Towards Zero-Emission Inland Water Transportation: Integrated approaches for optimizing logistics and energy systems

WP4: Transport Chain

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PATH2ZERO CONSORTIUM MEETING
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Main Research Question

*How can **integrated models for logistics and energy systems** be developed to optimize the **transition to zero-emission energy** carriers within the IWT chain?*

Research Questions

1. *How can new energy systems be* ***strategically integrated*** *to facilitate the* ***gradual adoption*** *of zero-emission energy carriers in the transportation chain?*

2. *How does the choice of zero-emission energy carriers influence* ***scheduling and voyage planning****?*

3. *How can* ***day-to-day operations*** *be optimized with the adoption of zero-emission energy carriers?*

Levels of Operations Planning

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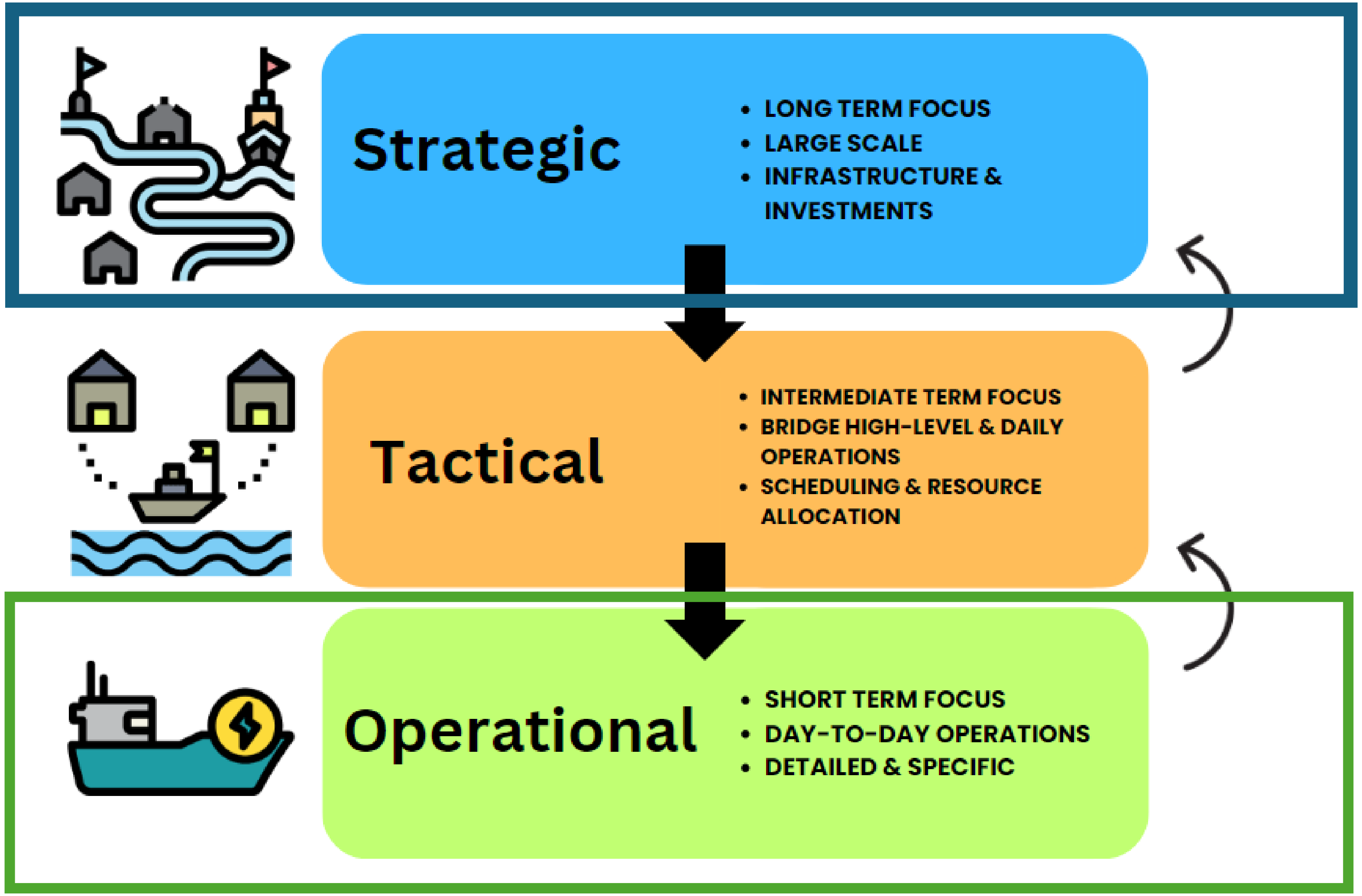
Levels of Operations Planning

Model 1
BSS Location



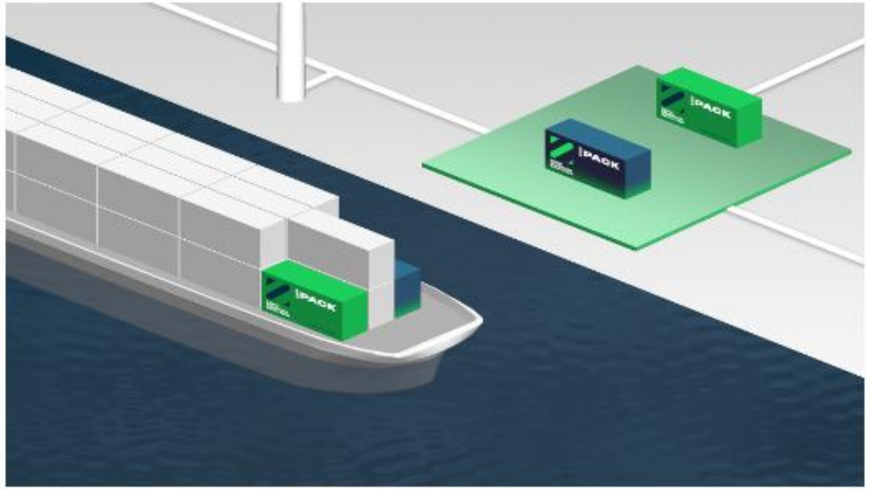
Model 2
BS Voyage Plan

Research Progress

Multi-period Capacitated Flow-Refueling Location Model

- Problem: How do you optimally locate battery swapping stations (BSS) in the Dutch IWW? **(RQ1)**

- Objective: Develop a BSS development plan that maximizes the energy demand coverage of the stations, considering multiple planning periods.



