Technology Readiness	Supply Chain Readiness	Availability of Resources	Comments
Offshore Platform H_2 System	TRL 6	Moderate risks or delays expected	Moderate risks or delays expected	– Concept studies describe hydrogen production platforms up to 800 MW
Offshore transformer/converter	TRL 9	No risks or delays expected	Moderate risks or delays expected	– Potential bottlenecks due to other competing large-scale projects
Offshore desalinator	TRL 7	Moderate risks or delays expected	Moderate risks or delays expected	– Onshore desalinations systems have been tested successfully and are expected to be adapted to offshore use cases
Offshore electrolyser	TRL 7	Moderate risks or delays expected	Moderate risks or delays expected	– Tests are being run in offshore environment to prove and evaluate feasibility
Offshore H_2 compressor	TRL 6	Moderate risks or delays expected	Moderate risks or delays expected	– Concept studies exist, additional system specifications from H_2 have not yet been tested in offshore environment
Offshore H_2 collection and transmission pipeline	TRL 9	No risks or delays expected	Moderate / No risks or delays expected	– H_2 ready pipelines exist in the Baltic Sea – No significant bottlenecks expected

No risks or delays expected · Moderate risks or delays expected · High risks or delays expected

TRL Level: 5 – Proof of function in simulated environment, 6 – Demonstration in simulated environment, 7 – Demonstration of prototype(-system) in operational environment, 8 – Qualified system with proof of function in operational environment, 9 – Qualified system with proof of successful operation

Pipeline infrastructure allows earlier commissioning than cable system, enabling it to achieve the 10 GW target by 2035

SCHEDULE



COMMENTS

- 11 offshore H_2 platforms have to be manufactured and installed in parallel to reach 10 GW by 2035
- 2 offshore compressor platforms need to be manufactured and installed in parallel
- The 10 GW system is assumed to be managed by one consortium – planning to commissioning is synchronised along all components
- Relevant political support and no interim project plan changes are assumed as given
- Under these assumptions, the project can be finalised by 2033 if it is launched in 2023

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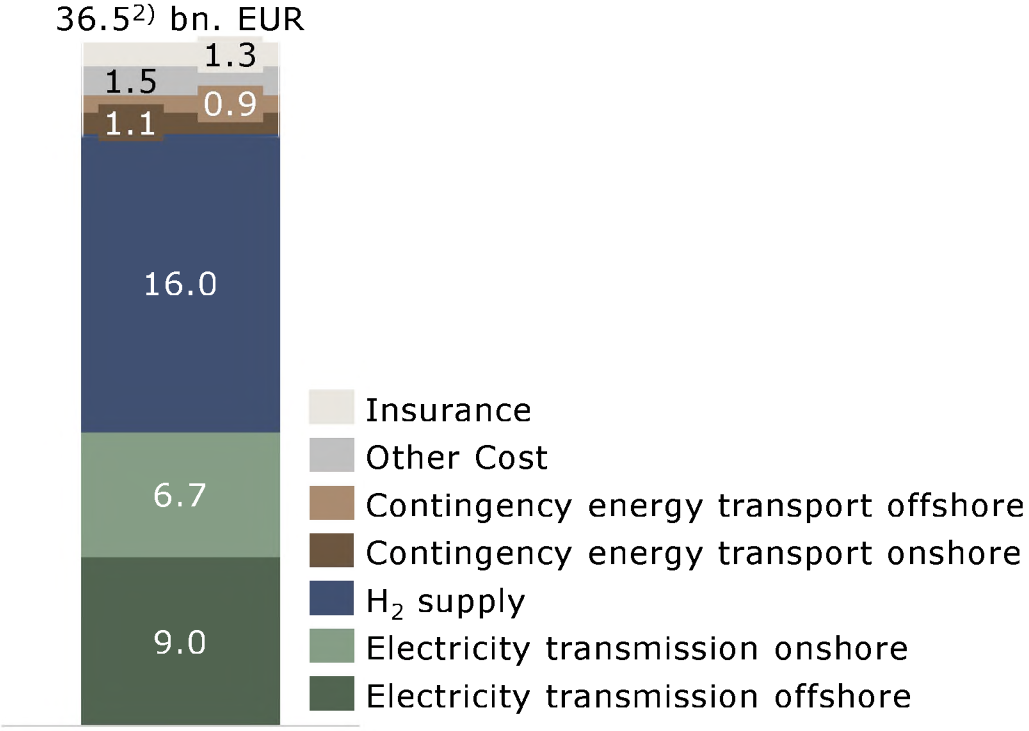
Content

