MAGPIE

SMART GREEN PORTS

TRANSPORT ENERGY REQUIREMENTS

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Executive Summary

Greening transport is a key objective of the European Green Deal. Transport accounts for 25% of the EU's greenhouse gas emissions. Green transport developments focus on the supply chain and use of green energy carriers. MAGPIE project task 3.1 has been set out to map the current (supplied by fossil fuels) and the future energy demand (supplied by green energy carriers) associated with the different transport modalities that co-exist in a port ecosystem (using the port of Rotterdam as use-case). The main goal is to provide a first indication of the order-magnitude of the demand (present and future) for the transport sector. This will be the starting point for the development of the green energy supply chains in the MAGPIE project. Other aspects, such as analysing the impact of cost and infrastructural constraints are out of scope in task 3.1, but is included in upcoming tasks of Work Package 3.

Transport in the port of Rotterdam can be split in the following generic modalities: maritime shipping, inland shipping, truck and rail. In this deliverable an estimate of the current and future energy demand for these modalities is described. When it comes to the current energy demand for the different modalities, that resulted from this report, maritime shipping is by far the largest with approx. 400 000 TJ, then inland shipping with 6766 TJ and road (i.e., trucks) with 6433 TJ and lastly rail with 369 TJ. Although this numerical comparison is being provided, conclusions should only be extracted after analysing how the calculations per modality were carried out since the considered assumptions and (geographical) scope vary.

For each modality different future energy carriers are considered in this report, based on current market trends. Below an overview per modality is given, several are described in more detail in Annex B. Note that the current focus is on the green versions, so green hydrogen and bio-methanol. However, there might be alternative or complementary paths that include, for example, blue hydrogen or e-methanol. The actual path will be a result of supply and demand interaction and will be addressed in further MAGPIE tasks. For inland shipping and road/rail transport, emissions were also analysed to provide additional insights. Note that the use of Well-to-Wheel (WtW) or Tank-to-Wheel (TtW) emissions differs.

Table 1 Energy carrier for different modalities

Modality	Energy carrier
Maritime shipping	(Bio-)Methanol, Bio-diesel, Green Hydrogen, Ammonia, (Bio-)LNG and Electricity
Inland shipping	Green Hydrogen, (Bio-)LNG, Bio-diesel (in the form of Hydrogenated Vegetable Oil (HVO)), Bio-Methanol and Electricity
Trucks	Green Hydrogen, (Bio-)LNG and Electricity
Rail	Electricity

Within the project a challenge has been the availability of the right (quality) data to provide good insights in the current energy demand. This differs for each modality and uncertainties have been described as part of the results. Similarly for each modality, geographical scope and flexibilities are different. Maritime shipping may be able to avoid bunkering in a specific port, whereas other modalities are more limited in their choice.

Maritime shipping

There is a lot of uncertainty around the future of bunkering for marine vessels. This is directly related to the choice of fuel and bunkering approach of ship operators. The fuel choice is influenced by safety, availability, commercial viability and technical feasibility. Taking this into account a range is provided for energy demand of the energy carriers investigated in this project: (Bio-)Methanol, Biodiesel, Hydrogen, Ammonia, (Bio-)LNG and Electricity.

A big issue with the future energy carriers is the lower energy density compared to traditional maritime fuels. This means that the range of a vessel is diminished when bunkering the same volume of fuel. As a result, more frequent bunkering or larger fuel storage onboard will be needed. This might alter the way vessels and transport networks are operated. For example, instead of sailing roundtrips, more hub-spoke networks might occur, concentrating cargo in bigger ships with large ranges, while using smaller short-range ships for further distribution. The basis for such decisions will be researched within the MAGPIE project, but it is currently too early to take such changes in patterns into account.

The method estimates a minimum and a maximum consumption, based on trip data and the assumption that the maximum bunkering interval is 25 days. This is categorized by ship type, size (in DWT) and trip length to link the energy demand to a future energy carrier. Suitability of a certain energy carrier for a specific category is based on energy density (weight and volume), technical feasibility and safety. The current energy demand is better described by the bunkering data than by those overviews, which are used to make the future estimate. A total of approximately 9.2M ton of marine fuels (fuel oil, MDO, MGO) was bunkered in Rotterdam in 2018 with an approximate energy of 400 mln GJ. The result of the translation of the current range in energy demand and suitable energy carrier for the different categories is shown in below table.

Table 2 Total energy demand modality – maritime shipping

Energy carrier	2030 (mln GJ)	2040 (mln GJ)	2050 (mln GJ)
(Bio-)Methanol	49 - 244	49 - 244	49 - 244
Biodiesel	55 - 395	55 - 395	55 - 395
Hydrogen	6 - 72	6 - 72	6 - 72
Ammonia	0 - 0	0.4 - 167	49 - 244
(Bio-)LNG	30 - 130	30 - 130	30 - 130
Electricity	8 - 153	8 - 153	8 - 153

It is clearly visible that all energy carriers have different timelines, this mainly has to do with their technical feasibility. The range indicates that there is uncertainty, part of this is also authorities, ports and port stakeholders taking the right actions to enable ship operators to make choices and to ensure attractiveness of bunkering in the port. It is also important to understand the bunkering approach that operators will implement for the alternative energy carriers that have different volumetric energy densities compared to the current fuels.

Inland shipping

To quantify the current and future energy demand and emissions for inland shipping to and from the Port of Rotterdam, a model was developed, covering bulk/goods and container transport, for a reference year (2020) and evolution to 2050 in three different scenarios: business-as-usual (BAU), conservative (CONS) and innovative (INOV). By generating these scenarios, based on different technological options to decarbonize inland shipping, the new energy supply chains (e.g., shifting from diesel to electricity or hydrogen) can be analysed.

The model calculates the energy demand for IWT for the different scenarios, based on the specific energy use per vessel type estimated from reported values for the GHG emission factors and inland shipping activity data: i.e., type, quantity and distance travelled by cargo per vessel type and journey. The model includes the energy requirements of all the journeys departing from and arriving to Rotterdam. The total energy demand per energy carrier (and technology) up to 2050 is shown in Table 3. A more detailed model is also described in the report for future reference, this model requires additional data. All scenarios were generated under the assumption that inland shipping activity remains largely unchanged - approx. 34 billion tkm in 2020, with an increase of 6% towards 2050.

Table 3 - Total energy demand for Inland Shipping in TJ from 2020 to 2050 under the scenarios

Final Energy in TJ	REF	BAU			CONS			INOV		
Energy carrier	2020*	2030	2040	2050	2030	2040	2050	2030	2040	2050
Diesel	6766	6106	5568	5139	4777	2713	618	4730	2701	707
HVO	0.0	0	0	0	907	1630	2182	406	480	270
LNG	0.0	32	45	41	115	109	0	98	92	0
Bio-LNG	0.0	0	0	0	79	433	1014	209	395	558
Electricity	0.0	0	0	0	8	69	173	147	317	504
Hydrogen	0.0	0	0	0	1	96	267	67	456	1113
Bio-methanol	0.0	0	0	0	11	154	407	51	367	901
Total	**6766**	**6138**	**5613**	**5180**	**5898**	**5203**	**4661**	**5707**	**4808**	**4053**

* The total consumption for the reference year was validated against overall European demand and proportionality of the Dutch inland shipping sector, which was within a bandwidth of less than 5%.

There is a wide disparity in the adoption of different technologies, and deployment of new low-carbon energy carriers, envisioned for the three scenarios implemented in the model. The BAU assumes only minor changes, mainly moving towards replacing the current diesel technologies by Stage V diesel engines and a gradual improvement in overall efficiency of transport per tkm of IWT activity, driven by smart logistics, digitalization, and improved planning across modalities. Under BAU there are significant overall improvements to the total energy use in the sector and GHG emissions (approximately 23% and 17%, respectively), but the sector is largely unchanged continuing to depend on fossil fuels (diesel).

The CONS and INOV scenarios are based on the analysis carried out by the Central Commission for the Navigation of the Rhine (CCNR) that aims for zero-emissions inland shipping by 2050. Both scenarios reach at least 80% GHG emission reduction for IWT but do so under different technology deployments. The CONS scenario has a conservative view on the deployment of lower TRL technologies (i.e., hydrogen, electricity) and opts for accelerated deployment of HVO and Bio-LNG, which can be mostly adapted and retrofitted in existing commercial technologies. Under INOV, HVO plays a much smaller role in the decarbonization of inland shipping, with Hydrogen, Bio-methanol, Bio-LNG and electricity-based technologies driving the transition towards zero-emissions IWT.

Road and rail energy requirements

Throughout Europe, the truck and rail sectors are major players in the hinterland transport of cargo from and to ports. Unlike inland shipping, these modalities are not constrained by access to suitable rivers for (large) barges and, as such, are present across all major European ports. Typically, rail transport is preferable between the port and a large consumer/producer or a distribution hub, where the containers can then be individually delivered to their final destination. On the other hand, truck transport tends to be geared towards smaller industries, transporting cargo directly to the final destination.

An estimate of the current energy demand (MJ of Diesel) for the road and rail sector was carried out, shown in Table 4. For rail transport, the focus was on diesel locomotives that operate within the port area and whose activity is associated with shunting actions and/or first-last mile delivery. Long-haul locomotives were not analysed since most of the railways that connect ports to major hubs are already electrified. It is not expected that this type of locomotives will shift to a different energy supply chain.

Table 4 Total current energy demand (per modality)

Energy carrier	Present Rail (MJ)	Present Road (MJ)
Diesel	3.699E+08	6.43E+09

In the deliverable, results are presented with a higher granularity i.e., demand volumes are associated with different cargo types and route characteristics. Two main reasons justify this:

- Different operational characteristics within the same transport modality may lead to different transition paths (i.e., different green energy carriers).
- Identifying the impact of each cargo type on the energy consumption (and GHG emissions) may be a good way to prioritize in the transition of the truck/train fleet.

Energy scenarios (2030, 2040, 2050) for the road and rail sector were built. Two main aspects were considered in these scenarios: cargo evolution trends (including modal shift) and the impact of green energy carriers.

Three decarbonization technologies for the road sector were included: electrification, green hydrogen and NG (compressed and liquified). Table 5 shows the energy scenarios for the road sector. These were built considering two perspectives:

- An extreme-case approach where all diesel-powered demand is transferred to electricity or H2 by 2050. No values were calculated for 2030 and 2040 since the objective was to access the absolute maximum demand for each energy carrier. While the materialization of these extreme scenarios is not expected, this is a useful input for the supply chain sizing tasks (T3.2 to T3.5). LNG/CNG was not considered in this approach since it is not a complete decarbonization carrier.
- A mixed scenario where all green energy carriers contribute to the energy transition. The demand share allocated to each energy carrier was based on inputs found on the literature and on interviews conducted with field experts.

Table 5 Future energy demand modality – Road transport

Scenario	Energy carrier	2030	2040	2050
100% electric	Electricity	-	-	2.85E+09
100% H2	H2	-	-	3.88E+09
Mixed scenario	Diesel	3.96E+09	2.57E+09	0
	Electricity	3.08E+07	3.34E+08	9.81E+08
	H2	3.56E+08	9.03E+08	2.54E+09
	LNG/CNG	5.52E+08	1.10E+09	0

Similarly, rail energy scenarios were analysed, the results are shown in Table 6. A single pathway was considered: electrification. This is justified by the operational profile of a shunting locomotive which indicates that batteries will be the most promising technology.

Table 6 Future energy demand modality – Rail transport

Scenario	Energy carrier	2030	2040	2050
Mixed scenario	Diesel	0	0	0
	Electricity	7,98E+07	9,31E+07	1,06E+08

The insights provided by the energy scenarios are important for the further tasks of Work Package 3. With estimates of the future demand for each green fuel, task 3.2 (Electricity Supply Chain), task 3.3 (Green Hydrogen Supply Chain) and task 3.5 (BioLNG Supply Chain) have a starting point to study how these supply chains will need to evolve.

1 Introduction

Greening transport is one of the key objectives of the European Green Deal. Transport accounts for 25% of the EU's greenhouse gas (GHG) emissions. Green transport developments focus on the supply chain and use of green energy carriers. The energy carriers considered in this project are batteries, green hydrogen, ammonia, (Bio-)LNG and green methanol.

In this context, seaports will play a major role in boosting the use of cleaner technologies, green energy carriers and logistics concepts in maritime transport, port operations and hinterland transport to reduce GHG emissions. As linking pins, ports should facilitate and accelerate the supply and the use of green energy carriers. The energy supply chain for high potential green energy carriers will be matured within this project, together with stakeholders demonstrating innovations that fill the gaps in the chain together with stakeholders.

The objective of the WP3 is to deliver a roadmap to develop supply chains: electricity/batteries, hydrogen, ammonia and (Bio-)LNG. The work package encompasses demonstrators linked to BioLNG production and Shore Power applications, with links to demos in WP5 and WP6. And provides input to WP4, WP7, WP8, WP9 and WP10.

This all starts by understanding which share of the energy consumed is related to a specific area, in this case the port of Rotterdam. Therefore, task 3.1 has set out to map the current and future energy demand in the port of Rotterdam for the different transport modalities, which functions as a starting point for the entire green energies supply chain related to transport.

There are many influential factors, the major ones being: development of transport movements, efficiency measures, regulatory impact, technological developments, availability and affordability of green energy carriers. Several of the factors are investigated in tasks following 3.1 and others our outside our circle of influence, this therefore means that this is a first indication that gives an order-magnitude estimate.

Transport in the port of Rotterdam can be split in the following generic modalities: maritime shipping, inland shipping, truck and rail. In separate chapters an estimate of the current and future energy demand of the different modalities is described. This includes an introduction into the context, a description of the sources and method used, as well as the assumptions and uncertainties and the results. Below the chapters related to the subtasks are listed.

Chapter 2 describes Subtask 3.1.1: Shipping energy requirements (TU Delft)

Chapter 3 describes Subtask 3.1.2: Inland shipping energy requirements (INESCTEC)

Chapter 4 describes Subtask 3.1.3: Trucking and Rail energy requirements (EDP)

Chapter 5 provides the combined conclusions from task 3.1

Chapter 6 provides the combined recommendations from task 3.1

Within the project a major challenge has been the availability of the right (quality) data to provide good insights in the current energy demand of the different modalities. This differs for each modality and uncertainties have been described as part of the results. The original task description is included in annex A.

2 Shipping energy requirements

2.1 Context

Fuel demand for maritime services is around 250 mln tons (10,700 mln GJ) of which the Port of Rotterdam is providing approximately 3% at the moment. About 85-90% of that demand is provided by the top 20 bunker locations in the world (50-60% by the top 10). In other words, the energy supply is very concentrated. This might not be the same for the future. A big issue with the future energy carriers is the lower energy density, compared to fossil fuels. This means that the range of a vessel is diminished when the same volume of fuel is taken on board. In many cases, taking on board more fuel is not possible due to space restrictions. As a result, more frequent bunkering/charging will be needed. This might alter the way vessels and transportation networks are operated. For example, instead of sailing roundtrips, more hub-spoke networks might occur, concentrating cargo in bigger ships with large ranges, while using smaller short-range ships for the further distribution. Such decisions will be researched within the MAGPIE project in the future, but not considered within this report.

This research makes an initial estimate of the current and future energy demand in Port of Rotterdam, considering the issues above to identify the plausible ranges of future fuel demand.

2.2 Methodology

2.2.1 Introduction to the methodology

Given the impact of new fuels on range, it is of interest to consider the trip duration as an indication for energy demand directly after the trip. This would be the most extreme situation, where vessels need to bunker after each trip. This approach of the energy demand for shipping at port level uses a detailed trip analysis combined with a consumption analysis. As 2018 was the last regular year without a COVID pandemic or conflict in Ukraine, this year was chosen to do the baseline comparison on. The following approach was used to model the port energy demand:

1. A broad study of vessel classes, future fuels and matches between them was conveyed.
2. A database on vessel movement[1] was used to collect all trips to Rotterdam performed with seagoing vessels
3. The ships were divided into categories using vessel type and DWT. Categories were smaller in lower DWT ranges to accommodate the diversity and larger number of vessels in these size categories better, whereas in the higher DTW ranges variety is more gradual with size and categories can therefore contain a larger DWT range.
4. The identified trips were divided in four categories:
    a. 1 day which usually indicated a trip within the ARA (Antwerp-Rotterdam Area)
    b. 2-4 day trips, relatively short trips from neighbouring countries including the Great Britain
    c. 5-10 day trips, intermediate trips, predominantly within Europe.
    d. 10+ day trips, cross Atlantic and to the Pacific basin.
5. Overviews of average durations and the total number of trips were created with MS Excel.

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[1] Data service provided by Thomson Reuters, Thomson Reuter (2020), Voyage data collection, https://www.thomsonreuters.com

6. The MRV-Thetis database[2] (where ships report consumption on a yearly basis to the EU) was used to identify the consumption of each vessel and link this to the trip data using the IMO numbers.
7. The combination of the two databases and the suitability of the potential fuels allows the calculation of the future energy demand based on the trips to Rotterdam.

2.2.2 Categorization

Before discussing the results, it should be noted that a more detailed vessel classification is possible on the basis of both MRV-Thetis and the vessel movement registration. However, classifications differ significantly between the two datasets on the subtype level. Furthermore, in both classifications, a large set of such sub-types did not contain enough vessels to call the average reliable. Hence it was decided to only use the broad classification of one of the databases.

All alternative fuel options require more space and more weight. For each fuel this increase is different per aspect and some fuels are primarily weight driven while others are volume driven. The same holds for vessels. Broadly speaking tankers and bulk carriers are weight driven, while the other vessels (Containers/RoRo, Passenger and Miscellaneous) are volume-driven. A weight-driven vessel means that if more weight is used by the fuel, less cargo can be transported. There is usually some room to increase the volume of the fuel, as empty spaces are used to create enough buoyancy to carry the desired cargo weight. For volume-driven vessels this is the other way around. If the consumption of similar vessel types is comparable, subgroups are joined into larger groups to limit the subdivisions. After checking the data, it was concluded that this was not the case. To illustrate this the average for each class is presented below. Fuel type is not specified but as HFO is still the predominant fuel it is assumed within the report. Each class contains all seagoing vessels that have visited an EU port and reported the yearly consumption. This was averaged per vessel to a day use, which was averaged per class for this table. Although this is the overall average, the differences also hold for each size category (and sometimes are even larger than for the average).

Table 7 Average fuel consumption per ship type

Ship type	Average Fuel Consumption
Bulkers	6.98 Ton/Day
Tankers	10.5 Ton/Day
Miscellaneous	8.90 Ton/Day
Container/RoRo	29.7 Ton/Day
Passenger	45.7 Ton/Day

As mentioned at the start of this chapter, for the smaller ships, smaller steps are taken to be able to see the results in detail. This led to the following range limits in DWT 0, 1250, 2500, 5000, 10000, 25000, 50000, 75000, 100000, 150000, 200000, 250000,500000. After studying the first result it was identified that different vessel types showed similarities over different size classes, but this was almost never identical for all vessel types. The only concession that could be made was grouping the first three groups, removing the range limits of 1250 and 2500. Leading to a final set of size ranges limited by 0, 5000, 10000, 25000, 50000, 75000, 100000, 150000, 200000, 250000, 500000 DWT.

2.2.3 Development of total energy demand

In general, it is expected that the amount of transport movements keeps increasing for the coming years. Estimates, however, vary between an increase of 50%-250%. At the moment

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[2] EMSA(2020), MRV-THETIS database, https://mrv.emsa.europa.eu/#public/emission-report.

regulations related to carbon emissions and pricing, including market-based measures like the EU-ETS are proposed, which will also influence vessel movements and possibly their bunkering patterns. On top of that, vessel operators and port operators are looking at ways to increase the efficiency of the entire operation. If we can be effective on all levels, we can reach a maximum efficiency of 30-55%. This includes logistics & digitalization, hydrodynamics and machinery. Though efficiency measures, like hull cleaning, can never be perfectly implemented and not all vessels will choose solutions like air lubrication.

These effects are currently kept out of scope, but when actual impact and trends become more apparent these should be considered to make the next iteration.

2.2.4 Future fuels

In the grant agreement, a total of 6 green energy carriers are identified: Methanol, Biodiesel, Hydrogen, Ammonia, LNG and Electricity. Background information on each of these energy carriers is provided in Annex B.

Within this chapter, the energy demand ranges based on 2018 are matched to the specifics of the fuels and vessels. The table below shows the summary of the suitability of fuels for various routes and vessel sizes. The vessel types have been combined into volume limited and weight limited to save space. However, the details provided in this report allow for further refinement follow-up tasks of their supply.

As batteries are heavy and the range is limited to at most a day, electricity is only suited for volume-limited ships on 1-day trips. Hydrogen has a similar limitation, requiring long bunkering times to transfer it, or very expensive bunkering equipment. Unlike batteries, it is primarily volume driven and therefore more suited for the weight-limited vessels on the 1 day and short trips. Biodiesel is almost like regular diesel and thus can be used by all vessels, as it is already available, it can be used also for each time horizon. An LNG installation is relatively expensive and takes up a significant amount of space, this is the reason for not applying it to vessels under 25,000 DWT. Passenger ships could be an exception to this, as they have very high fuel consumption and could benefit from the price difference between LNG and HFO. As these differences are uncertain, it was decided not to add them to this overview. Methanol is already available, albeit primarily grey, also the engine techniques and legislation are already provided, this is why methanol can be used from 2030 onward. As it requires more volume and weight than HFO and diesel, it was decided to not use methanol engines for the 1-day trips as options with less impact on the operations are available there, however, all other ranges could use methanol. Finally, Ammonia is still in the development stage, this means that it is not expected to be market-ready and scalable before 2040, based on time to market for other alternative fuels. In that year the first vessels could sail on it, but as it is a new fuel the short-range was chosen as the most likely start. Despite the fact that ammonia as a fuel will be best suited for the medium- and long-range in the end. The short-range offers a more controlled environment to test the fuel and engine.

Table 8 Alternative Energy Carriers Categorization

1 Day	2030	2040	2050
Volume (Container, Roro, Miscellaneous)	Electricity, Biodiesel, LNG (>25,000)	Electricity, Biodiesel, LNG (>25,000)	Electricity, Biodiesel, LNG (>25,000)
Weight (Bulker, Tanker)	Hydrogen, Biodiesel, LNG (>25,000)	Hydrogen, Biodiesel, LNG (>25,000)	Hydrogen, Biodiesel, LNG (>25,000)
Short (2-4 days)	**2030**	**2040**	**2050**
Volume (Container, Roro, Miscellaneous)	Electricity (<10,000), Biodiesel, LNG (>25,000), Methanol	Electricity (<10,000), Biodiesel, LNG (>25,000), Ammonia, Methanol	Electricity (<10,000), Biodiesel, LNG (>25,000), Ammonia, Methanol

Weight (Bulker, Tanker)	Hydrogen, Biodiesel, Methanol	Hydrogen, Biodiesel, Ammonia, Methanol	Hydrogen, Biodiesel, Ammonia, Methanol
Medium (5-10 days)	**2030**	**2040**	**2050**
Volume (Container/ Roro, Miscellaneous)	Biodiesel, LNG (>25,000), Methanol	Biodiesel, LNG (>25,000), Methanol	Biodiesel, Ammonia, LNG (>25,000), Methanol
Weight (Bulker, Tanker)	Biodiesel, LNG (>25,000), Methanol	Biodiesel, LNG (>25,000), Methanol	Biodiesel, Ammonia, LNG (>25,000), Methanol
Long (>10 days)	**2030**	**2040**	**2050**
Volume (Container/ Roro, Miscellaneous)	Biodiesel, LNG (>25,000), Methanol	Biodiesel, LNG (>25,000), Methanol	Biodiesel, Ammonia, LNG (>25,000), Methanol
Weight (Bulker, Tanker)	Biodiesel, LNG (>25,000), Methanol	Biodiesel, LNG (>25,000), Methanol	Biodiesel, Ammonia, LNG (>25,000), Methanol

2.3 Results

2.3.1 Current energy demand

The table below presents the number of trips as well as the demand in GJ to make the values convertible and identifies the total requirement for each range, vessel type and size category.

Table 9 Current energy demand (min)

		Energy demand in 1000 GJ, trip based – visit based			
	DWT	Day Trips (1 day)	Short trips (2-4 days)	Medium trips (5-10 days)	Long trips (>10 days)
Bulk carriers	0-5000	670 - 163	1317 - 907	640 - 1,003	127 - 506
	5000-10000	145 - 32	236 - 144	148 - 227	106 - 350
	10000-25000	82 - 22	100 - 82	69 - 138	122 - 488
	25000-50000	34 - 8	62 - 41	29 - 43	113 - 481
	50000-75000	18 - 4	26 - 15	23 - 34	74 - 333
	75000-100000	20 - 7	9 - 8	58 - 150	139 - 1,007
	100000-150000	1 - 0	1 -	5 - 14	12 - 102
	150000-200000		2 - 2	9 - 29	117 - 1,385
	200000-250000				19 - 136
	250000-500000				1 - 5
Containers Ro-Ro's	0-5000	88 - 41	157 - 171	8 - 22	2 - 12
	5000-10000	1180 - 649	1415 - 1,855	120 - 414	24 - 266
	10000-25000	2577 - 1,433	2698 - 3,465	244 - 787	58 - 632

	25000-50000	127 - 114	281 - 600	48 - 287	91 - 1,080
	50000-75000	102 - 140	286 - 93	100 - 961	39 - 646
	75000-100000	46 - 67	119 - 431	28 - 303	3 - 63
	100000-150000	75 - 126	245 - 1,033	258 - 3,472	41 - 824
	150000-200000	52 - 106	239 - 1,129	104 - 1,794	2 - 45
	200000-250000	27 - 59	66 - 343	37 - 634	1 - 24
Miscellaneous	0-5000	1484 - 529	223 - 192	81 - 186	72 - 606
	5000-10000	3495 - 1,245	290 - 215	19 - 42	13 - 85
	10000-25000	45 - 15	38 - 35	12 - 29	27 - 188
	25000-50000	545 - 132	46 - 24	5 - 11	12 - 71
	50000-75000	3 - 2	4 - 7	3 - 17	4 - 87
	75000-100000				2 - 29
	100000-150000				1 - 14
	250000-500000			1 - 6,941	2 - 19
Passenger	0-5000	32 - 25	31 - 50	2 - 11	1 - 28
	5000-10000	9 - 17	192 - 757		
	10000-25000	5 - 12	129 - 604		
Tankers	0-5000	2081 - 592	1358 - 985	290 - 533	39 - 179
	5000-10000	789 - 220	955 - 697	286 - 522	81 - 346
	10000-25000	467 - 135	791 - 627	251 - 482	129 - 596
	25000-50000	300 - 105	345 - 333	347 - 818	295 - 1,643
	50000-75000	54 - 17	33 - 33	50 - 121	98 - 545
	75000-100000		9 - 43	27 - 320	28 - 813
	100000-150000	29 - 18	132 - 265	311 - 1,365	155 - 1,681
	150000-200000	9 - 5	32 - 61	41 - 179	130 - 1,568
	200000-250000		13 - 28	8 - 34	44 - 734

In general, it can be observed that on short routes smaller ships are used, while on longer trips larger vessels are dominant. The only exception to this seems to be the Containers / Ro-Ros category. As container ships sail routes with multiple ports in an area before crossing to the other side of the world and repeating this process. This means that there might be relatively more short trips than expected based on the size of the vessel. It could be argued that this underestimates the energy requirement, however, the actual ranges achievable with new fuels is still highly uncertain as this is impacted both by the energy content of the fuel as well as the commercial considerations of the owner and the extent to which a larger ship can be accommodated on the route. The latter refers to the fact that quayside, locks and draft restrictions may apply on the intended route.