- In collaboration with Zero Emission Services (ZES)

Methodology

Inputs:
- Range
- Network
- OD pairs
- Potential locations

First stage:
Pre-generation of paths

↓

Inputs:
- # of BSMs
- BSM capacity
- Flows O-D pairs

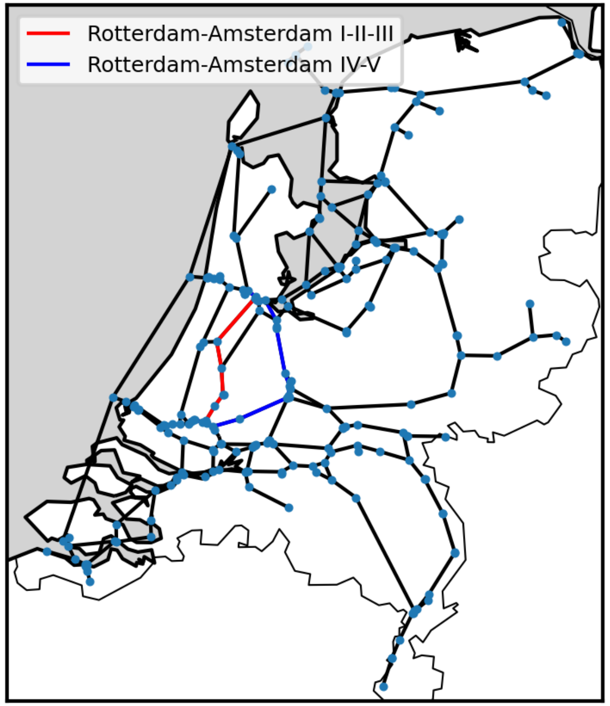
Second stage:
Optimization

↓

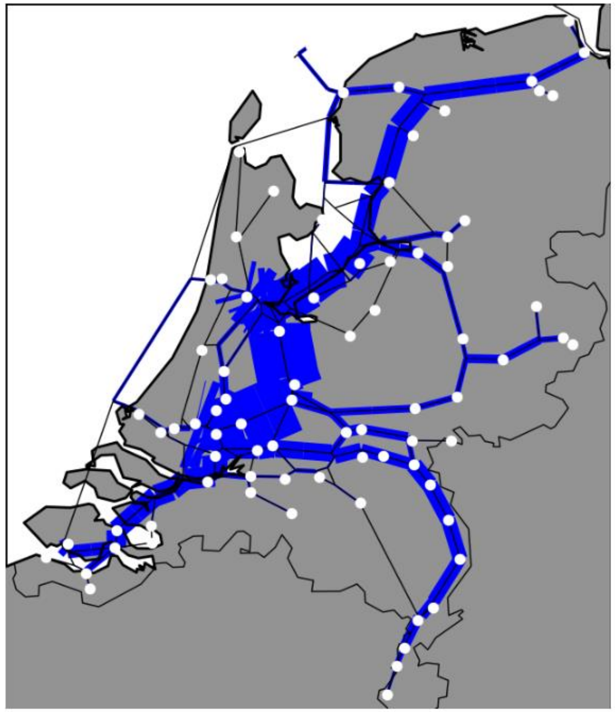
Outputs:
- Optimal stations layout
- Flow covered
- Routes Supported

Data

- RWS Trip data (2023)
- Simplified network (potential loc: ports)
- RWS Vessel Specifications
- ZES BSS Specifications



Visualization of two routes in the network



Dutch IWW energy demand density

Methodology: 2^{nd} Stage

Decision Variables

n_{kt} Number of swapping modules at a station located at location *k* at period *t*

y_{fht} Proportion of flow *f* that is covered by facility combination *h* at period *t*

Parameters

- Swapping module capacity
- Volume of flow v_{ft}
- Max number of swapping stations at a location
- Number of stations to be located s_t

Objective

$$Max \sum_{t \in T} \sum_{f \in F} \sum_{h \in H} v_{ft}\, y_{fht}$$

Constraints

- Capacity Constraint
- # of BSM per location should not exceed the maximum
- # of BSM to be located should not exceed the target
- Multiperiod constraint

Base

Range: 70km

BSM capacity: 48MW

Max BSM at loc: 1

Number of BSM:

T1: 2

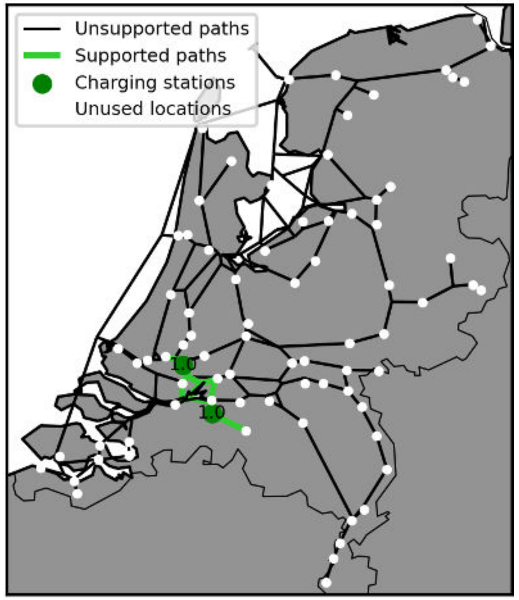
T2: 4

T3: 8

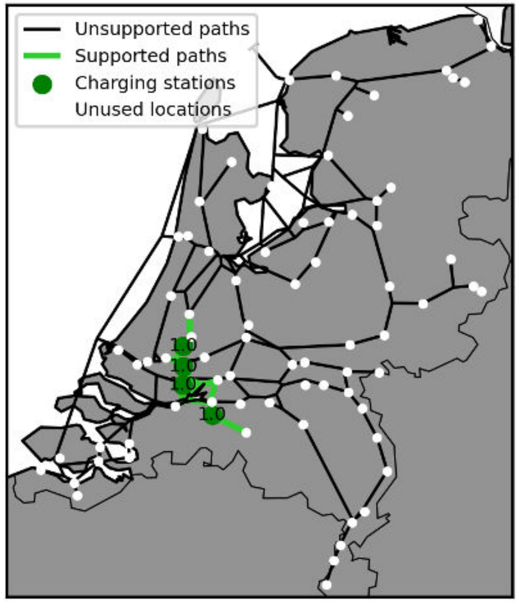
T4: 12

T5: 16

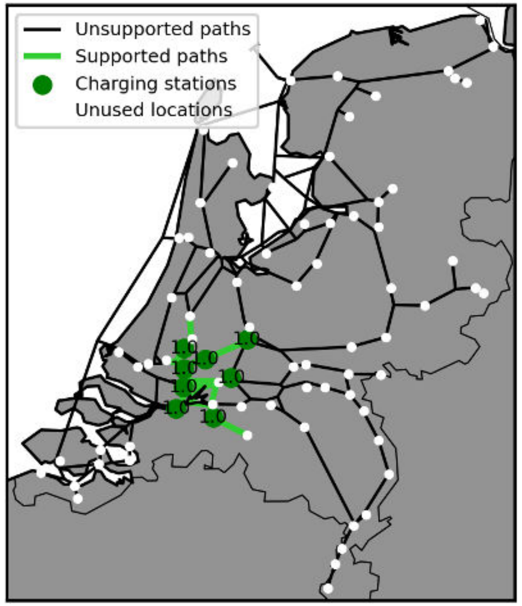
T6: 20



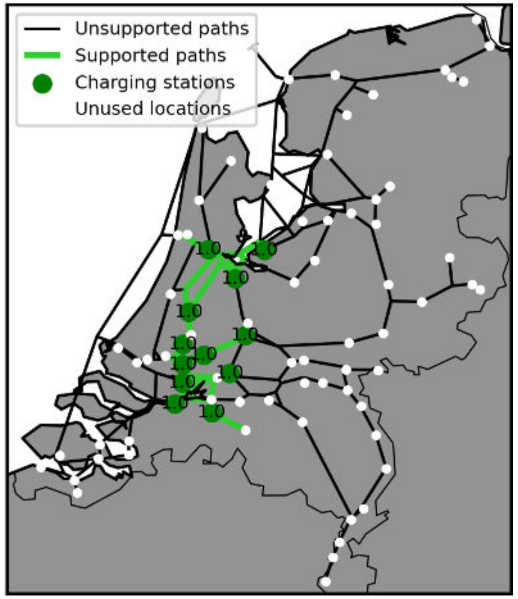
T1 (2 BSS)



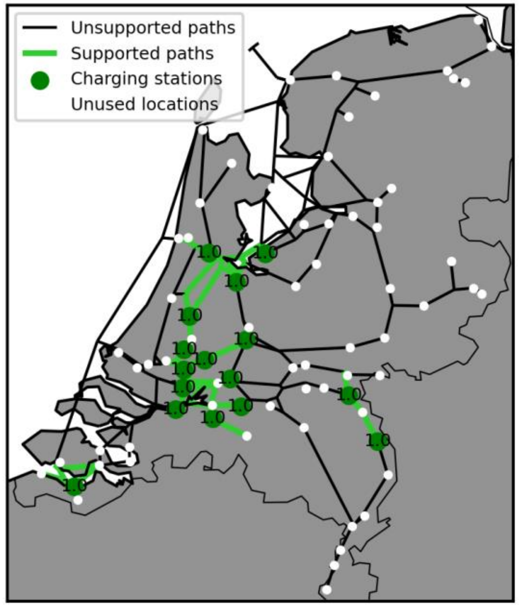
T2 (4 BSS)



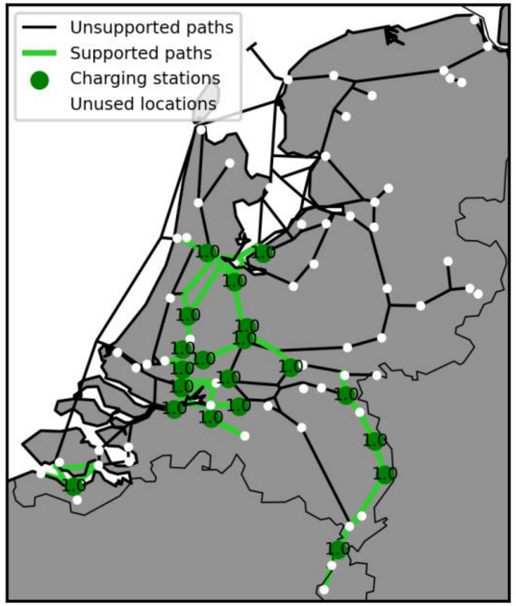
T3 (8 BSS)



T4 (12 BSS)



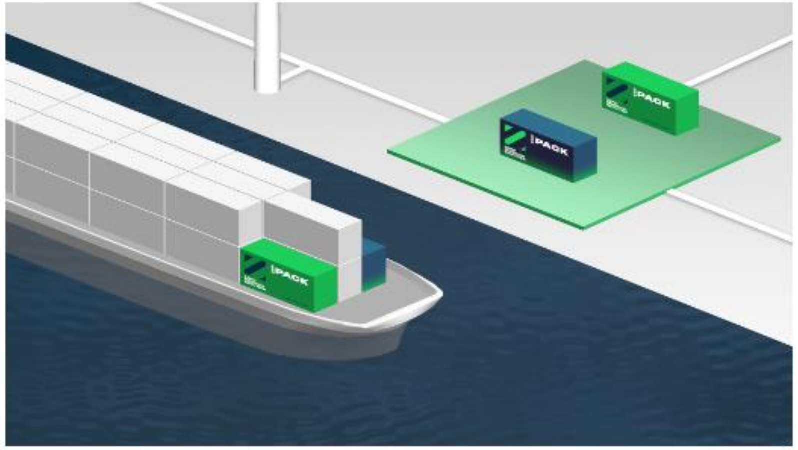
T5 (16 BSS)



T6 (20 BSS)