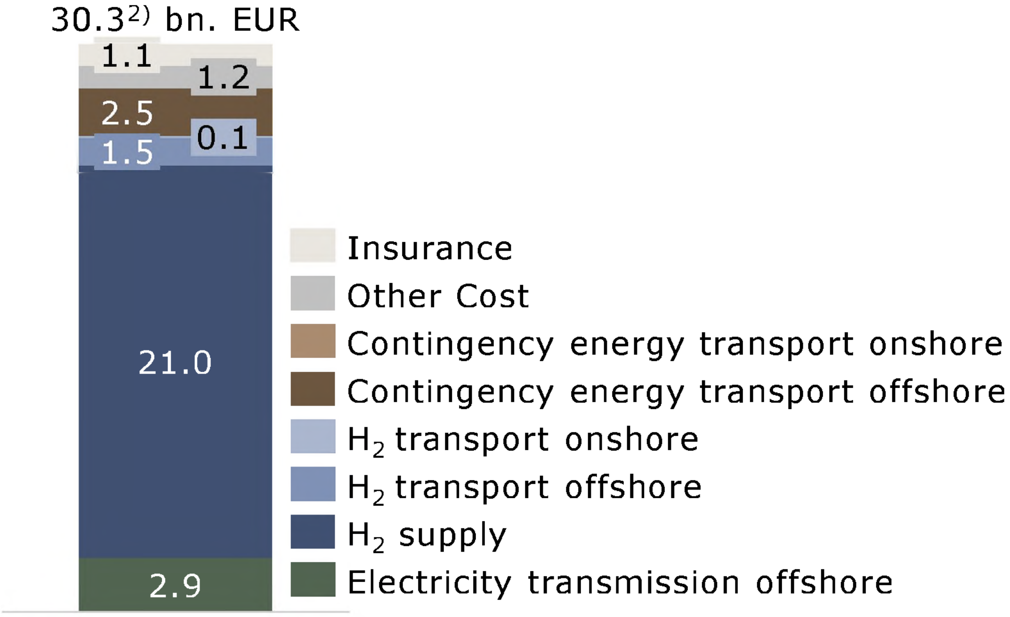



10 GW scenario: comparison of total system cost shows offshore H_2 production with pipeline transport to shore as favourable option[1)]

