MAGPIE

SMART GREEN PORTS

Gaps and developments Electricity supply chain for future demand

Funded by the European Union

This project has received funding from the European Union's Horizon 2020 (MFF 2014-2020) research and innovation programme under Grant Agreement 101036594

D3.2 - GAPS AND DEVELOPMENTS ELECTRICITY SUPPLY CHAIN FOR FUTURE DEMAND

GRANT AGREEMENT NO.	774253
START DATE OF PROJECT	1 October 2021
DURATION OF THE PROJECT	60 months
DELIVERABLE NUMBER	D3.2
DELIVERABLE LEADER	EDP CNET
DISSEMINATION LEVEL	PU
STATUS	V0.4
SUBMISSION DATE	31-03-2023
AUTHOR	João Vieira da Silva, EDP, joao.vieirasilva@edp.pt Gonçalo Calado, EDP, goncalo.calado@edp.pt André Lisboa, EDP, andre.lisboa@edp.pt João Megre, EDP, joao.megre@edp.pt Yves-Marie Bourien, CEA, yves-marie.bourien@cea.fr Eric Francois, CEA, eric.francois@cea.fr Philipp Theile, EWI , philipp.theile@ewi.uni-koeln.de Zenaida Mourão, INESC TEC, zenaida.mourao@inesctec.pt Karol Gonçalves, INESC TEC, karol.b.goncalves@inesctec.pt Hesam Naghash, TUD, h.naghash@tudelft.nl Pedro Vergara Barrios, TUD, p.p.vergarabarrios@tudelft.nl Larissa Nogueira, TNO, larissa.nogueira@tno.nl Joost Stralen, TNO, joost.vanstralen@tno.nl Juan Giraldo, TNO, juan.giraldo@tno.nl Linda Punt, EUR, punt@rsm.nl Yashar Ghiassi, EUR, y.ghiassi@rsm.nl

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774253.

Modification Control

VERSION #	DATE	AUTHOR	ORGANISATION
V0.1	24-11-2022	João Silva, Gonçalo Calado, André Lisboa, João Megre	EDP CNET
V0.2	01-01-2023	João Silva, Gonçalo Calado, André Lisboa, João Megre	EDP CNET
V0.3	17-02-2023	Yves-Marie Bourien, Eric Francois, Philipp Theile, Zenaida Mourão, Karol Gonçalves, Hesam Naghash, Larissa Nogueira, Joost Stralen, Juan Giraldo, Pedro Vergara Barrios, Linda Punt, Yashar Ghiassi	CEA, EWI, INESC TEC, TUD, TNO, EUR
V0.4	10-03-2023	João Silva, Gonçalo Calado, André Lisboa, João Megre	EDP CNET
V0.5	30-03-2023	João Silva, Gonçalo Calado, André Lisboa, João Megre	EDP CNET

Release Approval

NAME	ROLE	DATE
João Silva	WP Leader	12-03-2023
Arne-Jan Polman	Peer Reviewer	16-03-2023
Dingena Schott	Peer Reviewer	17-03-2023
Maarten Flikkema	Scientific Coordinator	24-03-2023
Arne-Jan Polman	Project Coordinator	31-03-2023

1. Table of Contents

Abbreviations

4PM, Four-Parameter Model

aFRR, Automatic Frequency Restoration Reserve

AI, Artificial Intelligence

BEAM, Building Model by Electric Analogy

BESS, Battery Energy Storage System

CAES, Compressed Air Energy Storage

CCGT, Combined Cycle Gas Turbine

CCS, Carbon Capture and Storage

CCUS, Carbon Capture, Utilisation and Storage

CHP, Combined Heat and Power

DER, Distributed Energy Resources

DLR, Dynamic Line Rating

DOE, Department of Energy

DSM, Demand-side Management

DSO, Distribution System Operator

EGD, European Green Deal

EMS, Energy Management System

EMT, Energy Matching Tool

ENU, e-Navigation Underway

EPBD, Energy Performance of Buildings Directive

EREC, European Renewable Energy Council

ESPO, European Sea Ports Organisation

EU, European Union

EV, Electric Vehicle

FCR, Frequency Containment Reserve

GDP, Gross Domestic Product

GHG, Greenhouse Gas

HDV, Heavy Duty Vehicle

HV, High Voltage

HVAC, Heating, Ventilation and Air Conditioning

IEA, International Energy Agency

IMO, International Maritime Organization

IoT, Internet of Things

LNG, Liquified Natural Gas

MDM, Multi-Diode Mode

MINLP, Mixed-Integer Nonlinear Programming

MV, Medium Voltage

NLP, Nonlinear Programming

OPERA, Option Portfolio for Emissions Reduction Assessment

OPS, On-shore Power Supply

PFSS, Primary Fire Suppression System

PHS, Pumped Hydropower Storage

PMIS, Port Management Information System

SDM, Single-Diode Model

SFSS, Second Fire Suppression System

SOC, State-of-Charge

SOE, State-of-Energy

SSP, Shore-to-Ship Power

TDM, Two-Diode Model

TSO, Transmission System Operator

UPS, Uninterruptible Power Supply

USV, Unmanned Surface Vessel

V2G, Vehicle-to-Grid

WITCH, World Induced Technical Change Hybrid

WRF, Weather Research and Forecasting

Executive Summary

Commercial trades at a global level strongly rely on ports. They work as connection points between multiple stakeholders, who several times constitute large consumption hubs. Also, the ports themselves are huge consumptions hubs. Particularly the so-called industrial ports typically characterized by the presence of hard-to-abate businesses (e.g., refineries, steel, alumina). Therefore, the impact of decarbonizing the port ecosystem will go far beyond its geographical area.

The MAGPIE project focuses on studying the role of green energy supply chains (electricity, hydrogen, ammonia, bioLNG) to reduce the greenhouse gas (GHG) emissions resulting from port's activity. This deliverable relates with the electricity supply chain (production, storage, distribution) and its main objective is to identify the gaps that might difficult the fulfilment of a growing demand for clean renewable electricity. By perceiving such gaps, it will also be possible to realize the developments that need to be carried across the entire supply chain.