Operational Decision: Voyage planning

- **Problem**: How can operators optimize battery swapping decisions and energy management for zero-emission vessels?
- **Objective**: Develop voyage optimization model that determines:
  - Battery configuration choice
  - Ideal cruising speed
  - Battery swap scheme



Optimization Problem

Objective

$$\text{Min} \sum_{p \in P} \sum_{k \in K} y_{pk} c_k^{swap} + \sum_{l \in L} e_l \; c_l^{energy} + \sum_{p \in P} \tau_p \; c_p^{idle}$$

Swap cost | Energy cost | Idle time cost

Parameters

- Costs (energy, swapping, idle)
- Capacity of configuration *k* *(kWH)*
- Time (swapping, stop, time windows)
- Swapping ports and stop ports

Decision Variables

b_{lv}	**speed** *v* **for leg** *l* (binary)
c_{pk}	**battery configuration** *k* at port *p* (binary)
y_{pk}	**Swap decision**: configuration *k* at port *p* (binary)
e_p^a, e_p^d	**Energy level** at arrival and departure at p
t_p^a, t_p^d	**Arrival and departure time** at *p*

Power and Energy Calculation

- Based on vessel characteristics (length, width, draft)
- Engine efficiency
- Water condition (depth & current speed)

Resistance (Holtrop & Mennen, 1982)

$$R_T^l = R_F^l(1+k_1) + R_W^l + R_{APP}^l + R_{TR}^l + R_A^l$$

For shallow water resistance: (Zheng et al.,2019) $\left(\frac{depth}{draft} \leq 4\right)$

$$C_f^l = C_{f0}^l + (C_{f,shallow}^l - C_{f,Katsui}^l)\frac{S_B}{S}\left(\frac{V_s^l + \Delta V_l}{V_s^l}\right)^2$$

Power:

$$P_E^l = R_T^l\, V_s^l$$

$$P_B^l = \frac{P_E^l}{\eta_D \eta_S \eta_G}$$

Energy:

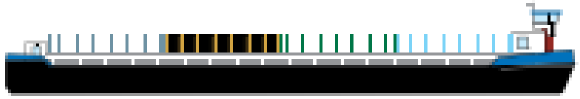
$$E_{l,v}^{trip} = P_B^l T_v^l$$

Travel time:

$$T_v^l = \frac{dist_l}{v + v_{water}}$$

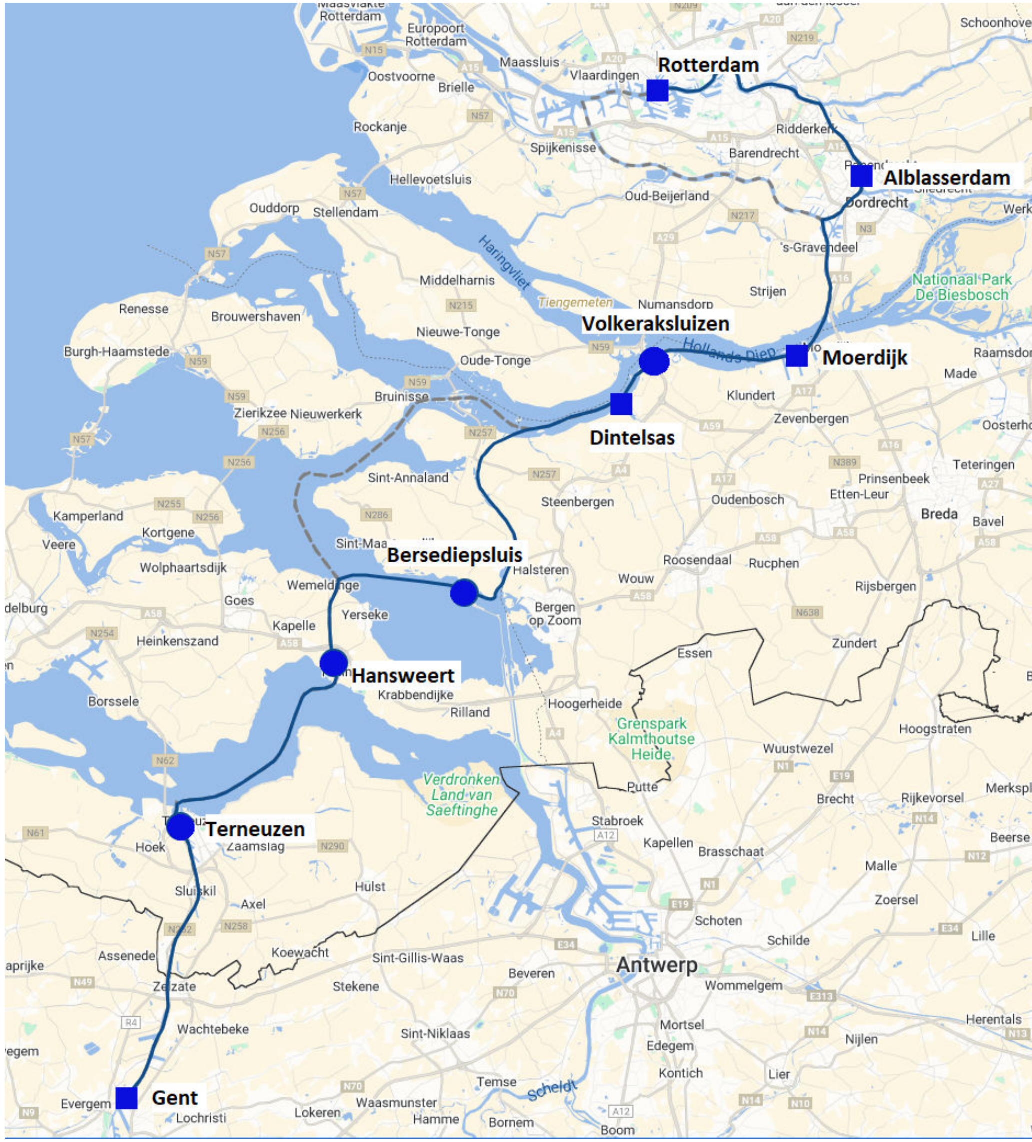
Operational Decision: Voyage planning

- Proposed route: Rotterdam-Gent roundtrip
- Vessel



Neokemp
Lengte 63 meter - breedte 7 meter -
diepgang 2,50 meter - laadvermogen 840 ton / 32 teu