When compared to the actual bunkering of 2018 (approximately 10 mln ton), a large discrepancy can be observed. This value is about eight times higher than the energy demand based on trips prior to arrival in the port. This difference can be explained by the role Port of Rotterdam currently has as a bunker hub (belonging to the top three of bunker ports worldwide[3]). This means the vessels visiting Rotterdam currently choose to bunker here instead of elsewhere on their trips. It is uncertain how this changes in relation to the availability and energy density for the alternative fuels, but knowledge of the current bunkering volumes can be used to come to an upper bound estimation for the energy demand. This upper bound will be linked to the current bunkers and follow the current practice more closely. A complex approach could be considered to take into account differences, compensating for the container vessel issue identified and any other aspect. This would however include a large number of assumptions that could all be challenged and discussed. Therefore, a simpler approach was taken and considering Port of Rotterdam is a bunker hub, providing approx. 3% of all bunkers worldwide, each visit was now assumed to bunker a significant amount no matter the trip length. It was discovered that a value of a 25-day consumption per visit would bring the total in line with the total bunkers. This value also aligns with the common bunker capacities of vessels, which is around 30-35 days of sailing. Of course, you do not empty your bunkers, so slightly less is a prudent amount. The results of this are presented in the next table, providing a maximum expected demand, compared to a minimal expected demand as presented in the table above. The two values are the results of two different approaches one bottom-up based on trips and one top-down based on bunker sales and fixing a bunker amount per visit. The chosen future fuel will influence the potential for each trip and vessel type, hence this representation is kept.

It should furthermore be noted that this approach is true for bunker hubs like Rotterdam, however for other ports the first part of the approach is identical, but this result will exceed the bunkering sales of the same year most likely. In that case, the results generated from the maximum, not the minimum energy demand and a different approach has to be identified to match the minimum with the existing demand.

Finally considering the result in the table below, one final note should be made. As the long trips sometimes exceeded the limit of 25 days, the minimum given could be larger than the maximum. For clarity, this has still been presented as the minimum, but of course, for practicality, it should be reversed.

Table 10 Current energy demand (max, based on bunkering at least every 25 days)

		Energy demand in 1000 GJ, trip based – visit based			
	DWT	Day Trips (1 day)	Short trips (2-4 days)	Medium trips (5-10 days)	Long trips (>10 days)
Bulk carriers	0-5000	163 - 4082	907 - 8023	1003 - 3899	506 - 774
	5000-10000	32 - 811	144 - 1320	227 - 828	350 - 593
	10000-25000	22 - 556	82 - 678	138 - 468	488 - 828

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[3] Top 10 Bunkering Ports in the World | Maritime Fairtrade, Bunkering in Rotterdam | Port of Rotterdam

	25000-50000	8 - 190	41 - 347	43 - 162	481 - 633
	50000-75000	4 - 98	15 - 141	34 - 125	333 - 402
	75000-100000	7 - 168	8 - 76	150 - 488	1007 - 1170
	100000-150000	0 - 10	1 - 10	14 - 49	102 - 118
	150000-200000		2 - 23	29 - 102	1385 - 1323
	200000-250000				136 - 139
	250000-500000				5 - 4
Containers Ro-Ro's	0-5000	41 - 1035	171 - 1846	22 - 94	12 - 24
	5000-10000	649 - 16237	1855 - 19471	414 - 1651	266 - 330
	10000-25000	1433 - 35821	3465 - 37503	787 - 3392	632 - 806
	25000-50000	114 - 2858	600 - 6324	287 - 1080	1080 - 2048
	50000-75000	140 - 3490	932 - 9785	961 - 3421	646 - 1334
	75000-100000	67 - 1685	431 - 4359	303 - 1026	63 - 110
	100000-150000	126 - 3148	1033 - 10284	3472 - 10830	824 - 1721
	150000-200000	106 - 2654	1129 - 12198	1794 - 5308	45 - 102
	200000-250000	59 - 1466	343 - 3583	634 - 2009	24 - 54
Miscellaneous	0-5000	529 - 13218	192 - 1986	186 - 721	606 - 641
	5000-10000	1245 - 31120	215 - 2582	42 - 169	85 - 116
	10000-25000	15 - 379	35 - 320	29 - 101	188 - 227
	25000-50000	132 - 3305	24 - 279	11 - 30	71 - 73
	50000-75000	2 - 50	7 - 66	17 - 50	87 - 66
	75000-100000				29 - 39
	100000-150000				14 - 19
	150000-200000			7 - 19	19 - 39
Passenger	0-5000	25 - 613	50 - 594	11 - 38	28 - 19
	5000-10000	17 - 427	757 - 9104		
	10000-25000	12 - 289	604 - 7463		
Tankers	0-5000	592 - 14798	985 - 9657	533 - 2062	179 - 277
	5000-10000	220 - 5497	697 - 6654	522 - 1993	346 - 564
	10000-25000	135 - 3375	627 - 5716	482 - 1814	596 - 932

	25000-50000	105 - 2614	333 - 3006	818 - 3023	1643 - 2570
	50000-75000	17 - 425	33 - 260	121 - 394	545 - 771
	75000-100000		43 - 333	320 - 999	813 - 1036
	100000-150000	18 - 454	265 - 2065	1365 - 4865	1681 - 2425
	150000-200000	5 - 135	61 - 478	179 - 613	1568 - 1944
	200000-250000		28 - 210	34 - 129	734 - 712

2.3.2 Future energy demand

By combining the overview in Table 8 above with the minimum and maximum data on the energy required a possible range for each fuel can be given, not taking into account the competition with other fuels for the same segment. The results of this calculation are given below and serve as a range for the maximum energy demand for each fuel for the Port of Rotterdam. The lower value is solely based on the previous trip, while the higher value assumes a bunkering for 25 days sailing after each trip that arrives in Rotterdam.

Table 11 Total energy demand modality – maritime shipping

	2030 (mln GJ)	2040 (mln GJ)	2050 (mln GJ)
Methanol	49 - 244	49 - 244	49 - 244
Biodiesel	55 - 395	55 - 395	55 - 395
Hydrogen	6 - 72	6 - 72	6 - 72
Ammonia	0 - 0	0.4 - 167	49 - 244
LNG	30 - 130	30 - 130	30 - 130
Electricity	8 - 153	8 - 153	8 - 153

It should be clearly stated that the ranges above cannot be added, there is competition between fuels for different segments of the fleet. For instance, ammonia and methanol are both vying for the same demand, both are not available in a quantity that is even close to the global demand and many aspects can influence which of the two will become the preferred demand. Of course, that is, if biodiesel turns out not to be viable at all e.g., due to political or social concerns. The further research into the supply chains and especially the costs and speed to scale up production once demand is there, will further support these investigations.

2.4 Discussion

2.4.1 Replicability & scalability

The data and method used here, can be used for different ports as well. Due to the significant uncertainties still, it will be relevant to investigate bunkering behaviour more to improve the model and its underlying assumptions.

2.4.2 Validation

As indicated in the results, the results of current energy demand have been checked against the current bunker volumes in Rotterdam, which lead to an indication of a range.

2.4.3 Uncertainties

There are many uncertainties related to the future energy demand in the Port of Rotterdam related to maritime shipping. An important part of this is the fact that marine ships have the flexibility to bunker in other ports, but also that there is no straightforward transition path with a clear energy carrier. Several energy carriers are still being considered and besides technical and safety limitations, availability and commercial viability are very important factors. Therefore, it is important to closely monitor these developments and also stay connected to ship operators who may be first movers in terms of bunker approach and choices.

In the transition period the actual demand might be further complicated by multifuel engines used by vessels as production is a limiting factor as indicated above and supply certainty may be a serious issue, similar to the issues with low sulphur fuels at the start of the sulphur limitations. This means that vessels can select the cheapest fuels in the ports they need to bunker and price has not yet been considered in this demand overview. Although this does come at an extra impact on space requirements within the vessel.

Finally, the simplifications and assumptions made in these estimations can influence the minimum and maximum potential demand as well. Although we believe a good balance was struck, ensuring a realism in the estimations, although this does mean that the future demands are currently less complex. On the other hand, these complexities will be worked out further in the models of T3.6 and support a more in-depth study later on in the project.

2.4.4 Conclusions & recommendations

There is a lot of uncertainty around the future of bunkering for maritime vessels. This is directly related to the choice of fuel and bunkering approach of ship operators. The fuel choice is influenced by safety, availability, commercial viability and technical feasibility. Taking this into account a range is provided for energy demand of the energy carriers investigated in this project: Methanol, Biodiesel, Hydrogen, Ammonia, LNG and Electricity.

The method estimates a minimum and a maximum consumption, based on trip data and the assumption that the maximum bunkering interval is 25 days. This is categorized by ship type, size (in DWT) and trip length to link the energy demand to a future energy carrier. The current energy demand is better described by the bunkering data than by those overviews, which are used to make the future estimate. A total of approximately 9.2M ton was bunkered in Rotterdam in 2018 with an approximate energy of 400 mln GJ.[4]

The result of the translation of the current range in energy demand and suitable energy carrier for the particular category is shown in below table. Be aware that under the first condition the maximum energy demand is 55 mln GJ and under the second condition this is 395 mln GJ. The demands below are maxima and should not be added, they represent the maximum fraction of the total that could be demanded for that particular energy type. Divisions will be modelled later in Task 3.6, as they are complex and multifaceted

Table 12 Total non-exclusive energy demand modality – maritime shipping

	2030 (mln GJ)	2040 (mln GJ)	2050 (mln GJ)
Methanol	49 - 244	49 - 244	49 - 244
Biodiesel	55 - 395	55 - 395	55 - 395
Hydrogen	6 - 72	6 - 72	6 - 72
Ammonia	0 - 0	0.4 - 167	49 - 244
LNG	30 - 130	30 - 130	30 - 130
Electricity	8 - 153	8 - 153	8 - 153

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[4] Bunkering in Rotterdam | Port of Rotterdam

It is clearly visible that different energy carriers have different timelines, this mainly has to do with technical feasibility of the energy carrier.

The range clearly indicates that there is uncertainty, but part of this is also the Port of Rotterdam taking the right actions to enable ship operators to make choices and to ensure attractiveness of bunkering in the port. It is also important to understand the bunkering approach that operators

Items that are interesting to investigate in the future are:

Effect of efficiency measures on energy demand
Effect of rules & regulations on transport movements
Bunkering patterns and approach
Commercial dimension related to global production and availability of alternative energy carriers
Development of transport movements

Different tasks in MAGPIE will aid to remove uncertainties and work towards more insight in the requirements and possibilities.

3 Inland shipping energy requirements

3.1 Context

Inland shipping is one of the most efficient transport modalities in terms of energy consumption per tonne of goods transported, when compared, for example with freight road and air transport[5][6]. Additionally, inland shipping is 50 times safer than road and 3 times safer than rail[7] and given equivalent infrastructure investments, the increment in inland shipping transport capacity for the same investment is 17 times larger than that of road and 3 times larger than that of rail[7].

A significant growth of containers transport is expected, particularly from the port of Rotterdam, over the next years. Although, inland shipping has shown a past stable share of 6% in the EU transport sector[6], this potential for growth stems from the significant unused available capacity of inland shipping and considering also the lower environmental impact compared to other transport modalities. Nevertheless, and considering the significant challenges experienced recently (summer 2022) due to the extensive drought felt throughout Europe, the expansion of the IWT activity may be severely limited in the future. Thus, the scenarios explored in this section do not envision a significant change to the overall volumes transported via inland shipping.

Since freight inland shipping is overwhelmingly based on diesel, there is still a large decarbonization potential for the inland shipping modality. Considering the relatively lower investment needs related to the increase in volume capacity, future scenarios for the decarbonization of the freight transport rely on a significant shift to inland shipping, with improvements envisaged for infrastructure upgrades[5], investment in new technologies and digitalization to improve energy efficiency and emissions reductions due to technology shifts and improved logistics management (e.g., using longer vessels, reducing the number of empty or partial load journeys)[8], and the shift to alternative low-carbon final energy carriers[9][10] e.g., HVO, hydrogen, bio-methanol, bio-LNG, or batteries, some of which will be tested in the MAGPIE project.

To quantify the current and future energy needs and emissions for inland shipping to and from the Port of Rotterdam, a model was developed in Task 3.1.2, covering bulk/goods and container transport, for a reference year (2020) and evolution according to three different scenarios to 2050: a business-as-usual (BAU), conservative (CONS) and an innovative (INOV) pathway. By generating alternative scenarios to the BAU, the model can quantify the impacts of shifting freight activity to the inland shipping mode, technology changes towards zero carbon shipping and the new fuel supply chains (e.g., shifting from diesel to electricity, hydrogen, bio-methanol, bio-LNG). Furthermore, the model is also easily customizable to quantify some of the impact of upscaling some of the solutions being tested

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[5] M. van I. en Waterstaat, 'Inland Shipping - Freight transport - Government.nl', Dec. 12, 2011. https://www.government.nl/topics/freight-transportation/inland-shipping (accessed Jul. 07, 2022).

[6] Karin Jacobs and European Parliamentary Research Service (EPRS), 'Inland waterway transport in the EU'.

[7] A. Fan, J. Wang, Y. He, M. Perčić, N. Vladimir, and L. Yang, 'Decarbonising inland ship power system: Alternative solution and assessment method', *Energy*, vol. 226, p. 120266, Jul. 2021, doi: 10.1016/j.energy.2021.120266.

[8] 'Zero carbon inland shipping?' https://www.workboat.com/viewpoints/zero-carbon-inland-shipping (accessed Jul. 07, 2022).

[9] 'Decarbonization of U.S. waterways poses unique challenges', *Vanderbilt University*. https://engineering.vanderbilt.edu/news/2021/decarbonization-of-u-s-waterways-poses-unique-challenges-2/ (accessed Jul. 07, 2022).

[10] IRENA, 'A pathway to decarbonise the shipping sector by 2050', p. 118.

within the MAGPIE living lab approach, e.g., ZES green container – for battery electric barges.

The geographical scope of the model was discussed with MAGPIE partners, to decide whether the analysis should: (i) cover inland shipping energy requirements within to the port (considering, for example, refuelling and in port consumption) and extended to a limited area close to the port, or (ii) include the energy requirements of all the journeys departing from and arriving to Rotterdam. The spatial boundaries of the study were determined by the available data, and accordingly scope (ii) was adopted for this analysis.

This chapter describes two modelling approaches, one based on a more detailed model, and one based on a simplified model suited to the data collection and availability according to this modelling task timeline. The final approach selected was the simplified model due to the data availability. However, the detailed model may be implemented and used should additional data become available.

It is important to stress that data on inland shipping energy use and emissions is known to be sparce, incomplete, or inconsistent in existing literature[11][12]. There are also scarce public sources of data. An ongoing study for the Port of Rotterdam based on AIS data from vessels (e.g., from HESP - Haven Emissie Service Platform) may be able to provide a more consistent and complete dataset for further analysis, but the outputs of the study will only be available at the end of 2022. Thus, the inland shipping model proposed in this section is based on data from the Prominent project and adopts the vessel type classification proposed therein[13]. This provides a consistent starting point for the quantification of the energy requirements and emissions for the reference year (2020) and the evolution to 2050 as implemented by the BAU, CONS and INOV scenarios.

Another potential source of energy consumption data, that has been used to estimate energy requirements for inland shipping in the scope of the EU[14], and that may be explored in subsequent improvements of the initial estimation presented here, are the datasets containing vessel fuel consumption collected within the "Convention on the Collection, Deposit and Reception of Waste Generated during Navigation on the Rhine and other Inland Waterways" (CDNI) agreement[15]. This reporting system covers most of the inland waterway transport in the Rhine and subsidiaries. However, the datasets are not public but may be available upon request.

3.2 Methodology

3.2.1 Introduction to the methodology

As commented in section 3.1, two methodologies A (simplified) and methodology B (detailed) were developed to estimate the energy requirements of the inland shipping modality covering freight transport to and from the Port of Rotterdam, but only methodology A could be effectively applied considering the immediate availability of data on inland shipping activity and energy use.

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[11] F. Hofbauer and L.-M. Putz, 'External Costs in Inland Waterway Transport: An Analysis of External Cost Categories and Calculation Methods', *Sustainability*, vol. 12, no. 14, Art. no. 14, Jan. 2020, doi: 10.3390/su12145874.

[12] 'D3b - EEA GHG Efficiency Indicators — European Environment Agency'. https://www.eea.europa.eu/publications/rail-and-waterborne-transport/rail-and-waterborne-best/d3b-eea-ghg-efficiency-indicators/view (accessed Jul. 22, 2022).

[13] 'Prominent-IWT'. https://www.prominent-iwt.eu/ (accessed Jul. 07, 2022).

[14] 'Rail and waterborne — best for low-carbon motorised transport — European Environment Agency'. https://www.eea.europa.eu//publications/rail-and-waterborne-transport (accessed Jul. 22, 2022).

[15] CDNI, 'Convention on the Collection, Deposit and Reception of Waste Generated during Navigation on the Rhine and other Inland Waterways', *CDNI*. https://www.cdni-iwt.org/dashboard/?lang=en (accessed Jul. 22, 2022).

The initial plan was to use the detailed model (B) - which takes as inputs data on vessel capacity, fuel type and technology, GHG emissions factors, final energy use during sailing/in port/(un)loading activities and times associated with in port/(un)loading/sailing – as this would allow for greater flexibility in generating future scenarios and better reproduce the energy use for this modality. However, a simplified model (A) had to be developed and used instead due to data inconsistencies and unavailability – e.g., often data originated from various sources adopting different classifications and allocation of types of vessels, inconsistent definition of routes, or types of transported goods.

This section describes the simplified methodology (model A) and its implementation to determine the energy requirements and GHG emissions for a modelled reference year (2020), and to quantify the same outputs until 2050 corresponding to: BAU - a scenario with no additional policies put in place for the sector, CONS – a scenario considering deployment of higher TRL low-carbon and zero-emission technologies for the inland shipping sector, and, INOV – a scenario with accelerated deployment of lower TRL technologies – including Hydrogen, bio-methanol and electricity (battery). These scenarios are based on the scenarios and projections presented in the CCNR report "Study on financing the energy transition towards a zero-emission European IWT sector"[16].

The more detailed approach (model B) is described in section 3.6 and could be a good future reference to be applied when more extensive and detailed data become available following efforts in improved monitoring and data collection.

Methodology A.

This section describes the implementation of model A, including its inputs, outputs, and the mathematical formulation. To evaluate whether model A was overall able to reproduce the current final energy use in inland shipping, a comparison is made for the reference year – 2020, for the total fuel used in IWT calculated by the model and the energy statistics available for this modality (aggregated numbers).

Model A uses as inputs the average GHG emission factors per type of vessel, cargo weight and distance[17] combined with the representative journeys of the Rhine[23], to estimate the total fuel consumption for each vessel type and journey. The calculations for the reference year assume that the fuel use is 100% diesel for all existing vessels. The inputs for model A are shown in Table 13.

The main outputs of model A are the final energy use for the base year and for the BAU, CONS and INOV scenarios to 2050 and the associated emissions. These outputs can be grouped into vessel types, type of cargo or considering the different routes from and to the port of Rotterdam.

Table 13 - Inputs for Model A

Inputs Model A	
Vessel Information	Emission factor per vessel type
	Percentage of cargo type per vessel type
Journey Information	Estimated distance by journey
	Overall cargo transported by journey and cargo type

The calculation of the total energy requirements per year for inland shipping to and from the port of Rotterdam requires information on the specific energy use for each technology –

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[16] CCNR study on energy transition towards a zero-emission inland navigation sector. Available at: https://www.ccr-zkr.org/12080000-en.html .

[17] A. Lewis, 'GHG emission factors for Inland Waterways Transport'. Available at: https://www.smartfreightcentre.org/pdf/GLEC-report-on-GHG-Emission-Factors-for-Inland-Waterways-Transport-SFC2018.pdf

which in this context means the combination of vessel class (or type) and the final energy carrier used. As previously mentioned, these data are available for a vessel classification system that does not match the vessel types that were set as the basis of this analysis after discussions with MAGPIE partners (and corresponding to the classifications used in the PROMINENT project). Thus, the specific energy use per vessel type was instead calculated from reported values for the GHG Emission Factor (EF_t)[17] per vessel type, cargo and kilometre, which had a compatible vessel classification system. The specific consumption ($Scons_t$) per vessel type, cargo (weight in tonnes) and distance (in km), was then calculated according to equation (1), using the values for the diesel GHG Emissions Intensity (D) and the Diesel Energy Density (ED).

$$Scons_t = \frac{EF_t \times ED}{D} \qquad (\text{in } MJ/tkm) \tag{1}$$

With the specific energy use per vessel type, as calculated in equation (1), and using additional data on the weight and type of goods transported per route ($Cargo_j$ shown in Table 15), distance per route/journey ($Dist_j$ shown in Table 16) and the distribution of the cargo transported per cargo and vessel type ($Perc_{t,j}$ shown in Table 17), the total final energy use (consumption) per technology t for a given year can be calculated according to equations (2) and (3). Each journey is represented by the subindex j.

$$TC_{t,j} = Cargo_j \cdot Perc_{t,j} \qquad (\text{in } MJ) \tag{2}$$

$$Cons_t = Scons_t \cdot TC_{t,j} \cdot Dist_j \qquad (\text{in } MJ) \tag{3}$$

3.2.2 Variables & (data) sources

The data sources for the full set of input data necessary for the implementation of model A, including the data available from the PROMINENT Project, are shown in Table 14.

The cargo transported shown in Table 15 and the Estimated Distance shown in Table 16 for the reference year for each journey used in model A have as the main source the Annex A2 of the Prominent project[18], where only the routes that have Rotterdam as destiny or origin were considered. It is important to note that the estimated distance of each journey j given in Table 16 is related to the one-way journey from origin to destiny, without considering the roundtrip. This means that the energy use for potentially empty returns was not considered in the preliminary calculations for the energy requirements for the base year and the BAU scenario.

Finally, there is a need to allocate the different vessel types to the journeys in Table 15, but since these data were not readily available, an estimation of which vessel type can carry which cargo type was made. This assumption carries several implications, such as the fact that it is always considered that vessels can navigate any route, regardless of any physical limitations for specific waterways.

The estimated allocation of cargo per vessel type is presented in Table 17 and was used to establish the relationship between vessel types and the type of cargo transported, which was

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[18] Stichting Projecten Binnenvaart, 'D1.1 List of operational profiles and fleet families – V2 (PROMINENT Project)'. [Online]. Available: https://www.prominent-iwt.eu/wp1-state-of-play/ , Annex A2.

then combined with the data presented in Table 16 to determine the activity per journey presented in Table 15.

Table 14 - Data sources

Data	Source
Vessel types	Port of Rotterdam and PROMINENT Project [23]
Representative journeys for the Rhine / ARA	PROMINENT Project (WP1 Annex A3)[23]
Max. Payload per vessel type and representative journey for 1 year (t)	PROMINENT Project (WP1 Annex A3)[23]
Waiting/(un)loading time per type of vessel and representative journey for 1 year (h)	PROMINENT Project (WP1 Annex A3)[23]
Average speed per type of vessel and representative journey for 1 year (km/h)	PROMINENT Project (WP1 Annex A3)[23]
Distance per type of vessel and representative journey for 1 year (round trip in km)	PROMINENT Project (WP1 Annex A3)[23]
Total power main engines per type of vessel and representative journey for 1 year (kW)	PROMINENT Project (WP1 Annex A3)[23]
Total time roundtrip incl. waiting time / (un)loading (hours) per type of vessel and representative journey for 1 year (h)	PROMINENT Project (WP1 Annex A3)[23]
Distance per journey for 1 year (km)	PROMINENT Project (WP1 Annex A2)[23]
Tonnes of cargo type by journey for 1 year (t)	PROMINENT Project (WP1 Annex A2)[23]
Percentage of Cargo type per vessel type (%)	Delta Port and Federal Statistic Office of Germany
Diesel CO2 Intensity - European Standard EN16258 (g_CO2e / l_Diesel)	GLEC Report on GHG Emission Factors for Inland Waterways Transport[17]
Emission factor per type of vessel, cargo weight and km (g_CO2e /t/km)	GLEC Report on GHG Emission Factors for Inland Waterways Transport[17]

Table 15 - Overall cargo transported (ton) by journey[12].