SYSTEM COSTS OF SUBMARINE CABLE WITH ONSHORE H_2



SYSTEM COSTS OF OFFSHORE H_2 WITH PIPELINE

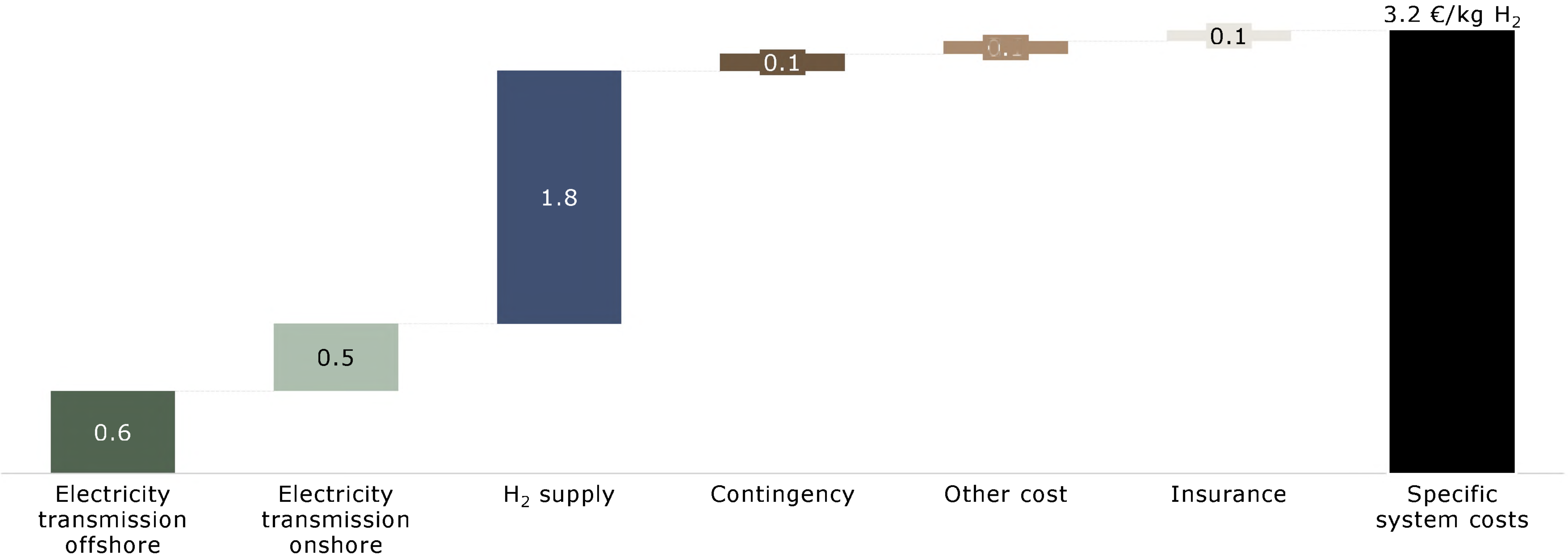


If project scales beyond 10 GW pipeline solution has structural lesser cost than powerline since pipeline capacity can be increased trough use of higher operating pressures

1) Base year of this analysis is 2021 hence, CAPEX are given in EUR2021 and on 2021 cost levels (no future cost reductions taken into account);
2) Excluding investment costs for offshore wind generation

The specific system costs for the Submarine Cable & Onshore H_2 system are at 3,2 €/kg H_2 1)

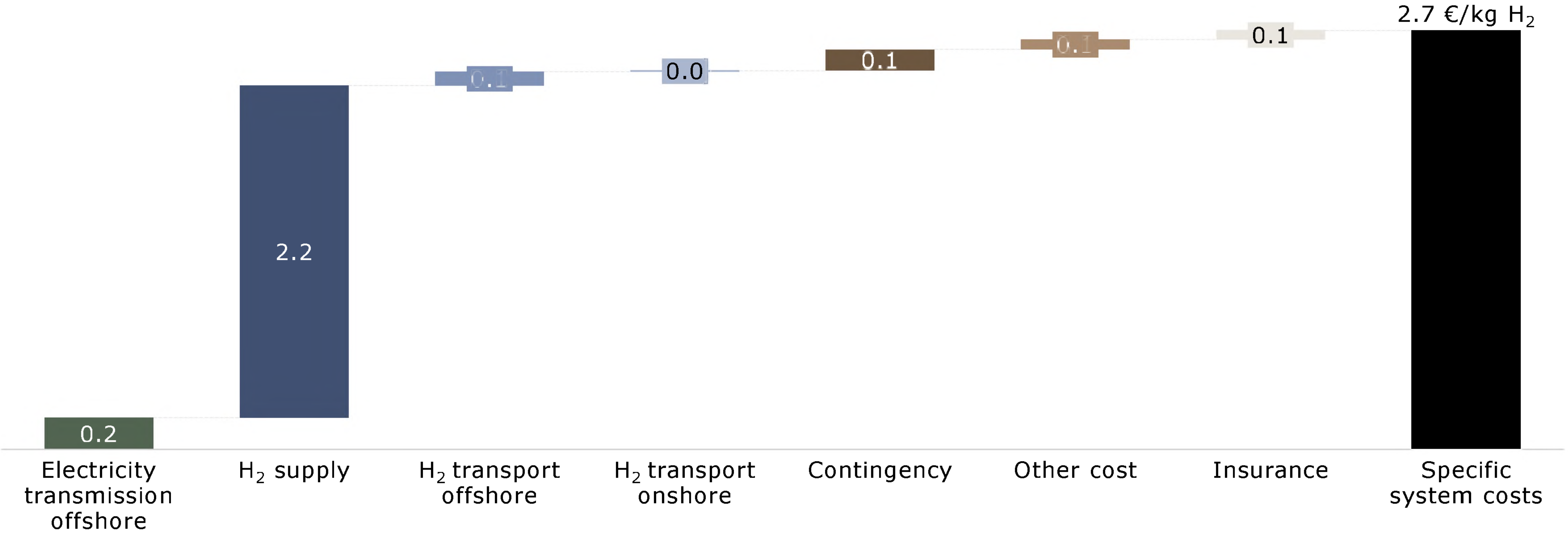
DELIVERY COSTS – SUBMARINE CABLE & ONSHORE H_2 (LCOE, 2021)*