To achieve this objective, two complementary approaches were followed. First, a comprehensive literature review was carried out and dedicated interviews with several MAGPIE partners were conducted, namely with Port authorities and demonstration leaders. This provided a general view on the current status and foreseen evolution of the electricity supply chain in port ecosystems. Then, dedicated models of the electricity supply chain were described, and their goal is to provide an answer to the questions displayed in Table 1. By doing so, long-term scenarios of energy demand and availability can be explored. Consequently, the developments needed in the electricity supply chain can be mapped.

Table 1 - Modelling the electricity supply chain

Sector	Questions
Demand	1. Which are the present/future energy requirements? 2. Which transition pathway (i.e., future fuel mix) will be followed? 3. Where will heavy-duty electrical vehicles recharge their batteries?
Production & Storage	4. What are the available potential forces Renewable Energy Sources (RES) in the port ecosystem? 5. What is the optimal RES/storage sizing?
Distribution System (planning & operational domains)	6. How to ensure that the electrical grid constraints (including energy balance) are respected while minimizing the costs?

Besides focusing on the supply chain sectors (production, storage, distribution), the questions presented in Table 1 also target the demand side. Indeed, an accurate modelling of the supply chain is dependent on a realistic estimation of the future demand for green electricity. How each of these questions was addressed through the Modelling work is described below.

Demand sector

The MAGPIE project has the ambition to demonstrate the usage of green energy supply chains/vectors in the logistic sector. This deliverable will complement this ambition by analysing other demand sectors, such as industries and buildings. Having this overarching vision of the demand side is important when comes to model the electricity supply chain. D3.1[1] already started this work, but purely focused on the transport sector. Moreover, the future demand per energy vector was assessed based on exogenous information.

The first models described in D3.2 focus on questions n° 1 and 2 (Table 1). They aim to estimate how the energy requirements of the transport and industrial sectors will evolve and how they will be supplied (i.e., future fuel mix). Depending on the model, a mix of exogenous (i.e., external to the model) and endogenous (i.e., developed within the model) information will allow to estimate the associated growth trends. For the building sector, a specific use case related with air heating/cooling needs will be analysed. To fulfil such needs, the electrification of the consumption will be the accessed option. Below, a brief description of each model is provided:

a) Global Integrated Assessment model – The WITCH (World Induced Technical Change Hybrid) model is a non-linear optimization dynamic global method that captures the dynamics of long-term economic growth and links them to the evolution of the energy sector in which transportation is included. The model foundations are associated to the Utility theory, a branch of economics that studies how individuals make choices and allocate their resources. 5 years' time-steps are considered, and the time horizon goes until 2150 (initial years are used for calibration, and the last 50 years are eliminated to avoid the end-of-horizon effect).

b) National Integrated Energy System model – OPERA (Option Portfolio for Emissions Reduction Assessment) is a technology-rich energy system (Linear Programming) optimization model for the Netherlands. It computes the cost-optimal energy transition pathways (including for the transport sector), under specific constraints, by minimizing an objective function that expresses the total system costs for a given future year[2].

c) Trajectory and profile model of the industrial cluster – A model capable to design energy demand pathways/trajectories for the industrial cluster in a port based on exogenous assumptions. Moreover, a second model provides synthetic profiles for the actual shape of this demand, an important input for operational simulations.

d) Building model – An electric analogy model that estimates heating/cooling energy needs of a given building.

The global and national integrated energy models will primarily be used to analyse the transition pathways for the transport sector. While the former establishes a link between global economic growth and the transition pathway of freight transport, the latter goes deep on the specific characteristics of the Netherlands. Concerning the "trajectory and profile model of the industrial cluster", the objective is the same, but focused on the industrial sector.

[1] MAGPIE Project, D3.1 – Transport Energy Requirements
[2] https://doi.org/10.1007/s10666-020-09741-7

Question n°3 of Table *1* is specific to the transport sector. Contrary to industries or buildings, transport's consumption does not have a fixed location. Therefore, realizing what the demand will be for recharging actions at port premises is a complex task. This report details a simulation model that aims to estimate this while considering logistic (e.g., truck driving regulations) and technical (e.g., battery state-of-charge) constraints. The model will provide important insights concerning the recharging infrastructure needed in a port.

Although being described in a deliverable focused on the electricity supply chain, the majority of these demand-oriented models will provide relevant outcomes for all other supply chains studied within the MAGPIE project.

Production & Storage sector

To realize what is the best energy mix to produce (and consequently store) electricity is dependent on what % of the demand will shift towards electrification. Therefore, a successful answer to the Demand questions (Table *1*) will be the trigger to model the Production & Storage sectors.

Although with different characteristics, production and storage planning/sizing studies cannot be dissociated. On the one hand, defining the best energy mix (where it is included non-dispatchable resources) depends on the available storage options. On the other hand, sizing a storage system depends on the excess of energy that is produced. Therefore, this deliverable details a joint production-storage model oriented to a port ecosystem that has the following goals: 1) estimate the potential of producing electricity from RES; 2) size the RES and storage systems; 3) produce hourly generation time-series for each of the considered RES. Concerning the sizing study, it is an optimization exercise that depends on several different factors, namely economic, environmental, and regulatory.

Distribution system

While demand for electrification, non-dispatchable RES penetration and storage needs will increase, what will happen to the electrical grid? Ensuring the security of supply and quality of service will become a significant challenge. Two different decision-support models are proposed in this deliverable to tackle this topic. One focus on operational actions (i.e., day-ahead) while the other intends to support the Distribution System Operators (DSOs) on planning decisions (i.e., years-ahead). Nonetheless, both have the same objective: ensure the electrical grid balance is kept, and no overloads arise while minimizing/maximizing a specific objective function (e.g., minimization of operational/plannings costs; maximization of RES injection).

The planning-oriented model focuses on assessing how policy/investment decisions will impact on the long-term behaviour of the electrical grid. In other words, this model will define which grid investments are needed (e.g., transmission lines, substations, storage assets) to effectively adapt to future energy scenarios (where flexible sources will be a reality).

The operational-oriented model focusses on the optimal management of the available resources at minimum cost. It exploits available flexibility options to ensure that hourly grid balance is accomplished while not contributing for the arising of other network constraints. To ensure these objectives are fulfilled, the model suggests which are the active power set-points that should be followed by the flexible assets.