Origin	Destination	Agricultural products	Foodstuffs and animal fodder	Solid mineral fuels	Petroleum products	Ores and metal waste	Metal products	Crude and manufactured minerals, building materials	Fertilizers	Chemicals	Machinery, manufactured articles and misc.
Rotterdam	Duisburg	54531	1689372	5285750	1773883	16043974	889847	1300875	8165	1259520	2442229
Rotterdam	Antwerp	54255	144114	44885	631432	131581	187201	608386	25885	186781	19983784
Rotterdam	Amsterdam	56176	667677	44922	7631208	86620	94776	831260	7316	2419064	1357125
Moerdijk	Rotterdam	221375	402523	124187	835797	61260	56868	1236012	6549	551809	2051112

Terneuzen	Rotterdam	104574	73705	59039	1310065	86222	26454	1371067	72849	1002608	624315
Rotterdam	Gent	36067	332434	225906	793266	153775	39478	719498	37773	261460	1770706
Rotterdam	Karlsruhe	73555	12626	0	2669405	236957	23363	180881	2411	610870	98571
Rotterdam	Ludwigshafen am Rhein	20371	757053	5531	769299	0	26414	358	84267	1345312	755373
Rotterdam	Herne	604	4975	2184994	1022195	24839	123660	216522	0	22677	40
Rotterdam	Nijmegen	228554	466978	60527	1649358	79892	33655	606020	1016	148256	284178
Maastricht	Rotterdam	92315	54788	235916	618137	68656	29356	1317370	26326	306566	726462
Rotterdam	Utrecht	34887	76125	0	767020	493	1076	1531288	14683	56930	804134
Rotterdam	Liège	7247	7586	601571	537266	68300	17303	419877	10359	143472	897546
Rotterdam	Köln	0	5706	27421	665859	88585	31696	69660	0	1335183	424753
Rotterdam	Kampen / Zwolle	105992	350504	1930	1045466	71598	51	36914	2539	47758	548487
Rotterdam	Strassbourg	322368	86676	0	725462	93274	39777	284306	426	364553	206089
Rotterdam	Groningen / Harlingen	6086	44946	1873	447271	3870	9685	786043	0	158654	328180
Rotterdam	Gutavsburg	0	0	0	1051236	0	0	1326	1444	75575	383627
Rotterdam	Basel	34145	56617	74697	28209	5517	12116	25149	351	9935	1201445
Rotterdam	Breisach	0	4775	0	134438	169403	34369	921350	0	56559	26639
Rotterdam	Oldenburg	45066	744691	81119	217492	0	33585	0	366	178760	9029
Rotterdam	Gelsenkirchen	31339	16775	0	456795	69167	2203	118037	0	518103	686
Rotterdam	Genk	1726	4154	6264	169617	70999	41258	314447	32159	172092	336467
Rotterdam	Koblenz	0	3508	2765	515416	3907	50767	347421	0	55411	139044
Rotterdam	Thionville	0	0	688984	1004	104019	13522	69.534	0	128619	4871

Table 16 - Estimated distance (km) by journey [23]

Origin	Destiny	Estimated distance (km)
Rotterdam	Duisburg	253.95
Rotterdam	Antwerp	153.47
Rotterdam	Amsterdam	126.83
Moerdijk	Rotterdam	98.62
Terneuzen	Rotterdam	166.01
Rotterdam	Gent	222.00
Rotterdam	Karlsruhe	928.24
Rotterdam	Ludwigshafen am Rhein	424.20
Rotterdam	Herne	343.75
Rotterdam	Nijmegen	167.63
Maastricht	Rotterdam	245.88
Rotterdam	Utrecht	79.82
Rotterdam	Liège	330.03
Rotterdam	Köln	281.11

Rotterdam	Kampen / Zwolle	269.76
Rotterdam	Strasbourg	789.36
Rotterdam	Groningen / Harlingen	365.36
Rotterdam	Gutavsburg	581.58
Rotterdam	Basel	910.78
Rotterdam	Breisach	928.24
Rotterdam	Oldenburg	450.00
Rotterdam	Gelsenkirchen	281.11
Rotterdam	Genk	266.82
Rotterdam	Koblenz	424.20
Rotterdam	Thionville	742.32

Table 17 - Percentage of Cargo type per vessel type (the "Push boats" category includes push boats covering rated power of <500kW, 500 to 2000kW and above 2000kW, which are typically represented as 3 distinct categories).*

Vessel Type (vert.) & Cargo type (horiz.)	Push boats*	Motor vessel dry cargo ≥ 110m	Motor vessel liquid cargo ≥ 110m	Motor vessel dry cargo 80-109m	Motor vessel liquid cargo 80-109m	Motor vessels <80 m	Coupled convoys
Agricultural products	0.0%	44.9%	0.0%	41.7%	0.0%	6.3%	7.1%
Foodstuffs and animal fodder	0.0%	10.2%	9.9%	22.1%	43.2%	13.0%	1.4%
Solid mineral fuels	42.5%	23.6%	0.0%	19.1%	0.1%	0.5%	14.2%
Petroleum products	1.5%	0.0%	29.9%	0.0%	67.4%	1.3%	0.0%
Ores and metal waste	61.4%	17.8%	0.6%	12.5%	0.0%	0.9%	6.8%
Metal products	0.0%	48.9%	0.0%	40.0%	0.0%	6.7%	4.3%
Crude and manufactured minerals, building materials	0.0%	74.3%	0.0%	22.1%	0.0%	1.3%	2.3%
Fertilizers	0.0%	25.9%	0.0%	57.2%	0.0%	6.5%	10.4%
Chemicals	0.3%	18.6%	10.7%	9.9%	57.4%	1.4%	1.6%
Machinery, manufactured articles and misc.	0.0%	86.3%	0.0%	9.4%	0.0%	0.4%	3.9%

3.2.3 Categorization

The categorization of the vessel types was discussed with the MAGPIE partners, and a classification corresponding to the one adopted by the PROMINENT Project was adopted. The categories used in this analysis are shown in Table 18.

Table 18 - Vessel types considered in this analysis

General Category	Vessel Type
Push boats	Push boats < 500 kW (total propulsion power)
	Push boats 500-2000 kW (total propulsion power)
	Push boats ≥ 2000 kW (total propulsion power)
Motor vessels liquid cargo	Motor vessel liquid cargo 80-109m length
	Motor vessel liquid cargo ≥ 110m length
Motor vessel dry cargo	Motor vessel dry cargo 80-109m length
	Motor vessel dry cargo ≥ 110m length
Other Motor vessels	Motor vessels <80 m. length
Coupled convoys	Coupled convoys (mainly class Va + Europe II lighter)

3.2.4 Estimation of total energy demand to 2050

To estimate future energy requirements for IWT to 2050, three future scenarios were considered, with different underlying assumptions in adoption of low- and zero- emissions technologies for IWT for a given evolution of inland shipping activity and of the fleet in line with the BAU, conservative (CONS) and innovative (INOV) scenarios considered in the recent CCNR study on the transition of the European IWT sector[19].

Accordingly, the scenarios adopted in this analysis, consider the following evolution in fleet, cargo transported and vessel technologies:

- Overall inland shipping freight transport activity has only modest changes to 2050 (approximately 6% increase in tkm relative to the reference year).
- The rates of change in fleet proposed in the CCNR study are adopted for the individual vessel types considered in this analysis (as per Table 21).
- For the reference year, the vessel technologies are assumed to be fuelled by diesel only, with the fleet corresponding to the composition described in the PROMINENT project, as this was the basis for the data used in the calculations for the base year (the small percentage of LNG vessels is not considered).
- For future fuels:
    - For the BAU scenario, mainly technologies based on use of diesel were considered (e.g., replacement of existing fleet of unregulated or CCNR 1 engines by CCNR 2 or stage V diesel technologies) with a small share (less than 1% of overall final energy for IWT) of LNG in 2050 for some vessel types,
    - For the CONS and INOV scenarios, the change in technologies is taken from CCNR analysis, and is presented in Table 19 and Table 20 respectively.
- The future demands up to 2050 by vessel category were then estimated on a yearly basis for all scenarios considering the changes in technologies, the distribution of activity (in tkm) per different routes and vessel category, and the specific energy consumption presented in Table 22.
- The specific energy consumption for the existing technologies in the reference year (2020) calculated according to equation (1) was used as the basis for the estimation of the specific energy consumption for the other fuels, based on information from the CCNR report and other sources, and own assumptions (as reported in Table 22)

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[19] Central Commission for the Navigation on the Rhine (CCNR), 'Assessment of technologies in view of zero-emission IWT - Edition 2'. [Online]. Available: https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf

Table 19 - Shares of future technologies and carriers by vessel category for CONS scenario (source CCNR[19]).

		Push Boats		Motor vessel dry cargo ≥110m		Motor vessel liquid cargo ≥110m		Motor vessel dry cargo 80-109m		Motor vessel liquid cargo 80-109m		Motor vessels <80 m		Coupled convoys	
Technology	**Energy Carrier**	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050
CCNR2 and below	Diesel	31%	0%	5%	0%	0%	0%	34%	0%	13%	0%	40%	0%	0%	0%
CCNR2 + SCR		1%	0%	10%	0%	0%	0%	6%	0%	16%	0%	2%	0%	0%	0%
Stage V ICE		41%	19%	52%	15%	58%	20%	32%	10%	42%	5%	29%	5%	67%	15%
Stage V ICE	HVO	26%	61%	25%	35%	23%	30%	26%	50%	26%	55%	26%	64%	24%	42%
LNG ICE	LNG	0%	0%	5%	0%	10%	0%	0%	0%	0%	0%	0%	0%	5%	0%
Bio-LNG ICE	Bio-LNG	0%	0%	3%	35%	9%	40%	0%	0%	0%	0%	0%	0%	3%	33%
Battery	Electricity	1%	8%	0%	5%	0%	0%	1%	15%	1%	10%	1%	10%	1%	10%
H2 FC	Hydrogen	1%	8%	0%	5%	0%	5%	0%	5%	0%	5%	0%	5%	0%	0%
H2 ICE		0%	0%	0%	0%	0%	0%	0%	5%	0%	5%	0%	0%	0%	0%
MeOH FC	Bio-methanol	0%	3%	0%	0%	0%	0%	1%	10%	1%	15%	1%	8%	0%	0%
MeOH ICE		0%	0%	0%	5%	0%	5%	0%	5%	0%	5%	1%	8%	0%	0%

Table 20 - Shares of future technologies and carriers by vessel category for INOV scenario (source CCNR[19]).

		Push Boats		Motor vessel dry cargo ≥110m		Motor vessel liquid cargo ≥110m		Motor vessel dry cargo 80-109m		Motor vessel liquid cargo 80-109m		Motor vessels <80 m		Coupled convoys	
Technology	**Energy Carrier**	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050
CCNR2 and below	Diesel	31%	0%	0%	0%	0%	0%	34%	0%	14%	0%	42%	0%	0%	0%
CCNR2 + SCR		1%	0%	5%	0%	0%	0%	6%	0%	16%	0%	2%	0%	0%	0%
Stage V ICE		48%	17%	57%	15%	62%	15%	32%	15%	42%	10%	34%	20%	48%	20%
Stage V ICE	HVO	9%	6%	10%	5%	20%	5%	10%	5%	10%	5%	10%	5%	21%	15%
LNG ICE	LNG	0%	0%	5%	0%	5%	0%	0%	0%	0%	0%	0%	0%	5%	0%
Bio-LNG ICE	Bio-LNG	0%	0%	12%	20%	7%	20%	0%	0%	0%	0%	0%	0%	6%	15%
Battery	Electricity	8%	31%	7%	20%	1%	10%	13%	30%	12%	25%	7%	20%	11%	10%
H2 FC	Hydrogen	0%	6%	2%	20%	1%	15%	1%	15%	1%	15%	2%	20%	5%	5%
H2 ICE		1%	15%	0%	5%	0%	5%	1%	15%	2%	20%	2%	20%	1%	10%
MeOH FC	Bio-methanol	0%	1%	0%	5%	2%	20%	0%	5%	1%	15%	0%	5%	0%	5%
MeOH ICE		2%	24%	1%	10%	1%	10%	1%	15%	1%	10%	1%	10%	2%	20%

3.2.5 Assumptions

The following assumptions were made in this analysis:

- Overall:
    - It is assumed that the current fleet uses 100% diesel technologies.
    - Vessels are assumed to travel at 100% capacity in each journey and energy requirements of return journeys are not considered in model A.
- Energy requirements for the reference year – 2020:
    - This study considers 2020 as the reference year, but this does not correspond to real 2020 data - the fleet data from the PROMINENT project are from 2013/2014 and the GHG intensity factors that were used to calculate the specific final energy consumption for the different vessel types are for year 2019. Thus, it was assumed that the composition and overall number of vessels in the fleet in 2020 is the same as that of 2013/2014 and that there is no change in the GHG emission factors or IWT activity from 2019 to 2020.
- Energy requirements and GHG for future scenarios:
    - The BAU, CONS and INOV scenarios consider that the total volumes and types of goods transported, and the distribution per type of vessel, stay the same though to 2050, and that any improvements in the fleet are due to renewal of the fleet and introduction of more efficient technologies according to the specific technology adoption strategies for each scenario.
    - Another important assumption, in line with the CCNR report, is that the fleet renewal is accompanied by a change in the relative composition of the fleet with total number of vessels in some categories expected to increase while others decrease to 2050, according to the percentage changes presented in Table 21.
    - Several assumptions were made for the specific consumption of the new technologies, which are defined from the measured specific energy efficiency of different vessel types taken from the PROMINENT project. The assumptions for each technology and final energy carrier are described in Table 22.
    - Finally, an overall improvement in efficiency of the whole fleet of 15% through to 2050 was also considered in the analysis, in line with the CCNR report. This is the result of more efficient practices in the sector (e.g., digitalization, improvements in logistics operations, driving more efficiently).

Table 21 - Number of vessels per type in 2020 and changes through to 2050.

Vessel type	Number of vessels per type in 2020	Change in number of vessels from 2020 to 2050
Push boats	1155	-23%
Motor vessel dry cargo ≥ 110m length	580	19%
Motor vessel liquid cargo ≥ 110m length	599	11%
Motor vessel dry cargo 80-109m length	1713	-3%
Motor vessel liquid cargo 80-109m length	631	5%
Motor vessels <80 m. length	4282	-57%
Coupled convoys (mainly class Va + Europe II lighter)	140	21%

Table 22 – Specific final energy consumption (in MJ/tkm) considered for the different energy carriers and technologies per vessel category.

Technology	FE vector	Push Boats	Motor vessel dry cargo ≥110m	Motor vessel liquid cargo ≥110m	Motor vessel dry cargo 80-109m	Motor vessel liquid cargo 80-109m	Motor vessels <80 m	Coupled convoys	Assumptions
CCNR2 and below	Diesel	0.12691	0.20697	0.20076	0.21638	0.21638	0.32650	0.18063	From PROMINENT project[13]
CCNR2 + SCR		0.12818	0.20904	0.20277	0.21854	0.21854	0.32977	0.18243	1% more compared to CCNR2[16]
Stage V ICE		0.12567	0.19662	0.19072	0.20556	0.20556	0.31018	0.17160	3% more for <300kW, 5% less for >300kW[20]
Stage V ICE	HVO	0.12567	0.19662	0.19072	0.20556	0.20556	0.31018	0.17160	Same as for diesel stage V
LNG ICE	LNG	0.13196	0.20645	0.20026	0.21584	0.21584	0.32569	0.18018	5% more energy consumption than diesel (CCNR study[16])
Bio-LNG ICE	Bio-LNG	0.13196	0.20645	0.20026	0.21584	0.21584	0.32569	0.18018	Same as LNG
Battery	Electricity	0.05907	0.09241	0.08964	0.09661	0.09661	0.14578	0.08065	47% of diesel stage V, based on EV for road from CE Delft study[20]
H2 FC	Hydrogen	0.08860	0.13862	0.13446	0.14492	0.14492	0.21868	0.12098	1.5 times energy use of EV[20]
H2 ICE		0.12567	0.19662	0.19072	0.20556	0.20556	0.31018	0.17160	Same as stage V diesel (own assumption)
MeOH FC	Bio-methanol	0.08860	0.13862	0.13446	0.14492	0.14492	0.21868	0.12098	Same as H2 FC (own assumption)
MeOH ICE		0.12567	0.19662	0.19072	0.20556	0.20556	0.31018	0.17160	Same as stage V diesel (own assumption)

3.3 Results

3.3.1 Current energy demand

The energy requirements in 2020 per vessel type associated with the inland shipping transport to and from the port of Rotterdam according to model A, are shown in Table 23 and Figure 1. As mentioned before, the data used for the estimation of the energy requirements refer to different years, but it is assumed that there are no significant changes in the IWT fleet composition, technologies and volumes of goods transported between 2013 and 2020.

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[20] CE Delft, 2020. "STREAM Freight Transport 2020 - Emissions of freight transport modes". Available at: https://cedelft.eu/publications/stream-freight-transport-2020/

Table 23 - Total Consumption by Vessel type in reference year, $Cons_t$.

Vessel type	Total Diesel Consumption (millions l)	Total Final Energy Use (in TJ)
Push boats	15. 62	560.10
Motor vessel dry cargo ≥ 110m length	70.50	2527.60
Motor vessel liquid cargo ≥ 110m length	17.01	610.10
Motor vessel dry cargo 80-109m length	23.68	849.00
Motor vessel liquid cargo 80-109m length	50.02	1 793.70
Motor vessels <80 m. length	5.35	191.73
Coupled convoys (mainly class Va + Europe II lighter)	6.53	234.30
Total Diesel Consumption IWT to and from Port of Rotterdam	188.71	6 766.50

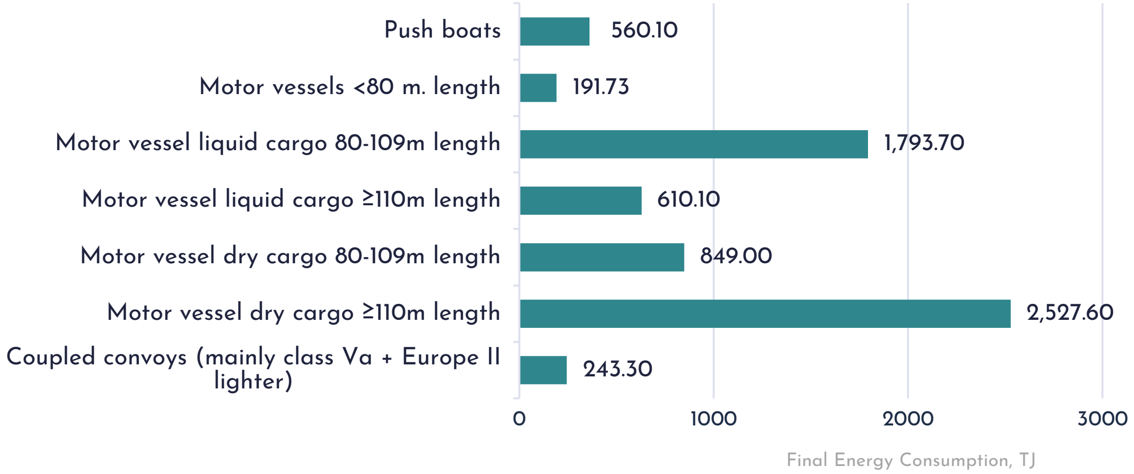

Figure 1 – Final Energy Consumption (TJ) by Vessel type, $Cons_t$.

The results show that transport with two vessel types – motor vessels transporting dry cargo (longer than 110m in length) and motor vessels transporting liquid cargo (80 to 109m in length) – are responsible for about two thirds (66%) of the total energy requirements of the freight inland shipping transport to and from the port of Rotterdam. Taking a closer look at the type of goods transported per vessel type (as per Figure 2 showing total final energy consumption by vessel and cargo type), the energy consumption of dry cargo motor vessels of more than 110m in length is associated with the transport of "machinery, manufactured goods and other goods" (54%), and "manufactured minerals and building materials" (22%). For the motor vessels of 80 to 109m length transporting liquid cargo, final energy use is related with the transport of petroleum products (67%), followed by chemicals and food products and animal fodder. This is particularly relevant since the expected reduction in use of fossil fuels and electrification, or otherwise substitution of fossil fuels by low-carbon alternatives, in the transport and industry sectors will have a major impact on the consumption of petroleum products. This means that the overall liquid cargo transport should also change very significantly in terms of volumes and composition of cargo transported.

The results also show that the transport of petroleum products, and machinery, manufactured and other products, are associated with approximately 50% of the total final energy use within the inland shipping modality. Additionally, the motor vessels 80-109m and over 110m in length carrying dry cargo, are the vessels that carry the biggest diversity of cargo types overall.

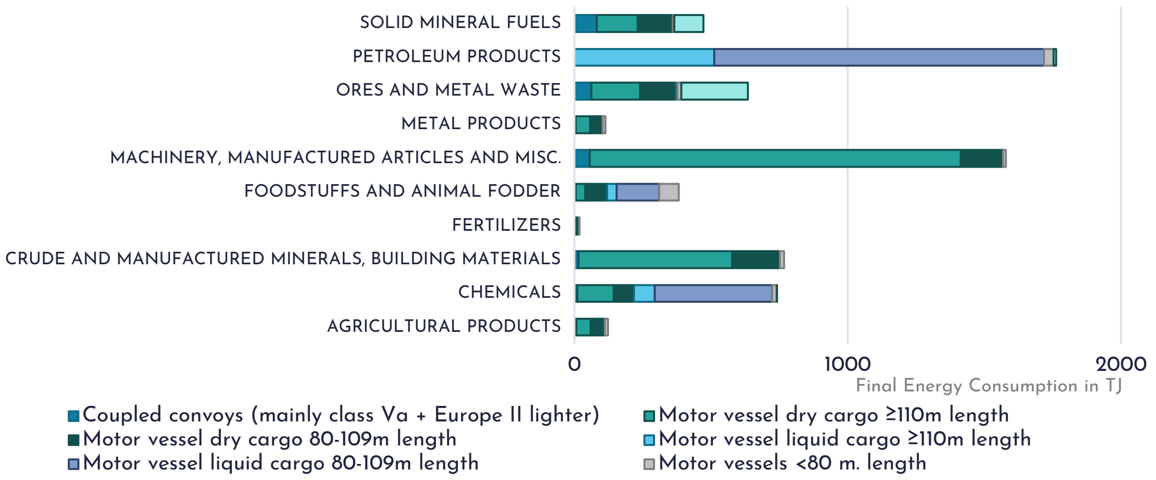

Figure 2 - Total final energy consumption (in TJ) by vessel and cargo type.

Considering the disaggregation of the energy use by vessel type and route, as per Figure 3, three routes – Rotterdam-Duisburg, Rotterdam-Karlsruhe, and Rotterdam-Antwerp -, represent approximately 45% of the total final energy use of the inland shipping transport to and from the Port of Rotterdam.

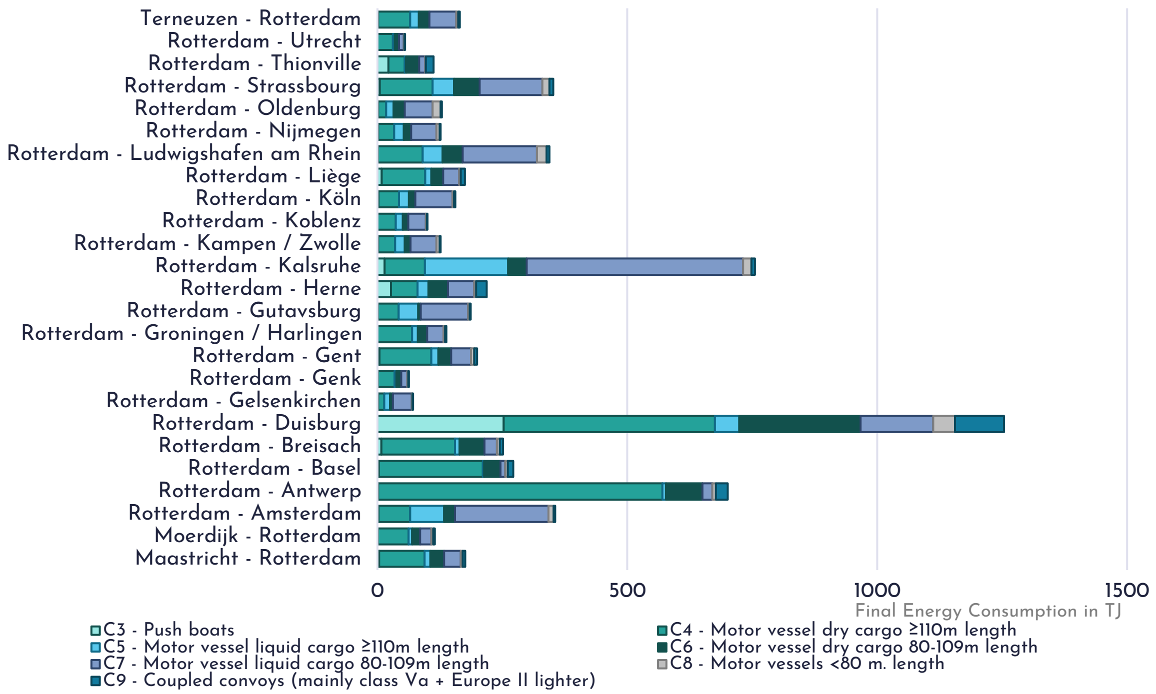

Figure 3 - Total final energy consumption (in TJ) by Vessel type and Journey j.

The relative final energy use per route, follows closely the transport activity of each route (Figure 4). The route of *Rotterdam – Duisburg* has the overall highest final energy consumption, which is due to this route having the highest overall transport activity – combination of weight transported and distance travelled. The two main cargo types transported through this route are "ores and metal waste" and "mineral solid fuels" (e.g., coal). The *Rotterdam – Karlsruhe* route has the second highest final energy consumption, corresponding to the route with the second highest transport activity, transporting petroleum products, and to a lesser extent, chemicals. The route of *Rotterdam – Antwerp* has the third highest final energy consumption, transporting mainly "machinery, manufactures articles and other miscellanea goods".

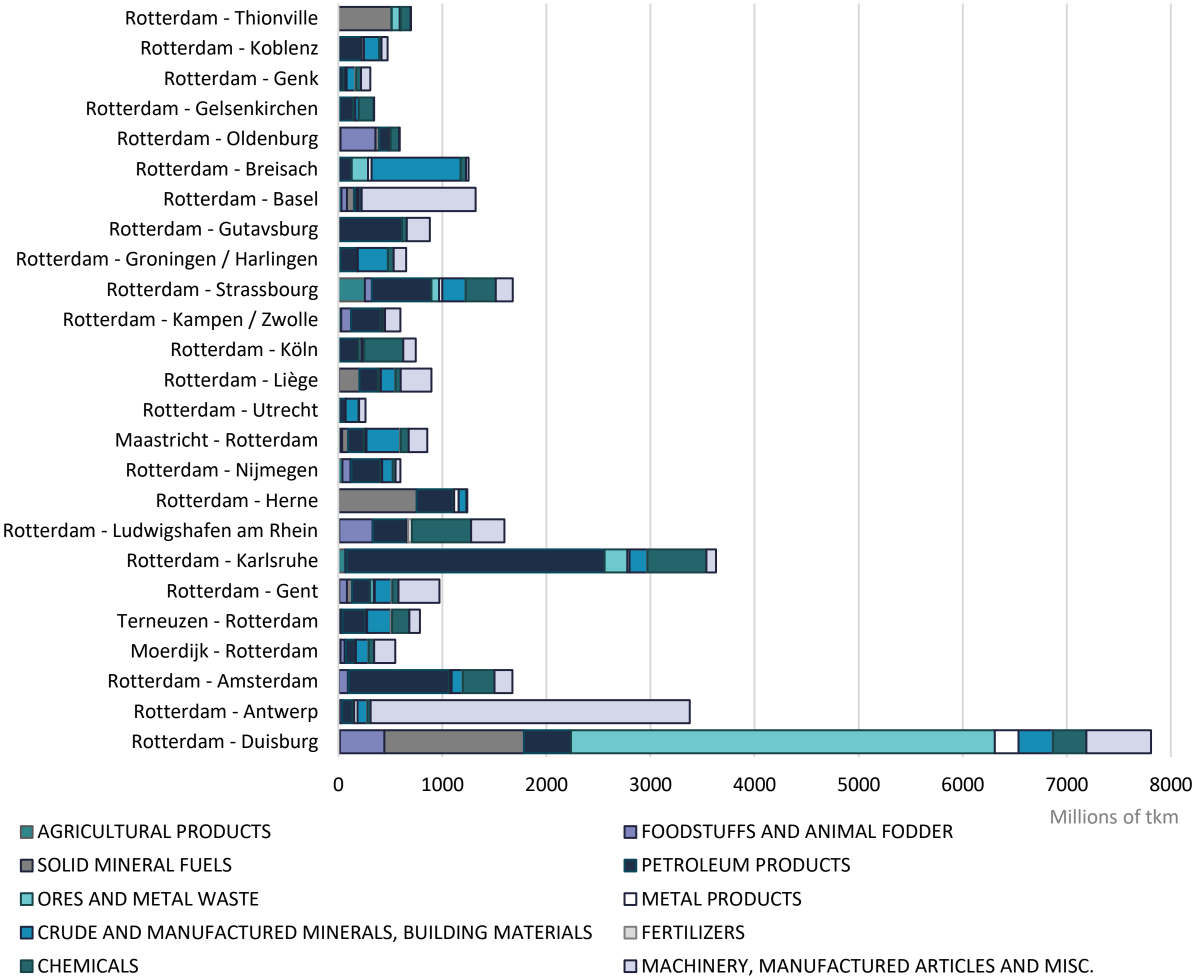

Figure 4 - Inland shipping to and from the Port of Rotterdam by cargo and journey in millions of tkm for the base year (transport activity) based on data from the PROMINENT project.

