Energy Demand and Cost Analysis for a Hydrogen Fueled RoPax Ferry Using Design Lab Framework

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Nordic Maritime Transport and Energy Research Conference

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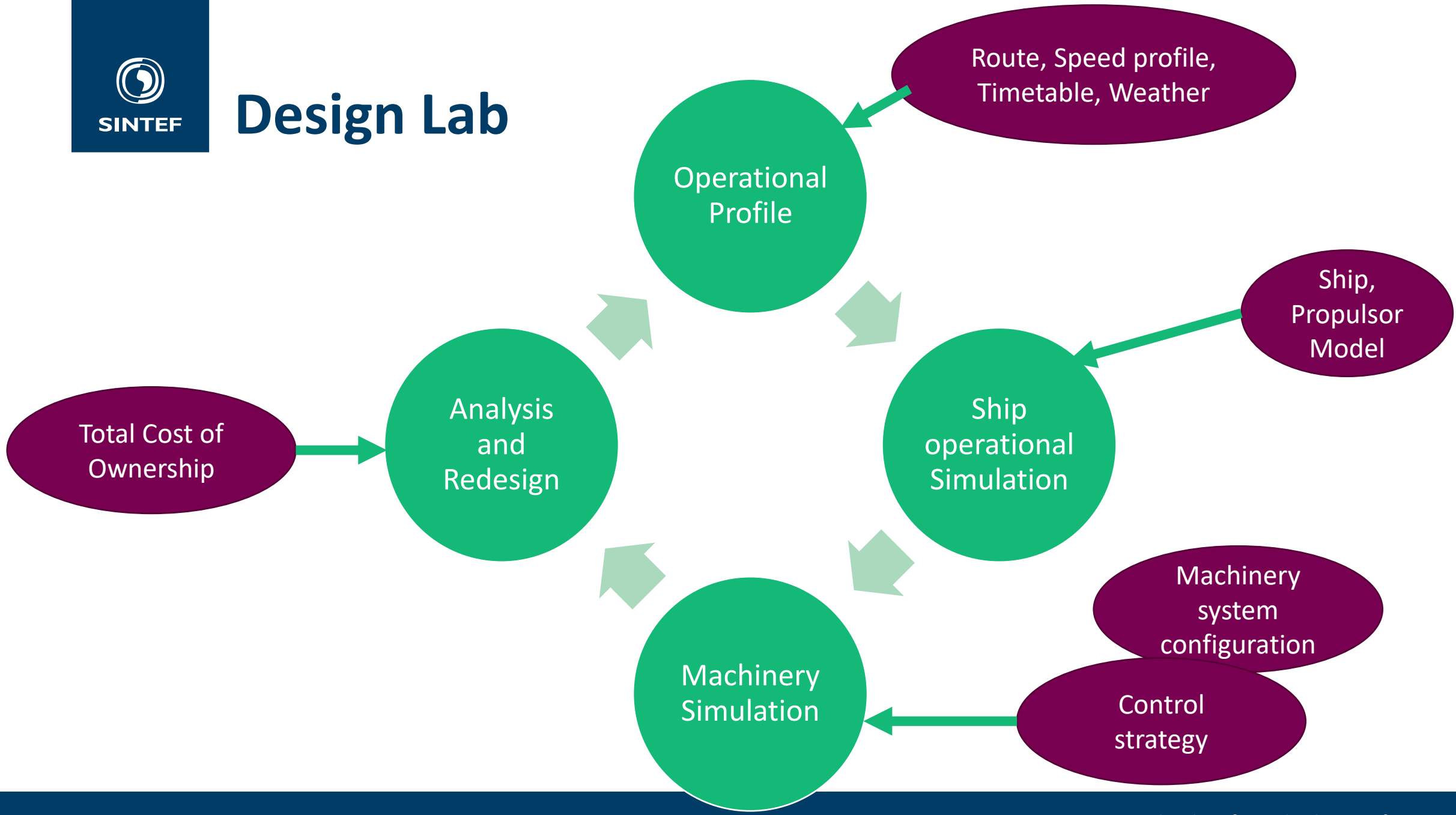
Fuel Cell Power Plant Sizing

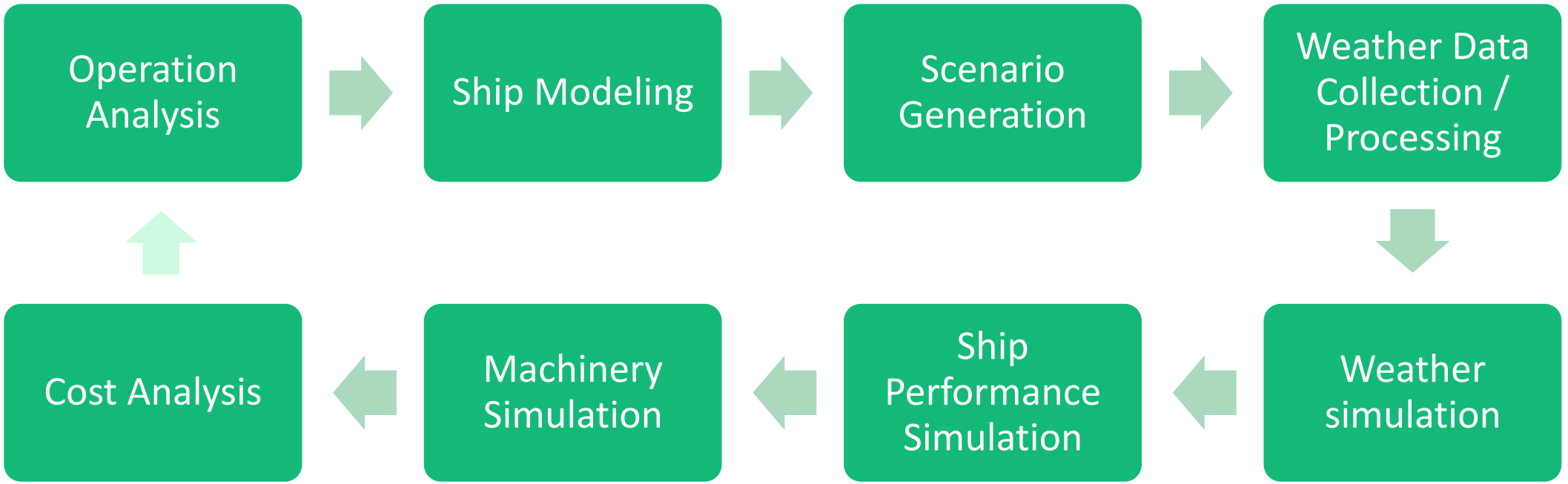
- Unit price
  - Fuel cost: 5 EUR/kg
  - Fuel cell cost: 1400 EUR/kW
  - Installation cost: 20% of fuel cell cost
  - Maintenance cost: 0.045 EUR/kWh
  - Storage cost: 1 mEUR/ton

Capacity	20MW	25MW	30MW
CAPEX [mEUR]	46.3	54.1	62.1
OPEX [mEUR/year]	18.308	17.497	17.008
Number of trips per year	1353	1353	1353
Energy production [kWh/trip]	38 458	38458	38458
Fuel consumption [ton/trip]	2.36	2.241	2.168
Levelized cost [EUR/trip]	16 392	16 271	16 403

Design Lab

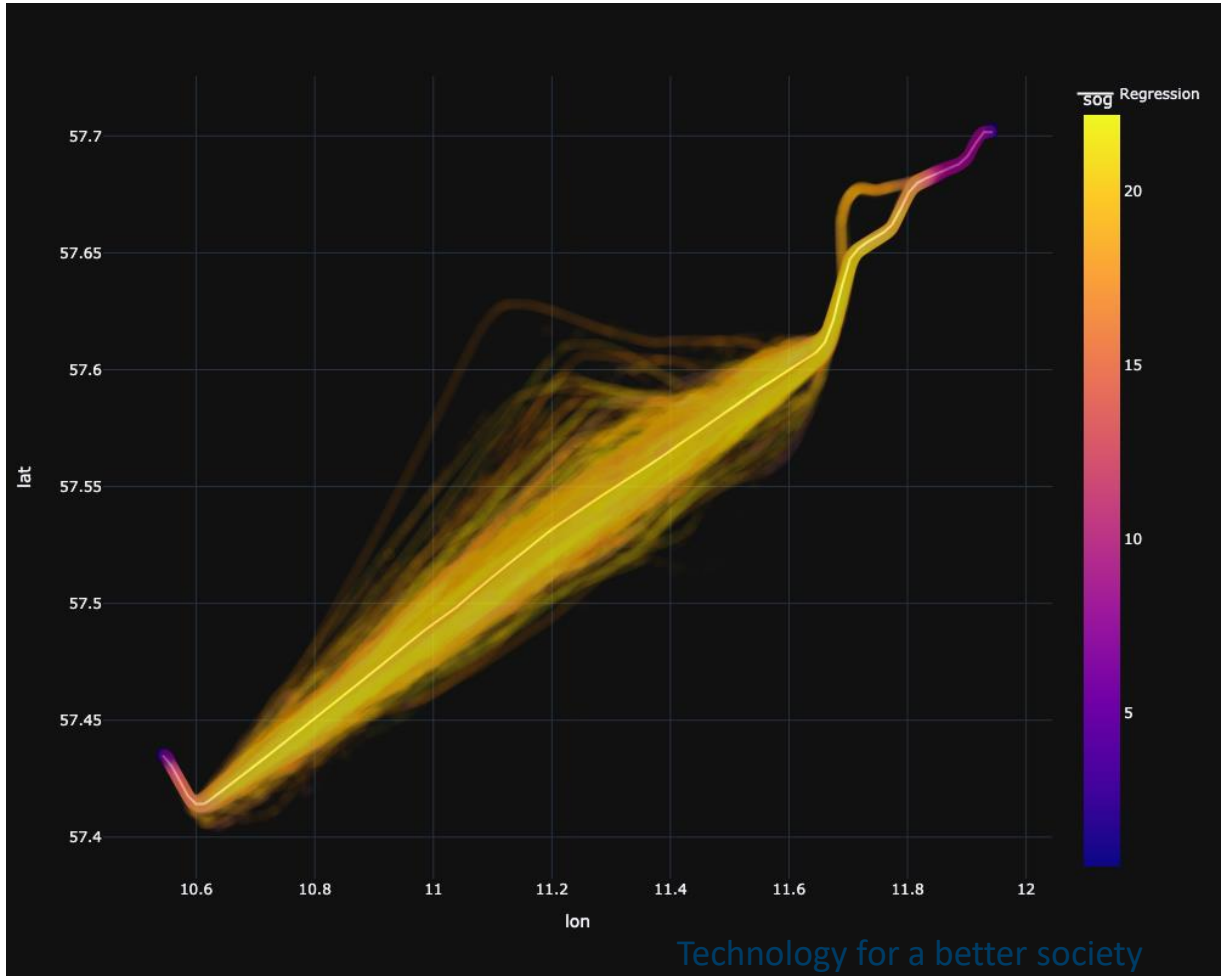

Route, Speed profile, Timetable, Weather
Operational Profile
Ship, Propulsor Model
Ship operational Simulation
Total Cost of Ownership
Analysis and Redesign
Machinery system configuration
Control strategy
Machinery Simulation