The joint work of the demand, production and storage models will allow to achieve one of the objectives of the MAGPIE project – the definition of reliable long-term scenarios of energy demands and availability. These will be vital to realize the developments needed in the electrical grid (distribution grid models). Moreover, they will provide important insights for the construction of the master plan for European green ports (final outcome of the MAGPIE project). Figure 1 shows a high-level vision of the links that will need to be established between the models to reach the final target. Although not being shown in this figure, the computation of reliable long-term scenarios might also benefit from a cascading communication between the models looking to longer and shorter time-horizons.

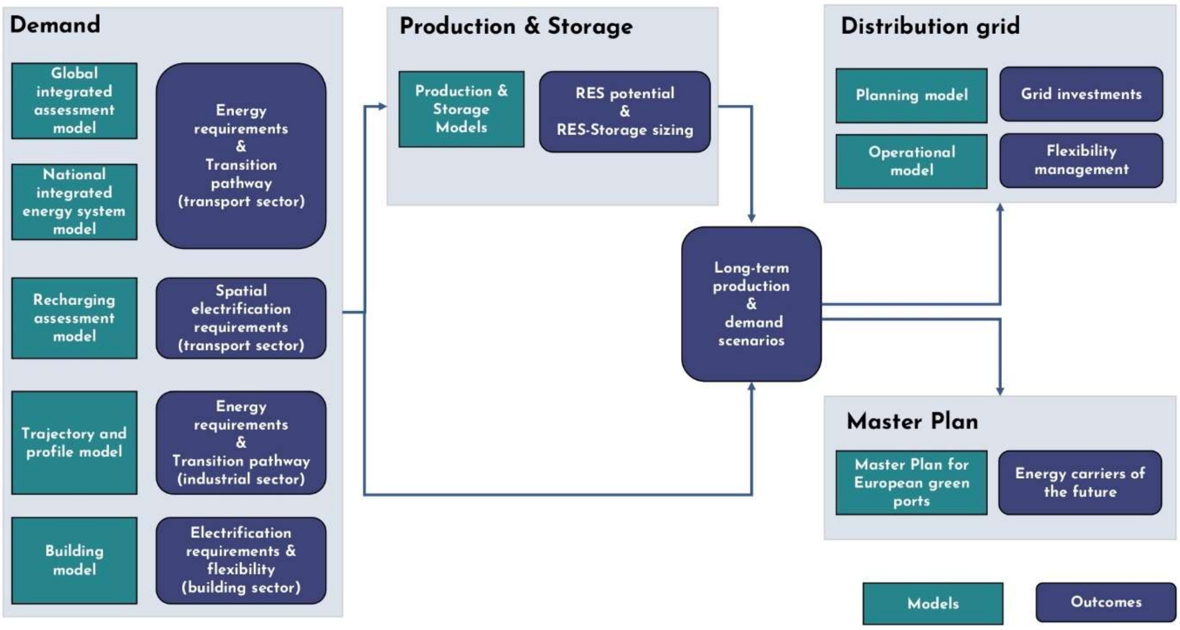

Figure 1 - High-level vision of modelling architecture

This deliverable focuses on describing each one of these models. Concerning their development, it is only starting now, in other MAGPIE tasks. In that sense, a more concrete vision on how the models will link with each other still needs to be defined.

1. Introduction

The Green deal is an ambitious plan set out by the European Commission. Its main goals are: 1) achieving no net GHG emissions by 2050; 2) decouple economic growth from resource use; 3) ensure that all persons/places make part of the transition process. Accomplish 1) is a muti-sectoral problem (transports, industries, buildings, etc) that requires adopting new green energy carriers or increasing the utilization of existing ones. Independently from which option is choose, it constitutes a broad and complex process that involves analysing all the sectors of a supply chain. Indeed, it is not possible to adopt a new energy carrier (or increase the use of an existing one) without an assessment of what will be the infrastructure needs in terms of production, storage, and distribution.

The MAGPIE project is an international collaboration working on demonstrating technical, operational, and procedural energy supply and digital solutions in a living lab environment to stimulate green, smart, and integrated multimodal transport and ensure roll-out through the European Green Port of the Future Master Plan and dissemination and exploitation activities. The consortium, coordinated by the Port of Rotterdam, consists of 3 other ports (DeltaPort, Sines and HAROPA), 9 research institutes and universities, 32 private companies, and 4 other organisations. The project is divided in 10 main Work Packages (WP) which include energy supply chains, digital tools, 10 demonstrators for maritime, inland water, road, and rail transport, non-technological innovations, and the development of a Masterplan for European Green ports.

WP3 focuses on ports and on how these ecosystems can facilitate and accelerate the supply and the use of green energy carriers, particularly in the transport sector. The following energy carriers are analysed in depth: electricity, hydrogen, ammonia, bioLNG. Methanol will also be considered (particularly in the maritime transport sector), but no dedicated analysis of its supply chain will be carried out considering the already on-going projects in this topic.

Aim

This report focuses on the electricity supply chain and aims to create the foundations for 1) establishing future energy demand scenarios; 2) assessing how the electricity supply chain (production, storage, distribution) needs to evolve to accommodate these future requirements.

Approach / methodology

First, a descriptive analysis of the existing gaps and needed developments across the electricity supply chain so that future demand can be accommodated is carried. Each sector of the supply chain is analysed in three dimensions: context, pathway towards decarbonization, deep dive on MAGPIE ports. The "context" section intends to provide a view on the current status of the electricity supply chain. The "pathway" section aims to anticipate the future challenges that the electrical grid will face and investigates potential options to overcome them. The "deep dive" section evaluates to what extent the MAGPIE ports are aligned with the present/future status described in the "context" and "pathway" sections. Port partner's insights gathered through dedicated interviews/questionnaires (Annex A) as well as literature contributions were used as the main information sources.

Then, dedicated models of the electricity supply chain are described. They build upon the work of D3.1[1] (i.e., estimation of transport future energy requirements), continues it and extends it. Extends it since the present/future energy requirements assessment is also carried for the industrial and building sectors. Moreover, endogenous models (and not literature inputs as in D3.1[1]) will access the most probable transition pathways. This will provide a more realistic view on which future energy requirements will need to be fulfilled by the electricity supply chain. Continues it since the described models also investigate how the production, storage and distribution sectors will need to evolve to comply with this future demand for electricity.