3.3.2 Future energy demand

Considering the current transport activity for inland shipping to and from the Port of Rotterdam, in terms of the types of goods transported, the ongoing energy transition is likely to have a significant impact on this modality in the time horizon till 2050. Especially considering the goals to reduce the use of petroleum products in the transportation sector and the eventual phase out fossil fuel-based combustion technologies (for heat and electricity generation). Additionally, the changes in fuel use and introduction of circular economy principles in the industrial sector will also have an impact on transport activity. On the other hand, the transport of fossil fuels may be partially substituted by the transport of new decarbonized or low-emission carriers (e.g., biomass, hydrogen) as the deployment of new technologies that use them accelerates. This means that the inland waterways transport activity of all the routes represented in Figure 4, used in the estimation of the energy requirements for the reference year (2020), are likely to undergo substantial changes in the timeline of 2020 to 2050. This change in activity, alongside changes in vessel technology, introduction of low-carbon and renewable final energy carriers (e.g., electricity, bio-LNG, hydrogen, bio-methanol), increased capacity of vessels, digitalization and improved logistics operations will lead to a significant reduction in primary energy use and in the overall GHG emissions of inland shipping.

Even though the decarbonization of the economy is likely to have a significant impact on inland shipping activity, and thus on energy requirements, the analysis presented here considers that overall activity remains very similar to current IWT activity (with 6% increase in total tkm to 2050).

As described in the previous section, the BAU, CONS and INOV analyses are based on a similar approach considered in the recently published CCNR analysis of inland shipping decarbonisation. All scenarios consider the technology deployment and changes in the relative composition of the vessel fleet transporting cargo to and from Rotterdam shown in Table 19, Table 20 and Table 21, with some classes of vessels increasing their total number while other decrease, and assuming more efficient operations of inland shipping transport overall, resulting from digitalisation, improved integration of transport modes and smart logistics. The overall results of the analysis are shown in Table 24 and Figure 5. Further details of the outputs can be found in Annex C.

Table 24 – Final energy consumption for the BAU, CONS and INOV scenarios.

Final Energy in TJ	**REF**	**BAU**			**CONS**			**INOV**		
Energy carrier	2020*	2030	2040	2050	2030	2040	2050	2030	2040	2050
Diesel (CCNR2 and below)	6766	3834	1861	732	2690	519	0	2616	449	0
Diesel (CCNR2+SCR)	0	451	612	526	403	382	0	315	298	0
Diesel (Stage V)	0	1821	3095	3882	1683	1813	618	1799	1954	707
HVO	0	0	0	0	907	1630	2182	406	480	270
LNG	0	32	45	41	115	109	0	98	92	0
Bio-LNG	0	0	0	0	79	433	1014	209	395	558
Electricity	0	0	0	0	8	69	173	147	317	504
Hydrogen FC	0	0	0	0	1	63	175	38	235	564
Hydrogen ICE	0	0	0	0	0	32	92	29	221	549
Bio-methanol FC	0	0	0	0	10	75	185	11	119	306
Bio-methanol ICE	0	0	0	0	1	79	222	40	248	595
Total	6766	6138	5613	5180	5898	5203	4661	5707	4808	4053

The results show that for the BAU scenario the total energy requirements for inland shipping will decrease, but only by approximately 23% with the final energy requirements in 2050 relative to the reference year 2020. This scenario does not meet the goal of reaching zero-emission IWT (or at least 80% of GHG emissions reductions relative to 2015). The scenarios that do meet at least 80% GHG emissions reductions, the CONS and INOV, show significant final energy consumption reduction (31% and 40%, respectively) and a profound change in the technologies and energy carries for all vessel types. The results also show that in the CONS scenario, the decarbonization of the sector is mainly driven by replacement of diesel technologies by the biofuels, specifically uptake of HVO and bio-LNG. Finally, for the INOV scenario, today's technologies are replaced by technologies driven by biofuels (bio-LNG, bio-Methanol), hydrogen and electricity.

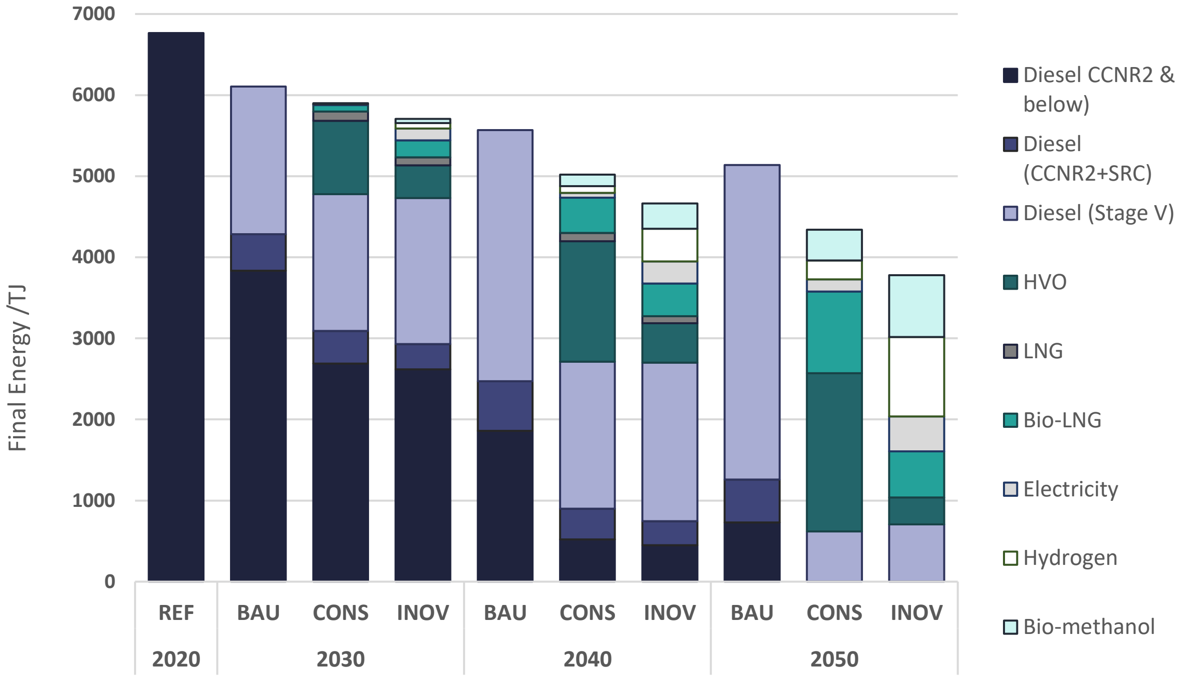

Figure 5 - Final energy consumption through to 2050, for all scenarios considered in the analysis.

3.4 Discussion

3.4.1 Replicability & scalability

Model A has been successfully used to calculate the energy requirements of the different scenarios for the evolution of the inland shipping energy demand through to 2050. Model B (section 3.6) could not be applied due to the current lack of data. However, this situation is expected to change considering the current focus on ports energy and emissions assessment and reduction strategies, which need new metering and data collection processes.

Both models are easily customisable to estimate the energy demand for additional scenarios for 2050 considering alternatives for the changes in type of cargo transported, changes in routes, different decarbonization strategies considered both for all economic sectors, as well as within the modality for different vessel types and the whole fleet. Additionally, it is expected that the results from the MAGPIE demonstrations that are related to inland shipping, green logistics and digitalization will be easily incorporated into the model when available.

3.4.2 Validation

To validate the model outputs, the calculated total diesel consumption for IWT for the base year was compared with the real Total Diesel Consumption calculated from literature values, as described below.

The output of model A, i.e., **1.88×10^{8}** litres as the base year final energy consumption to and from the port of Rotterdam, from Table 23, was compared with the literature values corresponding to the total diesel consumption for inland shipping in Europe for 2016 available from Reference[19] reports, which was 1.6 million tonnes of diesel. Considering the diesel density of $0.85\ (kg/l)$, the Diesel Fuel consumption for 2016 for Europe for IWT was thus $(1.6\ \times\ 10^{9}) \times 0.85 = 1.36 \times\ 10^{9}$ litres.

Existing data shows that the Netherlands accounts for 42% of all transported goods in Europe, for inland shipping navigation[21]. Additionally, Eurostat statistics[22] indicate that, on average for the last 10 years (2012 to 2021), 359 million ton of goods were transported in the Netherlands. These should then represent 42% of all Europe diesel consumption for inland shipping (for the year 2015, 1.6 million tonnes corresponding to 1 360 million litres)[19].

According to the values shown in Table 15, the goods transported from and to the port of Rotterdam add up to 123.7 million tonnes, which represents approximately 34% of all goods transported in the Netherlands. Using this same proportion to calculate the diesel consumption for inland shipping the overall final energy consumption that corresponds to the transport to and from Rotterdam is estimated at $1.36 \times 10^{9} \times 42\%\ \times 34\% = \mathbf{1.94} \times\ \mathbf{10^{8}}$ litres of diesel, which deviates 3% from the model A output.

This deviation is not considered significant and is an indication that the values calculated for the energy requirements corresponding to the base year are in accordance with general statistics for the modality. At least some of the difference may result from the approximation of considering that the routes shown in Table 15 represent all the journeys to and from the port of Rotterdam, and due to the approximation in the model of not considering the energy use of empty return of vessels.

3.4.3 Uncertainties

The uncertainty in the estimated energy requirements for the base year and BAU, CONS and INOV scenarios stem from the data, the use and approximations made in model A and the assumptions of the future scenarios. Specifically,

(i) the allocation of cargo per vessel type, for which no information was found specific to the routes with origin and destination in Rotterdam, may be a significant source of error,

(ii) the use of average emissions for each vessel type as the starting point for the calculation of specific energy use per weight of cargo transported per each type of vessel – a better alternative is the use of the specific energy use per vessel type of the fleet that serves the route from and to the port of Rotterdam,

(iii) the empty journeys were not considered, which leads to underestimating the energy needs – an additional term can be considered to account for the energy use of empty and partial load journeys, especially applied to model B (section 3.6),

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[21] 'Eurostat - Data Explorer'. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=iww_go_atygo&lang=en (accessed Jul. 04, 2022).

[22] 'Statistics | Eurostat'. https://ec.europa.eu/eurostat/databrowser/view/iww_go_anave/default/table?lang=en (accessed Jun. 28, 2022).

(iv) the use of the less granular approach of model A instead of model B is also a significant source of error for estimated energy use per vessel type, route and type of cargo transported – this source of error can be reduced by implementing model B when new data becomes available,

(v) the physical limitations of different waterways and the impacts of climate change on waterways were not considered – this can be at least partially corrected by setting limits to the types of vessels that can navigate specific routes,

(vi) the assumption that the type of cargo transported through to 2050 is roughly the same as today could be a major source of error – alternatively, several different scenarios for 2050 can be generated to provide a range of futures,

(vii) the assumption that in the future all energy carriers have zero CO_2 emissions from a wtw perspective – alternatively, different decarbonization pathways can be considered for the new energy carriers supply chains.

3.5 Conclusions & recommendations

There is a wide disparity in the adoption of different technologies, and deployment of new low-carbon energy vectors, envisioned for the three scenarios implemented in the model. The BAU assumes only minor changes to the current technologies, mainly moving towards replacing the current diesel technologies by Stage V diesel engines and a gradual improvement in overall efficiency of transport per tkm of IWT activity, driven by logistics, digitalization, and improved planning across modalities. Under BAU there are significative overall improvements to the total energy use in the sector and GHG emissions (approximately 23% and 17%, respectively), but the sector is largely unchanged continuing to depend overwhelmingly on fossil fuels (diesel) and associated technologies.

The CONS and INOV scenarios are based on the Central Commission for the Navigation of the Rhine (CCNR) analysis that aims for zero-emissions inland shipping by 2050. Both scenarios reach approximately 90% GHG emissions reductions for IWT but do so under very different technology deployments. This has a major impact on the fuel value chains, with the CONS scenario having a more conservative view of the future deployment of lower TRL technologies (i.e., hydrogen, bio-methanol, electricity) and opting instead to accelerated deployment of HVO and Bio-LNG based technologies, which can be mostly adapted and retrofitted from existing commercial technologies. Under INOV, HVO plays a much smaller role in the decarbonization of inland shipping, with Hydrogen, Bio-methanol, Bio-LNG and electricity-based technologies driving the transition towards zero-emissions IWT.

The INOV scenario has inherently higher uncertainty, as the deployment of many of the underlying technologies depend also on the development of the supporting infrastructure for transport and storage of the energy carriers as well as charging and refuelling. Additionally, there are also challenges related to the sustainability of all new energy carriers associated with both the CONS and the INOV scenarios, as the whole value chain of the energy carriers will have to be developed in a way that guarantees low- to zero- emissions from a perspective of cradle-to-grave. Accordingly, the sources of all energy carriers included in the analysis are assumed to be fully renewable, including also fully renewable electricity.

Finally, the models proposed can be customized and improved to deal with most of the sources of uncertainty of the estimated energy requirements and new scenarios can be generated to calculate energy needs per energy carriers and vessel technologies according to different decarbonisation pathways, new policies for the transport sector and the changes in economy that will lead to changes in the type and volumes of cargo transported and their distribution through the routes considered.

3.6 Alternative methodology for the calculation of IWT energy use

This section describes the general inputs, outputs, and mathematical formulation for the more detailed modelling approach. The inputs needed to apply the detailed analysis (model B) and the resulting outputs, are shown in Table 25 and Table 26. Even though this model was not used in the initial estimation of the modality energy requirements provided in this deliverable, it can be used as the basis for improvement of the initial estimates and for further studies of the decarbonization of the energy supply chains to be carried out in WP3. Additionally, this section can also serve as a guide to useful data to be collected in the future and identification of currently available sources of inland shipping data and the associated limitations. A detailed description of the variables, parameters, and respective units is provided in Table 27.

Table 25 - Inputs for model B, including categories, names of the variables used and availability of data

Category	Name	Availability of data
Vessel Information	Vessel types	Available, although several different classification systems are used in literature. The classification according to the Prominent project vessel types was adopted for this initial analysis (Port of Rotterdam and [12]).
	Number of vessels by vessel type	Partially Available[12]
	Capacity by vessel type	Not available
	GHG Emissions factor by vessel type	Available, but needs to be consistent with the vessel classification system adopted
	Sailing Specific final energy use by vessel type	Unavailable as a consistent set for IWT to/from Port of Rotterdam; consumption of individual vessels can be found or calculated from more detailed mathematical formulations[13] but for a different vessel classification system
	In port Specific final energy use by vessel type	Not available
	Loading/unloading final energy use by vessel type	Not available
Journey Information	Vessel type on each journey	Not available – Estimated using the PROMINENT Project WP1 Annex A3[23]
	Cargo carried (type and weight)	Available (PROMINENT Project WP1 Annex A2[23])
	Origin and Destiny	Available (PROMINENT Project WP1 Annex A2[23])
	Total Distance of each journey	Available (PROMINENT Project WP1 Annex A2 [23])
	Empty returns of vessels by journey	Not available
	In port time	Not available

Table 26 - Outputs Model B (per year)

Category	Name
Sailing energy requirements and GHG emissions	Sailing consumption of each unit by vessel type and journey
	Total sailing final energy use by vessel type
	Total sailing final energy use by journey
	Total sailing final energy use

	GHG Sailing Emissions of each unit by vessel type and journey
	Total GHG Sailing Emissions by vessel type
	Total GHG Sailing Emissions by journey
	Total GHG Sailing Emissions
In port energy requirements and GHG emissions	In port consumption of each unit by vessel type and journey
	Total in port final energy use by vessel type
	Total in port final energy use by journey
	Total in port final energy use
	GHG in port Emissions of each unit by vessel type and journey
	Total GHG in port Emissions by vessel type
	Total GHG in port Emissions by journey
	Total GHG in port Emissions
Overall energy requirements and GHG emissions	Consumption by vessel type and journey
	Total final energy use by vessel type
	Total final energy use by journey
	Total final energy use
	GHG Emissions by vessel type and journey
	Total GHG Emissions by vessel type
	Total GHG Emissions by journey
	Total GHG Emissions

Table 27 - Variables and Parameters of model B

Variable	Description
t	Vessel type
j	Journey information from Annex A2 of the PROMINENT Project[23]
$j1$	Journey information from Annex A3 of the PROMINENT Project[23]
$Dem_{c,j}$	Weight of cargo in tonnes by journey for 1 year
$Dist_{c,j}$	Distance per journey for 1 year (km)
$Per_{c,t}$	Percentage of cargo per type of vessel
$Pl_{t,j1}$	Maximum payload per type of vessel and journey for 1 year
$Num_{u\in t}$	Vessel units per type
$WLU\_Time_{t,j1}$	Waiting/(un)loading time per type of vessel and journey for 1 year (h)
$Avg\_Speed_{t,j1}$	Average speed per type of vessel and journey for 1 year (km/h)
$Dist_{t,j1}$	Distance per type of vessel and journey for 1 year (round trip in km)
$P_{t,j1}$	Total power main engines per type of vessel and journey for 1 year (kW)
$Tot\_Time_{t,j1}$	Total time roundtrip incl. waiting time / (un)loading (hours) per type of vessel and journey for 1 year (h)
D	Diesel GHG emission factor – European Standard EN16258 (gCO2e /l_Diesel)
EF_t	GHG emission factor per type of vessel, cargo weight and km (gCO2e /tkm)
ED	Diesel Energy Density (MJ/l)
$CONWLU_t$	In port average energy consumption per vessel type (MJ/h)
$CONLU_t$	Loading/unloading average energy consumption per vessel type (MJ/h)

The mathematical formulation of model B is described by equations (4) to (29). The first step in the calculation is the estimation of the amount of cargo transported by type of vessel, type of cargo and journey j (considering the Rhine representative journeys to and from Rotterdam), as per equation (4). The values for the freight activity per journey (weight) are based on the values from Table 14 for $Dem_{c,j}$. The cargo distribution by vessel type is given by $Per_{c,\,t}$.

Tons of cargo by type of vessel, cargo, and journey for 1 year

$$Dem_{t,c,j} = Dem_{c,j}\ ´\ Per_{c,\,t} \tag{4}$$

The next step consists in calculating the average payload value by vessel type as per expression (5) which takes the average of the 25 journeys $j1$ to and from Rotterdam as defined and quantified in the Prominent Project[23]

Payload per type of vessel for 1 year (average of all journeys)

$$Pl_t = \frac{\sum_j Pl_{t,j1}}{\sum_{j1} 1} \tag{5}$$

The number of trips needed for each vessel type to deliver the full cargo in each journey j, is estimated by equation (6), considering the payload calculated in (5). This calculation assumes that all vessels considered can undertake the necessary journey to transport the payload calculated, regardless of the conditions of the waterways, e.g., river or atmospheric conditions. This assumption was necessary due to the lack of information on which vessel types are allowed to navigate the different waterways under different conditions, to complete a given journey.

Number of trips per vessel type, cargo type and journey

$$Trip_{t,c,j} = \frac{Dem_{t,c,j}}{Pl_t} \tag{6}$$

With the number of trips per vessel type, cargo and journey known, the total number of trips each vessel type needed to deliver all cargo in all journeys can be calculated through equation (7). In case the number of vessels per each vessel type is available, equation (8) can be used to verify the consistency of the values obtained through equations (4) and (6).

Number of trips per vessel type

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[23] Stichting Projecten Binnenvaart, 'D1.1 List of operational profiles and fleet families – V2 (PROMINENT Project)'. [Online]. Available: https://www.prominent-iwt.eu/wp1-state-of-play/ (per Annex A3).

$$Trip_t = \sum_{c,j1} Trip_{t,c,j1} \tag{7}$$

Trips per vessel unit of type t

$$Trip_{u\in t} = \frac{Trip_t}{Num_{u\in t}} \tag{8}$$

The sailing consumption per vessel type and journey $j1$ is given by equation (9) and used in equation (10) to estimate the average final energy use (consumption) per vessel type.

Sailing consumption per type of vessel and journey (in MJ/h)

$$Slcons_{t,j1} = Dist_{t,j1} \times P_{t,j1} \times 10^{-3} \times 3600 \tag{9}$$

Sailing consumption per type of vessel (in MJ/h)

$$Slcons_t = \frac{\sum_{j1} IPcons_{t,j1}}{\sum_{j1} 1} \tag{10}$$

The average sailing time per vessel type and journey $j1$ is calculated in equation (11), which is based on the average speed and the distance of each journey $j1$. The average sailing time is used in equation (12) to compute the total journey time (including in port times), and in equation (13), to compute the loading and unloading time per vessel type and journey $j1$.

Average sailing time per type of vessel and journey (in hours)

$$Avg\_STime_{t,j1} = Avg\_Speed_{t,j1} \times Dist_{t,j1} \tag{11}$$

Loading/unloading time per type of vessel and journey (in hours)

$$Tot\_Time_{t,j} = Avg\_STime_{t,j} + WLU\_Time_{t,j} + LU\_time_{t,j} \tag{12}$$

$$LU\_Time_{t,j1} = Tot\_Time_{t,j1} - (WLU\_Time_{t,j1} + Avg\_STime_{t,j1}) \tag{13}$$

The loading/unloading and in port time per vessel type are calculate in equation (14) and (15), respectively, using the values computed for journeys $j1$ and calculating an average by vessel type.

Loading/unloading time per type of vessel (in hours)

$$LU\_Time_t = \frac{\sum_{j1} LU\_Time_{t,j1}}{\sum_{j1} 1} \tag{14}$$

In port time per type of vessel (in hours)

$$WLU\_Time_t = \frac{\sum_{j1} WLU\_Time_{t,j1}}{\sum_{j1} 1} \tag{15}$$

Finally, the specific final energy use (consumption) per vessel type is calculated according to equation (16) and is obtained by using the GHG Emission factor (EF_t) of each vessel type.

Specific consumption per type of vessel, distance (km) and cargo (in MJ/tkm)

$$Scons_t = \frac{EF_t \times ED}{D} \tag{16}$$

Outputs of Model B

Sailing energy requirements and GHG emissions

The total GHG Emission factor per vessel type, cargo weight and journey j can be calculated from the value of the distance of each journey and the specific consumption of each vessel type, as described in equation (17).

GHG Emission factor per vessel type, cargo weight and journey (gCO2e/t)

$$Tot\_EF_{t,c,j} = Dist_{c,j} \times EF_t \tag{17}$$

The total specific consumption per vessel type, cargo weight and journey j is calculated by equation (18), using the distance of each journey and the specific consumption of each vessel type calculated according to equation (16).

Specific Consumption per vessel type, cargo weight and journey (MJ/t)

$$Tot\_Scons_{t,c,j} = Dist_{c,j} \times Scons_t \tag{18}$$

The emissions per vessel type, cargo type and journey j, are calculated according to equation (19) from the total GHG Emission factor (as per equation (17)), and the weight of the cargo transported in journey j. This value can then be aggregated per vessel type, as described in equation (20), or aggregated to get the total emissions, in equation (21).

Emissions per vessel type, cargo type and journey (gCO2e)

$$EM_{t,c,j} = Tot\_EF_{t,c,j} \times Dem_{c,j} \tag{19}$$

Total Emissions per vessel type (tCO2e)

$$EM_t = \sum_{c,j} EM_{t,c,j} \times 10^{-6} \tag{20}$$

Total Emissions (tCO2e)

$$EM = \sum_t EM_t \tag{21}$$

Finally, the final energy use (consumption) per vessel type, cargo and journey is calculated by equation (22) considering the specific consumption calculated in (18) and the weight of cargo transported by journey j. This energy consumption can then be aggregated per vessel type according to equation (20). The total final energy use during sailing is calculated according to equation (24).

Energy consumption per vessel type, cargo and journey (MJ)

$$CONS_{t,c,j} = Tot\_Scons_{t,c,j} \times Dem_{c,j} \tag{22}$$

Total sailing consumption per vessel type (GJ)

$$CONS_t = \sum\nolimits_{c,j} CONS_{t,c,j} \times 10^{-3} \tag{23}$$

Total sailing consumption (GJ)

$$CONS = \sum_t CONS_t \tag{24}$$

In Port energy requirements and GHG emissions

The in port time per vessel type, cargo type and journey j, is calculated according to equation (25), using the in port time per type of vessel calculated in equation (15) and the number of trips by vessel type calculated in equation (7).

In Port time per vessel type, cargo type and journey (in hours)

$$WLUtime_{t,c,j} = WUL\_Time_t \times Trip_{t,c,j} \tag{25}$$

Equation (26) calculates the loading/unloading in port time per vessel type, cargo type and journey j, using the values calculated in equations (13) and (7).

Loading/unloading in port time (in hours)

$$LU\_Time_{t,c,j} = LU\_Time_t \times Trip_{t,c,j} \tag{26}$$

The in-port final energy use (consumption) per vessel type, cargo and journey could then be calculated in equation (27) if $CONWLU_t$ and $CONLU_t$ data were available. Similarly, the aggregated values per vessel type and total consumption could be calculated using equations (28) and (29).

In port consumption per vessel type, cargo, and journey (MJ)

$$TIP\_CONS_{t,c,j} = WLUtime_{t,c,j} \times CONWLU_t + LU\_Time_{t,c,j} \times CONLU_t \tag{27}$$

Total in port consumption per vessel type (GJ)

$$IP\_CONS_t = \sum_{c,j} IP\_CONS_{t,c,j} \times 10^{-3} \tag{28}$$

Total in port consumption (GJ)

$$IP\_CONS = \sum_t IP\_CONS_t \tag{29}$$

4 Trucking and Rail energy requirements

4.1 Context

Throughout Europe, both the trucking and railing sectors are major players in the hinterland transport of cargo from and to ports. Unlike inland shipping, these two modalities are not constrained by the access to rivers and, as such, are present across all major European ports.

Typically, rail transport is preferable between the port and a large consumer/producer or a distribution hub, for example, coal to be delivered to an industrial consumer or containers being transported by rail to a distribution hub, where the containers can then be individually delivered to their final destination. On the other hand, truck transport tends to be geared towards smaller industries, transporting smaller amounts of cargo directly from the port to the final consumer, or vice-versa.

In general, both modalities are capable to transport the same types of cargo however their weight on the modal split for each cargo type is different[24]. This can be seen in Figure 8, which details the modal split for the port of Rotterdam.