Design Lab – Work Process

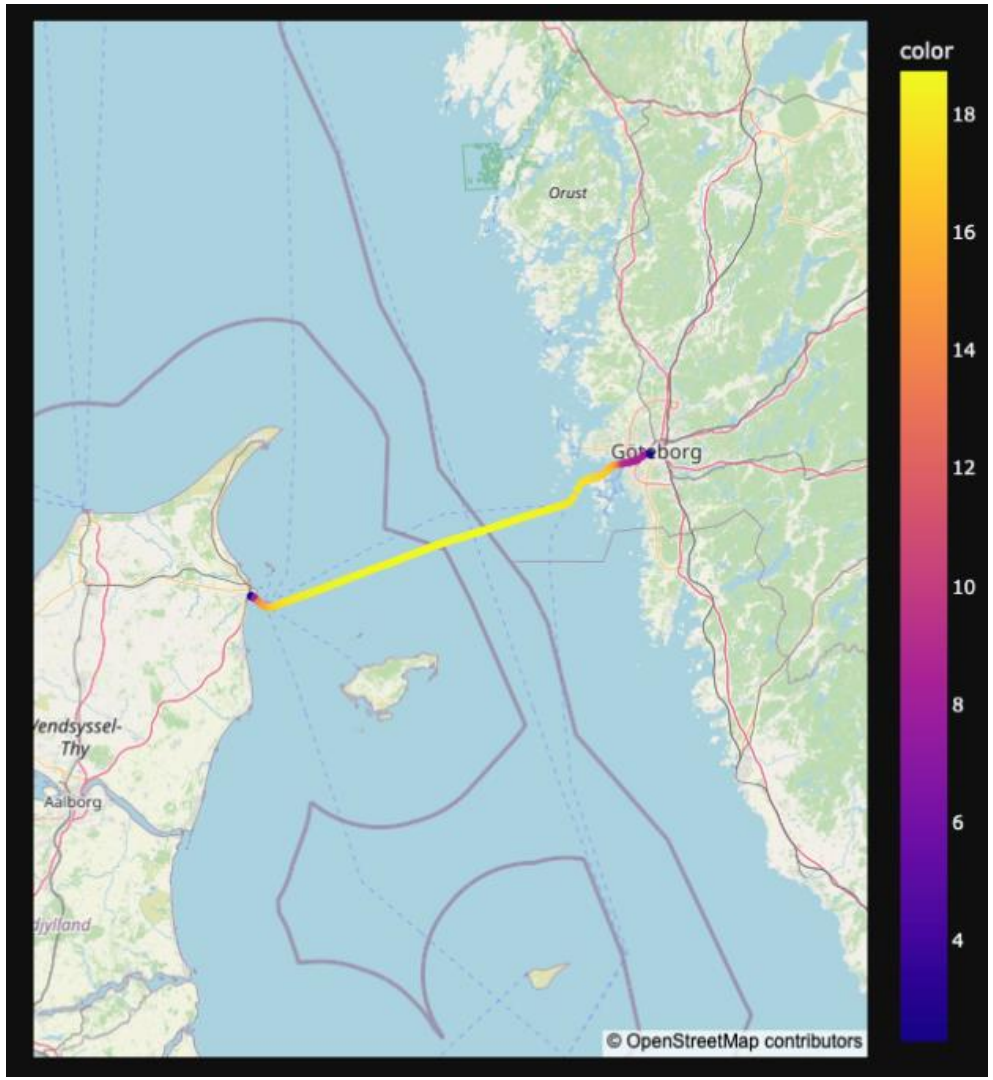


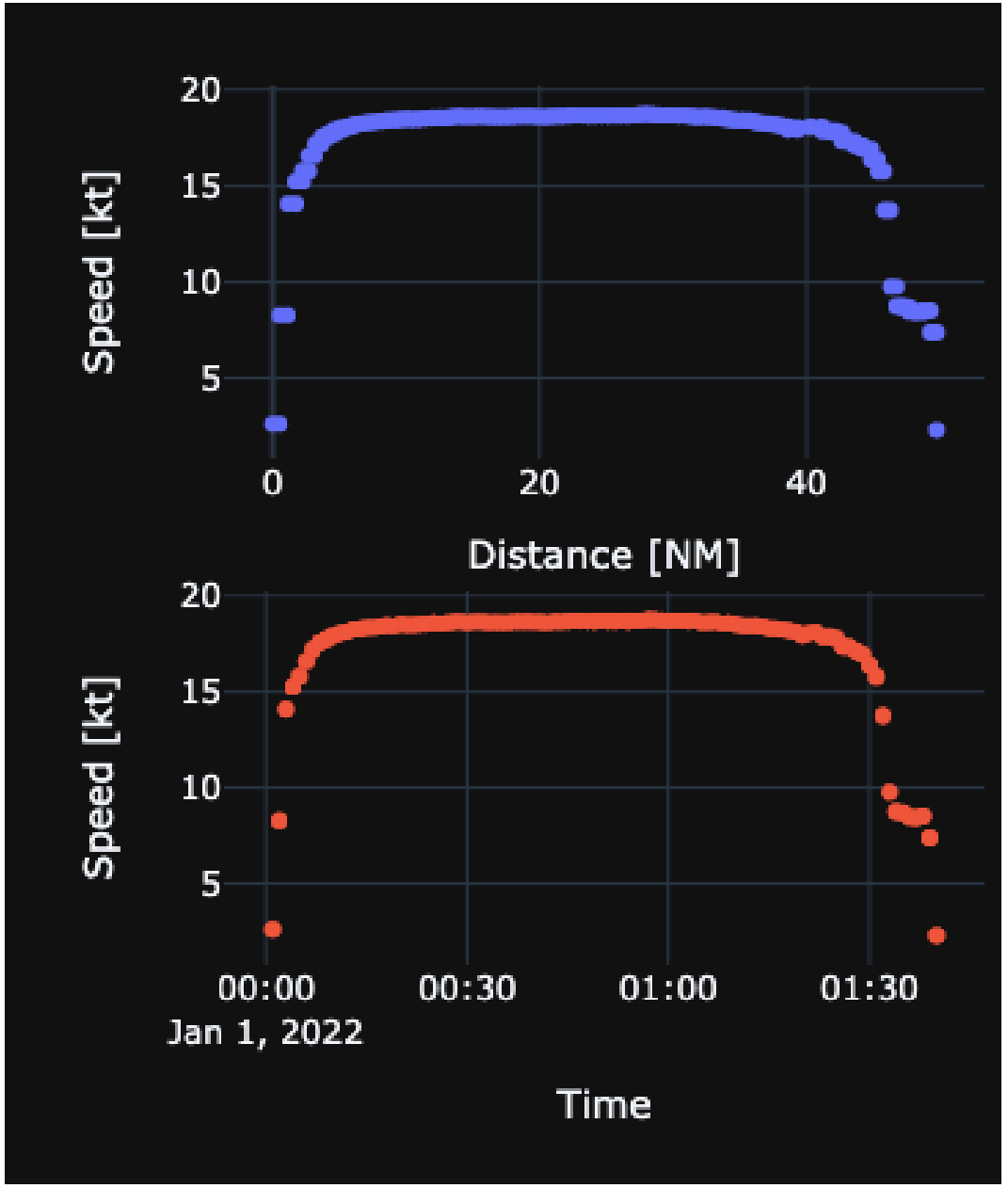
Operation Analysis

- Purpose
  - Finding the correct route and speed profile
- Method
  - AIS data collected for 2022 – 339002 points
  - Use a machine learning algorithm (Piece-wise spline line regression) to find the average route
  - Speed averaging for the nearest points on the average route

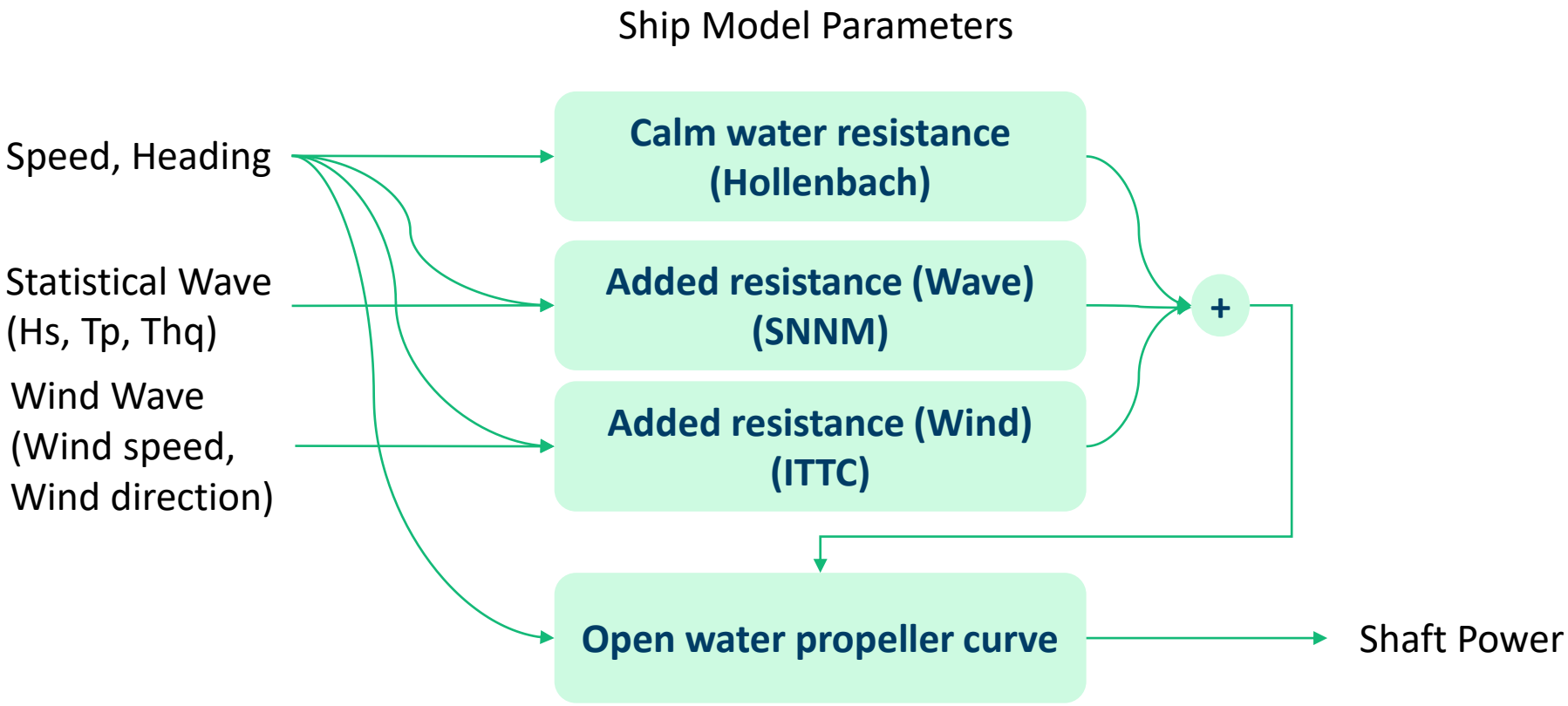


Speed Profile





Ship Modeling



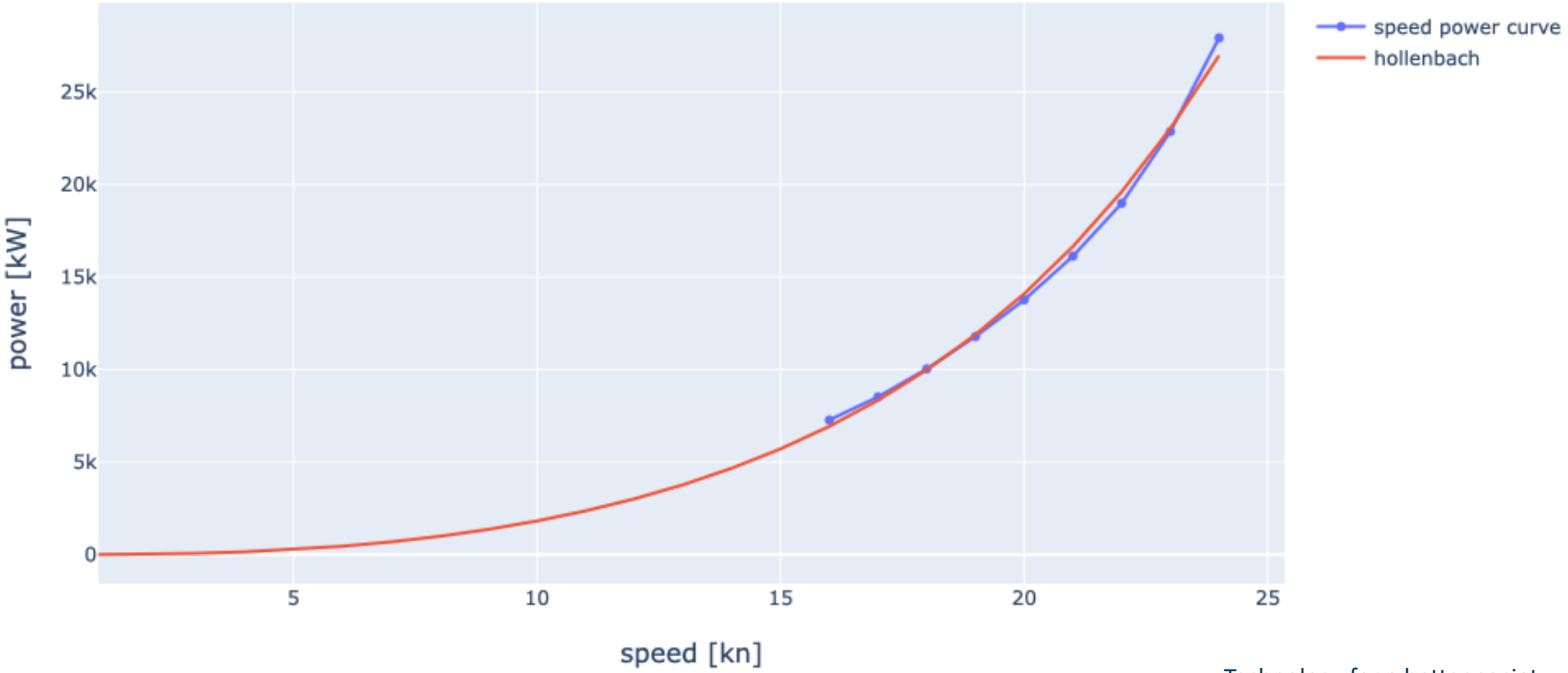
Parameters and validation of the ship model

Main dimensions	
Lpp [m]	201.9
Los [m]	212.0
Lwl[m]	212.0
B [m]	26.7
T [m]	6
C_B	0.58
Wetted surface area - Estimated [m2]	5982.6

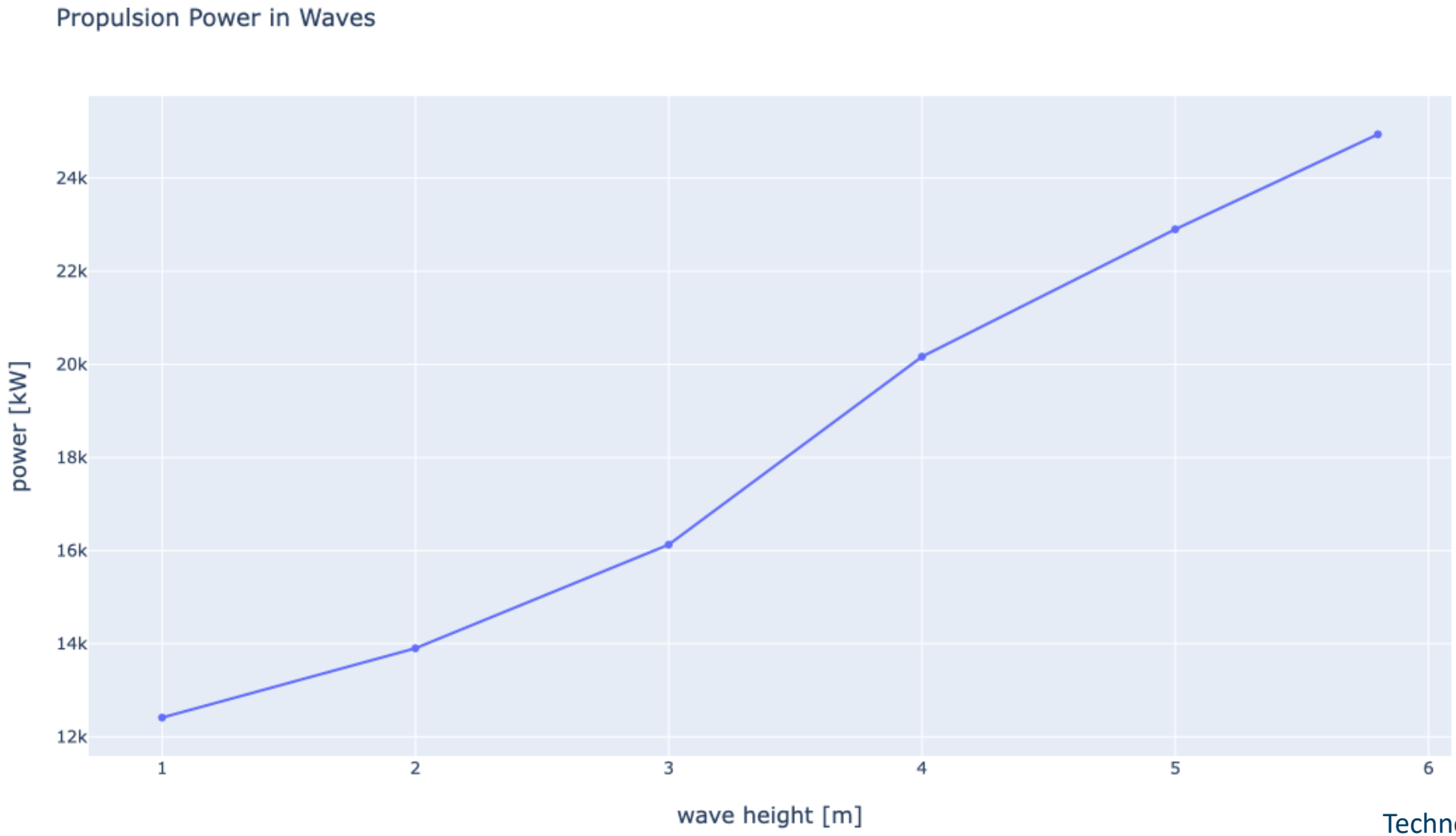
Propeller	
Diameter [m]	4.5
P/D	1.2

Speed-Power curve validation

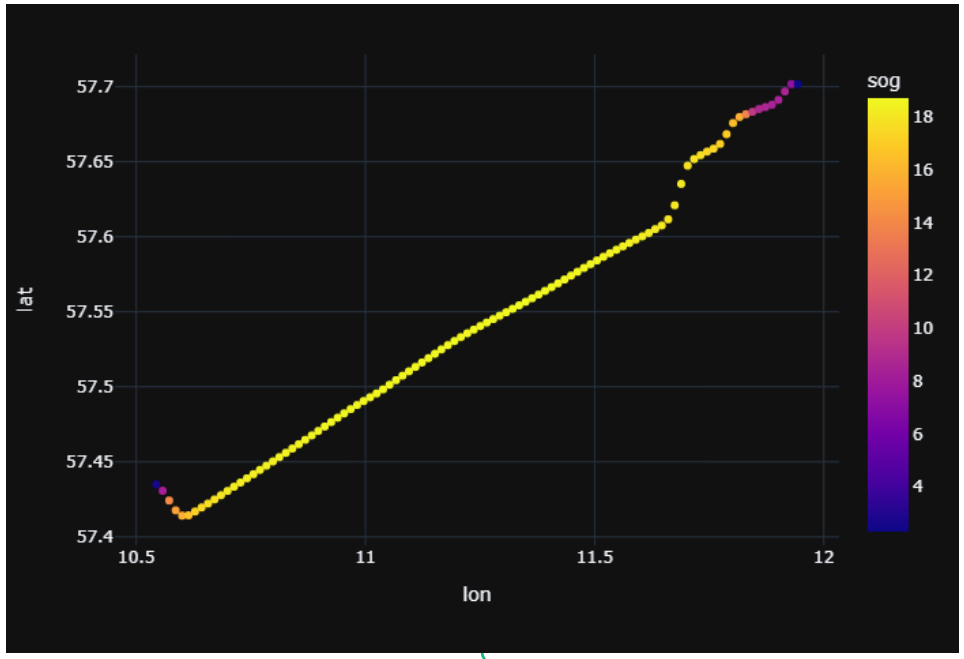
Correction factor: 1.105



Added resistance due to waves



Scenario Generation



Trip - 1

Weather data collection / processing (2021-2023)