1) Base year of this analysis is 2021 hence, CAPEX are given in EUR2021 and on 2021 cost levels (no future cost reductions taken into account);
* excl. investment costs for offshore wind generation

The specific system costs for the Offshore H_2 & Pipeline Transport system are at 2.7 EUR/kg H_2 1)

DELIVERY COSTS – OFFSHORE H_2 & PIPELINE (LCOE, 2021)*



1) Base year of this analysis is 2021 hence, CAPEX are given in EUR2021 and on 2021 cost levels (no future cost reductions taken into account);
* excl. investment costs for offshore wind generation

Content

The potential environmental impact for the construction phase shows a low-medium overall risk for all set-ups

ENVIRONMENTAL IMPACT ASSESSMENT – CONSTRUCTION PHASE

Risk	Onshore H_2 & Submarine Cable	Offshore H_2 & Pipeline	Offshore H_2 & Ship	Comments
Offshore noise emissions	Green	Orange	Orange	– Offshore piling noise requires countermeasures. Options are available but increase costs
Temporary land use onshore	Orange	Green	Orange	– Onshore construction requires more land to be occupied temporarily but can be restored afterwards
Land use conflicts onshore	Red + Orange	Orange + Green	Orange	– Onshore construction considerably increases potential for both social and environmental conflicts
Hazardous materials	Green	Orange	Orange	– Transport & disposal of hazardous materials more difficult and expensive for offshore platforms
Geological hazards	Green	Green	Green	– Offshore geological hazards will be managed following standard BSH protocols
ESG risk in supply chain	Orange	Green	Red + Orange	– Material sourcing for cable and ship more complex and resource required → Increases supplier ESG risks

Green: No risks or delays expected · Orange: Moderate risks or delays expected · Red: High risks or delays expected

The potential environmental impact for the operational phase shows medium to high risk for Onshore H_2 & Submarine Cable and Offshore H_2 & Ship

ENVIRONMENTAL IMPACT ASSESSMENT – OPERATIONS PHASE

Risk	Onshore H_2 & Submarine Cable	Offshore H_2 & Pipeline	Offshore H_2 & Ship	Comments
Permanent loss of land	Orange	Green	Orange	– Permanent loss of land for onshore greenfield projects is a significant environmental risk
Hazardous materials	Green	Orange	Red	– Transport and disposal of hazardous materials more difficult and expensive for offshore platforms, ships produce additional waste and emissions
Water extraction & brine discharge	Red	Orange	Orange	– Permission for near-shore discharge highly unlikely, the effect of offshore discharge requires closer examination
Loss at sea	Green	Green	Orange	– Boat traffic increases the risk of accidents, transport is weather-dependant
Noise levels	Green	Green	Orange	– Boat traffic contributes to marine noise pollution

Green: No risks or delays expected

Orange: Moderate risks or delays expected

Red: High risks or delays expected

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Protected coastal areas will require closer examination for permitting

- The map provides an overview about the relationship between the affected project area and the protected areas along the German coastline
- At sea, the Dogger Bank NATURA 2000 site will be slightly affected during the construction phase but is not expected to be affected during operation
- National parks and other reserves in the coastal areas will require more careful evaluation, as construction permissions may be limited depending on the type of protected area
- Discharge of brine in or near these protected areas will likely not be permitted

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