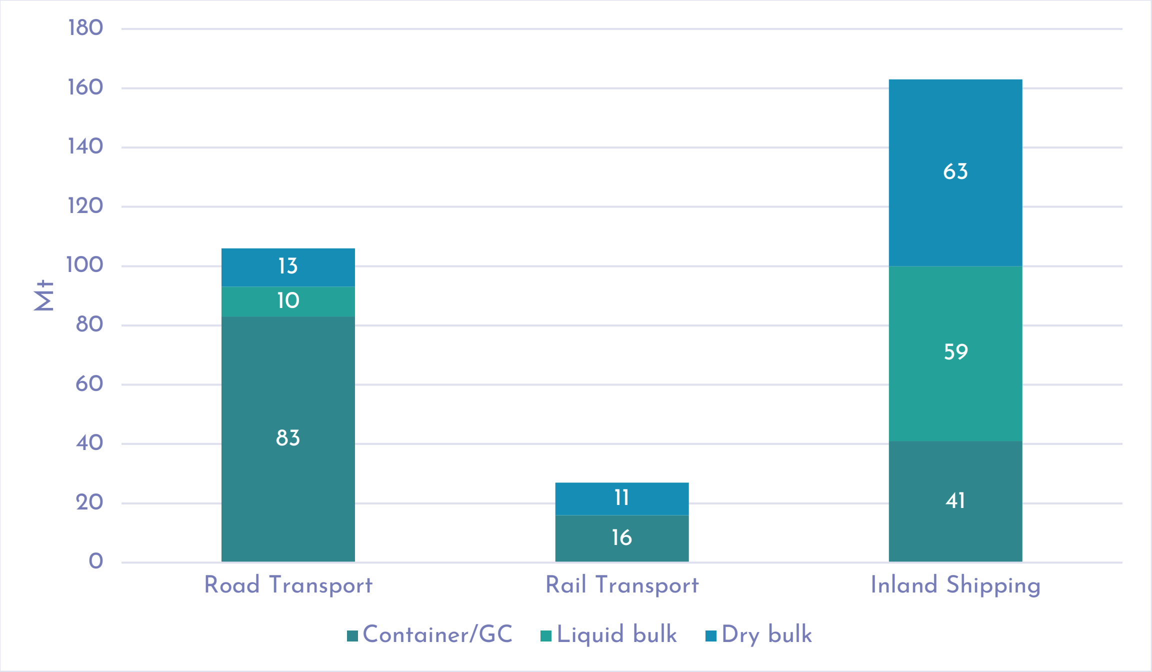

Figure 6 - Modal split for port of Rotterdam[24]

According to Figure 6, trucks were responsible for 28.7% of all hinterland transport in 2015. In terms of containers and general cargo throughput in the port, trucks were responsible for carrying roughly 59.3%. Rail transport plays a smaller role, transporting containers/general cargo and dry bulk (mostly coal and iron ore).

4.1.1 Trucks fleet characterization

In Europe, several classes of trucks are used for freight transport. They can be classified according to their chassis type (tractor+trailer or rigid chassis), number of axles (typically 4 or 6), engine power and cabin type (day cab vs sleeper cab). In order to standardize the

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[24] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

truck categorization, the EU truck market has been segmented it into 17 subgroups, with the most common ones being detailed in Table 28 taken from a study by Transport and Environment.

Table 28 – Truck subgroups in the EU [25]

Group description	Group	Subgroup	Cabin Type	Engine Power
Rigid, 4x2 axle, GVW > 16 t.	4	4-UD	All	< 170 kW
		4-RD	Day cab	≥ 170 kW
			Sleeper cab	≥170 kW, < 265 kW
		4-LH	Sleeper cab	≥ 265 kW
Tractor, 4x2 axle, GVW > 16 t.	5	5-RD	Day cab	All
			Sleeper cab	< 265 kW
		5-LH	Sleeper cab	≥ 265 kW
Rigid, 6x2 axle	9	9-RD	Day cab	All
		9-LH	Sleeper cab	
Tractor, 6x2 axle	10	10-RD	Day cab	All
		10-LH	Sleeper cab	

Since no specific information was found concerning the subgroups of trucks entering and leaving the port of Rotterdam, truck manufacturers were consulted and they highlighted that the sub-group 5-LH is the most common in Europe. In that sense, the study presented in this deliverable assumes that the entire truck fleet belongs to this sub-group.

Another relevant characteristic of diesel trucks is the vehicle emission standard that they follow. The most recent is the Euro VI standard[26], which limits even further the emission of hydro-carbonate, methane, NOx and PM. All diesel trucks manufactured from 2015 onwards must comply with this standard. Having this in mind and taking into account that the average lifetime of a truck tractor in the Netherlands is 7.4 years[27], all diesel trucks in this analysis were considered to comply with the Euro VI emission standard. Figure 7 shows a comparison between Euro V and Euro VI trucks, extracted from a study carried by the International Council on Clean Transportation.

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[25] Easy Ride: why the EU truck CO2 targets are unfit for the 2020s (Transport and Environment)
[26] A technical summary of Euro 6/VI vehicle emission standards (ICCT)
[27] Port of Rotterdam

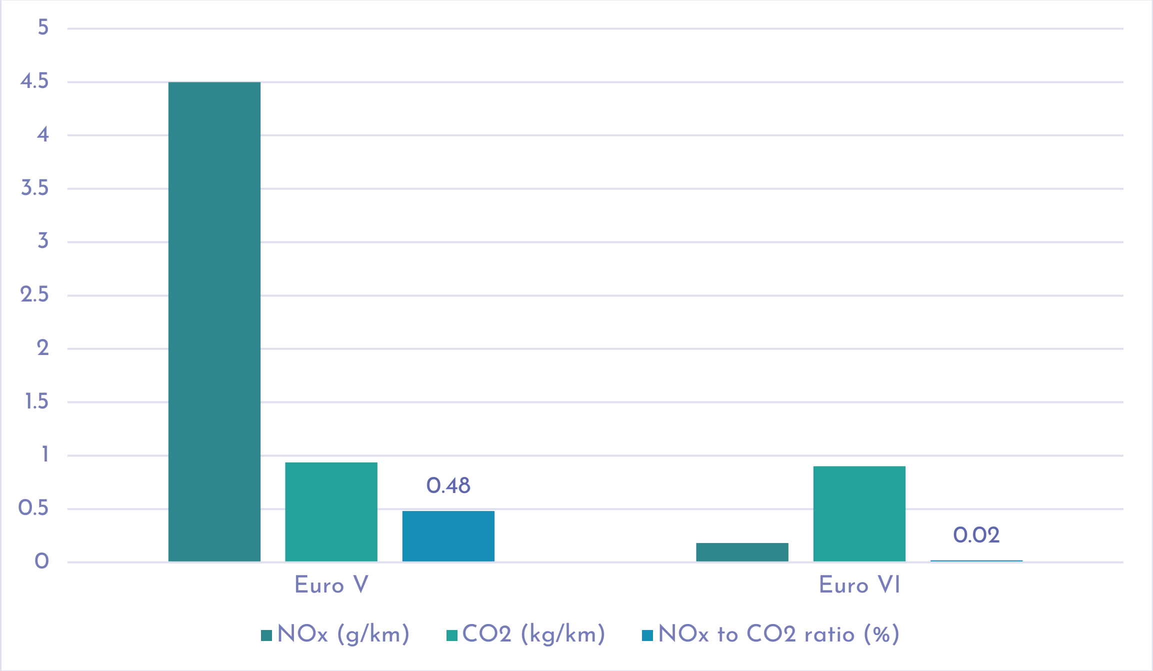

Figure 7 - Euro V/VI heavy duty vehicle emissions [28]

The main goal of the Euro VI standard was the reduction of NOx emissions while also achieving a small reduction in CO2 emissions. NOx emissions can be reduced by implementing additional components to the exhaust system such as Selective Catalytic Reduction (SCR) or Diesel Particulate Filter, resulting in a decrease of NOx emissions of around 95% when comparing Euro VI to Euro V standard (Figure 7).

Currently the vast majority of trucks in the EU are diesel-powered (98% in the Netherlands[29]), mainly due to its wide availability, low cost, good energy density and quick refuelling times. However, new technologies to decarbonize the trucking sector are being investigated, namely electric trucks (either battery powered or with a catenary system), hydrogen trucks, natural gas trucks (can run on high-pressure compressed natural gas or liquified natural gas) and trucks running on biofuels. Analysing these future energy streams, understand what are the main barriers for their settlement both at the technical, economic and regulatory levels and define recommendations for a fast uptake of these clean sources are the main goals of the MAGPIE project. Task 3.1 is the starting point of this analysis and will allow to map the transport energy needs that will need to be covered by these future green energy options.

4.1.2 Train fleet characterization

Contrary to what happens in the truck sector, rail transport is widely known for being one of the cleanest transport modalities[30]. Also, major European rail routes such as the ones that allow the connection to maritime ports have a high share of electrified railways, which are becoming increasingly powered by green energy. Therefore, the use of diesel locomotives in the port activity is usually restricted to shunting operations and first-last mile delivery tasks. Some examples of diesel shunting locomotives currently used in the Port of Rotterdam are the DB Class V 100 and the Vossloh G1206. These locomotives have between 809 and 1500

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[28] NOX emissions from heavy-duty and light-duty diesel vehicles in the EU: Comparison of real-world performance and current type-approval requirements (ICCT)
[29] OUTLOOK HINTERLAND AND CONTINENTAL FREIGHT 2020 (CE-DELFT)
[30] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

kW.A shunting operation is the process of sorting separate wagons into long-haul trains (or the reverse). Since these operations are usually performed in big shunting yards, their electrification is harder to execute than just electrifying a simple rail track. The first-last mile delivery in ports corresponds to the distance covered in the rail track at the entrance of a terminal, which often is not electrified.

Considering this, a typical train operation (Hinterland-Port route) starts with an electric long-haul locomotive coming from the hinterland and releasing the wagons on a shunting yard. Afterwards, a diesel shunting locomotive connects to the wagons (shunting operation) and moves them to the desired terminal (first-last mile operation). Focusing now on the operational profile of these diesel shunting locomotives, the two different moments that were highlighted – shunting and first-last mile – also correspond to two different consumption profiles. Shunting is characterized by low speed and frequent accelerating and braking actions, representing when the locomotive is in the shunting yard, either moving wagons or connecting to them. On the other hand, first-last mile is associated with a constant and higher speed than shunting, representing the moment when the locomotive travels between shunting yard and a terminal. However, there is still a third moment that needs to be considered: idling. In fact, a diesel shunting locomotive spends most of its time idling, this is not moving with its engine turned on.

Looking to the specific case of Rotterdam, most of the diesel shunting locomotives follow an operational profile similar to the one previously described. Most of the time is spent in the port (shunting, first-last mile operations or in idling mode) or going to Kijfhoek, a large shunting yard located 40km away from the port. There are some exceptions where the diesel shunting locomotives travel to other destinations in the Netherlands or even crossing into Germany. However, since these events are not common, the analysis hereby presented will not focus on them. Important also to mention that according to a 2018 report from TNO[31] where the operation of two diesel shunting locomotives in the Port of Rotterdam was analysed, between 75% and 84% of the time that the locomotive's engine is on, the locomotive is idling. Furthermore, idling was responsible for roughly half of the total fuel consumption and GHG emissions of these locomotives. As it will be observed in this report, this information is of utmost importance to carry a realistic estimation of the diesel shunting locomotives consumption.

Decarbonizing the shunting locomotives sector has several different options: 1) Have all the port railways electrified (as in the case of the port of Sines); 2) Battery hybrid locomotives, which can operate for periods of time without requiring an overhead catenary system (they recharge their batteries when they are able to connect again to overhead lines); 3) H2-powered locomotives.

4.1.3 The impact on emissions and energy consumption

Globally, heavy truck freight transport is the second subsector within the transport field that emits the most CO2, only emitting less than the light vehicle subsector. In 2020, 1776 Mt of CO2 were emitted by heavy trucks[32]. Alternatively, the rail sector is the less polluting one, with 94 Mt of CO2 emitted in 2020[32]. Focusing on the emissions only connected to hinterland transport in the Netherlands, the total CO2 emissions are roughly 4.6 Mt[33], with the trucking sector responsible for 63% of these and the rail sector responsible just for 0.1%. Narrowing

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[31] Insight into the energy consumption, CO2 emissions and NOx emissions of rail freight transport (TNO)

[32] Tracking Transport 2021 (IEA)

[33] OUTLOOK HINTERLAND AND CONTINENTAL FREIGHT 2020 (CE-DELFT)

the emissions to only the Port of Rotterdam, the hinterland emissions are 2.22 Mt[33] which corresponds to 9% of the total port emissions.

The truck sector is leader in terms of global and local emissions. Two main factors contribute to this: 1) trucks are responsible for transporting more cargo than other modalities; 2) trucks are the most polluting hinterland transportation method in terms of CO2/tkm (excluding aviation). Figure 8, compiled using data from the Wuppertal Institute's report[34], validates this information - the gCO2/tkm is clearly higher when comparing road transport to rail or inland shipping.

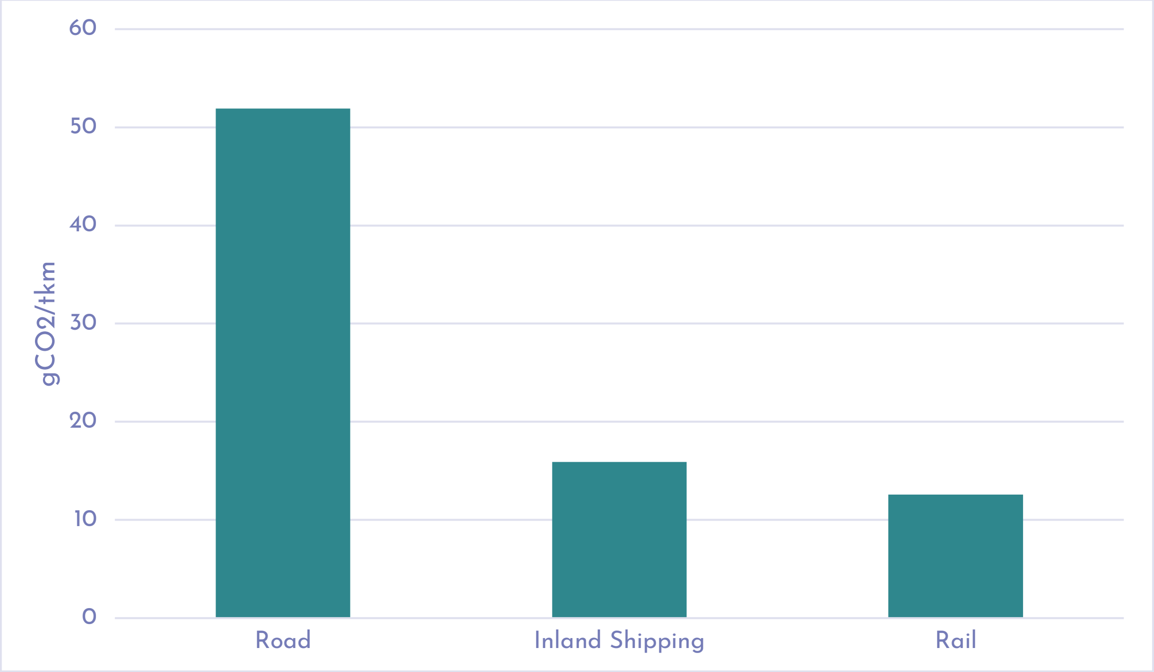

Figure 8 - Emissions of hinterland modalities by cargo and distance transported[34]

Following on the modalities' emissions, the same analysis can be performed for energy demand to assess the energy efficiency of each modality. Figure 9 highlights the consumption of each transport modality per tonne kilometre (MJ/tkm)[35]. The result is not surprising – among the different transport modalities, the heavy-duty vehicles present the highest consumption per tonne kilometre.

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[34] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

[35] Energy revolution: a sustainable world energy outlook 2015

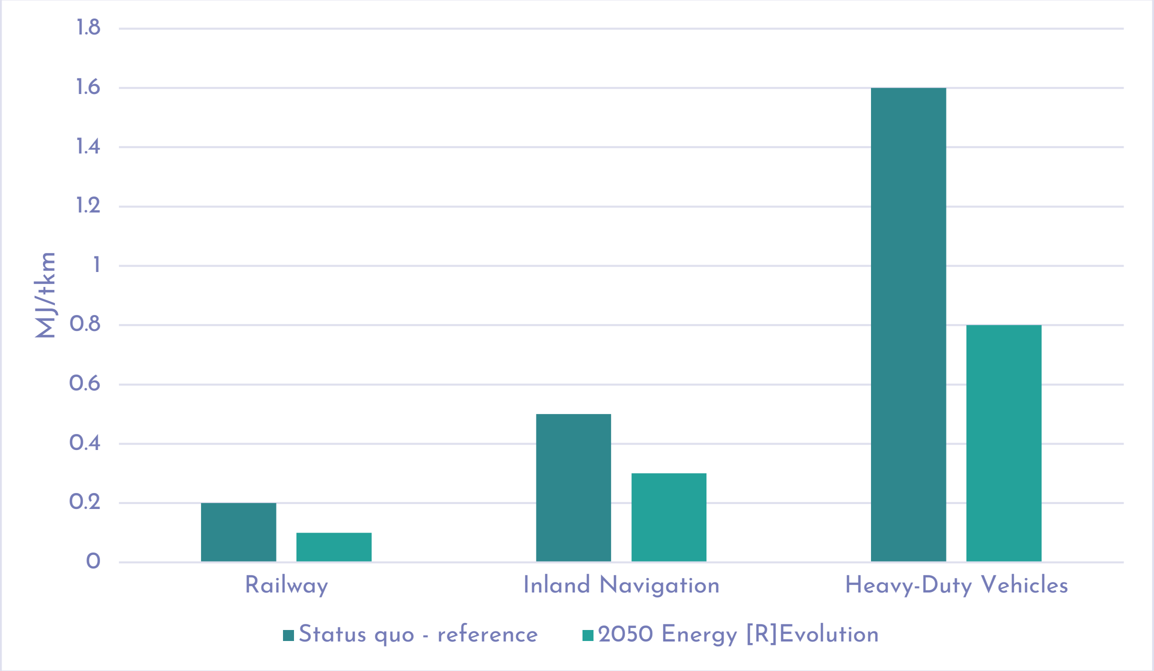

Figure 9 - Hinterland modalities energy consumption by cargo weight and distance[36]

Figure 9 is also interesting for another reason. It provides an estimation of how the energy consumption per tonne km will evolve until 2050. In general, all the transport modalities will become more efficient, which is expected to be the result of a gradual introduction of new green energy technologies. This is due to the fact that internal combustion engines have a much lower efficiency when compared to a fully electric drivetrain or a fuel cell based drivetrain[37]. This aspect is analysed in more detail in the next section.

4.1.4 Modal split & Green energy carriers

Modal split, as the name indicates, corresponds to a change on the typical transportation mode of a specific cargo type. Current decarbonization targets are quite demanding and, as such, exploring transport modalities that are already in place and are less pollutant is a viable (and probably economic) option. In that sense, it is expected that in the coming decades a modal shift away from road transport and towards rail or inland shipping is observed[38]. While inland shipping is heavily restricted due to geographical constraints (for example, the fellow port of Sines has no inland waterways), rail tracks can be built in most port locations which will enable rail transport to have a bigger role to play in future hinterland transport. Nevertheless, modal split will not always be a solution for the entire journey. A probable future scenario will exploit inland shipping or rail to transport cargo between the port and a distribution hub, with trucks distributing the cargo across the different locations. This would already contribute to a considerable reduction of the emissions and energy demand in the transport sector.

Independently on how modal split will evolve, one thing is certain: road transport will still play an important role when it comes to hinterland transport. The extensive road network connecting all the EU, the ease of transporting cargo from the port to the destination (or from source to port) and the inexpensive operating and infrastructure costs make road

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[36] Energy revolution: a sustainable world energy outlook 2015
[37] Analysis of long haul battery electric trucks in EU (Transport & Environment)
[38] Decarbonisation-driven future changes in European transport (Wuppertal Institute)

transport unique when compared to other modalities. Therefore, the efforts that are being carried out to introduce new green energy carriers in the road transport sector are of the utmost importance to reduce their carbon footprint.

The most researched decarbonization technology for trucks is their electrification. Electric trucks have several advantages, such as the wide availability of electricity and batteries, the high maturity of the technologies employed and their silent operation. The main drawbacks of a battery powered truck are the relatively low range, their increased weight and the time it takes to recharge their batteries, which hinders their ability to travel the same distance in a day as a diesel-powered truck. To overcome this disadvantage, studies are underway to assess the viability of implementing an overhead line on the major transport routes in the EU, which would deliver electricity to the truck as it is moving, meaning the truck would not have to stop to recharge[39].

Green Hydrogen technologies are also a promising decarbonization carrier. In fact, one of the MAGPIE demonstrations will focus on green Hydrogen-powered trucks. This kind of trucks may be better suited for long-haul transportation, as in theory they can be refuelled much faster than battery powered trucks (excluding the option of catenary powered trucks). These trucks run on compressed hydrogen, which is fed into a fuel cell to generate electricity to then power electric motors connected to the wheels. However, H2 trucks also have their disadvantages, particularly related with the fact that H2 is a technology that just recently started to be on the agenda of the energy stakeholders. These trucks require hydrogen refuelling stations to be available wherever they travel to. Whereas some new infrastructure for electric trucks is also required, the electricity supply chain is already present throughout the EU. Another disadvantage is the overall efficiency of the process to power the truck: green hydrogen production through electrolysis has an efficiency ranging from 50 to 68% and fuel cells have an efficiency ranging from 50 to 60%[40]. Even excluding other energy losses such as the ones related with electric motors and with the energy required to compress and transport the hydrogen, overall system efficiency can be between 25% to 40%. From an economic perspective, green hydrogen is currently expensive and even though it's forecasted to significantly decrease over the coming decades, the uncertainty surrounding the cost of operating a hydrogen powered truck is a point to be taken into account when analysing the viability of this technology.

Despite not being a complete decarbonization carrier for road transport, the use of natural gas trucks can be a first step to lower CO2 emissions of the sector. Nation-wide natural gas grids are already in-place, so the adoption of natural gas trucks requires less new infrastructure than hydrogen trucks. Regarding the available technology, the trucks can either run on compressed natural gas or liquified natural gas, with the latter requiring more expensive infrastructure and truck manufacturing, with the benefit of increased range and faster refuelling.

Given the present conflict in the Ukraine, the supply of natural gas from Russia to Europe has been severely limited, with overall natural gas price increasing to several times its previous value. This reduced supply served to highlight Europe's dependence on external energy sources, which can be easily put at risk with a situation similar to the Ukraine conflict. Due to these reasons, a strong push is being made away from natural gas across Europe, with countries implementing regulations to accelerate the change from gas boilers and heating towards electric-based solutions, increased RES to decrease the use of natural gas power plants, among other measures. Nonetheless, the current natural gas infrastructure can

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[39] Power from above? Assessing actor-related barriers to the implementation of trolley truck technology in Germany

[40] Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal (irena.org)

be used to transported bio natural gas or be retrofitted to transport hydrogen (both of which can be produced directly in Europe).

Similar to road transport, electricity and hydrogen are two green energy carriers undergoing research in the rail sector, albeit in a different perspective since a considerable volume of rail passenger and freight is already performed using fully electric locomotives. Hybrid battery electric locomotives are promising due to their first-last mile delivery capabilities. These locomotives have a catenary system, so they operate like a regular electric locomotive when on an electrified rail track, however, they have a battery that enables them to operate on non-electrified tracks for a short duration of time. The battery is then seamlessly charged using the locomotive's catenary system when it returns to an electrified track.

Hydrogen locomotives are promising due to their quick refuelling times and good range[41]. These locomotives can operate for longer distances without returning to an energy source, and when they do need to be refuelled this process is orders of magnitude faster than charging a battery, enabling them to have similar operating patterns as diesel locomotives. As with hydrogen trucks, the main drawbacks are the need for hydrogen refuelling stations alongside with the respective supply chain to deliver hydrogen and the low overall efficiency of the process. Hydrogen locomotives are then more suited to operate in mostly non electrified lines, where the autonomy required is greater than the autonomy provided by the hybrid battery electric locomotives.

The energy transition to these new green energy carriers will be a long path, full of barriers and obstacles to be overcome. To ensure that this transition will be successful, one of the first steps that should be taken is to realize the current consumption needs of each transport modality so that an estimation of the demand for future green energy carriers can be carried. Moreover, since this transition will happen over decades, future scenarios must be set to try to estimate how this demand for clean sources will evolve. This is exactly the main role of T3.1 of the MAGPIE project and the coming sections will detail the methodology that was to provide the expected outputs.

4.2 Methodology

4.2.1 Introduction to the methodology

A mathematical model was developed to estimate the current energy demand associated with the road and rail transport sectors. In essence, this estimation just depends on three variables: the specific energy consumption [MJ/km], the number of km covered [km] in each trip and the total number of trips to/from the port of Rotterdam. However, such variables are not static and depend on other aspects such as the route characteristics (e.g., travel speed), type of cargo transported, among others. Therefore, this model – which is explained in detail in the following sections – was executed for several different scenarios. Important also to mention that considering the marginal penetration of green sources in the freight transport sector, it was assumed that the current energy demand is entirely supplied by diesel.

A second step of the methodology is the definition of future energy requirements (2030, 2040, 2050) which takes into consideration forecasts on how the cargo throughput will change in the coming years, the modal shift expected to occur away from road transport and towards inland shipping and rail transport and the expected efficiency increase of new green technologies. Contrary to what is assumed in the current scenario, the future energy demand will become supplied by a mix of new green energy carriers. The demand share allocated to each specific green fuel was the result of a thoroughly review of the literature

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[41] Study on the use of Fuel Cells and Hydrogen in the Railway Environment – Report 3 (Europe's Rail)

and of interviews conducted with field experts. Nevertheless, this allocation exercise was based on the existing information, and it is important to recognize that there are many factors that can influence the energy transition trajectory (e.g., governmental orientations and/or incentives).

4.2.2 Categorization

In order to properly estimate the total energy demand for road and rail transport, the different types of cargo transported in the port were analysed separately, mainly due to the following facts: 1) each cargo type is handled in different locations of the port, which affects the total distance travelled (particularly important in ports with a considerable size such as the port of Rotterdam); 2) the payload of a truck/train affects the energy consumption and varies according to the type of cargo transported. Therefore, the model computes the energy consumption and emissions by cargo type and then combines the results to reach the final values per modality.

Two different information sources were used to support in the definition of this categorization for the truck sector – a study commissioned by the Netherlands Institute for Transport Policy Analysis[42] where the defined cargo types follow the categorization designed in BasGoed (a well-known goods transport forecast model) and the annual throughput reports made available by the port of Rotterdam. By doing so, it was possible to ensure that for each defined cargo type, input data would be available to feed the model. The final classification is shown below:

- Shortsea containers
- Deepsea containers
- Break bulk – RoRo
- Break bulk – Other (e.g., base metals and metal products)
- Dry bulk – Agri bulk
- Dry bulk – Other (e.g., salt, sand, gravel and clay)
- Liquid bulk – Other (e.g., chemicals, vegoils and renewables)

The containerized cargo was divided into shortsea and deepsea containers. While shortsea containers are transported by smaller ships travelling closer to shore and for smaller distances, deepsea containers are transported on large ships across oceans. This division was considered due to the terminals location that handle each type of container cargo - deepsea terminals are closer to sea in Maasvlakte area and shortsea terminals are closer to the center of Rotterdam in Waalhaven area.