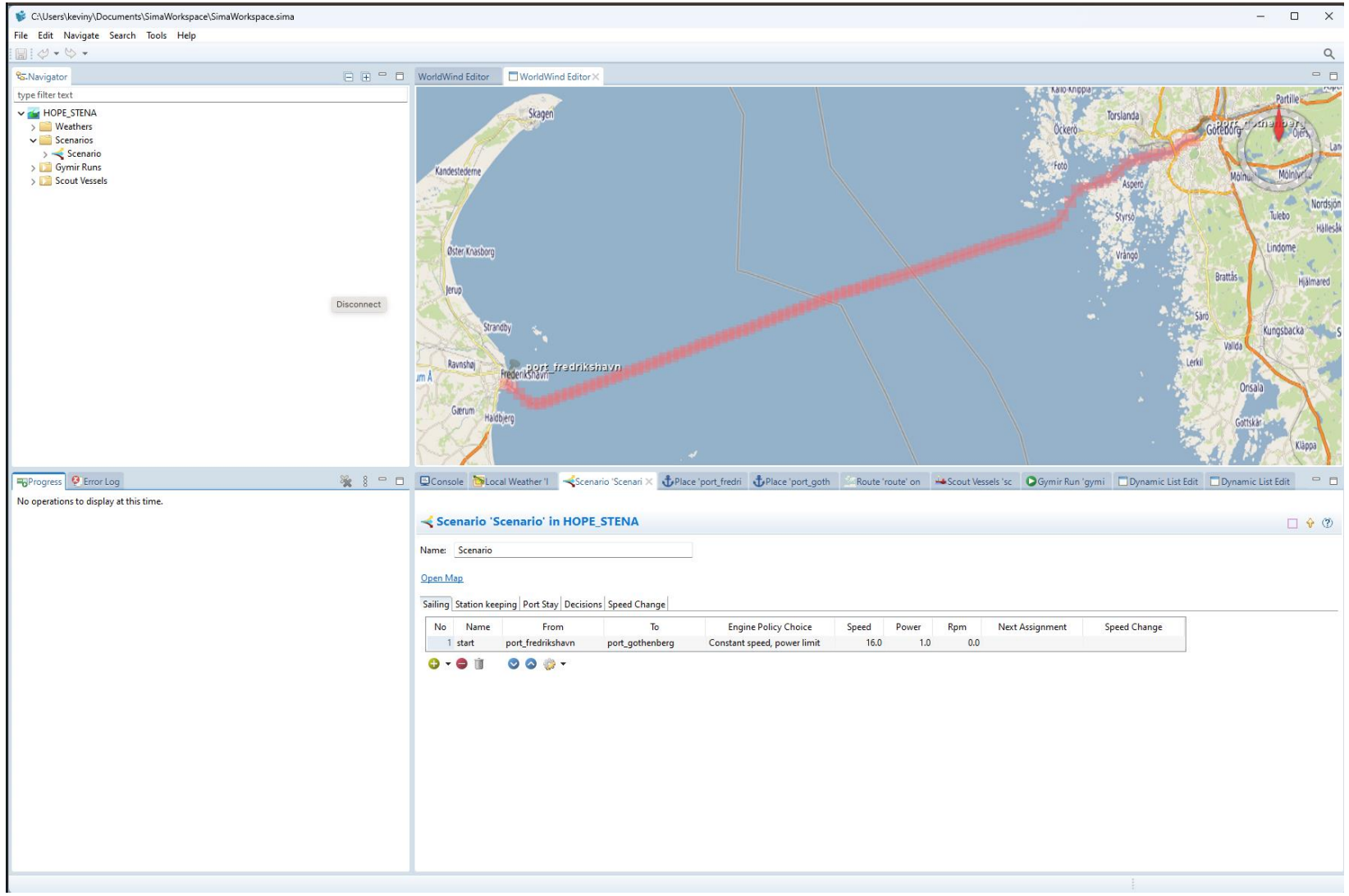
Parameters

- Waves
  - Significant wave height (Hs)
  - Peak period (Tp)
  - Mean wave direction (Thq)
- Wind
  - Mean wind speed
  - Mean wind direction
- Source: The Norwegian Meteorological Institute
  https://thredds.met.no/thredds/catalog/fou-hi/mywavewam4/catalog.html

Data meta-data

- 4km grid
- Hourly recording
- Europe and the Artic

GYMIR – Scout (Weather) Simulation



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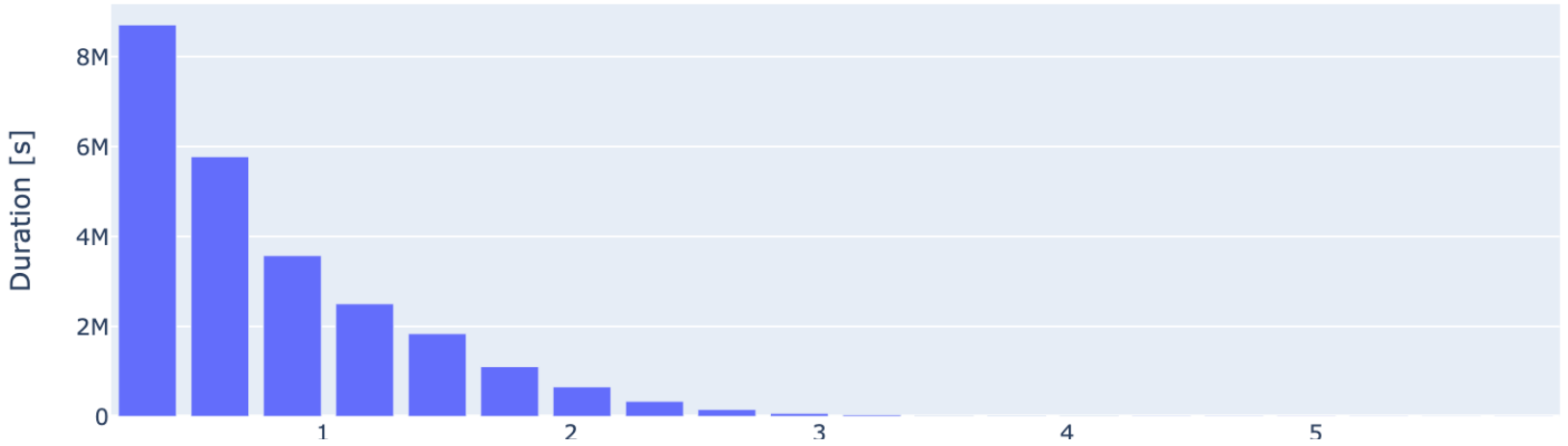
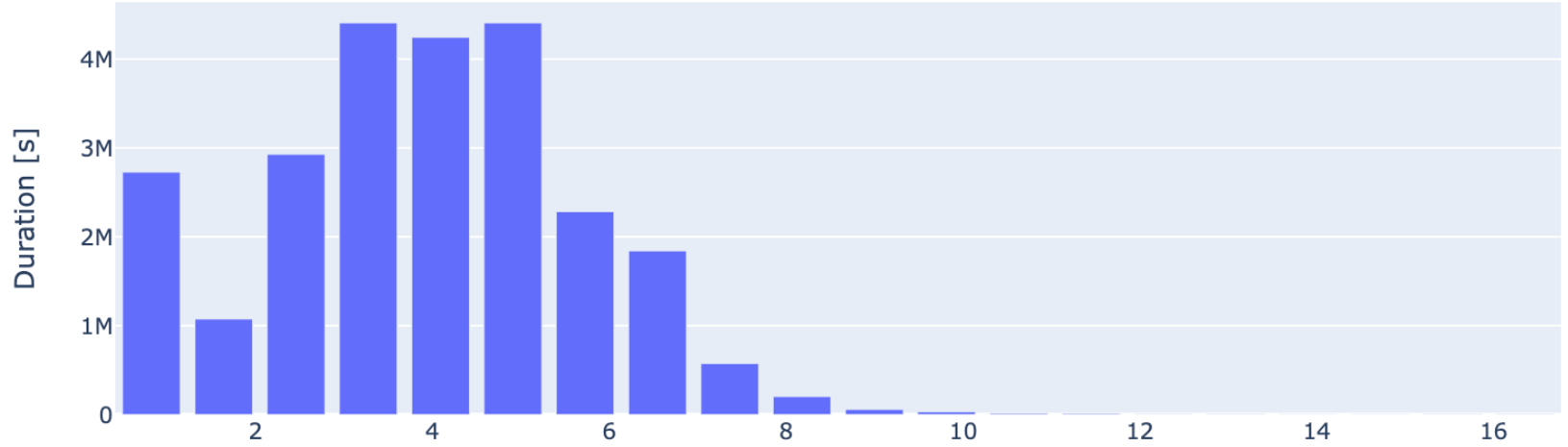
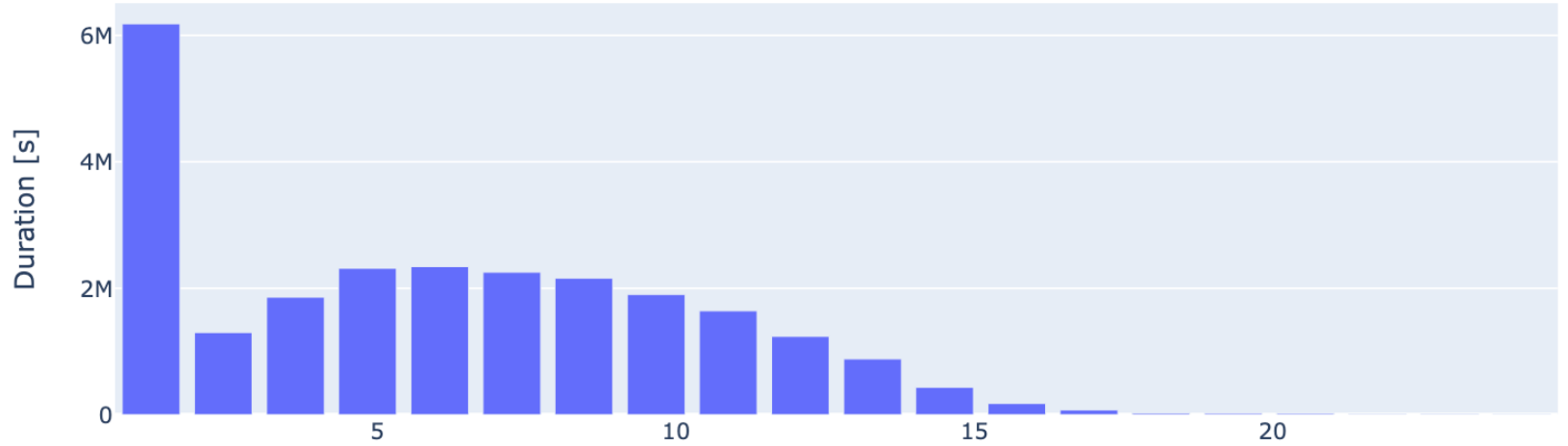
2021,
2022



Wave Height



Wave Period



Wind Speed

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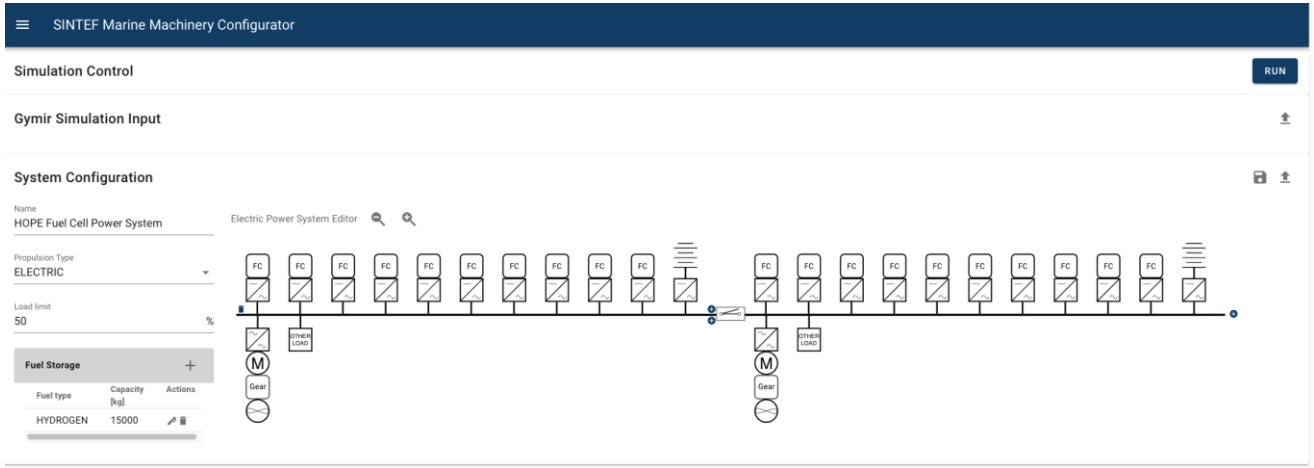
Performance Simulation