Structure of the report

All these topics are discussed following the report structure presented below:

- **Chapter 2** – Focuses on exploring the current status and future perspectives of the electricity supply chain (globally and at port level). This entails studying the demand side and how future changes on it will impact the production, storage, and distribution sectors. Considerations regarding the state of digitalization of the electricity supply chain are also carried in this chapter.

- **Chapter 3** – Focuses on describing the proposed models. Each one of them has its own characteristics and unique objectives. Simulation-based, optimization-based, and other model types are detailed in this chapter.

- **Chapter 4** focus on conclusions and next steps.

2. Analysis of the electricity supply chain

2.1 Introduction

The electrification process is crucial to achieve a low-carbon future and reduce greenhouse gas emissions. The increased demand for sustainable energy has led to a growing interest in the electricity supply chain, from production to distribution. As such, a clear understanding of this supply chain is essential to ensure that low-carbon and renewable electricity can meet the increasing demand in the coming decades. To develop a mature and future-proof electricity supply chain, a thorough analysis of each sector of the supply chain is required, and several actions are required to fulfil this objective, including:

- Estimating future electricity demand accurately
- Identifying the most cost-effective production solutions to reduce emissions and costs
- Identifying distribution and storage alternatives capable of providing low-cost electricity transmission and distribution

Additionally, major investment and engagement from both public and private players will also be required to assure long-term stability, cut costs and emissions, and achieve a balance between risk and return on investments. Moreover, it is important to consider specific sectors that may be hard-to-abate, such as the heavy industry with high-temperature heating processes or the heavy transport sector, including aviation, trucking, and shipping. These sectors will require a significant amount of low-carbon and renewable electricity, and therefore, may require unique solutions to meet their demand profile.

An analysis of the current status and future expectations of each sector of the electricity supply chain, alongside a focus on specific ports, can help identify gaps and necessary developments. Furthermore, this can help create a mature and future-proof electricity supply chain capable of meeting the growing demand for sustainable energy, ensuring a successful transition to a low-carbon future. Supported by an extensive literature review, chapter 2 examines each sector of the electrical supply chain (production, storage, and distribution) and offers current status and future aspirations from a global viewpoint in the context and the pathway towards decarbonization's subsections. In addition, a detailed investigation of the existing state of MAGPIE ports (in the Deep-dive on MAGPIE ports' sections) is carried out based on surveys completed by port partners. However, because it was not possible to obtain replies from APS (Administração dos Portos de Sines e do Algarve) in time for this deliverable, the analysis focuses on the Ports of Rotterdam, HAROPA, and DeltaPort.

2.2 Demand

2.2.1 Context

Sea and inland ports are important centres of economic activity, handling a significant portion of global trade and commerce. Consequently, they also constitute large consumption hubs, which are naturally supplied by a mix of different energy vectors. Among them, electricity has a pivotal role. As shown by Figure *2*, the major port electricity consumers are the industrial sector and all port-related activities where buildings and terminal operations are included. Until 2050, it is foreseen that electrification will reach other sectors such as transport. Therefore, each of these sectors currently experience different states of electrification.

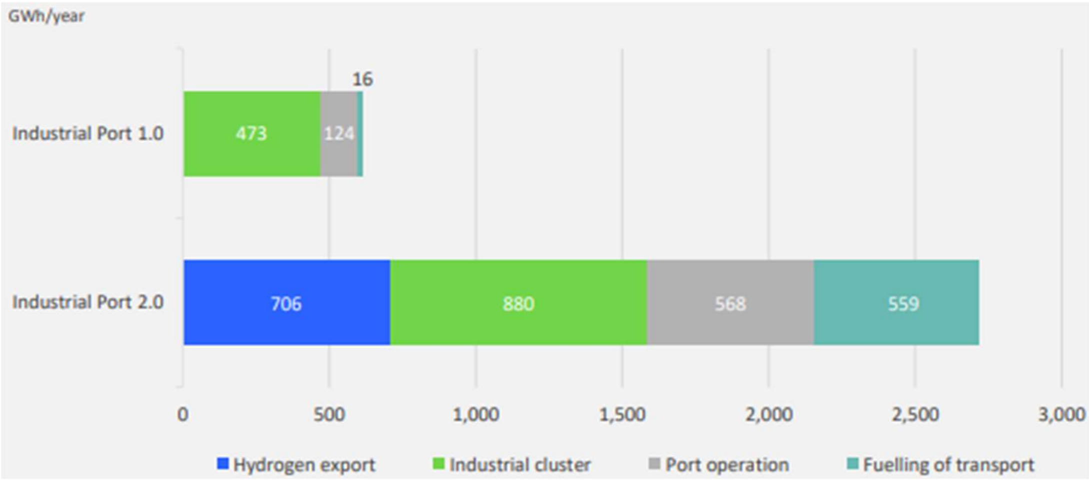

Figure 2 - Current status and future projections (2050) for electricity needs in a port ecosystem[3]

Concerning the transport modalities coexisting in a port ecosystem, electrification is still in its early stages. For some specific transports, a full electricity-powered propulsion may not even occur due to technical and economical constraints. On the maritime shipping sector, vessels almost entirely rely on fossil fuels to power their engines, propellers, and auxiliary systems. Although a hard-to-abate sector when looking to full electrification processes, the efforts in the maritime industry to diminish its fossil fuel dependency are significant. The On-shore Power Supply (OPS) systems are an example of that. OPS's allow vessels to plug into the electrical grid while moored thus reducing the need for on-board energy generation that usually comes from fossil fuels. As for maritime, inland shipping energy requirements are mostly fulfilled by pollutant sources. However, and due to the specific characteristics of inland shipping routes, full electrification options are already showing their potential (e.g., swappable batteries). In terms of road transport, diesel-powered trucks are still widely used, but the increasing availability of electric and hybrid alternatives is contributing to the steady replacement of the conventional fleet by logistics companies. On the other hand, ports are also investing in proper infrastructures to cover the upcoming recharging needs of e-trucks. Finally, the rail sector shows a different status when comparing with the remaining modalities as a significant share of the railways is already electrified. However, within the port areas, not always shunting locomotives have access to electrified railways. In such cases, diesel continues to be the main energy source. All the previous points provide a better understanding of why electricity needs for transportation are expected to grow significantly until 2050.