- Time window: 16hrs to Gent, 30hrs back to Rotterdam
- Battery Specs*:
  - 2MWh capacity
  - Min SOC: 20%
  - Swap cost: 500 €
  - Energy cost: 0.5 € / kwh
  - Idle cost: 100 € /hr



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Voyage planning

Table 1: Upstream voyage characteristic

	Name	Distance	Stop	BSS	Time Window	Depth
1	Rotterdam	0	-	✓	[0,10]	-
2	Alblasserdam	25.4	-	✓	[0,10]	8.58
3	Moerdijk	20.6	-	✓	[0,10]	11.40
4	Volkeraksluizen	13.2	✓	-	[0,10]	9.90
5	Dintelsas	4.0	-	✓	[0,16]	7.03
6	Bergsediepsluis	30.9	✓	-	[0,16]	8.53
7	Hansweert	20.0	✓	-	[0,16]	9.10
8	Terneuzen	21.6	✓	✓	[0,16]	23.10
9	Ghent	23.6	✓	✓	[0,16]	13.00

- Water speed: 1m/s
- Stop time: 45mins
- Swap time: 45mins
- Cargo loading/unloading Gent: 2hr

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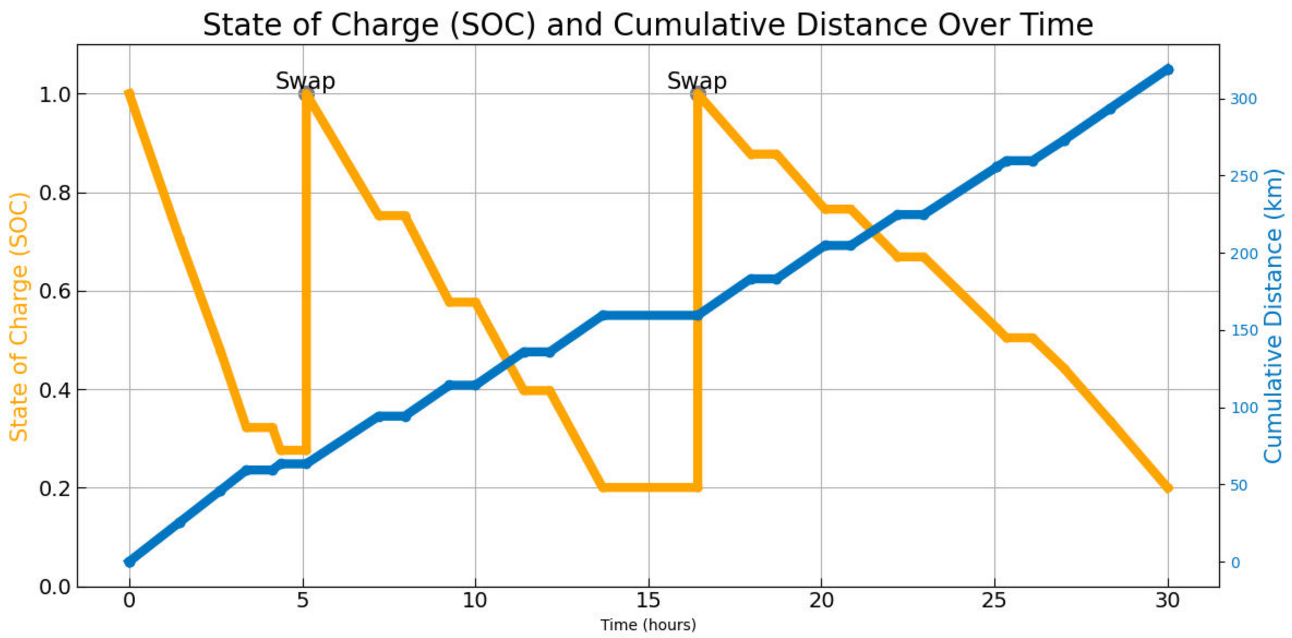
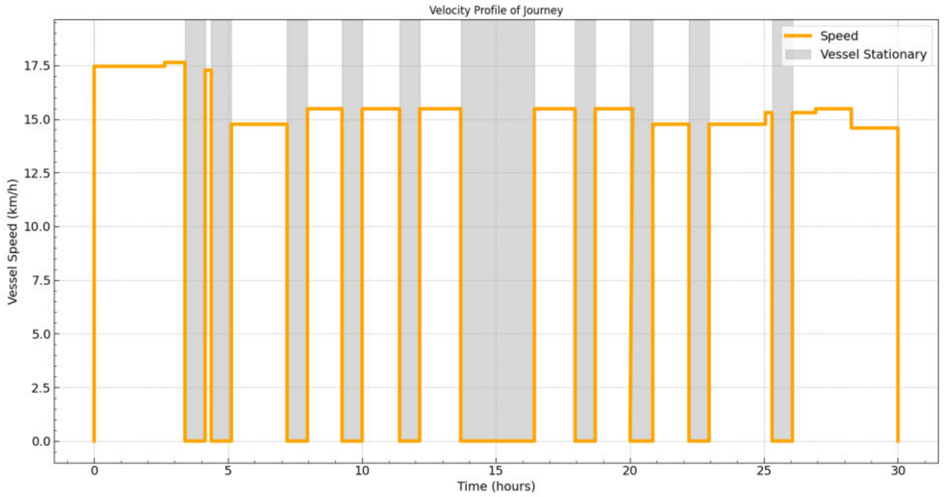
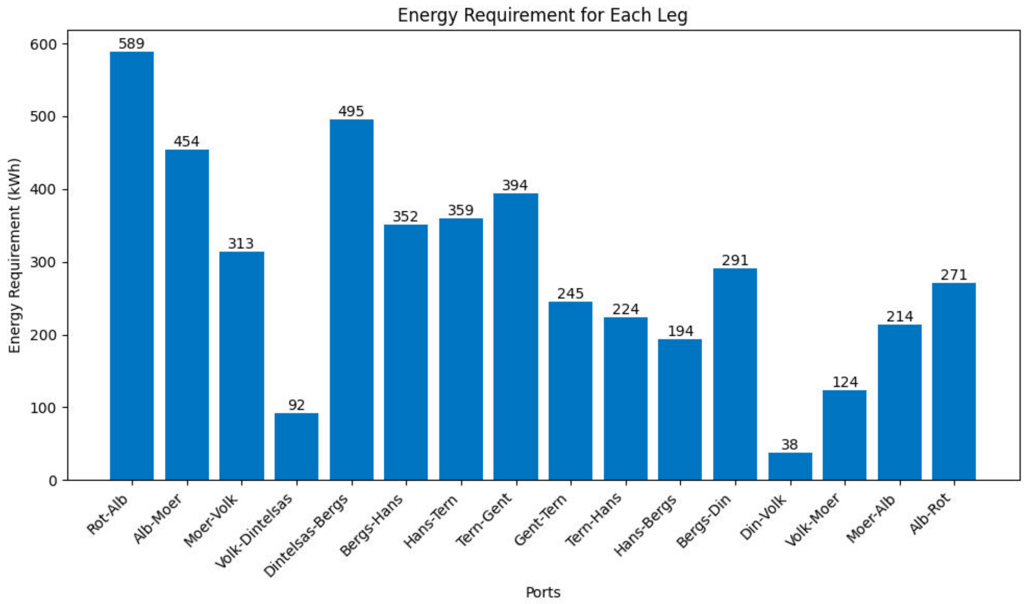
Base Result