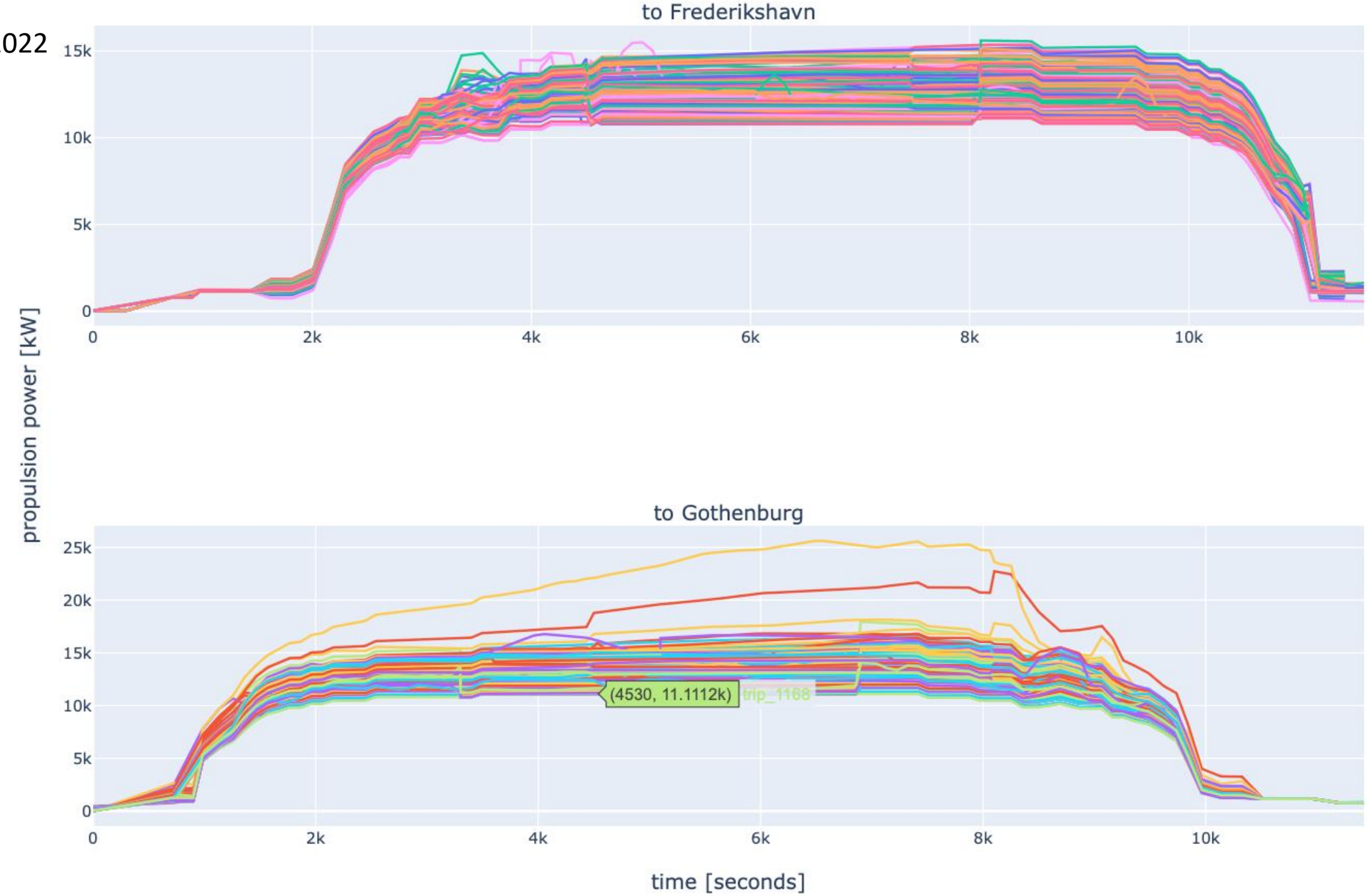
Speed / Weather Inputs

Ship Performance Simulation

Machinery Simulation



2022



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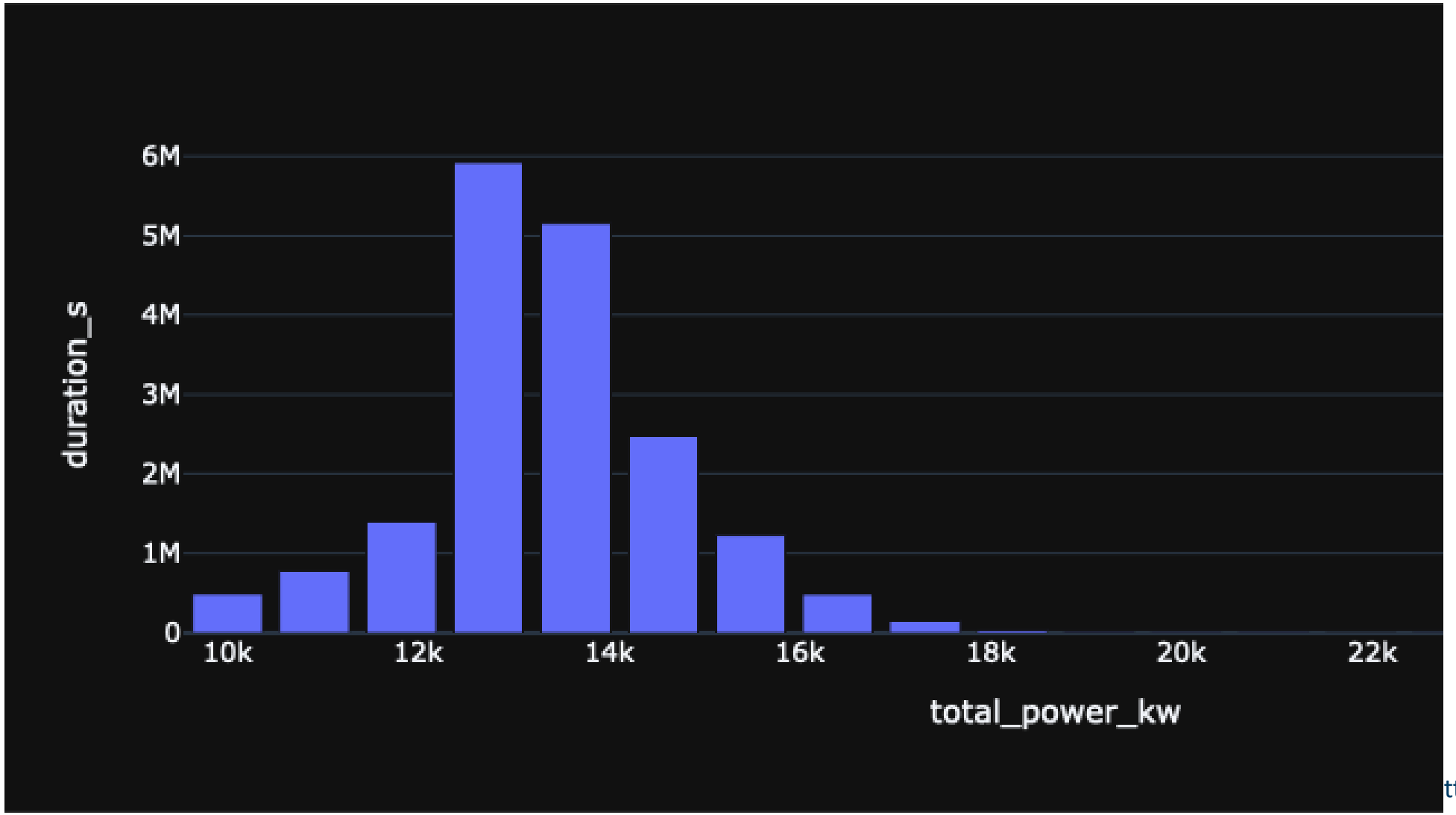
Power Profile Simulated – Histogram – 2021-2022



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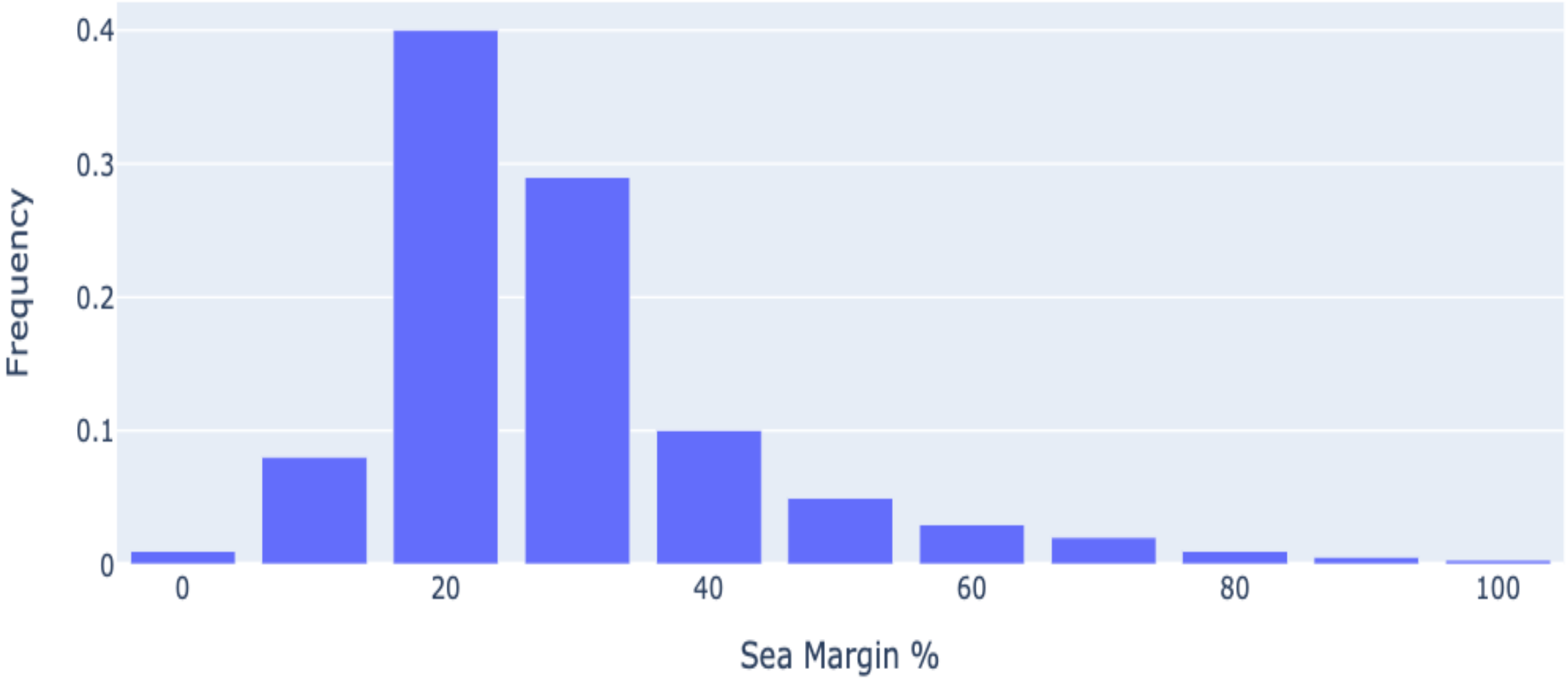
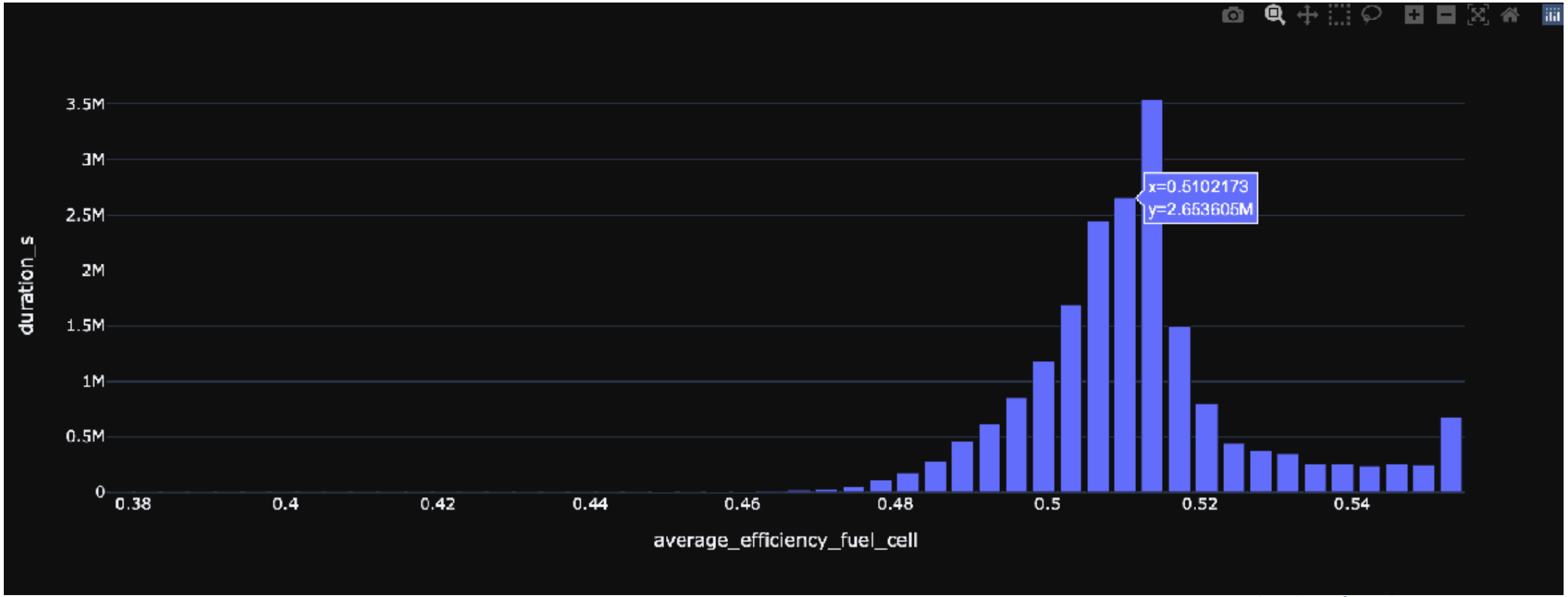
Power Profile - Recorded



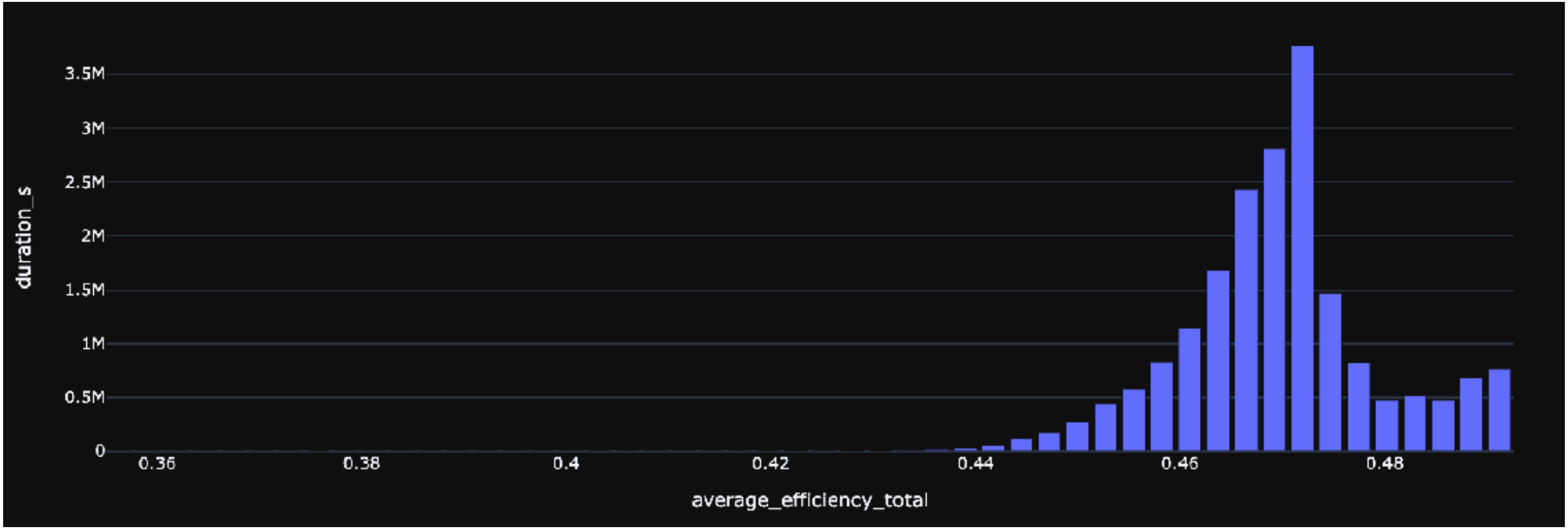
Machinery Calculation

- Rated Power: 25 MW
- Five fuel cell modules of 200kW are grouped. Treated as a single genset
- Maximum loading of fuel cell before turning on the new fuel cell group: 30%