Regarding port-based industries, they already present significant progress in terms of electrification of their processes. For instance, manufacturing, refining, and petrochemical industries use electricity for powering machines and equipment like pumps and compressors that are used to develop their products. Additionally, electricity is used to generate energy for their operations, such as steam generation for process heating and cooling. On the upcoming decades, more industrial processes are expected to become electrified (e.g., hydrogen production).

[3] Ports: Green gateways to Europe, DNV. https://sustainableworldports.org/wp-content/uploads/PORTS_GREEN_GATEWAYS_TO_EUROPE_FINAL29JUNE.pdf

Usually neglected when comparing with the transport and industrial sectors, port activities are also an important part of the energy demand. Even if the consumption needs of a building or warehouse cannot be compared to e.g., a hydrogen production facility, the way how this sector will evolve towards electrification will impact the grid infrastructure. In fact, an increase on the electrification requirements of port-related activities is foreseen (Figure *2*). Not surprisingly given the fact that port operations are still reliant on fossil fuels. A good example is related with how heating/cooling needs of buildings are fulfilled. Although renewable options such as electrification are having a more active role (from 21%[4] to 23.1%[5] between 2018 and 2020), there is still a lot of potential to be explored in this sector. Still within port activities, cargo handling and storage operations often use a mix of fossil fuels and electricity. Cargo handling actions commonly rely on electricity but some equipment like terminal tractors and ground support equipment are still in the early stages of energy transition.

Overall, an accurate identification and estimation of the major electricity demand streams (current & future) is crucial for the successful decarbonization of ports activity. By doing so, ports will be better equipped to make informed decisions that support the transition to a low-carbon future, while maintaining their important role as hubs of economic activity and trade. The modelling work described in section 3.2 has a special focus on this topic.

2.2.2 The pathway towards decarbonization

2.2.2.1 *Transport modalities*

To achieve a successful energy transition, a significant shift from fossil-fuel-based transportation to green fuels is crucial. There is not, however, a one-size-fits-all fuel solution, as different fuels are more suitable for specific modes of transportation – for the same transport fuel may change according to the transport working requirements. Figure *3* illustrates the expected changes in fuel consumption and the distribution of transport consumption by mode. It can be concluded that port-related transport, such as, road transport (primarily trucks), railways, and maritime transport (including barges and ships), are likely to maintain their energy consumption levels in the future.

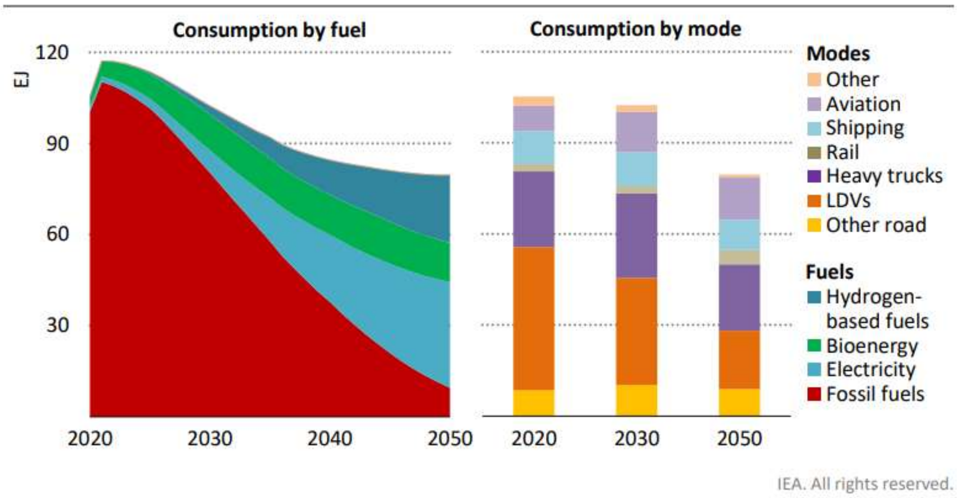

Figure 3 - Global transport final consumption by fuel type and mode in the Net Zero Emissions[6]

[4] Eurostat, https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200211-1
[5] State of the Energy Union 2022
[6] Net zero by 2050: A roadmap for the global energy sector, IEA, 2021

The main challenges associated with the electrification of transport, and other green fuels, e.g., methanol, hydrogen or ammonia, are similar and must be addressed to promote for a rapid and widespread acceptance and implementation of such fuels. Focusing on the electrification of transport, the identified challenges are:

- Limited range: The range of electric vehicles is limited, and heavy-duty vehicles require large amounts of energy to operate, making electrification challenging without significant investments in battery technology. The main issues being the need for time and recharge quantities required can also be an issue.
- Limited infrastructure: despite growing for the last years, there is currently limited number and options of charging infrastructure widespread, such as truck charging stations or onshore power supplies for ships. Lack of infrastructure means much more effort on planning and management of the transport routes, which also create barriers for electrification.
- Regulation barriers: Regulatory frameworks and standards for electric and renewable fuel vehicles are still evolving, which can create barriers to adoption. Moreover, regulation and incentives have also a large impact on the speeding up or delaying the port operators and other stakeholders' investment.

Adding to the general challenges of electrification, each transport modality also faces obstacles according to their operation requirements. When it comes to port transport modalities, progress has been made in electrification and transitioning to greener fuels (some modalities are easier to convert than others) and this trend is expected to continue in the future.