In the case of Dry and Liquid Bulk is important to highlight the existence of other commodity types. However, they were not considered here since the contribution of trucks for their hinterland transport is marginal. It is for example the case of coal (Dry Bulk) which is mainly transported by barge or train or the case of LNG (Liquid Bulk) where pipelines have a very significant role in its transport.

Focusing on the rail sector, the cargo categorization was slightly different and the reason for it was the unavailability of input data with the same type of granularity. As such, the cargo types for the rail transport were defined as follows:

- Shortsea containers
- Deepsea containers
- Break bulk
- Dry bulk

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[42] Cost Figures for Freight Transport (Netherlands Institute for Transport Policy Analysis)

- Liquid bulk
- Unit cargo

A major difference is the introduction of the unit cargo type. This corresponds to trains that usually transport different types of cargo until a big shunting yard to then be distributed through several long-haul locomotives.

In addition to the cargo categorization, other categories were created for the road sector. The specific energy consumption of trucks is heavily linked to their operational profile: in urban environments diesel trucks consume more fuel per km than in highways. Moreover, while diesel shunting locomotives mostly stay in the port, trucks can travel internationally to deliver their cargo, so the distance of travel is also a huge influencing factor. Due to these reasons, three different operating scenarios for road transport were defined: trips within the Rotterdam area, trips within the Netherlands and international trips.

4.2.3 Variables & (data) sources

This section focuses on presenting the input variables required to compute the energy demand related with the road and rail transport. Then, the mathematical formulas that compose the proposed model are also stated.

Starting with the road transport, the following input variables (for each cargo type) are considered:

- Payload weight -> not used directly in the calculations, but important to obtain specific energy consumption and emissions
- Specific energy consumption in MJ/km ($c_{sp,en}$)
- Specific CO2 emissions in gCO2/km ($c_{sp,CO2}$)
- Specific NOx emissions in gNOx/km ($c_{sp,NOx}$)
- Number of kms covered in the freight transport trip (d_{trip})
- Number of trucks required to transport the total cargo throughput (N)

d_{trip} is the aggregation of the distance covered within and outside the port area. Concerning the distance travelled within the port, it just depends on the type of cargo transported since the destination terminal will differ. The total energy demand per scenario (i.e., different cargo and route types) and energy carrier is then obtained using equation (*30*)and the CO2/NOx emissions are obtained using equation (31).

$$Total_{en} = c_{sp,en} \bullet d_{trip} \bullet N \tag{30}$$

$$Total_{CO2/NOx} = c_{sp,CO2}/c_{sp,NOx} \bullet d_{trip} \bullet N \tag{31}$$

For the rail transport, the required input variables and consequently the proposed model are different. Starting with the input variables, the following ones are needed:

- Hourly fuel consumption for A-B travel in kg/h ($c_{en,A-B}$)
- Hourly fuel consumption for shunting in kg/h ($c_{en,shunt}$)
- Hourly fuel consumption for idling in kg/h ($c_{en,idle}$)
- Specific CO2 emissions in gCO2/kg of fuel burned ($c_{CO2,kg}$)
- Specific NOx emissions in gNOx/kg of fuel burned ($c_{NOx,kg}$)
- Speed in A-B travel in km/h (v_{A-B})

- Number of kms per trip (d_{A-B}) -> only for the A-B travel stage
- Time spent traveling between A-B (t_{A-B})
- Time spent in shunting in h (t_{shunt})
- Time spent in idling in h (t_{idle})
- Number of trains required to transport the total cargo throughput (N)

There are two main factors that justify the differences observed in the input requirements for the road and rail sectors. The first regards to data availability. Studies addressing the operation of shunting locomotives are not vast, which impacts on the type of inputs available. On the other hand, the operating pattern of a shunting locomotive is not constant during a typical trip, which leads to a varying consumption profile ($c_{en,A-B}$, $c_{en,shunt}$, $c_{en,idle}$). Such profile can be divided into three stages: idling, shunting, A-B travel. Idling is associated with the moment when the locomotive is not moving, but its engine is turned on, Shunting represents the process of coupling and decoupling wagons and the movement inside the shunting yard, A-B travel corresponds to the trips between a shunting yard and a terminal. The characteristics of these different operational moments also allow to understand why the consumption was measured in hours spent rather than on km covered.

Still focusing on the three moments that characterize the operation of a shunting locomotive, it is important to highlight how the time spent in each of them (t_{A-B}, t_{shunt}, t_{idle}) was computed. The computation of t_{A-B} is the result of $\frac{d_{A-B}}{v_{A-B}}$, where d_{A-B} is the distance covered between the shunting yard and the destination terminal and v_{A-B} is the average shunting locomotive speed. Contrary to t_{A-B}, no direct information was available to calculate the time spent in idling and shunting. Therefore, these two variables were iteratively adjusted in order to comply with three different constraints: 1) on average, a shunting locomotive trip (i.e., t_{A-B} + t_{shunt} + t_{idle}) takes 2 to 3 hours in the port of Rotterdam[43]; 2) between 75% and 84% of the time that a diesel shunting locomotive engine is running, it is idling[44]; 3) idling time is at least 1h30m (brake test time).

Equation (*32*) and equation (33) shows how the above-mentioned variables are linked in order to compute the total energy demand and emissions. Still important to refer that 45.6 stands for the conversion factor between kg of diesel and MJ of energy (1kg has an energy content of 45.6 MJ)

$$\mathrm{Total_{en}} = \left(\mathrm{t_{A-B}} \bullet \mathrm{c_{en,A-B}} + \mathrm{t_{shunt}} \bullet \mathrm{c_{en,shunt}} + \mathrm{t_{idle}} \bullet \mathrm{c_{en,idle}}\right) \bullet 45.6 \bullet \mathrm{N} \tag{32}$$

$$Total_{CO2/NOx} = c_{CO2/NOx,kg} \bullet \frac{Total_{en}}{45.6} \tag{33}$$

In theory, equations (30) and) would be valid to compute both current and future energy requirements. However, due to data availability issues, it was not possible to obtain information on idling/shunting consumptions ($c_{en,shunt}$, $c_{en,idle}$) for electric shunting locomotives (future energy carrier). Nevertheless, it is also known that these consumptions are significantly lower than in diesel shunting locomotives. First, a diesel engine requires fuel even if no power is being provided, just for idling, while an electric motor and battery only use electricity whenever power is needed. This means that the energy consumption associated with the auxiliary systems and brake tests is much lower in electric shunting locomotives. Concerning the shunting stages, a battery hybrid electric locomotive can harness energy

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[43] Port of Rotterdam

[44] Insight into the energy consumption, CO2 emissions and NOx emissions of rail freight transport (TNO)

from braking (a constant action in shunting operations) thus also leading to a lower consumption when comparing with diesel shunting locomotives. A similar situation can be observed in electric vs internal combustion cars. Typically, electric cars have much lower consumption in urban driving than in highways, with the opposite being true for internal combustion cars. Due to all these reasons, idle and shunting consumptions were not taken into account to compute the total energy demand of hybrid battery electric locomotives. Moreover, $c_{en,A-B}$ was obtained in *tkm*, which justifies the multiplication by the locomotive payload (W_{load}).

$$Total_{en} = c_{en,A-B} \bullet W_{load} \bullet d_{A-B} \bullet N \quad (34)$$

Since the considered green energy carrier does not have local emissions, no formula to calculate emissions is required.

4.2.4 Assumptions

With the mathematical base of the model presented, it's also important to discuss the scope that should be considered for the total energy consumption and emissions. For example, on an international truck transport to Austria, we can estimate the total fuel consumption of the truck, however, it's clear that the total amount of fuel consumed on this trip will not be supplied within the port of Rotterdam. This differentiation between what falls (or not) under the Port responsibility will be accessed in the upcoming tasks of Work Package 3, particularly in task 3.6. Under task 3.1, energy demand and emissions will be completely allocated to the Port ecosystem. In this way, it's guaranteed that the results are not conservative.

Due to some gaps on the data inputs, assumptions were necessary to execute the calculations. In this section these assumptions are presented, organized as follows: first, the more technical variables for road transport (payload weight and energy consumption/ TtW emissions per km), followed by the number of kms for each trip and lastly the number of trips required. Then, the same order is followed for the rail transport.

The payload weight for containers, break bulk and dry bulk was obtained in the transport policy analysis[45] . Table 29 presents the payload weight for each cargo type:

Table 29 - Cargo weights

Cargo type	Weight (Tonnes)
Containers	13.2
Break bulk – RoRo	13.9
Break bulk – Other	13.2
Dry bulk – Agri products	5.4
Dry bulk – Other	11.6
Liquid bulk - Other	13.9

Regarding the energy consumption/emissions per km for road transport, the VECTO tool[46] was used to obtain all values for different payload weights and operational profiles (urban, regional and long-haul) for diesel, CNG and LNG. This tool was developed by the European Commission and is the official tool to determine fuel consumption and CO2 emissions from

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[45] Cost Figures for Freight Transport (Netherlands Institute for Transport Policy Analysis)

[46] Vehicle Energy Consumption calculation TOol – VECTO (European Commission)

heavy duty vehicles. When downloading the tool, it comes preloaded with generic information for each vehicle class and the simulations for different payload weights and operational profiles can easily be simulated. The fuel consumption in MJ/km and CO2 emissions in gCO2/km were then adapted in the model using a linear relation according to the weight and profile required for each cargo type and scenario.

Considering the three types of trips considered in the road transport model (trips within the Rotterdam area, trips within the Netherlands and International trips), the regional profile was used in trips within the Rotterdam area, with the long-haul profile being used for the other two types of trips. The regional profile contains a stretch of highway driving and some city driving, so it's a good representation of trips within the Rotterdam area as the trucks must cover part of the A15 highway and then deliver the cargo in a more urban environment (or the opposite if a truck is going to the port). The long-haul profile is mostly highway, which is consistent with trips within the Netherlands or abroad.

The distribution of trips is 40% of trips within the Rotterdam area, 50% within the Netherlands and the final 10% are international trips[47]. To calculate the average distance per type of trip, data regarding all traffic coming in and out of the port in 2014 was used. It is organized by number of trips between 0 km and 10 km, 10 km and 20 km and so on. The data is then sorted by trip length, total number of trips is calculated and then the total distance travelled by the first 40% is calculated, afterwards being divided by 40% of the total number of trips, reaching the average distance travelled by the first 40% of trucks. Then, the same procedure is repeated for the following 50% and for the final 10%. Table 30 contains the definition of the trip types.

Table 30 - Trip type characteristics

	Rotterdam Area	Netherlands	International
Type of route (VECTO tool)	Regional	Long-Haul	Long-Haul
Distance (km)	20.25	93.54	437.4
Distribution of trips (%)	40	50	10

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[47] Port of Rotterdam

The NOx emissions were calculated as a ratio of grams of NOx per fuel burned, obtained in a report from the EU on T2W emissions for heavy duty vehicles. Table 31 contains the values used in the model for energy consumption, CO2 and NOx emissions:

Table 31 - Energy consumption and emissions obtained in VECTO tool[48]

Energy Carrier	Operational Profile	Payload (kg)	Energy Consumption (MJ/km)	CO2 emissions (gCO2/km)	NOx emissions (gNOx/km)
Diesel	Regional	2600	9.96	730.5	0.249
		12900	12.4	909.81	0.310
	Long-haul	2600	9.24	677.39	0.231
		19300	12.2	891.12	0.305
CNG	Regional	2600	10.5	589.76	0.0292
		12900	13.1	734.67	0.0364
	Long-haul	2600	9.76	547.00	0.0271
		19300	12.8	719.58	0.0356
LNG	Regional	2600	10.5	593.70	0.0292
		12900	13.1	739.57	0.0364
	Long-haul	2600	9.76	550.64	0.0271
		19300	12.8	724.38	0.0356

The number of trips required was significantly harder to obtain and the method to calculate it varies greatly according to the cargo type. For containers, the throughput for the port of Rotterdam[49] was used to get total containers that passed through the port in 2021, which is 15.3 MTEU. Then the transhipment percentage is applied to get the number of containers that are transported to/from the hinterland (36% is the transhipment for 2020[50]), reaching a value of 9.79 MTEU. Afterwards, the modal split is applied, where 52% of containers are carried by truck[50], getting a value of 5.09 MTEU of containers being transported by truck yearly. Lastly, a statistic available in the port's website states that 2500 TEU of containers require 1560 truck trips on average to carry them. By applying this ratio to 5.09 MTEU, we get roughly 3.177 million trips.

To divide them by the trip type, since more accurate information wasn't found, the distribution by trip type was applied to all cargo types. Lastly, the containers need to be divided by deepsea and shortsea containers, which are 65% deepsea and 35% shortsea for the overall port[50].While there was no information if this division is also true for road transport, it was assumed it can be used.

For liquid bulk in the "other" category (the only one considered for road transport), there is a total of 33.326 Mt coming through the port in 2021[49]. The transhipment for liquid bulk is 5%[50] and the modal split was obtained in the Wuppertal report[51], where the liquid bulk transported by road was divided by the total liquid bulk transported to/from the hinterland, resulting in 7.09%. By applying the transhipment and modal split to the total "Liquid bulk – Other", a value of 2.24 Mt transported by road is obtained. With the average payload being 13.9t of liquid bulk, roughly 161 thousand trips are required to transport all the liquid bulk carried by trucks.

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[48] JEC Tank-to-Wheels Report v5: Heavy duty vehicles (European Commision)
[49] THROUGHPUT PORT OF ROTTERDAM 2021 (Port of Rotterdam)
[50] Port of Rotterdam
[51] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

The same procedure is used to calculate number of trips for dry bulk, the only differences is the modal split (which is 15% for agri products and 20% for "other"[50]) and the different payload weights.

Lastly, for break bulk, the total amount of cargo was obtained in the throughput report[49] and the modal split was considered to be the 100% for RoRo cargo (as this cargo is always transported by truck) and for "Break bulk – Other" the same modal split as the one used for containers was considered. Then, the payload weights are used to reach the number of trips.

Table 32 summarizes the number of trips for road transport by cargo type and trip type.

Table 32 - Number of yearly trips per cargo and trip type

Cargo type	Yearly number of trips			
	Trips within Rotterdam	Trips within Netherlands	International Trips	Total trips
Shortsea Containers	444823	556029	111206	1112058
Deepsea Containers	826100	1032625	206525	2065250
Break bulk – RoRo	691022	863777	172755	1727554
Break bulk – Other	102441	128051	25610	256102
Dry bulk – Agri products	95411	119264	23853	238528
Dry bulk – Other	105379	131724	26345	263448
Liquid bulk - Other	64595	80744	16149	161487

Focusing on the rail transport, there is an additional factor impacting energy consumption in locomotives (along with weight and operational profile). While trucks always have a similar length, usually carrying one trailer, trains can carry few heavy wagons or several times more wagons, only lighter. These two situations can result in a train with similar total weight, however the additional wagons on the latter example significantly increase the drag experienced by the locomotive when pulling the composition of wagons. Due to the lack of information and new level of complexity this would add to the model, it wasn't considered.

Table 33 presents the cargo weights for the types of cargo, which were provided by a source within the port of Rotterdam. Dry bulk payload weight is considered to be a combination of coal cargo (2400 tons) and iron ore cargo (3600 tons), knowing that the first is 7% of all trains and the latter is 15%.

Table 33 - Total train weight by cargo type

Cargo type	Weight (Tonnes)
Shortsea Containers	1700
Deepsea Containers	1700
Break bulk	1700
Dry bulk	2782
Liquid bulk	1000
Unit cargo	2000

For the energy consumption/emissions per km for rail transport, a different approach has to be taken to correctly model the different operational profiles related with a diesel shunting locomotive. No reliable values for energy consumption of a diesel shunting locomotive were obtained in MJ/km or even MJ/tkm, as for a locomotive the weight heavily impacts the consumption and is dependent on the operating conditions (speed, acceleration, braking, etc). Another issue is developing a model that can be adapted to an increase in number of trips, better efficiency of locomotives, changes in distance travelled and other changes that can impact total energy requirements.

In order to model the energy consumption, a value obtained from a European Environment Agency report[52] that provides fuel consumption for diesel shunting locomotives is being used. Since this value is an average value for typical operation, the time for each operational stage (A-B travel, shunting and idling) was estimated, added and multiplied by this value. The report also provides CO2 and NOx emissions for each tonne of fuel burned.

As a reminder, the shunting and idling time were estimated so that an average trip takes 2-3h and idling time is 75%-84% of the total time. The speed in A-B travel is 15 km/h for trips within the port and 40 km/h whenever a train goes to Kijfhoek[53]. Table 34 contains the values used in the variables common to all cargo types.

Table 34 - Rail transport variables

Variable	Value
Hourly diesel fuel consumption	90.9 kg/h[52]
Hourly electricity consumption	0.02 kWh/tkm[54]
CO2 emissions	3190 gCO2/kg diesel[52]
NOx emissions	54.4 g/kg diesel[52]
Speed in A-B travel (Port)	15 km/h[53]
Speed in A-B travel (Kijfhoek)	40 km/h[53]
Time spent in shunting	0.33 h
Time spent in idling	1.5h

With a shunting time of 0.33h (equivalent to 20 minutes) and an idling time of 1.5h, the trips take between 1.9h and 3.1h (the unit cargo trip takes the longest) and the idle time is 78% when calculating idle time as the sum of idle time for all trips divided by the total time for all trips.

Due to more information being available within the port of Rotterdam, the approach to calculate trip distance and number of trips was different to the one chosen for road transport. Starting with the number of trips required for each cargo type, it was obtained by combining the yearly number of trains in the port rail line for 2021[55] and the distribution of cargo that rail transport carries[55]. Distribution of cargo is the percentage of trains that carry each cargo type, totalling 100%. One remark is that the distribution of containers doesn't consider deepsea and shortsea containers, however, the same ratio as for road transport was considered, so 35% shortsea and 65% deepsea.

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[52] 1.A.3.c Railways 2019 (European Environment Agency)

[53] Port of Rotterdam

[54] Insight into the energy consumption, CO2 emissions and NOx emissions of rail freight transport (TNO)

[55] Port of Rotterdam

The final values for distribution of cargo and number of train trips in a year by cargo type are presented in Table 35.

Table 35 - Rail transport number of trips

Cargo type	Distribution of cargo (%)	Yearly number of trips
Shortsea containers	17.01	6394
Deepsea containers	31.59	11874
Break bulk	9.6	3608
Dry bulk	21.6	8119
Liquid bulk	7.6	2857
Unit cargo	12.6	4736

The number of kms for rail transport was considered to be the average distance between the main terminals for each cargo type and the closest shunting yard[55]. The only exceptions being for liquid bulk, which always goes to Kijfhoek, and unit cargo. Unit cargo carries several cargo types, so it must pass through different terminals and deliver the cargo to Kijfhoek (or go from Kijfhoek to the port if the cargo is inbound for the port). For this cargo type, the worst-case scenario was considered, where the locomotive goes from Maasvlakte to Kijfhoek. For the other cargo types, the main terminals were identified and the average distance was calculated taking into account the market share of each terminal, as is represented in equation (*35*) where $M_{\%}$ is the market share of that terminal and d_{T-S} is the distance between the terminal and shunting yard (Kijfhoek in the case of liquid bulk).

$$d = \sum_i M_{\%}^i \bullet d_{T-S}^i \qquad (35)$$

Table 36 summarizes the distance considered for each cargo type.

Table 36 - Rail transport distance covered for each cargo type

Cargo type	Distance (km)
Shortsea containers	1.5
Deepsea containers	8.55
Break bulk	5.89
Dry bulk	6.53
Liquid bulk	27.25
Unit cargo	50

An important distinction between road and rail transport is that in rail transport the train can be divided into smaller trains if required. Usually this is done either if a locomotive does not have the power to pull such a heavy train or if a terminal isn't prepared to receive a longer train. However, this isn't a common situation, so it was not considered in the model.

4.2.5 Development of total energy demand

Having presented the main characteristics of the current scenario (diesel-powered) and the assumptions that will be considered in the calculations, it is now time to focus on the factors that influenced the construction of future scenarios (green sources powered):

- Improvements in current and future energy carriers including fuel consumption decrease in new diesel trucks and advanced emission systems that can capture more CO2 and NOx;

- Modal shift towards more efficient and less polluting modalities (rail and inland shipping);
- Cargo growth and variation trends (e.g., in Rotterdam's case it is foreseen that containerized cargo will increase and liquid/dry bulk transport will decrease)
- Inclusion of new green energy carriers.

Starting with the improvements in energy carriers, for road transport only battery electric, hydrogen powered and natural gas trucks were considered. Regarding locomotives, only hybrid battery electric locomotives were considered as this technology can easily fulfil the requirements of shunting locomotive and first/last mile delivery, requires no change to existing infrastructure and is very mature, with a demo already being operated in the MAGPIE project.

The improvement considered for diesel trucks was a 30% reduction in fuel consumption and emissions in 2030 when compared to 2019's values. This is in accordance with the EU's targets for heavy duty trucks[56]. For battery electric trucks no improvement was considered as the technology is already very mature and efficient. For hydrogen trucks, only the efficiency gains of the fuel cell were considered since the drivetrain is identical to a battery electric truck[57]. Table 37 presents the efficiency and emission gains (in %) foreseen for the different energy carriers in road transport.

Table 37 - Reduction in energy consumption and emissions by technology

	Energy Consumption			CO2 Emissions			NOx Emissions		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Diesel	30%	30%	30%	30%	30%	30%	30%	30%	30%
Batteries	NA			NA			NA		
H2	5%	9%	13%	NA			NA		
CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%
LNG	0%	0%	0%	0%	0%	0%	0%	0%	0%

For diesel locomotives no improvement was considered as the locomotives operating in the port of Rotterdam are decades old and are expected to be replaced in the coming years, as is the case with most major European ports that still operate diesel locomotives. For hybrid battery electric locomotives, no improvements were considered as the technology is already very mature and efficient.

Regarding the modal shift and amount of cargo transported in the port of Rotterdam, the report published by Wuppertal[58] was used. In this report, scenarios for amount of cargo transported and modal shift in 2050 were estimated, so by combining this information with some assumptions (such as same transhipment as current one), an increase or decrease in the amount transported by road and rail for each cargo type can be calculated. Then, a linear relation between current times and 2050 is set to get values for 2030 and 2040.

Since the report does not distinguish between containers and break bulk, their increase/decrease was considered to be the same. Table 38 contains the considered change for road transport and Table 39 contains the considered change for rail transport per cargo type.

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[56] VECTO – Overview (European Commission)

[57] Vehicle Technologies and Hydrogen and Fuel Cell Technologies Research and Development Programs Benefits Assessment Report for 2020 (NREL)

[58] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

Table 38 - Road transport variation in cargo transported

	Variation in cargo transported		
Cargo Type	2030	2040	2050
Shortsea Containers	4.3%	8.5%	12.8%
Deepsea Containers	4.3%	8.5%	12.8%
Break bulk - RoRo	20,6%	41,1%	61,7%
Break bulk - Other	4.3%	8.5%	12.8%
Dry bulk - Agri products	-13,9%	-27,8%	-41,7%
Dry bulk - Other	-13,9%	-27,8%	-41,7%
Liquid bulk - Other	-3,3%	-6,7%	-10,0%

Table 39 - Rail transport variation in cargo transported

	Variation in cargo transported		
Cargo Type	Year 10	Year 20	Year 30
Shortsea Containers	87.3%	174.7%	262%
Deepsea Containers	87.3%	174.7%	262%
Break bulk	87.3%	174.7%	262%
Dry bulk	-19,8%	-39,5%	-59,3%
Liquid bulk	0,0%	0,0%	0,0%
Unit cargo	0,0%	0,0%	0,0%

A few remarks regarding the tables presented above are required to clarify some results. Starting with "Break bulk – RoRo", we know that this cargo type is exclusively transported by road, so any increase in the port's throughput of this cargo leads directly to an increase in the amount of cargo transported by road. On the other hand, containers and "Break bulk – Other" are subject to changes in modal split, which is why there is an increase in overall cargo transported for these cargo types, due to the large increase in this cargo's throughput (around 50%), but the decrease in modal split from 52% to around 39%.

The large increase of almost three-fold in containers and breakbulk transported by train is due to the increase in cargo throughput (50%) and modal split, from 10% to almost double, around 18%. No information was found for liquid bulk or unit cargo on the Wuppertal Institute's report[59], which lead to the assumption that no variation in future years would occur. This is a valid assumption for liquid bulk as liquid bulk throughput in the port is expected to significantly decrease, however, since unit cargo is represented by trains carrying more than one type of cargo, the analysis on how it will evolve in the future is hard to do.

Focusing on the future truck fleet composition, this was extremely hard to do due to the uncertainty surrounding how the European truck fleet will evolve in the coming decades.

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[59] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)

Furthermore, the fleet composition for trucks operating around the Rotterdam area will be vastly different to the ones operating across Europe, mainly due to the advantages and disadvantages of each technology. For trips around Rotterdam, battery electric trucks will most likely be dominant, since their lower range and longer refuelling times aren't as big of a hinderance, whereas for long distance trips, technologies such as hydrogen powered trucks or LNG are better suited do to quick refuelling times and longer ranges.

To overcome this challenge, two extreme scenarios were developed, which were only simulated for 2050 and considered that the entire truck fleet will either be battery trucks or H2 powered trucks. A third scenario was developed whereas the years progress, the share of diesel trucks decreases and the share of new energy carriers powered trucks increases, reaching 2050 with only battery trucks and/or hydrogen powered trucks. For this final scenario, the fleet composition is different depending on the trip distance. Table 40 contains the fleet composition for the mixed scenario.

Table 40 - Road transport fleet composition for mixed scenario

	Trips within Rotterdam			Trips within the Netherlands			International trips		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Diesel	75%	45%	0%	80%	50%	0%	85%	55%	0%
Battery	15%	40%	80%	0%	10%	40%	0%	5%	20%
H2	5%	10%	20%	10%	25%	60%	10%	30%	80%
CNG	5%	5%	0%	5%	5%	0%	0%	0%	0%
LNG	0%	0%	0%	5%	10%	0%	5%	10%	0%

In 2050 no natural gas trucks were considered since natural gas is viewed as a transitional technology from diesel to clean and renewable energy carriers, acting as a steppingstone.

4.3 Results

4.3.1 Current energy demand

For the current scenario, considering all trucks are diesel powered, the total energy demand is 6.43E+09 MJ of diesel (roughly 141 million litres of diesel), divided by trip and cargo type according to Table 41 in MJ.