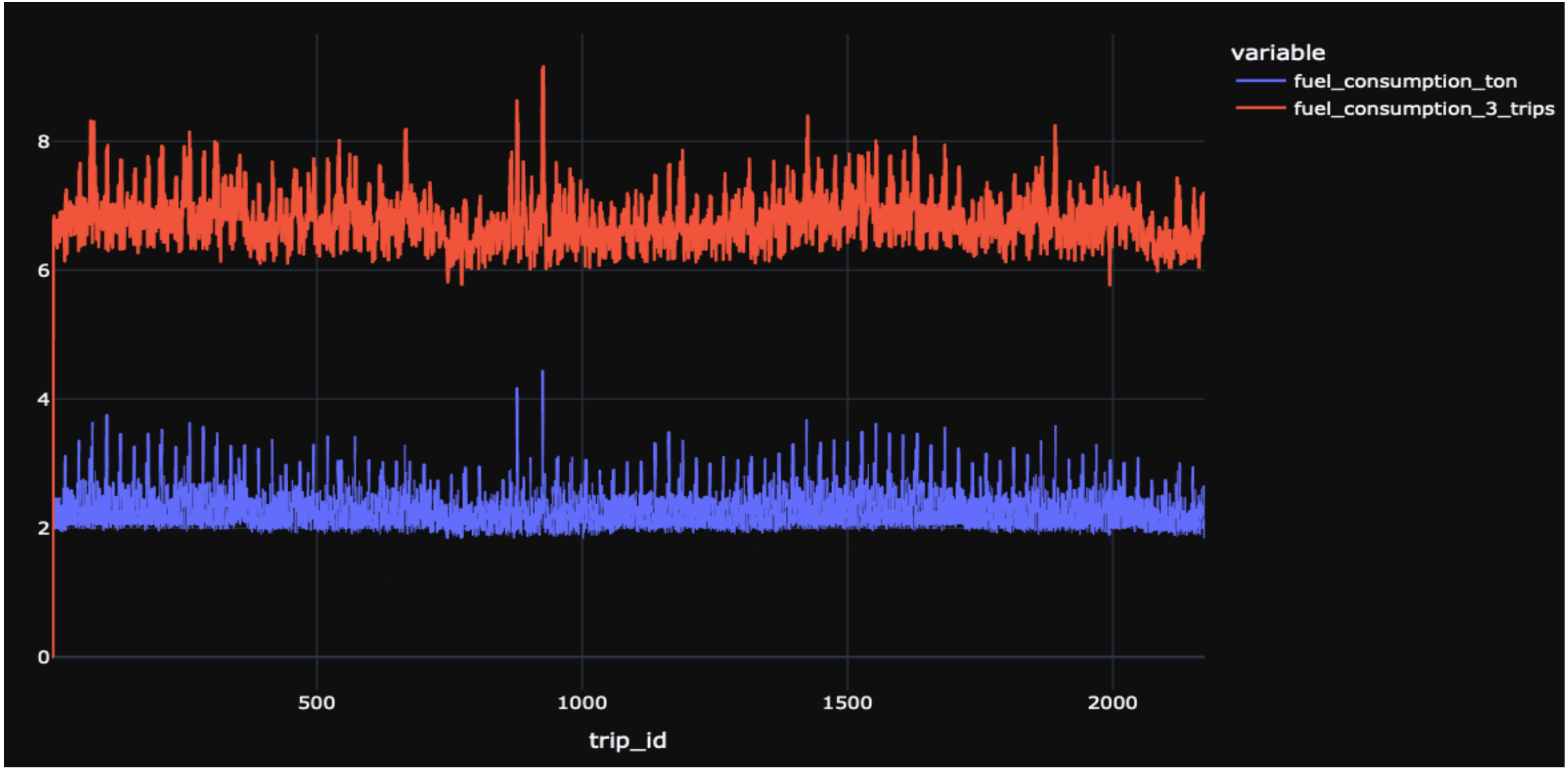
Efficiency of the fuel cells



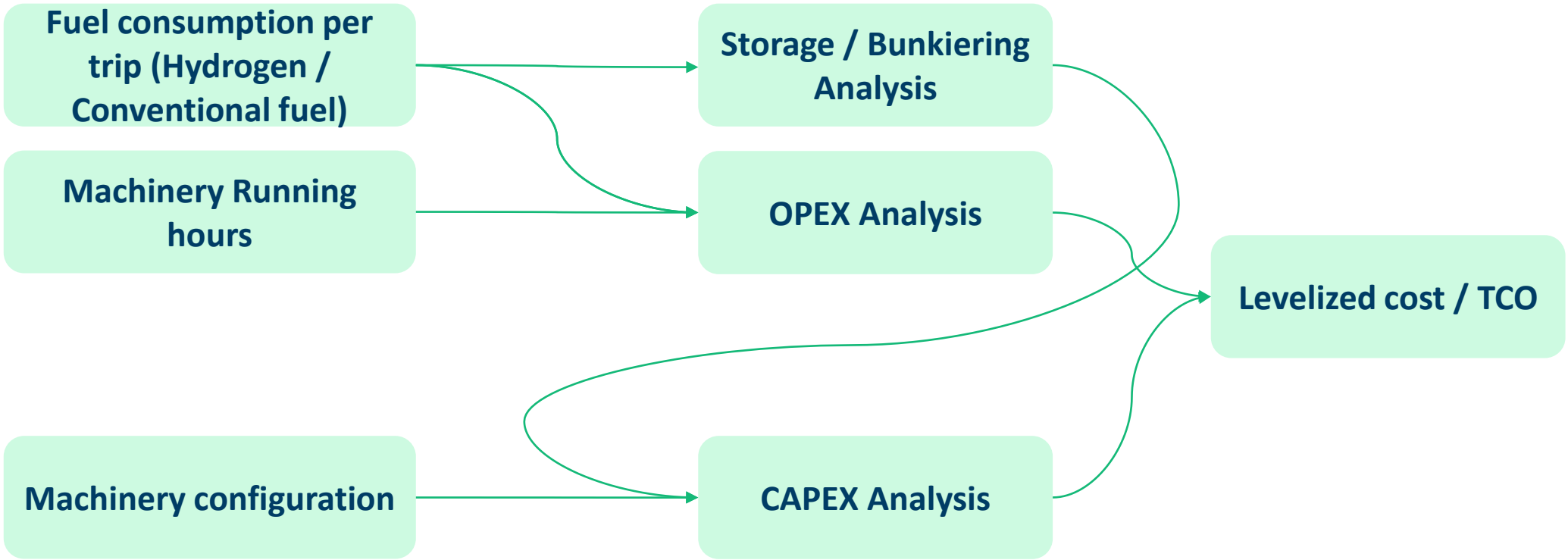
Efficiency of the system



Fuel consumption per trip



Analysis


Fuel consumption per trip (Hydrogen / Conventional fuel)
Machinery Running hours
Machinery configuration
Storage / Bunkiering Analysis
OPEX Analysis
CAPEX Analysis
Levelized cost / TCO

Cost estimation – Levelized cost of trip

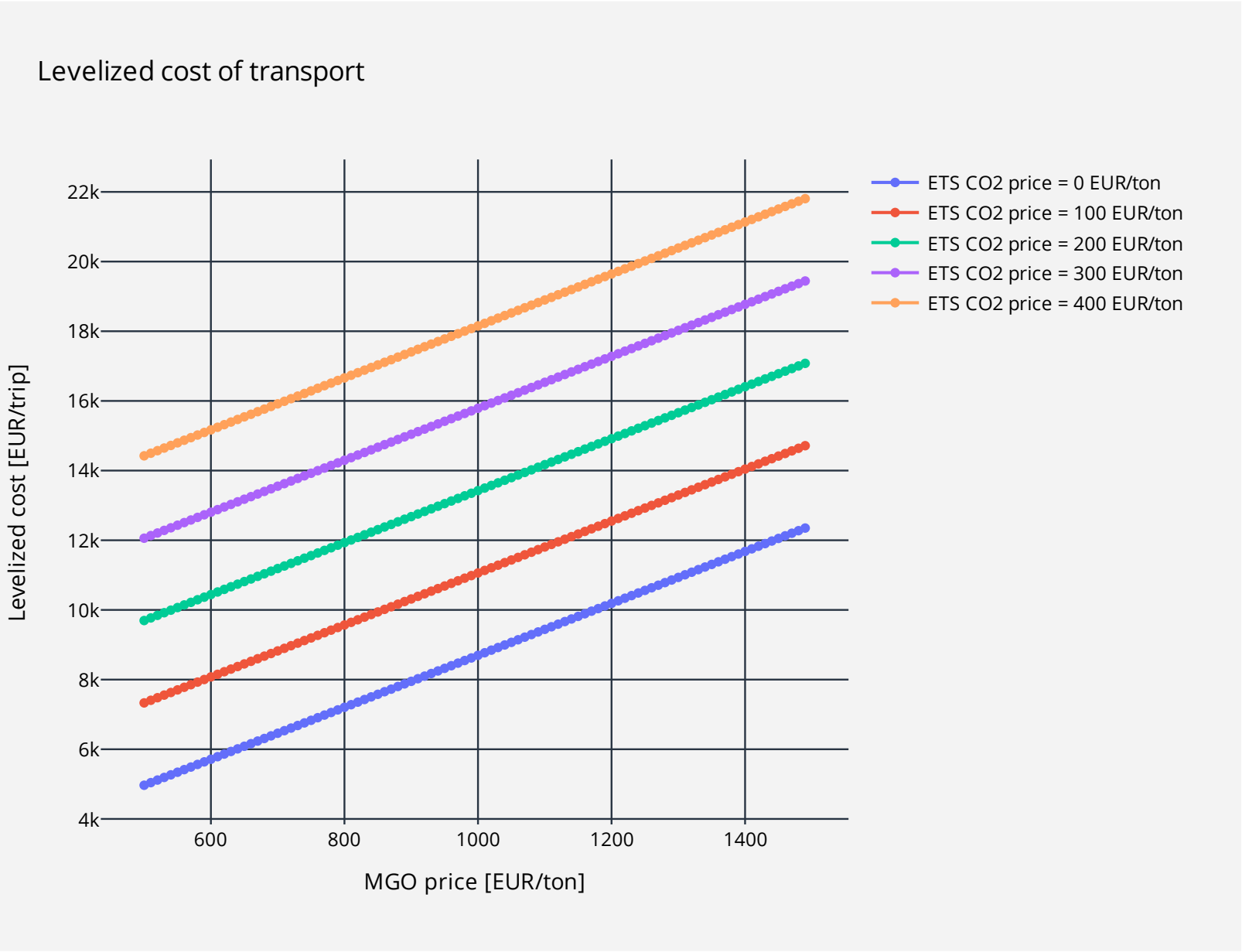
$$CAPEX = 1.2 \times (P_{rated} \cdot C_{power\ source} + M_{storage} \cdot C_{storage})$$

$$OPEX_{year} = m_{fuel} \cdot (C_{fuel} + c_{co2} C_{CO2}) \cdot n_{trips} + E_{power\ source} \cdot C_{maintenance}$$

$$LC = \frac{CAPEX + \sum OPEX_{year} \cdot (1+r)^{-i}}{\sum n_{trips} \cdot (1+r)^{-i}}$$

P_{rated}: Installed power [kW]
$C_{power\ source}$: Unit cost for the power plant [EUR/kW]
$M_{storage}$: Storage capacity [ton]
$C_{storage}$: Unit cost for storage [EUR/ton]
m_{fuel}: Fuel consumption per trip [ton]
C_{fuel}: Fuel unit cost [EUR/ton]
c_{co2}: CO2 conversion factor for fuel [kg/kg]
C_{CO2}: Cost of CO_2 emission [EUR/ton]
n_{trips}: Number of trips per year
$E_{power\ source}$: Energy production per year [kWh]
$C_{maintenance}$: Maintenance cost [EUR/kWh]
r: Discount rate

- Diesel Electric System
  - Diesel gensets cost: 400 EUR/kW
  - Maintenance cost: 0.012 EUR/kWh
  - Installation cost: 20% of diesel engine cost
  - 7.5% discounte rate



Fuel Cell Power Plant Sizing

- Unit price
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CAPEX [mEUR]	46.3	54.1	62.1
OPEX [mEUR/year]	18.308	17.497	17.008
Number of trips per year	1353	1353	1353
Energy production [kWh/trip]	38 458	38458	38458
Fuel consumption [ton/trip]	2.36	2.241	2.168
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Fuel Cell Power Plant Sizing