For maritime shipping, an important limiting factor in using alternative fuels is the range of fuel. Range of fuel is defined as the distance that a ship can voyage with a full tank of fuel without the need to refuel. Each vessel can dedicate only a certain amount of space/weight to fuel storage. Hence, the energy density (kJ/kg) and specific energy of fuels (kJ/m3) are the essential indicators to assess the range of marine fuels. In the case of battery-powered vessels, energy density, size, and type of battery are the main markers. Among different types of batteries, Lithium-ion batteries are the densest ones in terms of energy density and specific energy (e.g., in comparison to lead acid, Ni-Cd, and Ni-MH batteries). In longer voyages such as oceanic shipping, energy density constraints become more important. For voyages up to 10000 nautical miles, the attainment rate (reaching to destination without refuelling) of diesel is 100%, and those of ammonia, methanol, and methane are still above 90%. Hydrogen ranks below with 58-81%, and the Li-ion batteries show an attainment rate of only 5-23%[7]. There is a clear trade-off: the higher the attainment rate, the higher the efficiency losses in the production of an alternative energy carrier. There are two main ways that can improve the attainment rate of low-range fuels. The first one is the influence of refuelling stops. If ships could refuel once in course of the voyage, the attainment rate of liquified compressed hydrogen could be enhanced from 58-81% to 82%-92%. This increment is more obvious in the case of batteries, and they could go up from 5-23% to 25-55%. All other fuels could cover almost 100% of the voyage length. The second option is to cut a part of the cargo, to dedicate more space/weight to fuel. To cross the 99% attainment rate for all renewable fuels, 6% of cargo loss would have to be accepted8. All in all, battery-powered vessels are not suitable for long hauls due to the urge for refuelling and the lack of proper refuelling locations in the course of the voyage. They can play a role, however, in short-sea

[7] Stolz, B., Held, M., Georges, G. *et al.* Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nat Energy* **7**, 203–212 (2022). https://doi.org/10.1038/s41560-021-00957-9

[8] Refuelling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?, ICCT, 2020

shipping and inland shipping. This could change with innovation and designing renewable generation on the vessel itself to recharge the battery. This means that the refuelling patterns need to be re-evaluated, and more refuelling processes will take place in the ports.

The use of barges for hinterland waterways is recognized as an effective way to decarbonize freight transport due to their efficient consumption. In fact, one of the core goals of the European Union (EU) is to shift more cargo to Europe's rivers and canals and facilitate the transition to zero-emission barges by 2050 by promoting policies to make this happen[9]. Not only is the shift from freight road transport to waterborne transport being promoted, but also the electrification of barges. Similar to maritime shipping, the range of the battery is a critical parameter for e-barges, as is the charging infrastructure required for their operation. In addition to investments being made to develop e-barges, there is also a growing focus on addressing the challenge of charging options and infrastructure solutions, such as the innovative solution of using swappable batteries for barges[10].

Railways are an important mode of transportation in ports responsible for the movement of cargo within the port, as well as from and to the port. While railways are typically associated as being electrical transport, being preponderant on passenger rail, diesel locomotives are still widely, accounting for half of all freight rail movements. According to a report by the International Energy Agency (IEA), diesel fuel accounted for around two-thirds of the total energy consumption in the global rail sector in 2021[11]. The main drawback, that is limiting growing electrification of trains is the high investment costs in railway and grid infrastructure. Additionally, profitability can be an issue for railways that have low utilization rates. To address this issue, according to the same IEA report, there have been more towards alternative fuels, like hydrogen, which requires less changes in infrastructure, and more on the vehicle. Specifically in port operations, diesel locomotives are commonly used in the shunting area, where cargo is moved within the port. This is because there is often no overhead line in place for the last or first mile of transportation. Developments and demonstrations of solutions (like in the MAGPIE project) look to hybrid electric locomotives as a solution which can operate on an overhead line to operate and also charge their battery, as well as working relying only on battery in the last mile.

Road transport, in specific trucks, is also responsible to transport cargo within and outside the port. It is expected that road freight in the EU will increase by 55% by 2050 while at the same time it is aimed for the heavy-duty vehicle (HDV) operation decarbonization through electrification and/or use of alternative fuels[12]. Focusing on electrifying trucks, whether for short distance trips or long hauls, there are challenges related to the limited number of charging infrastructures and the range of battery for e-trucks when compared to diesel-powered trucks. Ports can count on different charging infrastructures to accommodate for different charging options, such as depot and fast charging. Depot charging (up to 50 kW stations) is associated with overnight charging and the benefits of lower electricity and investment costs but requires longer stopping times for the truck. Fast charging (from 150kW on), on the other hand, is more expensive in infrastructure and grid connection costs but can provide much more flexibility and autonomy for regional and long-haul electric trucks[13]. Investment has been made in depot charging stations, and more recently in fast charging

[9] https://transport.ec.europa.eu/transport-modes/inland-waterways/promotion-inland-waterway-transport/naiades-iii-action-plan_en

[10] https://www.currentdirect.eu/the-project/

[11] https://www.iea.org/reports/rail

[12] Decarbonisation of Heavy Duty Vehicle Transport: Zero emission heavy goods vehicles, JRC

[13] https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-heavy-duty-vehicles

stations[14]. The latter will be vital to adopt electrification for long-haul trucks, however, a larger investment is still needed. Another aspect is the importance of understanding how the demand for truck charging will be distributed in countries, regions, and more specifically the amount affected to the port, to provide a more comprehensive picture of the electricity demand and infrastructure required. Modelling and analysing the distribution of charging and its impact on the port is a complex task due to the dispersed charging possibilities in comparison to other transport modes mentioned earlier. To address the prediction of truck charging demand, there have been studies on the modulization predicting the most probable regions with higher demand[15], as well as more practical methods such as tracking trucks to gain insights into how the chargers could be dispersed[16]. To contribute to the understanding of the demand distribution for truck charging, and particularly how it affects the port, a model was developed in Section 3.3 to address this issue.

2.2.2.2 *Industries*

The industrial sector is a large electricity consumer, accounting for a significant share of total electricity demand in ports. It is critical to decarbonize the industrial sector by switching to renewable energy sources in order to attain a sustainable future and the electrification of the port industry sector is a promising avenue to achieving this goal.