- **Swap points:**
  - Dintelsas
  - Gent
- **Total cost: 4,773 €**
  - Swap cost: 1,500 €
  - Energy cost: 2,323 €
  - Idle cost: 950 €





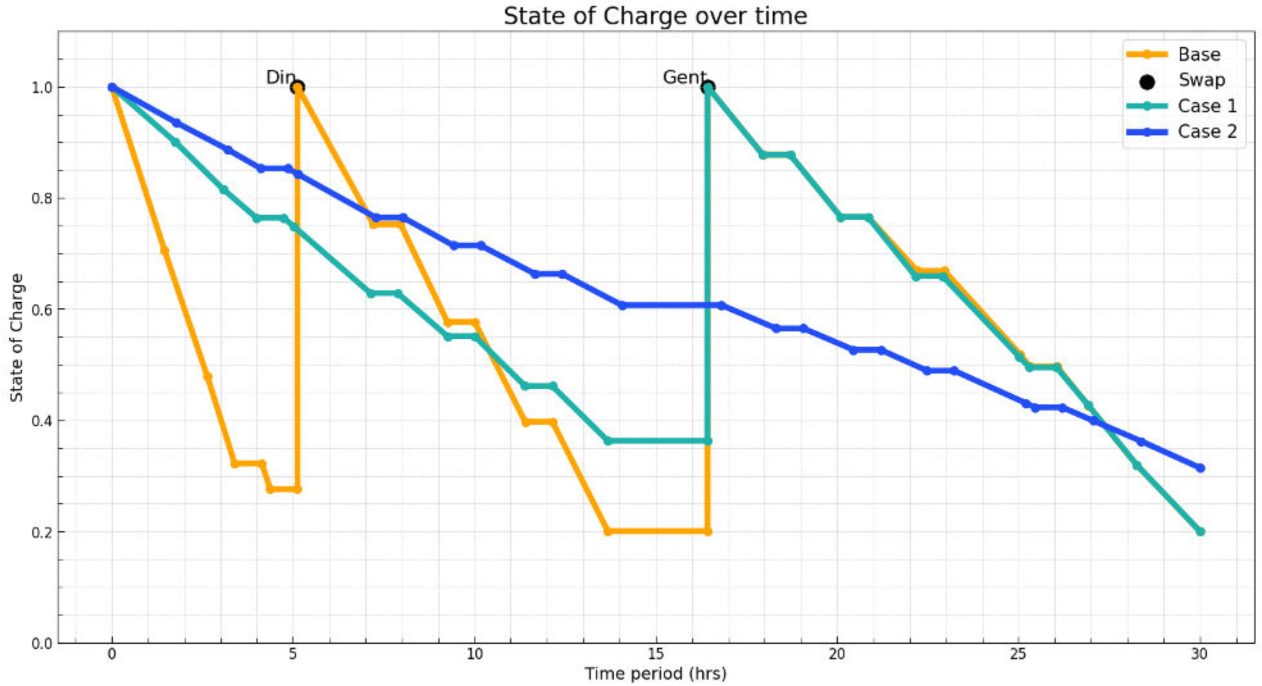


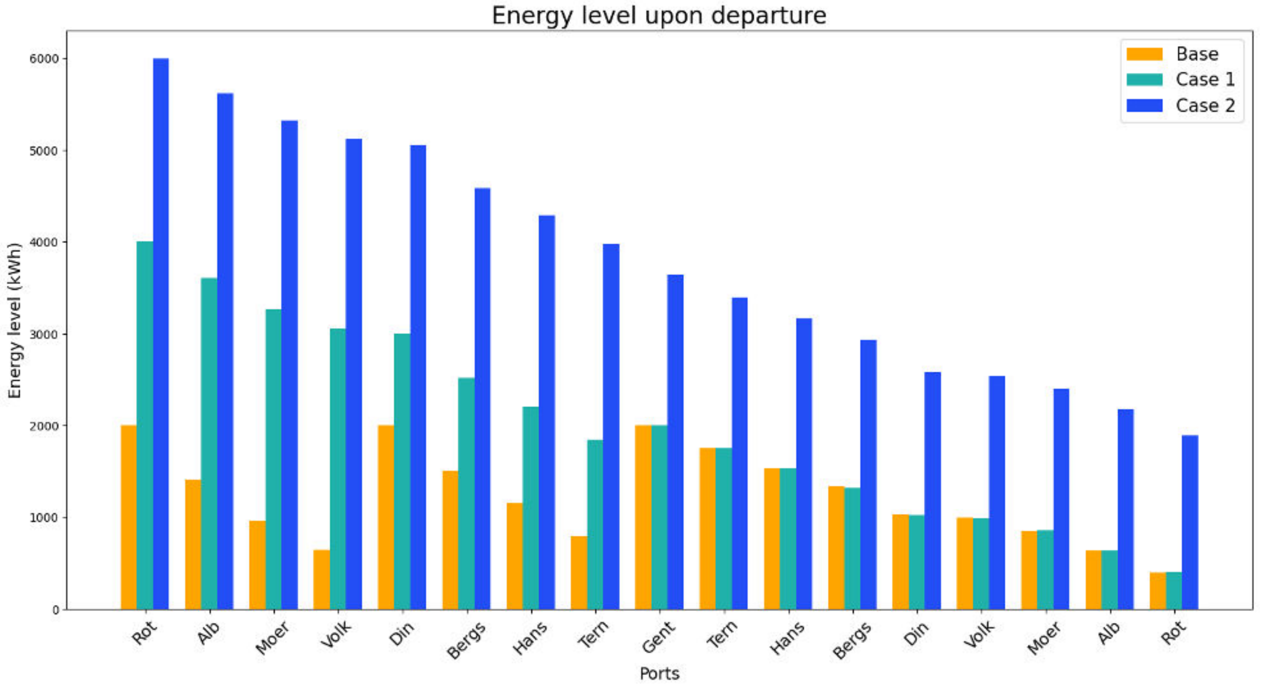
Scenario Results

of Batteries onboard:

# Batteries	Capacity kWh	Swap Time hrs	Cost EUR
1	2000	0.75	500
2	4000	1.5	1000
3	6000	2.5	1500

Case	Battery Options	Total Cost EUR
Base	1	4,773
Case 1	1, 2	4,448 (7.32%)
Case 2	1, 2, 3	4,431 (7.72%)