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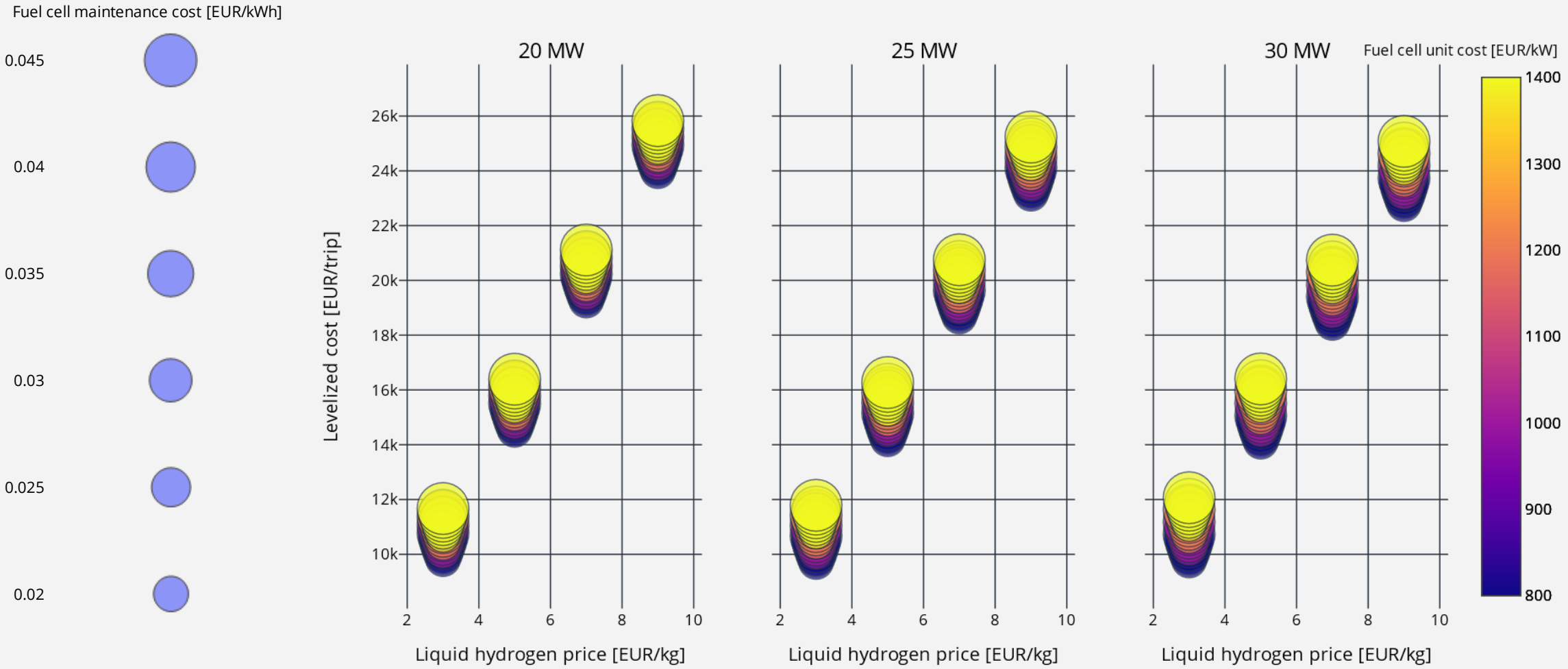
  - Maintenance cost: 0.044 EUR/kWh

Capacity	20MW	25MW	30MW
CAPEX [mEUR]	46.3	54.1	62.1
OPEX [mEUR/year]	31.081	29.622	28.741
Number of trips per year	1353	1353	1353
Energy production [kWh/trip]	38 458	38 458	38 458
Fuel consumption [ton/trip]	2.36	2.241	2.168
Levelized cost [EUR/trip]	25 833	25 233	25 076


Fuel cell maintenance cost [EUR/kWh]
0.045
0.04
0.035
0.03
0.025
0.02
20 MW
25 MW
30 MW
Fuel cell unit cost [EUR/kW]
1400
1300
1200
1100
1000
900
800
Levelized cost [EUR/trip]
26k
24k
22k
20k
18k
16k
14k
12k
10k
2
4
6
8
10
Liquid hydrogen price [EUR/kg]
Liquid hydrogen price [EUR/kg]
Liquid hydrogen price [EUR/kg]

Conclusion

- Design Lab provides a framework for a fast iterative method to evaluate the design of a hydrogen fuel cell
- AIS data processed by a machine learning method can provide a representative operation profile.
- Ship performance simulation with weather data history by semi-empirical method can provide a statistically valid power requirements for the ship.
- Machinery simulation by FEEMS can give a system efficiency and fuel consumption on various loads.
- Cost of hydrogen fueled propulsion will be significantly higher than fossil-based solution but can be equivalent with further development and carbon tax in place.

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Rasmus Parsmo and Karl Jivén
IVL

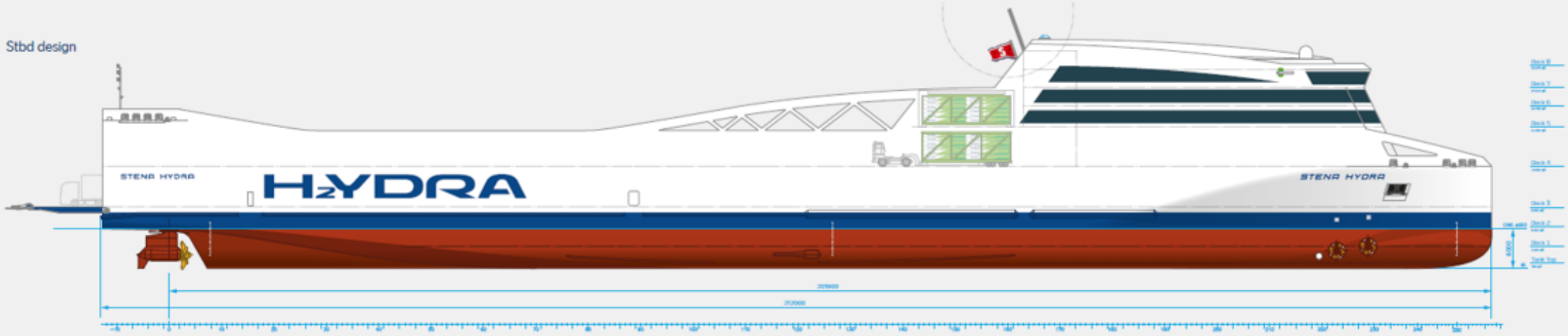
Mauricio Andres Latapi Agudelo
University of Iceland

From the HOPE Project

Nordic Energy Research

HOPE - Hydrogen fuel cells solutions in shipping – a Nordic perspective

Cost for marine hydrogen fuel cell solutions and assessment of emission impacts of potential uptake in Nordic fleet



Conference: The Nordic Maritime Transport and Energy Research Programme

4th of May 2023 - Rasmus Parsmo and Karl Jivén

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Cost for marine hydrogen fuel cell solutions

Karl Jivén, IVL

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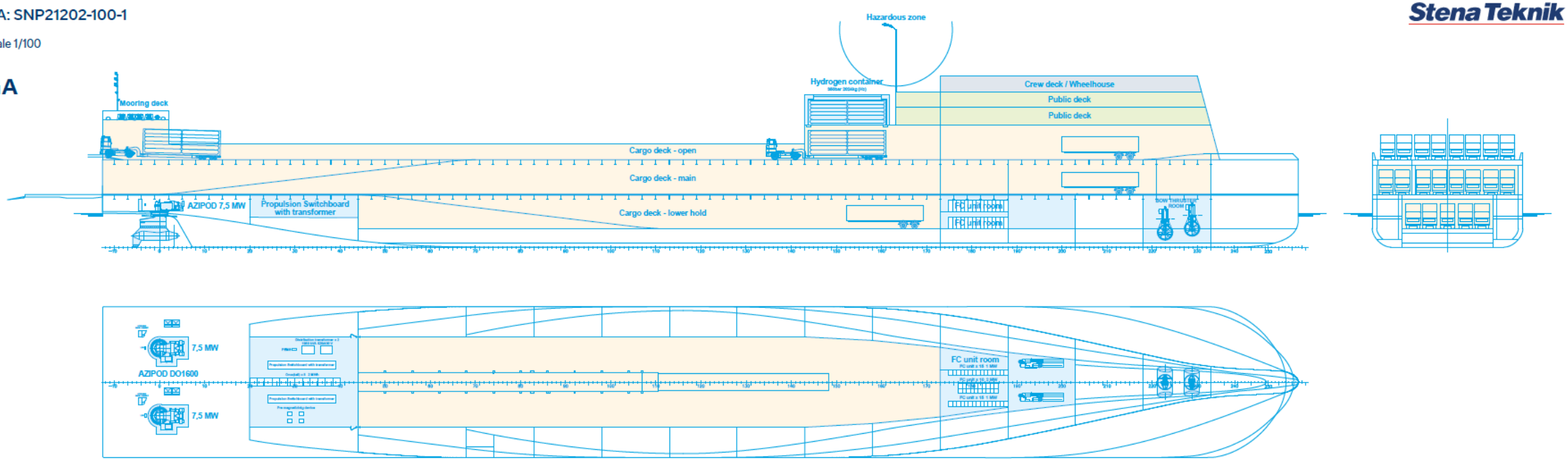
STENA HYDRA - COMPRESSED HYDROGEN CONCEPT

GA: SNP21202-100-1

Scale 1/100

GA



PRINCIPAL PARTICULARS

LENGTH O.A.	212.000 M
LENGTH P.P	201.900 M
BEAM	26.700 M
DESIGN DRAFT	6.000 M
SCANTLING DRAUGHT	6.300 M
PROPULSION POWER	2 x 7,5 MW
NET H2 STORAGE, approx	10 tons
OPERATIONAL RANGE	150 NM
SPEED	22 kn

CAPACITIES

DEADWEIGHT (metric tons)	Abt 6000
PAYLOAD (metric tons)	Abt 4500
LANE METERS	Abt 2500 M
PASSENGER FACILITIES	DAY FERRY
CREW CABINS	50 SINGLE

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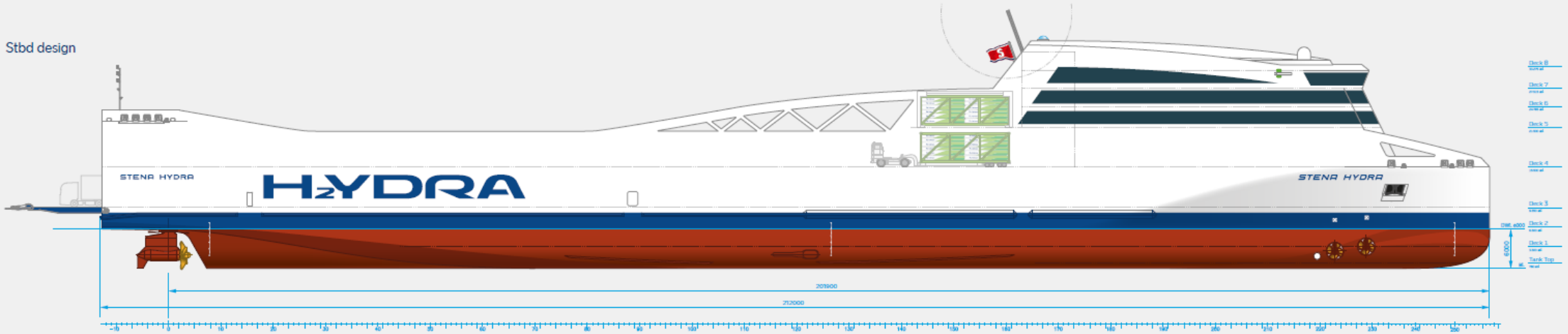
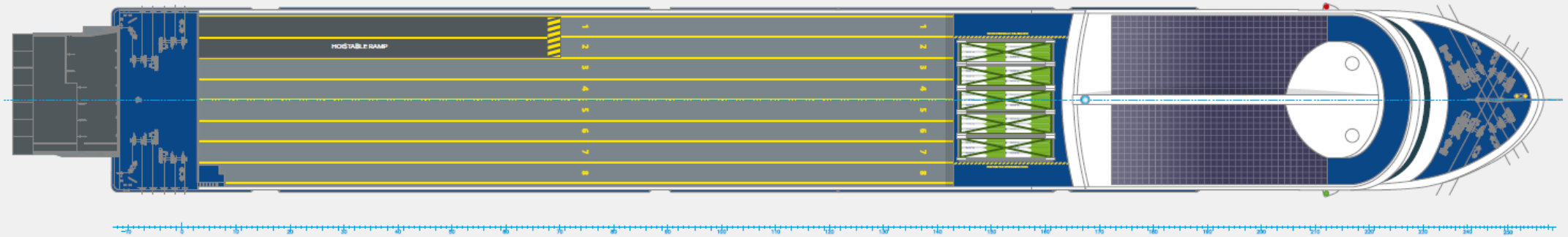
PROPOSAL

Stbd design



Top view



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Preliminary data

	Hydrogen	Electric	Ammonia	Methanol	LBG	MGO	
Fuel cost	11 621 597	5 686 401	17 625 224	13 112 486	11 239 274	5 658 662	EUR/y
Ship capital cost	10 955 971	10 955 971	10 955 971	10 955 971	10 955 971	10 955 971	EUR/y
Ship cost	3 000 000	3 000 000	3 000 000	3 000 000	3 000 000	3 000 000	EUR/y
Main engine investment cost	263 507	-	1 601 172	1 212 316	1 212 316	1 097 946	EUR/y
Propulsion maintanance	24 000	-	145 833	110 417	110 417	100 000	EUR/y
Fuel Cell Investment cost	4 940 758	-	-	-	-	-	EUR/y
Fuel cell replacement & maintance	2 289 482	-	-	-	-	-	EUR/y
Battery investment cost	56 951	1 708 530	-	-	-	-	EUR/y
Battery replacement cost	85 427	2 562 795	-	-	-	-	EUR/y
Battery O&M cost	4 000	120 000	-	-	-	-	EUR/y
Hydrogen swap container cost	311 497	-	-	-	-	-	EUR/y
Hydrogen swap container maintanance	66 000	-	-	-	-	-	EUR/y
Investment cost	439 178	439 178	263 507	263 507	263 507	263 507	EUR/y
Range extension / auxiliary O&M	80 000	80 000	48 000	48 000	48 000	48 000	EUR/y
Hotel consumtion Fuel / shore electricity	1 162 160	292 558	1 986 386	1 311 249	1 986 386	565 866	EUR/y
Manning cost	3 325 000	4 750 000	4 025 000	4 025 000	4 025 000	4 025 000	EUR/y
Capital	**16 967 862**	**13 103 680**	**12 820 650**	**12 431 794**	**12 431 794**	**12 317 424**	**EUR/y**
Operational / maintanance / replacement	**21 657 665**	**16 491 754**	**26 830 443**	**21 607 151**	**20 409 076**	**13 397 528**	**EUR/y**
Annual total costs	**38 625 528**	**29 595 433**	**39 651 093**	**34 038 945**	**32 840 870**	**25 714 953**	**EUR/y**
ETS	369 508	-	373 657	239 597	381 145	3 194 626	EUR/y
Annual total costs including ETS	**38 995 036**	**29 595 433**	**40 024 750**	**34 278 542**	**33 222 014**	**28 909 578**	**EUR/y**

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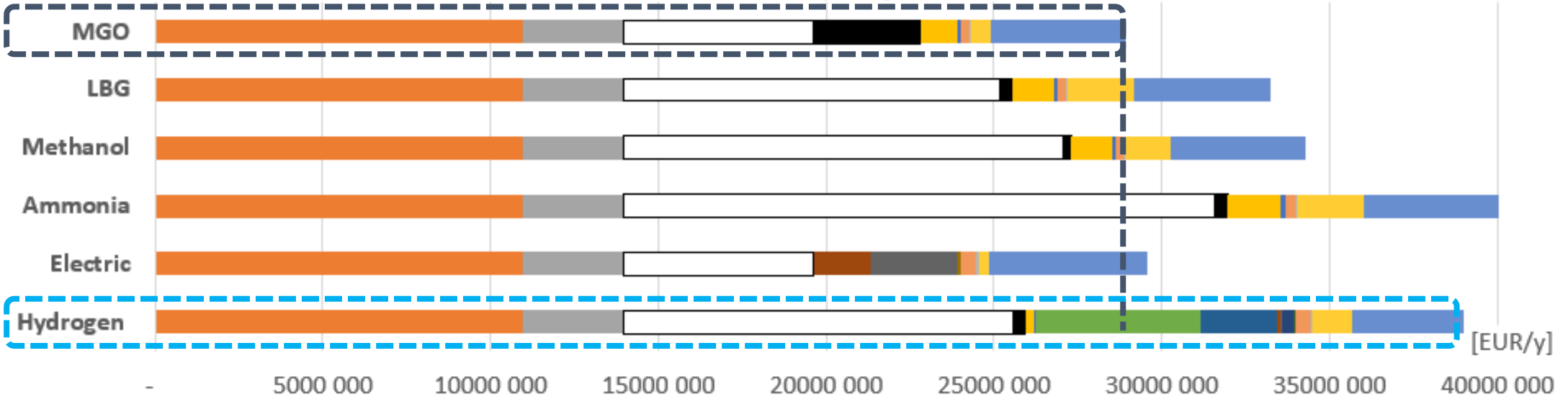
Preliminary data