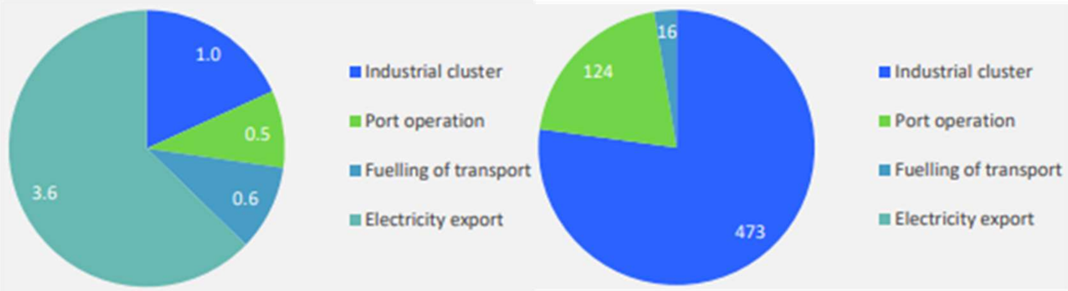

Figure 4 depicts the impact of the industry sector on carbon emissions and electricity consumption levels in a typical European industrial port, based on the average size and characteristics of the top 20 largest ports in Europe[17].

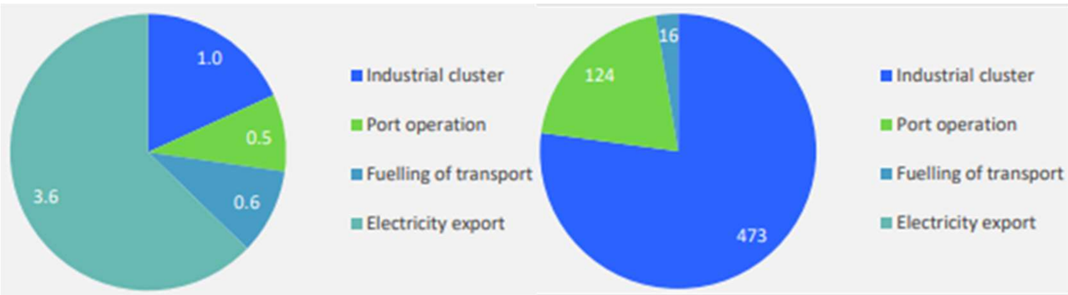

Figure 4 - Current CO2 emissions per sector in Mton/year (left) and electricity consumption in GWh/year (right) in industrial ports[17]

To begin with, it is important to understand the current electricity demand of the industry sector in ports. The industry sector comprises a diverse range of activities such as

[14] https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-pulse-build-europes-first-public-charging-corridor-for-electric-trucks-along-major-logistics-route.html
[15] Mobility Model for the Estimation of the Spatiotemporal Energy Demand of Battery Electric Vehicles in Singapore, Annette E. Trippe et al.
[16] https://isi.pages.fraunhofer.de/acea_truck_stops/
[17] https://sustainableworldports.org/wp-content/uploads/PORTS_GREEN_GATEWAYS_TO_EUROPE_FINAL29JUNE.pdf

manufacturing, refining, and petrochemical processes, each with varying levels of electrification and energy requirements. In the manufacturing process, for example, electricity is used for powering a range of machinery and equipment, including assembly lines, conveyor belts, and industrial robots. In the refining and petrochemical processes, electricity is used not only for powering pumps, compressors, fans, and other equipment that is involved in the production of refined products, but also to provide heat and cooling. In addition to these direct uses, electricity is also used in the industry sector within ports for a range of support activities such as lighting, heating, ventilation, and air conditioning (HVAC) systems, and other building services. These activities can account for a significant portion of the overall electricity demand within the industry sector.

The demand for electricity in the industry sector is expected to grow in the following decades as industrial activities expand and the use of electrified equipment and the adoption of new technologies that require more electricity increase. Additionally, as the global focus shifts towards decarbonization and the reduction of greenhouse gas emissions, many industries are likely to electrify their processes in order to reduce their carbon footprint.

As seaports and inland ports serve as key nodes in global supply chains and logistics networks, they often host a vast number of industrial facilities (some of them with electro intensive processes). Given the significant energy demands of these industrial operations, the global trends in electricity consumption and GHG emissions for the industrial sector can also be applied for ports. As shown in Figure 5, the IEA on its Energy Technology Perspectives 2020[18] predicts that the global electricity demand in the industry sector will more than double by 2070 for the Sustainable Development Scenario when compared to the 2019 consumption level's. In contrast, a sharp reduction in the global direct carbon emissions related to industrial activities is predicted by the IEA for the same scenario (see Figure 6).

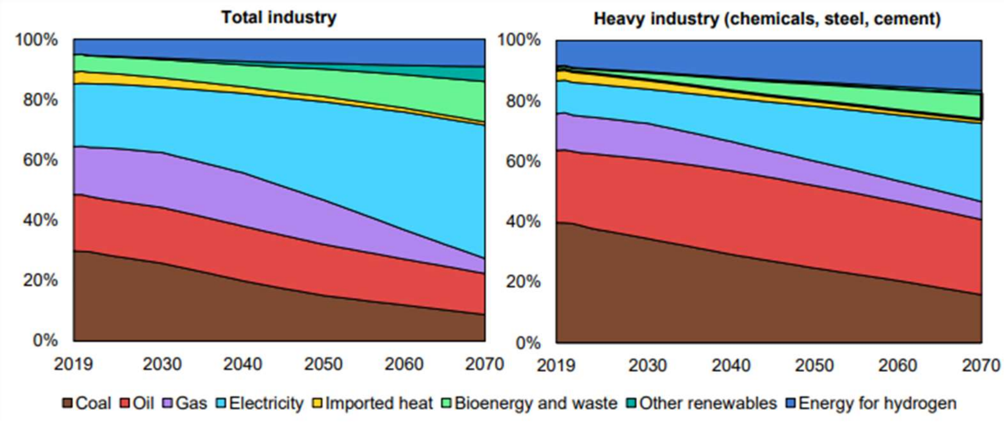

Figure 5 - Global energy demand in the industry sector by fuel shares, 2019-2070[18]