Table 41 - Road transport current energy demand (MJ)

	Trips within Rotterdam	Trips within the Netherlands	International trips	Total
Shortsea Containers	1,12E+08	5,78E+08	5,41E+08	1.23E+09
Deepsea Containers	2,09E+08	1,07E+09	1,00E+09	2.29E+09
Break bulk - RoRo	1,77E+08	9,08E+08	8,50E+08	1.93E+09
Break bulk - Other	2,59E+07	1,33E+08	1,25E+08	2.84E+08
Dry bulk - Agri products	2,05E+07	1,09E+08	1,02E+08	2.31E+08
Dry bulk – Other	2,58E+07	1,34E+08	1,25E+08	2.84E+08

Liquid bulk - Other	1,65E+07	8,49E+07	7,94E+07	1.81E+08

The developed model also calculates CO2 and NOx emissions, which for the current scenario are 470.5 kt and 160.8 t, respectively, roughly 518 kt of CO2eq calculated according to the Kyoto protocol[60]. Table 42 and Table 43 contain the results by trip and cargo type in g.

Table 42 - Road transport current CO2 emissions (g)

	Trips within Rotterdam	Trips within the Netherlands	International trips	Total
Shortsea Containers	8,24E+09	4,23E+10	3,95E+10	9.01E+10
Deepsea Containers	1,53E+10	7,85E+10	7,34E+10	1.67E+11
Break bulk - RoRo	1,30E+10	6,64E+10	6,21E+10	1.42E+11
Break bulk - Other	1,90E+09	9,74E+09	9,11E+09	2.07E+10
Dry bulk - Agri products	1,51E+09	7,96E+09	7,44E+09	1.69E+10
Dry bulk - Other	1,89E+09	9,77E+09	9,13E+09	2.08E+10
Liquid bulk - Other	1,21E+09	6,21E+09	5,81E+09	1.32E+10

Table 43 - Road transport current NOx emissions (g)

	Trips within Rotterdam	Trips within the Netherlands	International trips	Total
Shortsea Containers	2,81E+06	1,45E+07	1,35E+07	3.08E+07
Deepsea Containers	5,22E+06	2,68E+07	2,51E+07	5.72E+07
Break bulk - RoRo	4,42E+06	2,27E+07	2,12E+07	4.84E+07
Break bulk - Other	6,47E+05	3,33E+06	3,11E+06	7.09E+06
Dry bulk - Agri products	5,13E+05	2,72E+06	2,54E+06	5.77E+06
Dry bulk - Other	6,45E+05	3,34E+06	3,12E+06	7.10E+06
Liquid bulk - Other	4,13E+05	2,12E+06	1,99E+06	4.52E+06

As expected, the cargo types with the highest number of trips are the ones that consume more energy and pollute more, with the trips within Rotterdam being the less efficient in terms of diesel burned and emissions per tkm of cargo.

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[60] CO2 EQUIVALENTS (Climate Change Connection)

For the rail transport model, for the current scenario, the total energy demand is 3.69E+08 MJ of diesel (roughly 8.1 million litres of diesel), divided by cargo type according to Table 44 in MJ.

Table 44 - Rail transport current energy demand

Cargo Type	Energy Demand [MJ]
Shortsea Containers	5,11E+07
Deepsea Containers	1,18E+08
Break bulk	3,32E+07
Dry bulk	7,62E+07
Liquid bulk	2,97E+07
Unit cargo	6,05E+07

The total CO2 and NOx emissions are 25.8 kt and 440t, respectively, roughly 157 kt of CO2eq. Table 45 and Table 46 contain the results by cargo type in g.

Table 45 - Rail transport current CO2 emissions

Cargo Type	CO2 Emissions [g]
Shortsea Containers	3,58E+09
Deepsea Containers	8,26E+09
Break bulk	2,33E+09
Dry bulk	5,33E+09
Liquid bulk	2,08E+09
Unit cargo	4,23E+09

Table 46 - Rail transport current NOx emissions

Cargo Type	NOx Emissions [g]
Shortsea Containers	6,10E+07
Deepsea Containers	1,41E+08
Break bulk	3,97E+07
Dry bulk	9,10E+07
Liquid bulk	3,55E+07
Unit cargo	7,21E+07

The cargo types that contribute the most to the energy demand and emissions are container cargo and dry bulk, which is according to the expectations since these two cargo types represent 71% of the total cargo transported by train.

A more interesting analysis can be done by comparing the emissions of CO2 and NOx between road and rail transport. Energy demand and CO2 emissions are lower for rail transport than for road transport, matching with the lower amount of cargo transported by rail. However, NOx emissions are substantially higher than for road transport, which is in accordance with the use of much older technology in the diesel shunting locomotives employed in port of Rotterdam, since only more recent engines and exhaust systems focus on reducing NOx emissions.

4.3.2 Future energy demand

For the future scenarios and for the road transport model, Table 47 contains the energy demand in MJ for the three future scenarios developed along with a 100% diesel scenario to serve as a baseline.

Table 47 - Road transport future energy demand (MJ)

Scenario	Energy carrier	2030	2040	2050
100% diesel	Diesel	4.84E+09	5.18E+09	5.52E+09
100% electric	Electricity	-	-	2.85E+09
100% H2	H2	-	-	3.88E+09
Mixed scenario	Diesel	3.96E+09	2.57E+09	0
	Electricity	3.08E+07	3.34E+08	9.81E+08
	H2	3.56E+08	9.03E+08	2.54E+09
	LNG/CNG	5.52E+08	1.10E+09	0

The CO2 and NOx emissions are presented in Table 48 and Table 49, respectively.

Table 48 - Road transport future CO2 emissions (g)

Scenario	2030	2040	2050
100% diesel	3.54E+11	3.79E+11	4.03E+11
100% electric	-	-	-
100% H2	-	-	-
Mixed scenario	3,20E+11	2.48E+11	0

Table 49 - Road transport future NOx emissions (g)

Scenario	2030	2040	2050
100% diesel	1,21E+08	1.29E+08	1.38E+08
100% electric	-	-	-
100% H2	-	-	-
Mixed scenario	1.00E+08	6.95E+07	0

Starting with the baseline scenario of 100% diesel fleet composition, it is expected that the energy consumption will grow due to the increased cargo throughput in the port (namely containers), despite the modal shift away from road transport. In the 100% electric or H2 scenarios, the energy demand is lower for the electric scenario due to the increased efficiency of an electric powertrain when compared to a hydrogen powertrain, as the latter contains a fuel cell which reduces the overall efficiency.

In the mixed scenario, the diesel energy demand decreases as a shift towards more efficient energy carriers occurs. H2 has a higher energy demand in 2050 for this scenario not only due to the lower efficiency of hydrogen powertrains, but due to the types of trips associated with hydrogen trucks, which have a longer distance when compared to battery electric trucks, leading to overall higher energy demand.

The same conclusions are applicable to the CO2 and NOx emissions.

For the rail transport model, Table 50 presents the energy demand in MJ for the future scenarios, while Table 51 and Table 52 contain the CO2 and NOx emissions, respectively.

Table 50 - Rail transport future energy demand (MJ)

Scenario	Energy Carrier	2030	2040	2050
100% diesel	Diesel	5.31E+08	6.93E+08	8.54E+08
Mixed scenario	Diesel	0	0	0
	Electricity	7.98E+07	9.31E+07	1.06E+08

Table 51 - Rail transport future CO2 emissions (g)

Scenario	2030	2040	2050
100% diesel	3.71E+10	4.85E+10	5.98E+10
Mixed scenario	0	0	0

Table 52 - Rail transport future NOx emissions (g)

Scenario	2030	2040	2050
100% diesel	6.33E+08	8.26E+08	1.02E+09
Mixed scenario	0	0	0

With the combined effect of increased cargo throughput and modal shift towards rail transport, the energy demand for rail transport if all locomotives were still diesel is expected to substantially increase in the coming years, more than doubling. For the mixed scenario, with the total shift towards hybrid battery electric locomotives, a direct comparison with current scenario shouldn't be performed due to the different energy carriers in both scenarios. Nonetheless, from 2030 to 2050 the electricity demand for rail transport in the port of Rotterdam is expected to rise by around 30%.

Regarding emissions, no emissions are expected from 2030 onwards with the total replacement of diesel shunting locomotives with the hybrid battery electric locomotives removing any local emissions.

4.4 Discussion

4.4.1 Replicability & scalability

Due to the modular way model is structured, the parameters for the simulations made can be easily adjusted, both from a technical standpoint of the vehicles (new energy carriers, different consumption/emissions) and from the port standpoint (number of trips, average distance, future fleet composition, among others).

Furthermore, the model can easily be applied to different ports for the same reasons, possibly with some assumptions or slight changes made to better accommodate the specific characteristics of each port.

4.4.2 Validation

Unfortunately, the energy requirements couldn't be checked against any source. However, the total number of trucks calculation for 2021 is in line with the number of trucks coming in and out of the port in 2014[61], considering the increase in port throughput from 2014 to 2021.

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[61] Port of Rotterdam

4.4.3 Uncertainties

On the road transport model, the number of trucks considered was estimated using some assumptions, so there is a certain level of uncertainty around its accuracy that needs to be considered. Assumptions surrounding modal split and transhipment for each cargo type were also taken, however, the most uncertain assumption was using total port throughput per cargo type, applying the modal split and transhipment along with average payload per truck to estimate number of trucks. Furthermore, average trip distances were used in the scenarios. Even though these average distances were calculated using information specific to the port of Rotterdam operation, some assumptions were still necessary. One assumption was that the trip distances considered were the same for all cargo types, which doesn't portray the reality.

For the rail transport model, the consumption for idle, shunting and A-B are extremely hard to obtain due to the dependence on locomotive operation, type of locomotive and so on. This led to the use of an average operating value of a typical shunting locomotive, instead of being able to separate the locomotive's consumption in idle, shunting and A-B travel. Another aspect that wasn't considered is that locomotive consumption is heavily dependent on number of wagons and total weight of the train, making their energy consumption in shunting operations not only hard to estimate, but also to directly relate it to amount of cargo transported.

Furthermore, the typical operation of a shunting locomotive consists of dropping/picking up the wagons to be loaded/unloaded at the terminal while going to another location to perform some other activity, or even carrying cargo from several terminals in a row The assumption that a long-haul locomotive arrives from the hinterland, drops the wagons in a shunting terminal, a shunting locomotive picks them up, carries them to a terminal where they are loaded/unloaded was taken, with the opposite being considered for an outgoing trip (terminal to hinterland). This leads to a different interpretation on the typical operation of a shunting locomotive, with its impact on the results being another uncertainty. Regarding all future projections (future truck/train fleet composition, reduction in consumption/emissions and cargo growth trends), these were all estimated based on studies or projections. Since they are all projections on how technology/port activities will progress along decades, it's extremely uncertain whether these data will be similar to what the future will hold. That is why it is relevant to keep reflecting as we build our knowledge.

Future projections also consider that some aspects remain constant which probably won't, such as transhipment, % of truck movements that are divided according to the three trip types defined, among others. On a technical standpoint, consumption of trucks and locomotives running on new energy carriers are mostly estimated as there are reports containing this information, however, they differ quite a lot amongst each other. Other consumptions weren't considered due to being hard to evaluate and low impact on the overall energy requirements. These include, among others, idle consumption for trucks and the consumption of a hybrid battery electric locomotive while idling.

It's important to highlight that all assumptions present in the model were only decided after a thorough literature review and extensive talks with the relevant partners with knowledge on a technical level for technical assumptions regarding road and rail transport. Regarding assumptions based on port activities, the relevant partners with insight into truck flow within the port of Rotterdam were consulted to validate the non-technical assumptions in the road transport model (categorization, movements, trip distance and so on), while the non-technical assumptions of the rail transport model were validated by partners with knowledge on train operations within the port of Rotterdam.

4.5 Conclusions & recommendations

Concluding, the energy demand for road transport in the port of Rotterdam is expected to increase despite the shift towards more efficient modes of transportation from an energy need for tkm of cargo transported and more efficient energy carriers. Currently, around 141 million litres of diesel are consumed for road transport in the port, with 470.5 kt and 160.8 t of CO2 and NOx emitted, respectively, corresponding to 518 kt of CO2eq.

Regarding the renewable future technologies and their implementation, battery electric trucks are expected to be primarily used in more urban environments, travelling shorter distances throughout the day so not to be affected by their smaller range and longer recharging times. On the other hand, hydrogen powered trucks are more suited towards longer distance operation, taking advantage of their longer range and fast refuelling times. Concerning LNG/CNG-powered trucks, it was considered that they will make part of a transition phase, but they will not have an impactful role in the long-term due to the associated GHG emissions. In a future analysis, it might be important to also analyse the long-term role of Bio-LNG, which is characterized by lower WtW emissions.

Rail transport is expected to significantly increase over the next decades, with the old diesel shunting locomotives being replaced by hybrid battery electric locomotives. Currently, rail transport consumes 8.1 million litres of fuel and emits 25.8 kt and 440t of CO2 and NOx, respectively, corresponding to 157 kt of CO2eq.

Rail transport is one of the most efficient methods of hinterland transportation per tkm and outside ports, the railways are mostly electrified so it's also a very clean method of transportation in general. With the introduction of hybrid battery electric locomotives, short sections of non-electrified railway are no longer a limitation on the usage of electricity as the energy source for rail transport in ports, namely shunting operations and first/last mile delivery can be performed without using diesel locomotives.

By comparing the emissions of CO2 and NOx between road and rail transport, both energy demand and CO2 emissions are lower for rail transport than for road transport, matching with the lower amount of cargo transported by rail. However, NOx emissions are substantially higher than for road transport, mostly due to the use of old diesel locomotives compared to modern trucks which have strict environmental regulations.

Focusing on the uncertainties of the model, the assumptions taken in the methodology lead to some uncertainties surrounding some parts of the model. These assumptions were taken based on a thorough literature review and by having extensive talks with technical partners in road and rail transport and partners operating within the port of Rotterdam with knowledge on typical truck and train movements. As a result, the assumptions were formulated in a way that attempts to represent the reality as much as possible, minimizing the uncertainties.

Nevertheless, the quality and detail of the data available has room to improve to facilitate a future iteration of an energy demand estimation model for hinterland transport. The identification of areas where difficulties were experienced in estimating energy demand is an important aspect of this task, so that improvements over the course of the MAGPIE project can be implemented in order that in the second part of this task (last 6 months of the project) more accurate information might be available. The recommendations here made can be applied on all ports across Europe to facilitate the estimation of current and future energy demand.

The estimation of the energy requirements using this model has several points of improvement, from aggregating trips by cargo type to calculating the number of trips required by using total cargo transported and general modal splits. There are several variables that can start being more carefully tracked and stored so that future studies can utilize more detailed data, leading to more accurate results. Starting with the road transport model, the following data should be tracked:

- Number of trucks entering and exiting each terminal
- Destination/origin of each truck
- Weight of cargo transported
- % of trucks per terminal that arrive loaded and leave unloaded
- % of trucks per terminal that arrive unloaded and leave loaded
- % of trucks per terminal that arrive and leave loaded

For rail transport, different data should be tracked to consider the different operational profiles of locomotives. Notably, locomotives usually drop the wagons to be loaded/unloaded at the terminal while going to another location to perform some other activity, later returning to the terminal to transport the wagons. Furthermore, the locomotives can pass through several terminals while loading all the wagons it's transporting, which means the estimation of energy requirement in relation to cargo is harder to achieve than for road transport. This relation is an essential characteristic of any model estimating energy requirements as it enables the model to be able to adapt to different scenarios, otherwise it's limited to the scenario for which the data was obtained.

In terms of specific energy consumption and emissions, for road transport there is widely available information to estimate these parameters in terms of type of route and weight of the cargo transported, information that would be available if the suggested data above is tracked.

However, the same isn't applicable to locomotives, especially in port operations. Locomotive consumption is heavily dependent on number of wagons and total weight of the train, much more so than truck consumption and while a truck only carries one trailer, a locomotive can carry from one to dozens of wagons. Specifically in port operations, these locomotives spend over half of their operating time idling (even an electric locomotive consumes energy during this time, for example to perform the required brake tests). Moreover, energy consumption in shunting operations is not only hard to estimate, but also to directly relate it to amount of cargo transported. On a technical perspective, while truck models have small changes in engine size, power and chassis, locomotives can widely vary in weight and power, leading to different consumption profiles depending on the locomotive model used.

The future scenarios can also use this information, only adapted to match the forecasted growth of cargo, better efficiency of drivetrains, among others.

5 Conclusions

The main conclusions are formed by the current and future energy demand for the different modalities. These will therefore be presented here.

5.1 Current energy demand

When it comes to the current energy demand for the different modalities, that resulted from this report, maritime shipping is by far the largest with approx. 400 000 TJ, then inland shipping with 6766 TJ and road (i.e., trucks) with 6433 TJ and lastly rail with 369 TJ. Although this numerical comparison is being provided, conclusions should only be extracted after analysing how the calculations per modality were carried out since the considered assumptions vary.

5.2 Future energy demand per modality

Note that they cannot be visualized in one table, since the for the different modalities a different scope and approach was most suitable.

The result of the translation of the current range in energy demand and suitable energy carrier for the different categories is shown in below table. This provides a range.

Table 53 Future energy demand modality – maritime shipping

Energy carrier	2030 (mln GJ)	2040 (mln GJ)	2050 (mln GJ)
Methanol	49 - 244	49 - 244	49 - 244
Biodiesel	55 - 395	55 - 395	55 - 395
Hydrogen	6 - 72	6 - 72	6 - 72
Ammonia	0 - 0	0.4 - 167	49 - 244
LNG	30 - 130	30 - 130	30 - 130
Electricity	8 - 153	8 - 153	8 - 153

For inland shipping different scenarios were looked at which also provides a range for the different energy carriers.

Table 54 Future energy demand modality – Inland shipping

Final Energy in TJ	REF	BAU			CONS			INOV		
Energy carrier	2020*	2030	2040	2050	2030	2040	2050	2030	2040	2050
Diesel	6766	6106	5568	5139	4777	2713	618	4730	2701	707
HVO	0.0	0	0	0	907	1630	2182	406	480	270
LNG	0.0	32	45	41	115	109	0	98	92	0
Bio-LNG	0.0	0	0	0	79	433	1014	209	395	558
Electricity	0.0	0	0	0	8	69	173	147	317	504
Hydrogen	0.0	0	0	0	1	96	267	67	456	1113
Bio-methanol	0.0	0	0	0	11	154	407	51	367	901
Total	6766	6138	5613	5180	5898	5203	4661	5707	4808	4053

* The total consumption for the reference year was validated against overall European demand and proportionality of the Dutch inland shipping sector, which was within a bandwidth of less than 5%.

Similarly, for road transport scenarios are used to gain insight in future demand.

Table 55 Future energy demand modality – Road transport (MJ)

Scenario	Energy carrier	2030	2040	2050
100% electric	Electricity	-	-	2.85E+09
100% H2	Hydrogen	-	-	3.88E+09
Mixed scenario	Diesel	3.96E+09	2.57E+09	0
	Electricity	3.08E+07	3.34E+08	9.81E+08
	Hydrogen	3.56E+08	9.03E+08	2.54E+09
	LNG/CNG	5.52E+08	1.10E+09	0

Finally, rail future energy scenarios were analysed.

Table 56 Future energy demand modality – Rail transport (MJ)

Scenario	Energy carrier	2030	2040	2050
Mixed scenario	Diesel	0	0	0
	Electricity	7.98E+07	9.31E+07	1.06E+08

5.3 Future energy demand per energy carrier

Within this task scenarios had to be developed to look at future demand. This also results in different conditions around use of a certain energy carrier in a modality and even in a range or different outlooks. In order to make sure these differences are not disregarded, but the outlook for a specific energy carrier is as easily retrieved as possible, this paragraph combines the different tables per energy carrier. Please be aware of the units stated. Also note that for different modalities, different spacing and timing of the supply chain is required.

5.3.1 (Bio-)Methanol

Methanol can be found as an e-fuel, bio-based or even grey. Naturally the goal is to provide green supply, this task however only indicated demand. Methanol use is found in both shipping sectors. Note that different scenarios are presented below each other.

Table 57 Future energy demand per energy carrier – (bio-)methanol

Energy carrier	2030	2040	2050
Maritime shipping	49 - 244E+03 TJ	49 – 244E+03 TJ	49 – 244E+03 TJ
Inland shipping BAU	0 TJ	0 TJ	0 TJ
Inland shipping CONS	11 TJ	154 TJ	407 TJ
Inland shipping INOV	51 TJ	367 TJ	901 TJ

5.3.2 (Bio-)diesel, HVO

Bio-diesel, mainly looking at HVO is found inland and maritime shipping. In the road transport sector, diesel is also found, this may be of fossil origin still. In case of bio-diesel/HVO an addition of (bio) is provided in the first column. If this is not included the table refers to fossil diesel, this is important in case of any emission calculations. For marine shipping the fossil demand is not included. Note that different scenarios are presented below each other.

Table 58 Future energy demand per energy carrier – (bio-)diesel/HVO

Energy carrier	2030	2040	2050
Maritime shipping (bio)	55 – 395E+03 TJ	55 – 395E+03 TJ	55 – 395E+03 TJ
Inland shipping BAU (bio)	0 TJ	0 TJ	0 TJ
Inland shipping BAU	6106 TJ	5568 TJ	5139 TJ
Inland shipping CONS (bio)	907 TJ	1630 TJ	2182 TJ
Inland shipping CONS	4777 TJ	2713 TJ	618 TJ
Inland shipping INOV (bio)	406 TJ	480 TJ	270 TJ
Inland shipping INOV	4730 TJ	2701 TJ	707 TJ
Road mixed scenario	3.96E+03 TJ	2.57E+03 TJ	0

5.3.3 (Bio-)LNG

(Bio-)LNG is found in maritime shipping, inland shipping and road transport. In case of Bio-LNG an addition of (bio) is provided in the first column. If this is not included the table refers to fossil LNG (or CNG), this is important in case of any emission calculations. Note that different scenarios are presented below each other.

Table 59 Future energy demand per energy carrier – (bio-)LNG

Energy carrier	2030	2040	2050
Maritime shipping	30 – 130E+03 TJ	30 – 130E+03 TJ	30 – 130E+03 TJ
Inland shipping BAU (bio)	0 TJ	0 TJ	0 TJ
Inland shipping BAU	32 TJ	45 TJ	41 TJ
Inland shipping CONS (bio)	79 TJ	433 TJ	1014 TJ
Inland shipping CONS	115 TJ	109 TJ	0 TJ
Inland shipping INOV (bio)	209 TJ	395 TJ	558 TJ
Inland shipping INOV	98 TJ	92 TJ	0 TJ
Road mixed scenario	5.52E+02 TJ	1.10E+03 TJ	0 TJ

5.3.4 Hydrogen

Hydrogen is found in maritime shipping, inland shipping and road transport. Note that different scenarios are presented below each other.

Table 60 Future energy demand per energy carrier – hydrogen

Energy carrier	2030	2040	2050
Maritime shipping	6 – 72E+03 TJ	6 – 72E+03 TJ	6 – 72E+03 TJ
Inland shipping BAU	0 TJ	0 TJ	0 TJ
Inland shipping CONS	1 TJ	96 TJ	267 TJ
Inland shipping INOV	67 TJ	456 TJ	1113 TJ
Road 100% hydrogen	-	-	3.88E+03 TJ
Road mixed scenario	3.56E+02 TJ	9.03E+02 TJ	2.54E+03 TJ

5.3.5 Ammonia

Ammonia is found in maritime shipping.

Table 61 Future energy demand per energy carrier – ammonia

Energy carrier	2030	2040	2050
Maritime shipping	0 – 0 TJ	0.4 – 167E+03 TJ	49 – 244 E+03 TJ

5.3.6 Electricity

Hydrogen is found in maritime shipping, inland shipping, road transport and rail transport. Note that different scenarios are presented below each other.

Table 62 Future energy demand per energy carrier – electricity

Energy carrier	2030	2040	2050
Maritime shipping	8 – 153E+03 TJ	8 – 153E+03 TJ	8 – 153E+03 TJ
Inland shipping BAU	0 TJ	0 TJ	0 TJ
Inland shipping CONS	8 TJ	69 TJ	173 TJ
Inland shipping INOV	147 TJ	317 TJ	504 TJ
Road 100% electric	-	-	2.85E+03 TJ
Road mixed scenario	3.08E+01 TJ	3.34E+02 TJ	9.81E+02 TJ
Rail	7.98E+01 TJ	9.31E+01 TJ	1.06E+02 TJ

6 Recommendations

Several recommendations follow from this deliverable, some related to the outcomes and others related to the process. The recommendations for the different modalities have been included in the respective chapters, this chapter provides generic recommendations that are overarching.

Items that are interesting to investigate in the future are:

- Development of transport movements and effect of efficiency measures on energy demand
- Effect of rules & regulations on transport movements
- Bunkering patterns and approach including the related geographical scope that is relevant.
- Commercial dimension related to global production and availability of alternative energy carriers, including impact of regulations.
- Technological readiness of different alternative energy carriers, including the development of new types of energy carriers that have not been considered within the scope of MAGPIE and are still in early TRL.

The actual impact of these factors will become clear over the years when more and more knowledge is gained and influential measures are implemented, for example for maritime shipping think about ETS (European) and CII (IMO). It is very important that these are monitored while looking at future developments.

Some more detailed and process related recommendations are listed below

- Affordability of green energy carriers is mentioned above, but this needs to be highlighted separately as this is a point of supply and demand where we may expect that in the near future the availability of green energy carriers may not meet the demand. The transport sector, especially maritime shipping, is generally not the sector that will be able to pay the highest price compared to other industries. This may result in limited supply for the transport sector, which is important to consider when looking at the speed of implementation.
- The focus within this task was clearly on the demand side, as stated above, there is interaction with the supply side in this case, since both are undergoing change and development. How these impact each other has to do with the commercial dimension, which is already mentioned, but also with uncertainties on both sides as well as those related to technical feasibility. In order to make the green transition work, we need to work together to remove those uncertainties and create the future demand and future supply in simultaneously. Note that this is also different for maritime shipping compared to the other modalities, a part of maritime shipping moves long distances across the globe, which broadens their possibilities and removes the need to bunker in Rotterdam or its vicinity. This is something that also needs to be kept in mind when looking at the future.
- For the different modalities it is important to keep geographical scope and flexibilities in mind. This varies greatly across all modalities and pricing and availability of future fuels may for some impact the position of port of Rotterdam as a bunkering hub significantly. Whereas ocean-going vessels can easily find their energy in other locations, trains and trucks are not as flexible. This has to do with range.
- Data for the different modalities came from different (types of) sources and therefore the approaches between the modalities have been formulated differently.

Besides modalities also differ drastically in transportation patterns and flexibility. Before the end of 2022 a tool called HESP, which is being developed within the Port of Rotterdam, should be able to provide energy demand insights for the port of Rotterdam in a standardized way across all modalities. For those working with the data it is recommended that they keep an eye on this development and use it to validate this work.