Cost distribution - RoPax - propulsion alternatives



+ 35 %

- Ship capital cost
- Ship cost
- Fuel cost
- ETS
- Main engine investment cost
- Propulsion maintanance
- Fuel Cell Investment cost
- Fuel cell replacement & maintance
- Battery investment cost
- Battery replacement cost
- Battery O&M cost
- Hydrogen swap container cost
- Hydrogen swap container maintanance
- Investment cost
- Range extension / auxiliary O&M
- Hotel consumtion Fuel / shore electricity
- Manning cost

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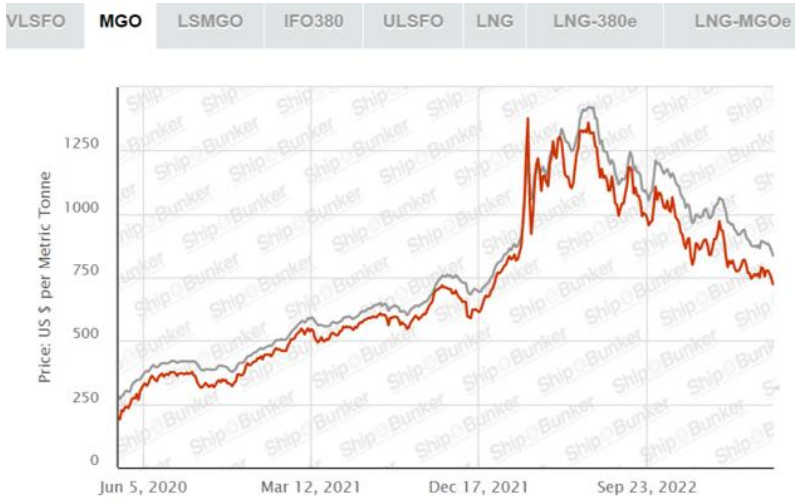
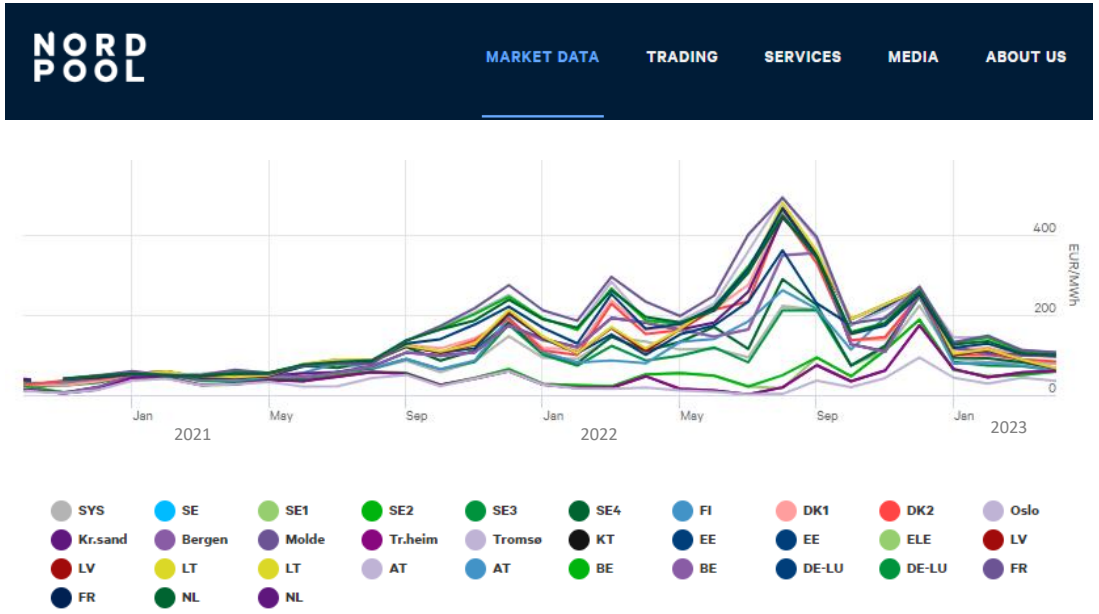


https://shipandbunker.com



https://www.nordpoolgroup.com

Energy prices fluctuate greatly, and future cost levels are difficult to predict

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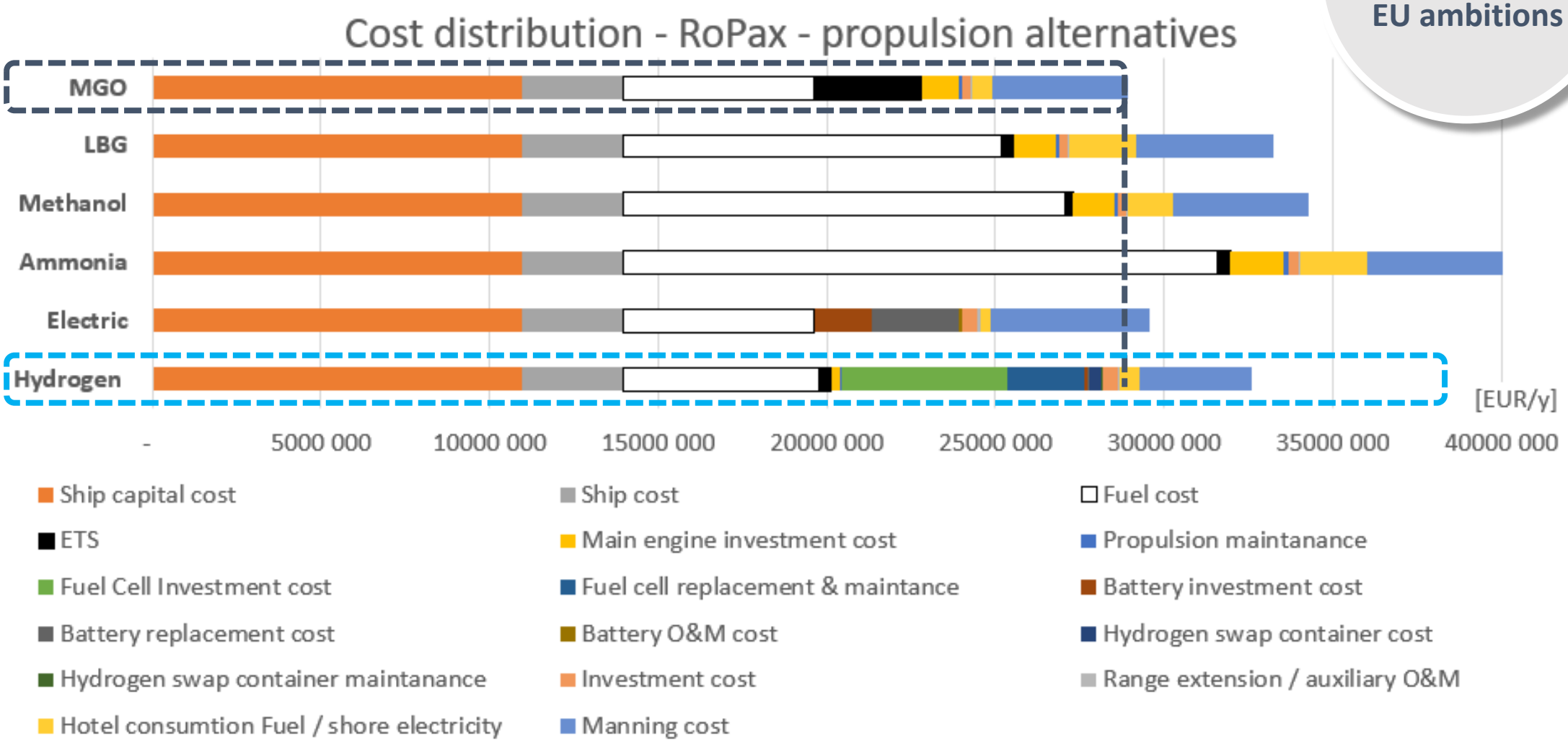
Hydrogen costs more in line with EU ambitions

Preliminary data



+ 13 %

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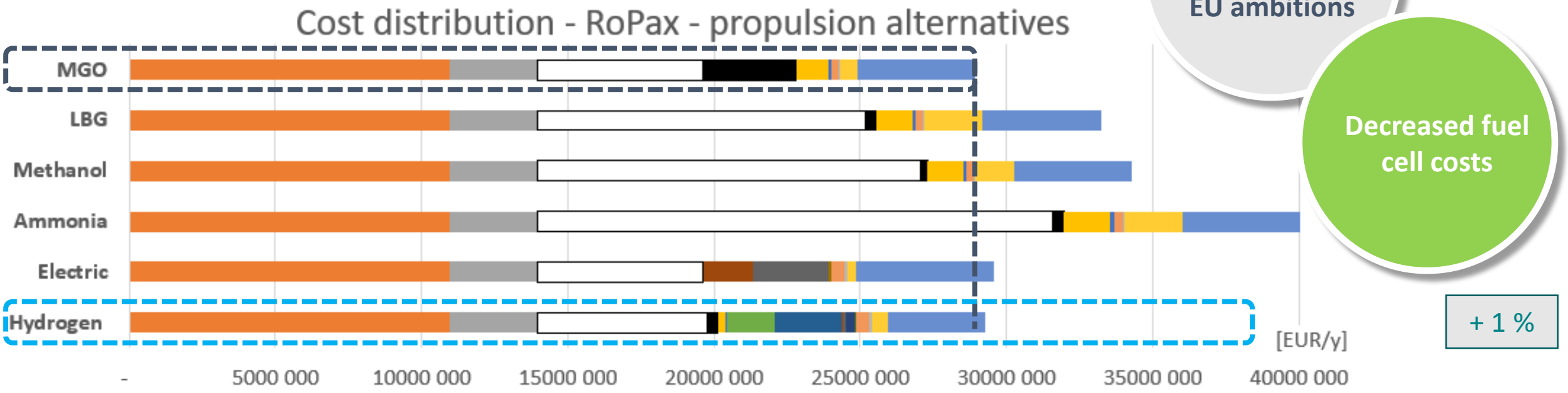
Preliminary data

Hydrogen costs more in line with EU ambitions

Decreased fuel cell costs



+ 1 %

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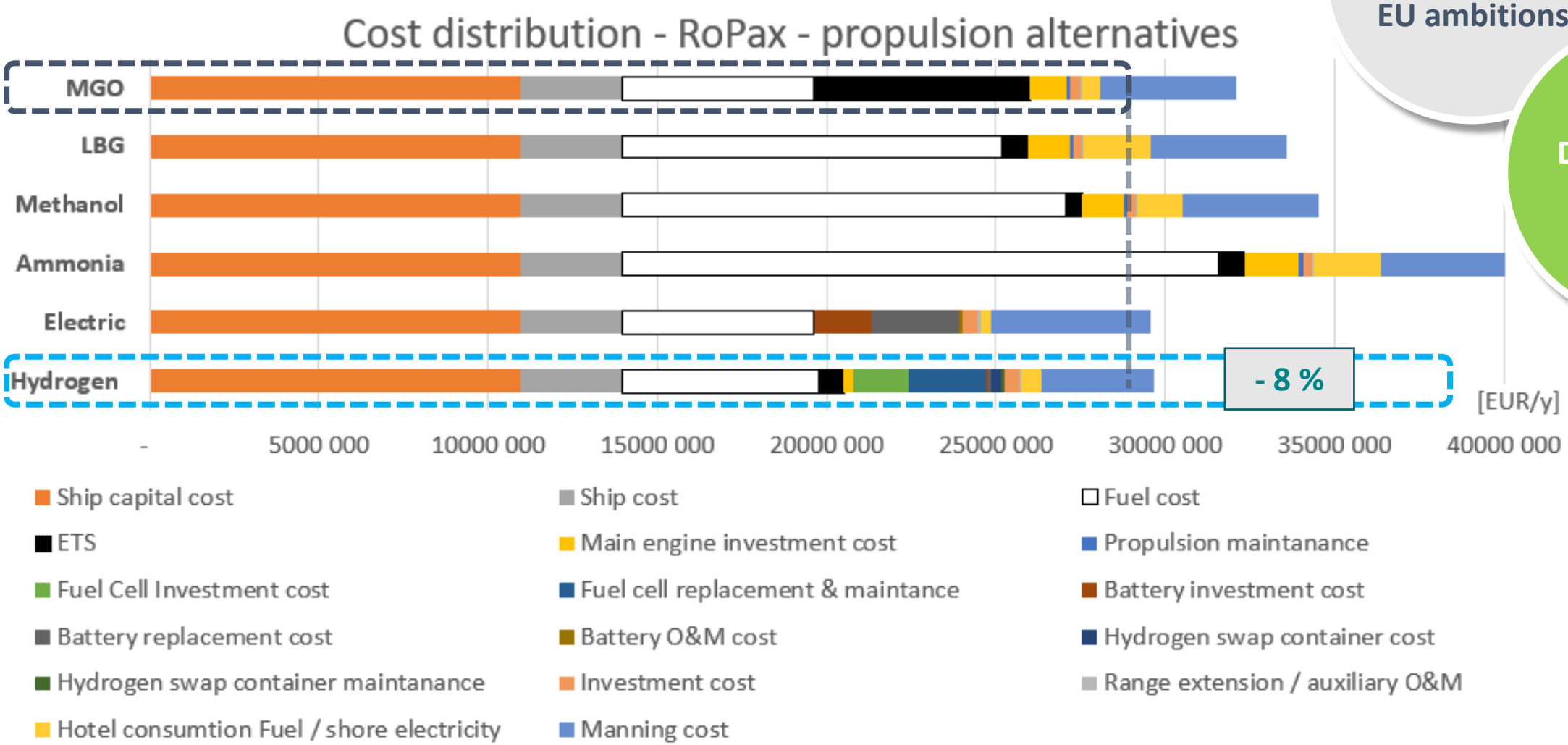
Preliminary data

Hydrogen costs more in line with EU ambitions

Decreased fuel cell costs

Increased ETS (100 EUR/ton => 200 EUR/ton



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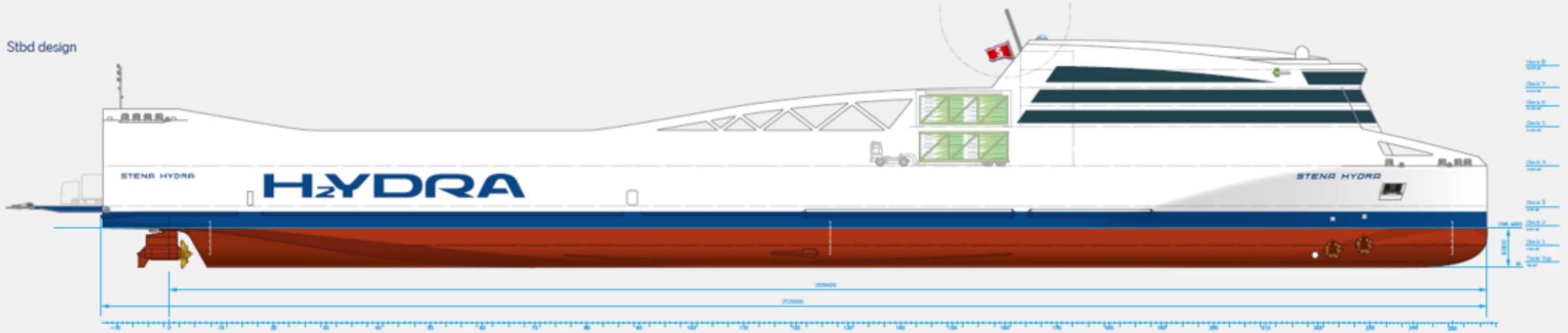
Is fuel cell RoPax feasible?