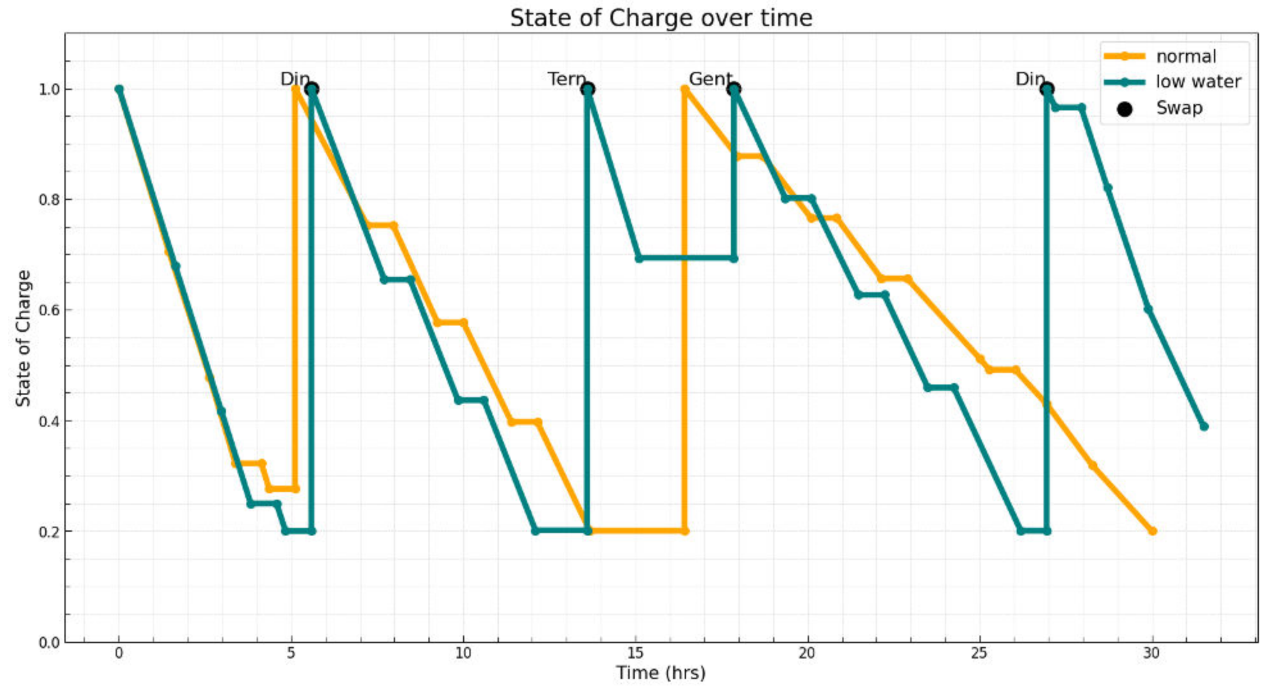


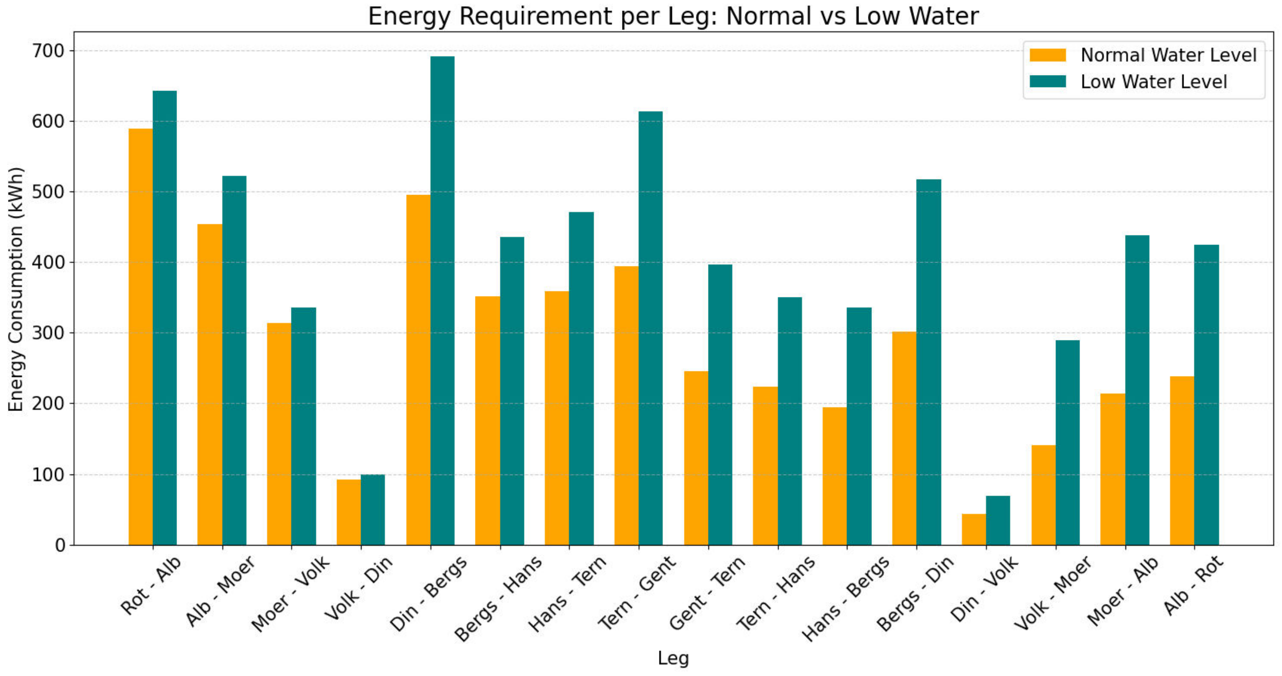
Scenario Results

Low water:

- 4m depth on all legs
- 1 battery onboard (2MWH)
- Same draft (2.5m)

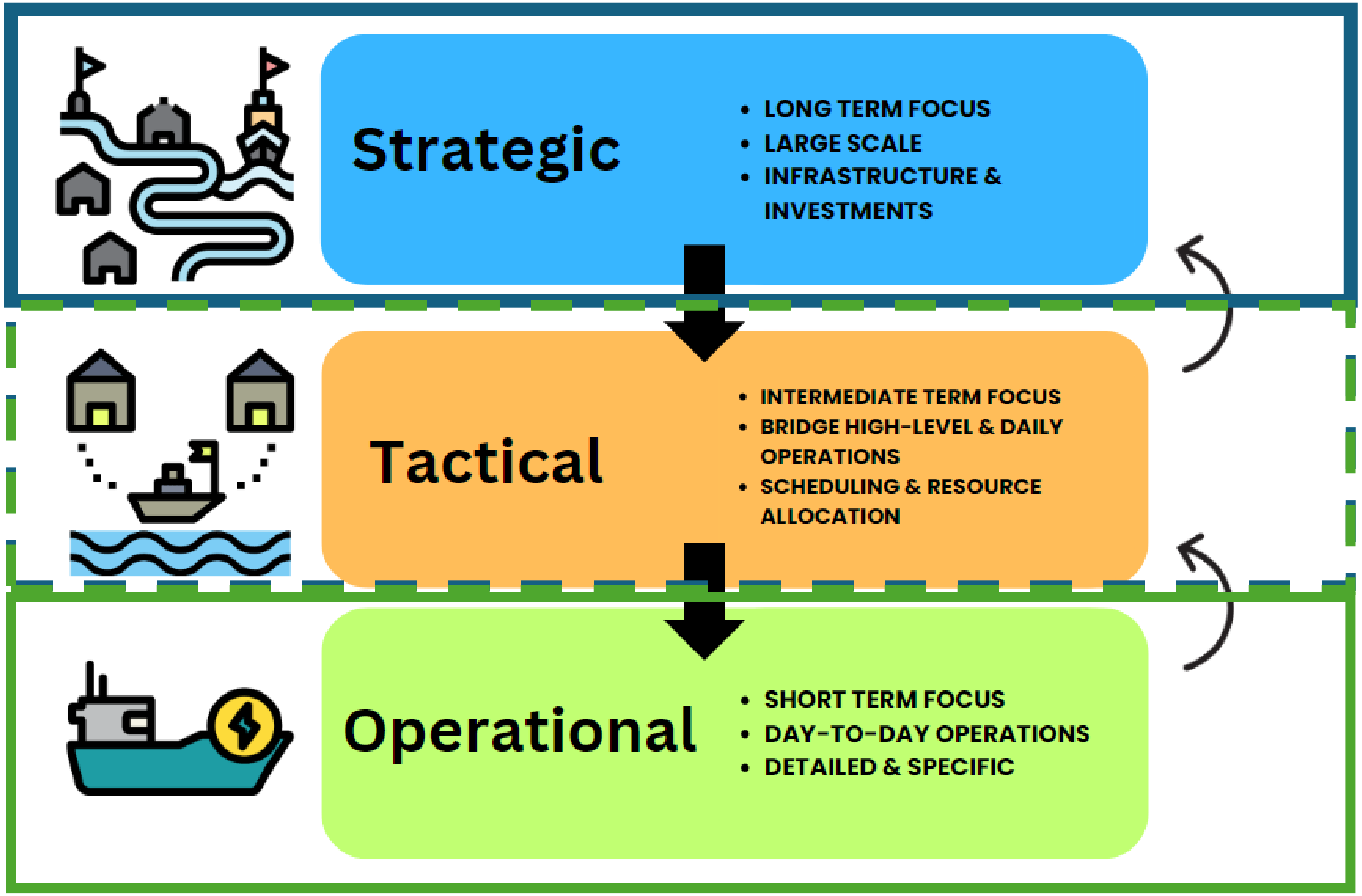
Case	Battery Options	Total Cost EUR
Base	1	4,773
Low water	1	6,984 (46.4%)





Next Steps

Model 1:
BSS Location
+ Fleet Deployment and Routing



Model 2:
BS Voyage Plan +
Scheduling

Next Steps:

- **Bi-level Strategic-Tactical Model**
  - Location (Upper level) and Fleet Deployment + Routing (Lower level)
  - Represent the decision of two players (developer & operator) in one model
  - Analyze how the location of swapping station affect the decisions of the vessels
- **Voyage Planning + Scheduling Model**
  - Considers multiple vessels and limited availability of batteries
    - Headway constraint
    - Swapping time availability constraint
  - Consider cargo capacity + loading & unloading demand at ports
  - Minimize idle time for both the vessels and the batteries

Thank you for listening!

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Questions & Feedback
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