- Data is very scattered throughout different partners and even external parties. Some data was expected to be easily accessible at the start and was found to be unavailable. The uncertainties around this and the many sources that needed to be consulted cost a lot of time. Meanwhile models were built based on the expectation that data would be available at a later stage. The energy demand question can be answered at different levels and knowing earlier what data is available and shareable and what level of granularity can be worked with, would have saved a lot of time and effort.
- An average person that works for a company does not know the ins and outs of databases, data security and confidentiality. A dedicated data team for the MAGPIE project that would be very helpful to make a complete inventory of relevant data availability within the different organizations and possibly externally. They could also advise on subjects related to data. One might imagine that asking a question around data who also needs to consult other people and then get proper answers while not understanding the core task, leads to many delays and challenges.

Annex A: Original task description

Task 3.1 Transport energy requirements (M1-M9; M54-M60) [POR, EDP, EUR, ZCS, TUD, TNO, PPoint, INESCTEC]

Subtask 3.1.1: Shipping energy requirements (POR) - Note that this subtask has been executed by the TU Delft

This subtask aims to specify the maritime shipping energy needs, based on a multi-carrier carrier's analysis and vessel profile characterisation to establish the static and dynamic demand and related supply scenarios of the required energy carriers (e.g., wind energy deployment) in conjunction with PoR, Fellow Ports and stakeholders. Input to T3.9, T5.1 and T3.8. Basis for T3.4, T3.5, T3.6, T3.7 and WP4.

Subtask 3.1.2: Inland shipping energy requirements (INESCTEC)

This subtask aims to specify the baseline of inland shipping energy scenarios and future energy volumes based on a multi-carrier carrier's analysis (H2, BioLNG and electricity). Relates to T3.8, WP6 and the use of ZES container concept in the demos. Relates to T3.5, T3.7, WP4 and WP10.

Subtask 3.1.3: Trucking and Rail energy requirements (EDP)

This subtask aims to specify the baseline trucking and rail transport energy scenario's (e.g., electricity and green hydrogen) at POR and hinterland routes. The analysis will benchmark the sustainability technology developments in the trucking and rail industry and related deployment. Output a detailed off-taker demand profile, input for T3.4, T3.5, WP4. Relates to WP2, WP4, WP6, WP8 and WP9.

Annex B: Description of energy carriers

A total of 6 future green energy carriers were identified: Methanol, Biodiesel, Hydrogen, Ammonia, LNG and Electricity. Within this chapter a description of the status of each energy carrier will be given as background information. This includes some additional information on the suitability of the energy carrier within maritime shipping.

In the table below key data on the current availability of green energy carriers is provided. The first column indicates the average GHG reduction that is achieved by the energy carrier. These are values commonly found in literature, but which are open to debate. E.g., for biodiesel and bio-LNG not biofuels are assumed to be used during the growth/production phase. Furthermore, LNG is scoring worse due to the fact that currently methane slip is in the order of 1-2% of the fuel. Methane has a 25 times larger GHG impact than CO_2, so 1% slip is 25% GHG reduction loss. It is assumed this is addressed to reach a level below 1% in the calculation below.

The second and third column present the current green worldwide production capacity. As can be seen only biodiesel and green electricity are anywhere near a decent volume, but also are used currently for other transport modes. Although not researched within MAGPIE, the production of bio-ethanol is about 2.5 times that of biodiesel (115 bln litres) and could also be used as a fuel for transportation.

The last column gives a first insight into the energy density of the fuel, the higher this value the better. This value does not include the containment system. Especially in the case of hydrogen this will have a severe impact on the total energy density. The containment of hydrogen either at 600 bar or at very low temperatures requires a complex system around the liquefied gas, resulting in very low energy densities for the combined system. From this overview, it is clear that diesels (which have a similar value as biodiesel) are very well suited for storing energy.

Table 63 Summary of energy carrier properties concerning storage and production[62]

	WTW % GHG reduction	Green Production Capacity (mln litres)	Green Production Capacity (mln GJ)	Energy Density (MJ/L, MJ/kg)
Methanol	99%	<0.5	0.004	17.8, 22.4
Bio diesel	88%	~50,000	2106	34, 37.8
Hydrogen	100%	~3,000	0.04	8, 120
Ammonia	97%	0	0	11.5, 22.5
LNG	78%	~2.500	72	25, 45
Electricity	85%	-	2275	2.0-2.5, 2.0-2.5

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[62] https://ourworldindata.org/renewable-energy
https://www.iea.org/reports/global-energy-review-2021/renewables
https://nordsol.com/biolng-market/
https://iea.blob.core.windows.net/assets/1a24f1fe-c971-4c25-964a-57d0f31eb97b/Renewables_2020-PDF.pdf
https://www.statista.com/statistics/859104/hydrogen-production-outlook-worldwide-by-type/#:~:text=A%20little%20over%20one%20million,through%20electrolysis%20using%20renewable%20electricity.

Methanol

Methanol (CH3OH) is the simplest alcohol structure and has been around as a key component in the chemical industry for more than a century, it is used in various products ranging from plastic to paints and from furniture to fuels. Now it has been introduced as a long-term solution to reduce CO_2 emissions. Since methanol is one of the most traded chemical products in the world, its distribution infrastructure can be used to supply the product as a fuel for the shipping industry. But even being available in many ports around the world, the current global capacity is much less than what is needed for the global maritime energy demand. The global total annual methanol energy production is 2.2 million GJ compared to 12.8 million GJ global annual marine energy consumption, another issue is that the current bunkering infrastructure to transport methanol from the onshore storage to a ship is still a major challenge in many ports around the world.

Methanol also has its advantages, being a liquid fuel means that it can be stored in standards fuel tanks, meaning it does not require cryogenic installations to cool and pressurize fuel as needed for both LNG and hydrogen, but modifications to the fuel system are required due to the low flashpoint of the methanol. Also, there are already a few vessels operating on methanol like the Stena Germanica a roll-on, roll-off passenger vessel retrofitted in 2015 to run on methanol. The vessel provides ferry services between Gothenburg and Kiel, where there are methanol bunkering and support facilities in place, the Stena Germanica is equipped with four medium-speed 4-strokes diesel engines that have been converted to burn methanol in a dual fuel configuration. Waterfront Shipping has seven methanol carries running in methanol featured with low-speed 2-strokes DF MAN engines and by using water blending in the cylinders meet IMO Tier III regulations to limit NOx emissions.

Regarding regulations, the paper mentions the energy efficiency requirements in MARPOL Annex VI that are intended to reduce both emissions in general as well as GHG emissions specifically. The annex specifies to main measures which entered force in 2013 and are mandatory for all vessels of 400 gross tonnages and above, the Energy Efficiency Design Index (EEDII) which is a framework for fuel-saving and energy efficiency for new vessels that require ships to comply with minimum mandatory energy efficiency performance levels which increase over time through different phases. The other is the Ship Energy Efficiency Management Plan (SEEMP) which is an assessment tool for ship owners to improve energy efficiency for both new and existing vessels, intended to use operational measures such as weather routing, trim and draught optimization, speed optimization, just-in-time arrival at ports, among other things. The paper also mentioned the IMO strategy introduced in 2018 to reduce the total annual GHG emissions by international shipping by at least 50% in 2050 compared to the levels of 2008. EU has a more ambitious GHG emission reduction package for a 40% reduction in 2030 and an 80-95% reduction by 2050.

Specifically for methanol, the most significant emissions of its combustion are Nitrogen oxide (NOx) and GHG emissions. When the methanol is produced from fossil energy, the CO_2 emissions are roughly 8% lower than the regular marine diesel oil combustion but is produced from renewable or bioenergy, the CO_2 intake during the production phase of the fuel is considered equal to the CO_2 released during combustion which it results in zero total emissions.

There are also important fuel properties that impact the new power plant concept, such as energy density, flashpoint, and water solubility. Energy density can be explained using the concept of lower heating value (LHV), which is the amount of energy present in the fuel that is released as heat during combustion. Methanol has an LHV of less than half compared to the LHV of the regular MDO, this means that larger quantities of product will need to be injected into the engine´s cylinder to have the same power output, which also means that more quantities of methanol will need to be stored onboard which requires larger volume fuel tanks. One possible solution is to use the ballast tanks for methanol storage, as was done on the Stena Germanica.

Methanol is a low flash point fuel, which creates a safety risk in case of leakage in the fuel system, this way safe handling and storage are essential, and the methanol fuel system should comply with IMO´s International Code of Safety for Ships using Gas or other Low-flashpoint Fuels (IGF Code). In practice, this means modifications to the ventilation system, insulation of the electrical system, double-wall design of all high-pressure methanol fuel components, and additional fire detection systems are required. Regarding the water solubility, methanol completely dissolves in water, this means less environmental pollution in case of a fuel spillage.

Biodiesel

Drop-in biofuels are biomass-based fuels that can be used in a conventional Internal Combustion Engine (ICE) engine without the need for modifications. Their implementation is a solution that can immediately be used by the shipping industry. Biofuels have a carbon-neutral cycle, meaning that the biofuel feedstocks absorb the same amount of CO_2 than they release in the air when burned. This causes the GHG impact of biofuels to be significantly less when compared to fossil fuels. The transition to biofuels can be performed gradually by starting with blending them into fossil fuels. In the automotive sector, already, a percentage of biofuel is blended with conventional fuels. For the shipping industry, the same could be done, but there is uncertainty about which feedstocks can cover the demand while minimizing GHG emissions from well to tank. To make sure that biofuel demand can be fulfilled while decreasing GHG emissions, an efficient biofuel supply chain is required [56]. Biomass is not evenly spread across the globe, which might cause regions to import or export large quantities of feedstock, possibly decreasing the emission reduction potential. The goal of this thesis is, on the one hand, to determine the future marine biofuel demand in the most important shipping regions and, on the other hand, to determine the most feasible composition of the biofuel supply chain to fulfil this demand.

The carbon emitted during the life-cycle of a fuel can either be carbon positive, neutral, or negative. Fossil fuels are carbon positive, absorbing fossil resources from the soil and expelling it as CO_2 into the air, creating net positive emissions. The use of biofuels can be seen as a carbon-neutral solution. The CO_2 that the feedstocks absorb during their lifetime to grow returns to the atmosphere when the biomass is converted into energy. For accounting purposes, the TtW emissions of biofuels are considered.

There are various types of biofuels, which can all be produced from different feedstocks, using various conversion processes. An overview of these conversion pathways is shown in figure 1.1. Feedstocks are in this case divided into different categories. Usually, pre-treatment is performed to prepare the feedstock for processing. Pre-treatment includes processes like drying and milling of the feedstock. Consequently, a processing step is performed to convert the biomass into an intermediate bio-energy carrier. This intermediate product can then be processed again to convert it into a biofuel.

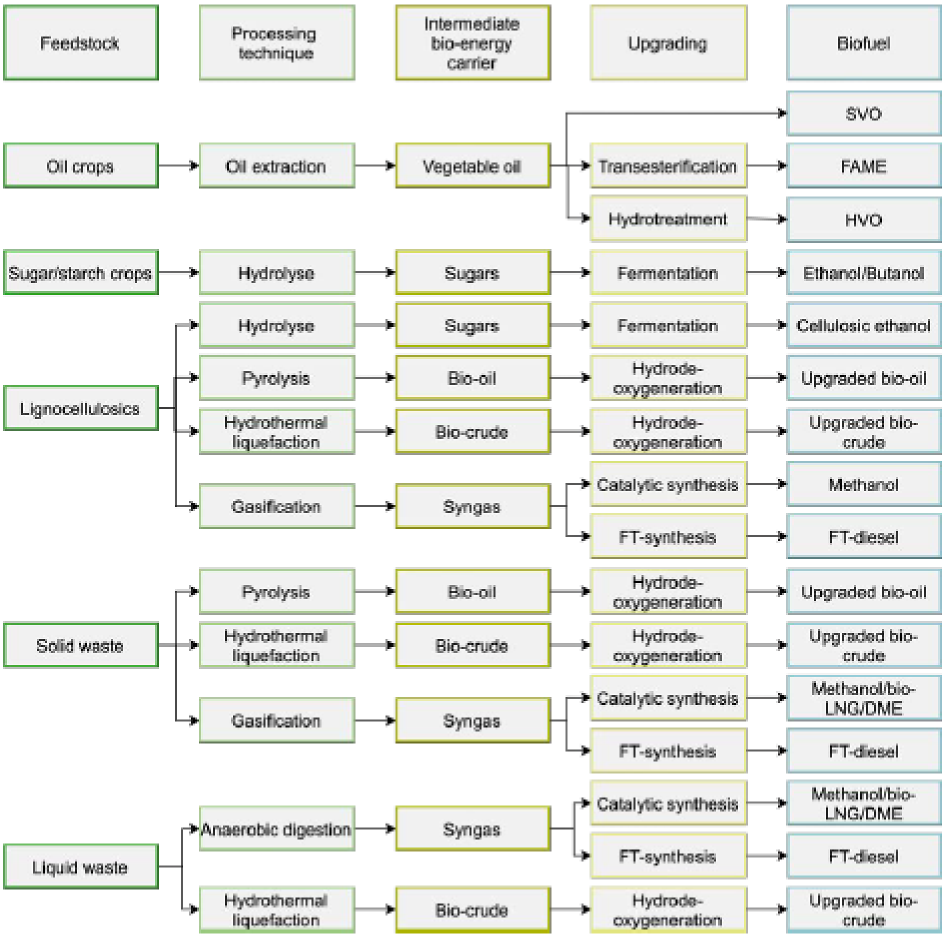

Figure 1.1: Various biomass-to-biofuel pathways.

EU regulations could greatly influence the deployment of biofuels in shipping. Despite the recognition of the fact that GHG emissions from shipping need to be addressed to comply with international targets like the Paris Agreement, there is no policy or target to reduce them at EU level. The EU has some general emissions reduction targets, but shipping is not included. Although there are no GHG emission targets for shipping yet, the EU has set some targets for the usage of renewable fuels in transport. These targets are set in the RED II, which is a revision of the Renewable Energy Directive (RED). The sub-target for renewable energy consumption in transport is set to 14% by 2030. This revision also raised the overall renewable energy resources consumption target for 2030 from 27% to 32%. On top of these new targets, RED II also stated sustainability criteria for biofuels to count towards the 14% target. One of the difficulties of biofuels is that the feedstocks may compete with other industries like the food industry. Another problem is Indirect Land Use Change (ILUC). When cropland is used as a biofuel feedstock, it results in the shift of agricultural land to non-cropland. This can lead to deforestation and the unwanted release of CO2, which is collected in the trees and soil. To prevent this from happening, RED II has implemented a limit to biofuels with high risk on ILUC.

Next to the limit on biofuels made from feedstocks that contribute to ILUC, also attention is given to so-called advanced biofuels. To stimulate the usage of certain feedstocks, multipliers are given when feedstocks are used that the EU believes are more sustainable than the ones currently used. These feedstocks are highlighted in RED II annex IX-A, and biofuels made from these feedstocks are defined as advanced biofuels by the EU. These biofuels are given a multiplier of two, meaning that the energy share obtained from the fuel may be counted double (virtually) for the target of 14%.

Hydrogen

Hydrogen has a low volumetric energy density and is therefore not suitable for long trips. Furthermore, it requires long bunkering times to transfer it, or very expensive bunkering equipment. Unlike batteries, it is primarily volume driven and therefore more suited for the weight limited vessels on the 1 day and short trips.

Ammonia

The annual production is approximately 180 million tons which approximately 80% is used for fertilizers. The chemical formula is NH_3 and it is inherently free of carbo, so when fully combusted as a fuel, the end product is only nitrogen and water, with the auxiliary of a standard exhaust treatment technology (SCR). Ammonia is conventionally produced from natural gas, and this way CO_2 is a by-product of its production. But the future green ammonia production can be produced from renewable electricity, air, and water which eliminates de CO_2 footprint.

Since nowadays ammonia requires natural gas to be produced, the ammonia plants are constructed in places with abundant feedstock like China, Russia, the Middle East, and North Africa, and with the shale gas production in the US, there is plenty of gas available for new ammonia plants. Also, even not having natural gas sources, India has many ammonia plants because of the LNG import to become self-sufficient in fertilizers supply. But since green ammonia does not need natural gas to be produced, new plants can be constructed in new regions where there are good sources of renewables such as Australia with solar and wind, and Iceland with geothermal and wind.

Being able to be produced with wind and solar, makes the green ammonia able to be produced in big quantities and replace a good part of the fossil energy consumed, but the demand for renewable fuel is not there yet, this is one of the big challenges in substituting the fossil fuels to renewable ones, storage is normally an issue. But in the case of ammonia, not so much since it can be easily compressed and stored as a liquid in either atmospheric tanks or pressurized tanks, so would just need to increase the number of such tanks which can be a challenge in the ports because of the space required. Regarding production cost, green ammonia is much more expensive than the conventional one, mostly due to the cost of capital invested in the new plants and the cost of energy, but it is expected that with new developments the cost of energy should decrease, so the present estimates can be conservatively high.

Large amounts of ammonia are transported today around the world via public roads, railways, ships, and pipelines, it is specified as a dangerous good and must be transported according to the legislation in place, it is also classified as toxic gas and must be properly marked and handled accordingly. One advantage is that ammonia has a smell, so it can be identified as possible leakage, and workers can evacuate the place.

Regarding ammonia marine infrastructure, it will require infrastructure for bunkering and ship maintenance. The 88 ports around the world that handle ammonia and have the necessary equipment and storage facilities will be the foundation of the network for ammonia distribution as ship fuel in the future. The ammonia today is shipped globally in standard semi-refrigerated and fully refrigerated gas carriers. With the currently established world grid of ammonia terminals and storage, a bunkering grid could be established quickly and cost-effectively small tanker vessels to bunker barges. The bunker operation itself would be very similar to when bunkering other gaseous fuels, except the main hazard would be the toxicity rather than the flammability, and the procedures for ammonia bunker barges would need to be developed.

When it comes to using ammonia as marine fuel there will be new systems onboard, with specific needs and risks, but it is not a new product on board, therefore technologies, materials, and procedures are already in place, just need to be adapted and developed towards the new application. When it comes to bunkering and storing ammonia on board, the vessels that already carry the product will probably be the first ones using it as fuel. The ship adaptation will probably be limited to installing a dedicated NH_3 fuel supply system (from now on Liquid Fuel Supply System) and the necessary upgrading of the engine. For a vessel that does not carry ammonia as cargo, the facilities of embarking and storing it onboard should be installed, as well as the above-mentioned LFSS and engine adaptations. The literature says that ammonia has a high auto-ignition temperature, low flame speed, and limited flammability limits. To be self-ignited, it requires a very high compression rate and temperature, also leading to high production of Nitrogen Oxide (NOx).

The fuel tank volume is to be calculated to secure the full availability of ammonia for the ship propulsion, it depends on the total installed power, the expected availability of the product in the ports the ship is calling, and the ammonia density energy. Because of its density, the net storage value for ammonia should be approximately 70% more than LNG and almost three times the equivalent of distillate. For the ships that do not carry ammonia as cargo, the availability of bunkering facilities in the ports and the possible impact on operation time should be aspects to consider.

Safety onboard is also another important issue when it comes to using ammonia as a marine fuel. Currently, the IMO International Gas Carrier Code (IGC) prohibits the use of cargoes identified as toxic products as fuel for a ship, while the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) does not cover the case of ammonia. This way, a revision will be necessary on does codes to be able to use ammonia as a marine fuel.

LNG

LNG is mainly composed of methane and emits less CO_2 compared to the usual marine fuels. Additionally, LNG engines can be modified to reduce NOx or can be fitted with an Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR). LNG can reduce NOx (86%), SOx (98%), CO_2 (11%), and PM (96%) compared to HFO. The United States shale gas revolution combined with their big fields of natural gas, causes a significant reduction in LNG costs, making it an attractive option for the shipping industry, and ensuring availability for the long term. There is also a way to obtain LNG through Renewable Natural Gas (RNG) that is produced from refining biogas, providing a sustainable way to obtain LNG. Even though it sounds like the perfect solution and the fact that there are already vessels sailing utilizing LNG as fuel, it has also a few issues. Not many vessels are equipped to burn LNG and it requires an expensive installation, the LNG system is complex and requires a lot of space, other than the specific engine, it also needs a containment system for storage and a process system for extraction and conditioning. Other risks are the high energy in tanks, the explosion by leakage, the required low temperature, and the crew training. The availability in the ports also restricts the area that the vessel can trade, with most of the LNG availability being in North-eastern European ports.

Electricity

As batteries are heavy and the range is limited to at most a day, electricity is only suited for volume limited ships on one day trips.

Regarding the renewable future technologies and their implementation, battery electric trucks are expected to be primarily used in more urban environments, travelling shorter distances throughout the day so not to be affected by their smaller range and longer recharging times.

Annex C: Further details of outputs of inland shipping scenarios

Table 64 shows further details for the results presented in chapter 3– e.g., more details in outputs per type of technologies and type of vessel.

Table 64 – Further details for outputs of BAU, CONS and INOV scenarios.

Final energy demand (TJ)		REF	BAU			CONS			INOV		
Type of vessel	**Technology & energy carrier**	**2020**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Push Boats	Diesel CCNR2 & below	560	355	196	79	271	89	0	271	89	0
	Diesel CCNR2 + SCR	0	4	6	6	4	4	0	4	4	0
	Diesel Stage V	0	132	223	280	130	147	67	152	168	69
	HVO ICE	0	0	0	0	80	156	227	26	32	21
	LNG ICE	0	0	0	0	0	0	0	0	0	0
	Bio-LNG ICE	0	0	0	0	0	1	2	0	1	2
	Battery Electric	0	0	0	0	1	6	13	11	27	46
	Hydrogen FC	0	0	0	0	1	8	20	1	7	17
	Hydrogen ICE	0	0	0	0	0	0	0	3	22	53
	bio-Methanol FC	0	0	0	0	0	3	7	0	2	5
	bio-Methanol ICE	0	0	0	0	0	0	0	6	37	88
Motor vessel dry cargo ≥110m	Diesel CCNR2 & below	2528	1379	566	51	888	83	0	800	0	0
	Diesel CCNR2 + SCR	0	177	250	232	177	168	0	89	84	0
	Diesel Stage V	0	799	1393	1800	729	799	307	813	879	307
	HVO ICE	0	0	0	0	351	585	716	140	169	102
	LNG ICE	0	0	0	0	74	70	0	74	70	0
	Bio-LNG ICE	0	0	0	0	44	307	752	177	319	430
	Battery Electric	0	0	0	0	0	17	48	46	112	192
	Hydrogen FC	0	0	0	0	0	25	72	20	121	288
	Hydrogen ICE	0	0	0	0	0	0	0	0	36	102
	bio-Methanol FC	0	0	0	0	0	0	0	0	25	72
	bio-Methanol ICE	0	0	0	0	0	36	102	14	85	205

Motor vessel liquid cargo ≥110m	Diesel CCNR2 & below	610	230	35	0	193	0	0	193	0	0
	Diesel CCNR2 + SCR	0	49	47	0	0	0	0	0	0	0
	Diesel Stage V	0	228	366	424	189	212	92	205	219	69
	HVO ICE	0	0	0	0	75	120	138	65	70	23
	LNG ICE	0	31	43	39	34	32	0	17	16	0
	Bio-LNG ICE	0	0	0	0	31	97	193	24	57	97
	Battery Electric	0	0	0	0	0	0	0	2	9	22
	Hydrogen FC	0	0	0	0	0	6	16	2	19	49
	Hydrogen ICE	0	0	0	0	0	0	0	0	8	23
	bio-Methanol FC	0	0	0	0	0	0	0	5	27	65
	bio-Methanol ICE	0	0	0	0	0	8	23	3	19	46
Motor vessel dry cargo 80-109m	Diesel CCNR2 & below	849	597	420	308	449	171	0	449	171	0
	Diesel CCNR2 + SCR	0	32	45	42	32	30	0	32	30	0
	Diesel Stage V	0	136	227	280	136	148	56	140	162	84
	HVO ICE	0	0	0	0	110	203	280	47	54	28
	LNG ICE	0	0	0	0	0	0	0	0	0	0
	Bio-LNG ICE	0	0	0	0	0	0	0	0	0	0
	Battery Electric	0	0	0	0	2	16	39	26	52	79
	Hydrogen FC	0	0	0	0	0	7	20	3	24	59
	Hydrogen ICE	0	0	0	0	0	10	28	4	34	84
	bio-Methanol FC	0	0	0	0	3	17	39	0	7	20
	bio-Methanol ICE	0	0	0	0	0	10	28	4	34	84
Motor vessel liquid cargo 80-109m	Diesel CCNR2 & below	1794	1057	559	272	719	143	0	731	154	0
	Diesel CCNR2 + SCR	0	165	242	243	188	178	0	188	178	0
	Diesel Stage V	0	410	696	871	391	393	64	401	425	128
	HVO ICE	0	0	0	0	242	478	704	93	111	64
	LNG ICE	0	0	0	0	0	0	0	0	0	0
	Bio-LNG ICE	0	0	0	0	0	0	0	0	0	0
	Battery Electric	0	0	0	0	4	25	60	53	103	150
	Hydrogen FC	0	0	0	0	0	16	45	7	54	135

	Hydrogen ICE	0	0	0	0	0	23	64	19	108	256
	bio-Methanol FC	0	0	0	0	7	54	135	7	54	135
	bio-Methanol ICE	0	0	0	0	0	23	64	9	54	128
Motor vessels <80m	Diesel CCNR2 & below	192	121	64	22	95	33	0	97	35	0
	Diesel CCNR2 + SCR	0	2	2	2	2	2	0	2	2	0
	Diesel Stage V	0	20	32	37	20	20	3	24	26	11
	HVO ICE	0	0	0	0	18	30	36	7	8	3
	LNG ICE	0	0	0	0	0	0	0	0	0	0
	Bio-LNG ICE	0	0	0	0	0	0	0	0	0	0
	Battery Electric	0	0	0	0	0	1	3	2	4	5
	Hydrogen FC	0	0	0	0	0	1	2	1	4	8
	Hydrogen ICE	0	0	0	0	0	0	0	1	5	11
	bio-Methanol FC	0	0	0	0	0	2	3	0	1	2
	bio-Methanol ICE	0	0	0	0	1	2	4	1	3	6
Coupled Convoys	Diesel CCNR2 & below	234	96	20	0	74	0	0	74	0	0
	Diesel CCNR2 + SCR	0	22	20	0	0	0	0	0	0	0
	Diesel Stage V	0	96	158	191	88	93	29	64	75	39
	HVO ICE	0	0	0	0	31	58	81	28	36	29
	LNG ICE	0	1	2	2	7	7	0	7	7	0
	Bio-LNG ICE	0	0	0	0	4	27	67	8	19	30
	Battery Electric	0	0	0	0	1	4	9	7	10	9
	Hydrogen FC	0	0	0	0	0	0	0	5	7	7
	Hydrogen ICE	0	0	0	0	0	0	0	1	8	19
	bio-Methanol FC	0	0	0	0	0	0	0	0	2	7
	bio-Methanol ICE	0	0	0	0	0	0	0	3	16	39
Total		**6766**	**6138**	**5613**	**5180**	**5898**	**5203**	**4661**	**5707**	**4808**	**4053**

Annex D: Contribution to the Knowledge Portfolio

This is not applicable.