- Seems technically and economically feasible with right conditions
- Increased operational range compared to battery-electric vessels
- Business case will to a large extend depend on hydrogen price

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Assessment of emission impacts of potential uptake in Nordic fleet

Rasmus Parsmo (PhD), IVL / Chalmers University of Technology

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BACKGROUND: NORDIC FLEET

Port call statics for ships (Marine traffic)

- Larger than 5 000 GT
- 2018
- Excluding fishing and services vessels

Distances between ports (Searoutes)

Average fuel consumption per ship

- $MRV data\ (CO\_2/NM)\ \ for\ each\ ship$
- 2018
- Like a 1/3 of the all travels was default values for ship segments. Many Norwegian ferries (excluded from MRV)

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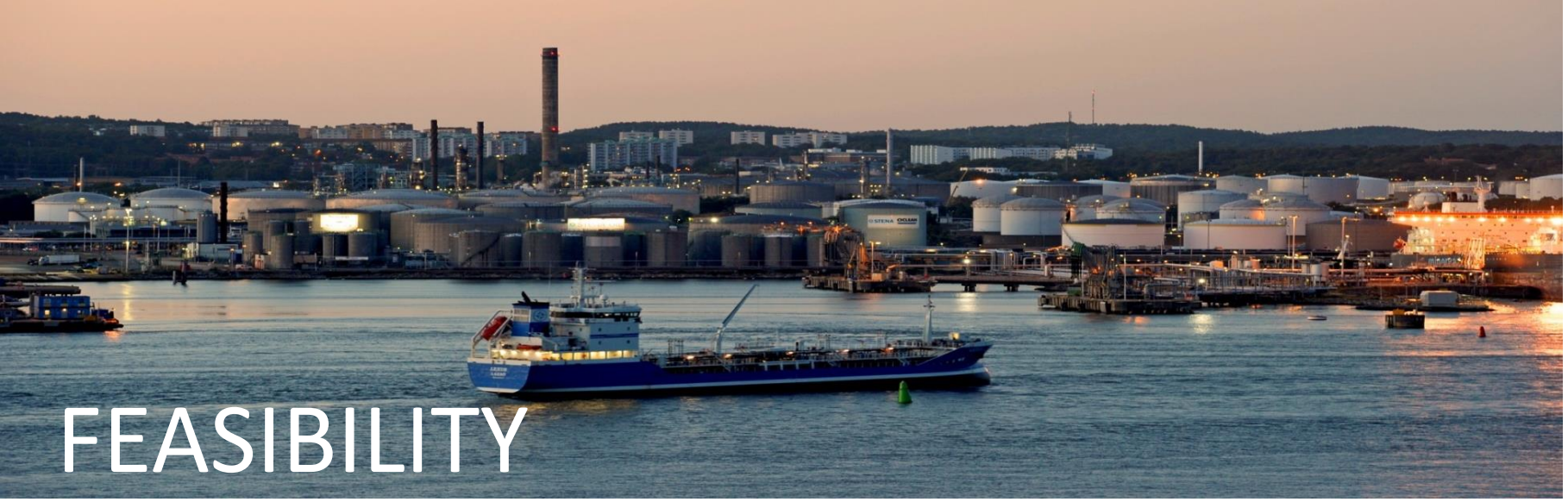

FEASIBILITY

- 100 – 500 NM
- For different ship segments
- Other ways for example:

  DNV: A weighted measure for MWh per voyages.

  Looking at shipping lines with high frequency in specific geographical location.

  Stolz et al. assesses feasibility for bulk ships. They used attainment rate.

NORDIC FLEET EMISSIONS

Inlcluding voyages up to	CO2e WTW reduction Final [Mtonnes]	PM [ktonnes]	NOX [ktonnes]	Final Energy at sea [10^6*MWh]
100 NM	1.97	2.99	43.9	2.82
200 NM	3.35	5.17	74.6	4.88
300 NM	4.18	6.49	93.2	6.06
400 NM	5.09	8.01	114	7.42
500 NM	5.65	8.92	127	8.23
Nordic fleet all voyages 2018	**13.3**	**21.6**	**300**	**19.6**

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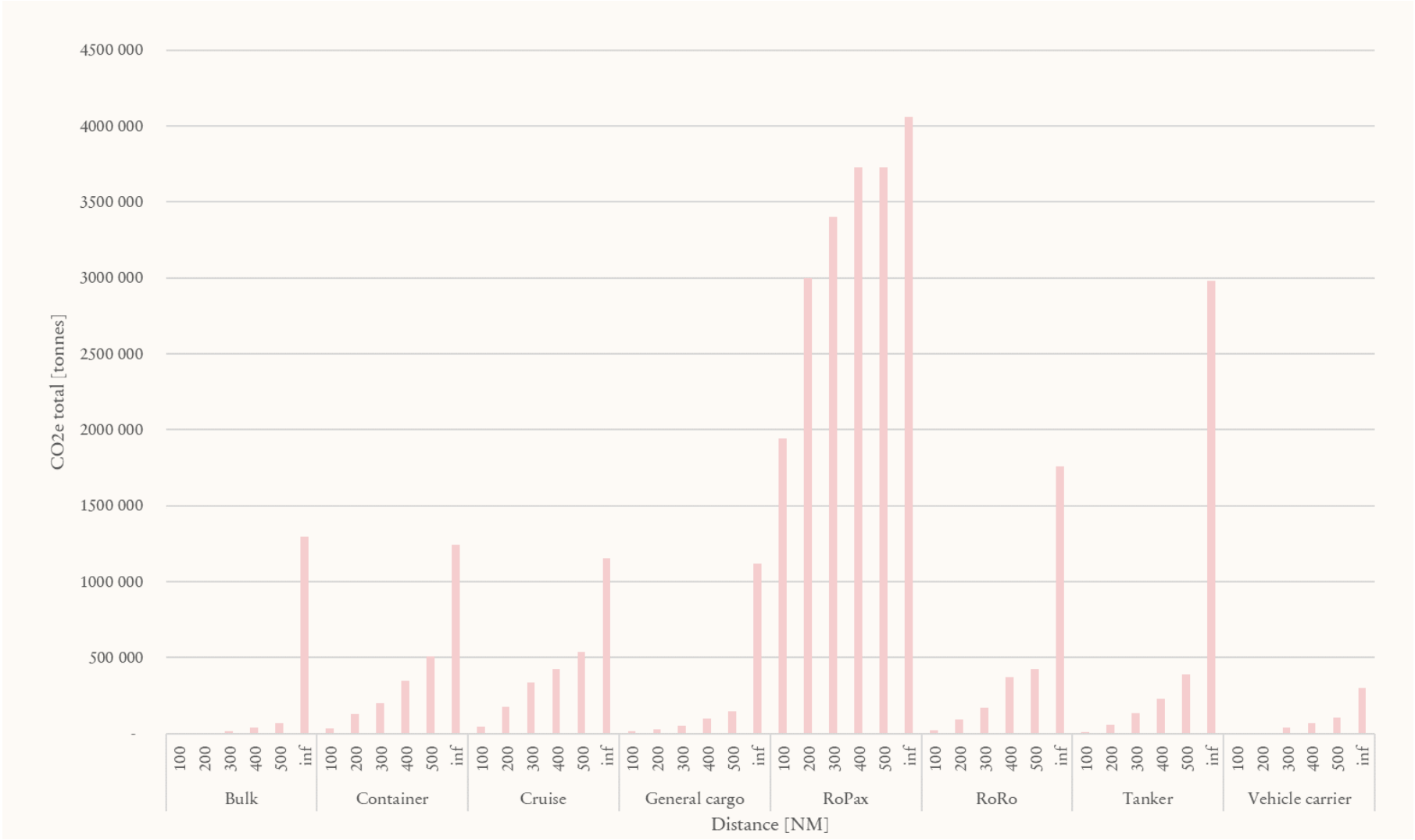
FEASIBILITY: DISTANCE



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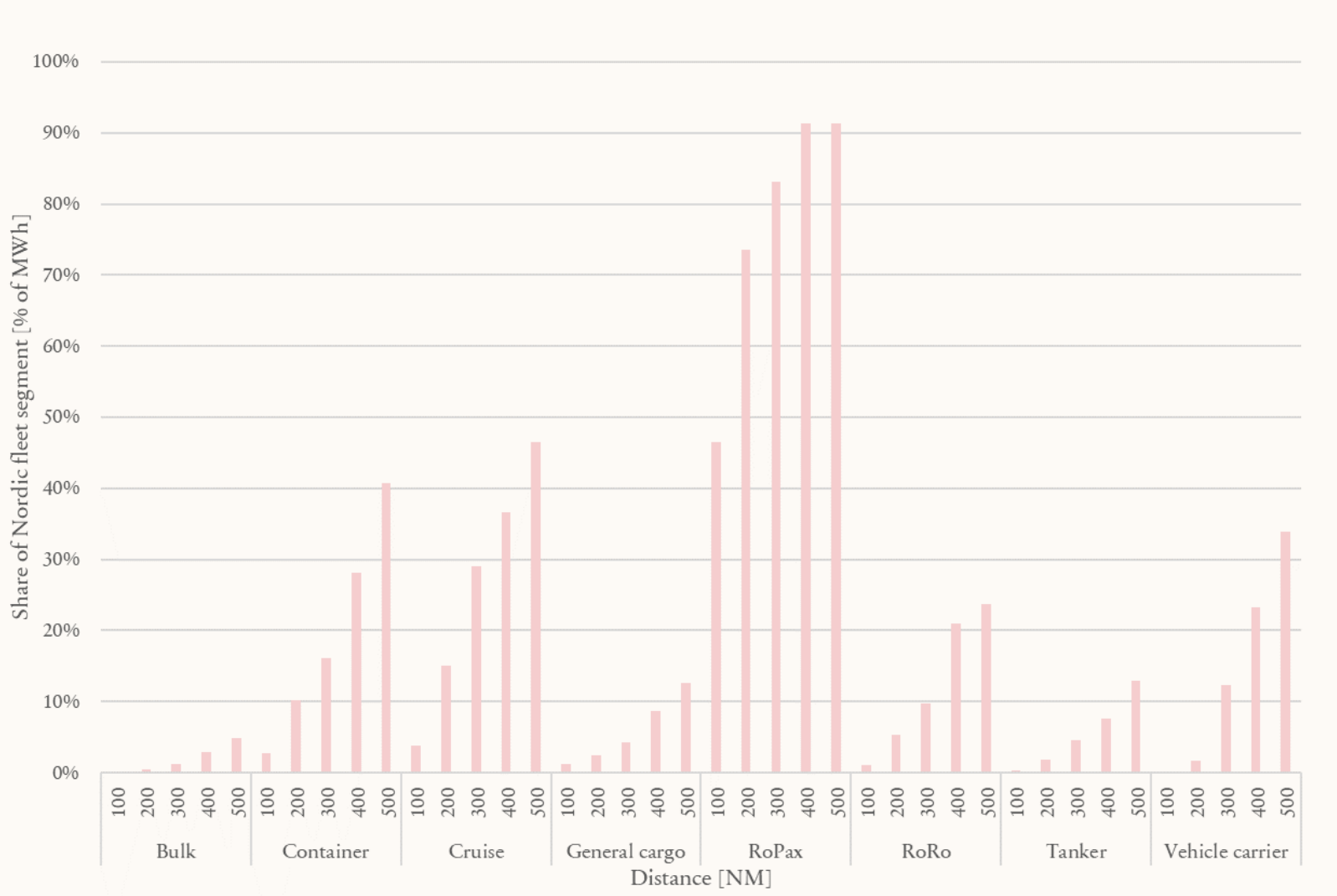
FEASIBILITY: DISTANCE



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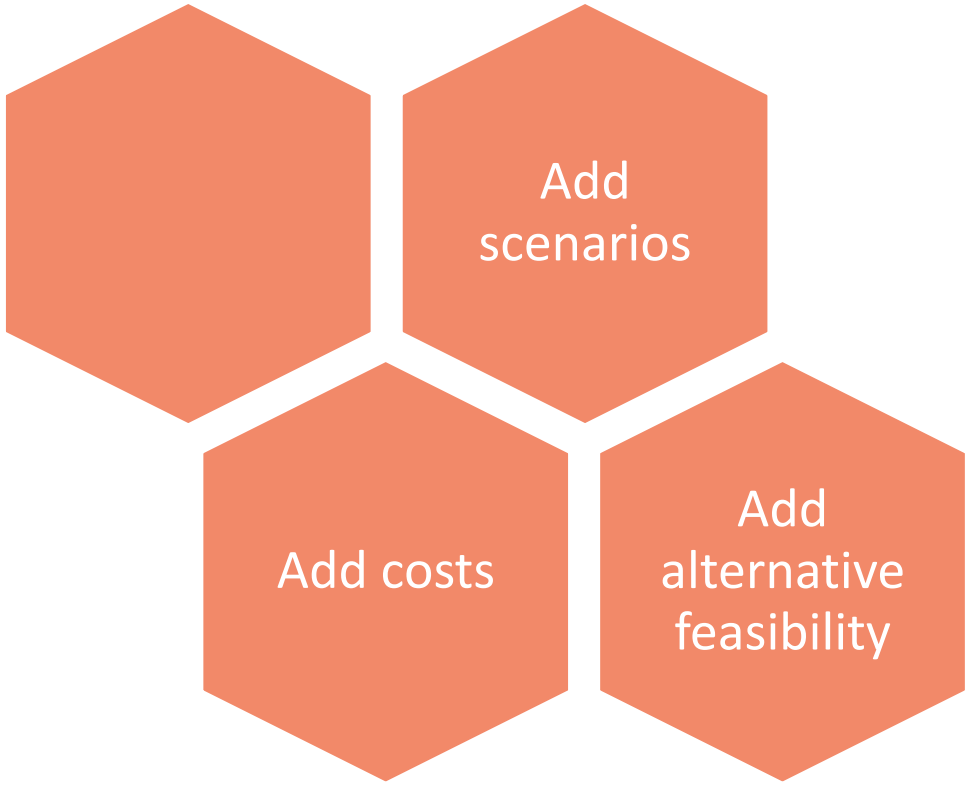
TO DO



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If you have any questions, please get in touch!

THANKS!

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