[18] https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf

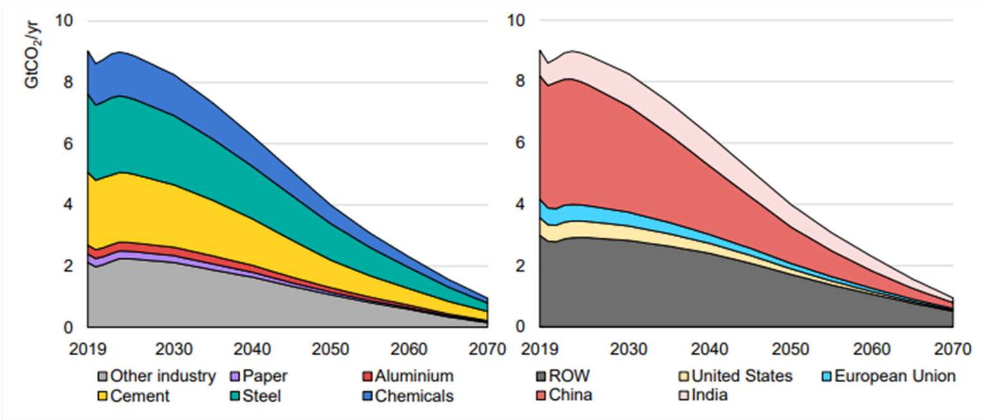

Figure 6 - Global carbon emissions in the industry sector, 2019-2070[18]

In fact, electrification is a promising pathway to decarbonize the industry sector in ports. Using renewable heat to run industrial processes, improving energy efficiency within existing processes, electrifying operations, using green hydrogen as a feedstock, adopting circular production models, and utilizing waste heat are all ways to decarbonize industries inside ports. Inclusive, there are already some innovative and helpful solutions to tackle this issue. For instance, the production of renewable biogas which can provide fuel (heat or energy) to power some industrial processes using a wood-based feedstock or agricultural residue[19] or a "plug-and-play" alternative for most hydraulic actuators (e.g., container handling trucks, forklifts, etc.) enabling electrification of heavy industrial equipment[19].

However, the electrification process will require significant developments in infrastructure, business models, and political decisions while the technological development continues. One of the main challenges is the availability of renewable energy sources. The deployment of renewable energy sources such as wind and solar power requires significant investments in infrastructure and technology, especially for ports with lack of local renewable sources and space. The development of battery storage technology is also crucial for the integration of renewable energy sources into the grid and more technological developments are required.

The definition and development of suitable business models that support the electrification of the industry sector in ports is also needed. The high upfront costs of electrification may be a barrier for some companies, particularly small and medium-sized enterprises. Innovative financing models such as power purchase agreements and green bonds may be needed to support the transition to electrification.

Finally, political decisions and policies play a crucial role in the electrification of the industry sector in ports. Governments have the power to shape the regulatory and financial landscape, providing incentives for private sector investment in electrification projects. For example, policies that encourage the use of renewable energy, such as tax incentives and feed-in tariffs, can help make electrification projects more financially attractive. Similarly, regulations that impose limits on emissions or require the use of low-emission technology can drive demand for electrification. Moreover, political decisions and policies can help to facilitate the development of the necessary infrastructure for electrification (e.g., charging stations, onshore power facilities, and smart grids) and can also provide funding for research

[19] https://www.innoenergy.com/discover-innovative-solutions/online-marketplace-for-energy-innovations/meva-power-plant/

and development, enabling the development of new technologies that can accelerate the electrification process.

2.2.2.3 *Buildings*

The buildings sector has a significant impact on overall EU consumption (approximately 40%) and GHG emissions (approximately 36%)[20]. Moreover, and as already mentioned, heating and cooling activities are a significant part of this problem. Currently, only 23.1% of these needs are fulfilled by renewables sources. However, there are several factors that allow to foresee a drastic change in the coming decades:

- The Energy Performance of Buildings Directive (EPBD, 2018/844/EU), which lays down energy performance requirements for the buildings sector, has the following targets: 1) 60% reduction of GHG emissions by 2030 (when compared to 2015); 2) Climate-neutrality by 2050.
- The EPBD requires that the member states establish sound long-term renovation strategies capable to achieve the aforementioned targets. It covers all existing building stock as well as new buildings.
- Renewable sources aim to cover 45% of all energy needs by 2030.

Although of crucial importance for the energy transition process, these targets are ambitious. It is worth to recall that two thirds of European buildings were built since many decades, when energy efficiency requirements were quite limited. Almost half of the EU's buildings have individual boilers installed before 1992, with efficiency of 60% or less. Nevertheless, and thanks to technological advances, an effective thermal renovation of buildings (including the ones present in ports) is expected.

The market has currently available several renewable options for heating and cooling, being electrification one of them. It is foreseen that the majority of small oil boilers and the totality of coal boilers will be replaced by renewable appliances such as heat pumps. This will constitute an important shift towards electricity use in the heating/cooling sector[21]. Other options to support the decarbonization of the buildings sector are hydrogen and biogas. According to the REPowerEU targets[22], biogas production from methane should reach an annual production of about 1.3% of the total primary energy consumption in Europe. Since the replacement of natural for biogas does not pose significant challenges, this has the potential to become an important source to heat buildings. Concerning biomass usage, it should not be downgraded, especially in collective housing districts or district heating. At this local scale, switch thermal power plants from oil/gas to biomass might be a good option. Lastly, hydrogen boilers can also make part of the overall energy transition solution. Important to refer that an increasing use of green hydrogen for heating purposes will automatically lead to increasing electronification needs.

The pathway towards decarbonization in the buildings sector is challenging. Particularly, heating/cooling needs will be fulfilled by a mixture of different energy vectors. In this report, the modelling work of section 3.5 will analyse only the electrification part. This particular focus is given because of the added flexibility options that can be offered by buildings to the electrical grid thus allowing a better match between supply and demand. Depending on

[20] https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en
[21] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016DC0051&from=EN
[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

their inertia, they could shift or shed loads without compromising the comfort set points or industrial ambient rules.

Concerning the MAGPIE project, it should be stressed that buildings are by far not the largest energy loads in ports area. Still, they are loads that belong to the energy supply chain of the MAGPIE ports. In that sense, their flexibility should be exploited. Shifting of buildings loads will permit to include more renewable energy into the heating and cooling services while ensuring not to compromise the comfort and ambient requirements in buildings. Providing more flexibility in the energy supply chains through heavy, high inertia building stock has great promise for RES deployment and thus CO_2 emissions reduction. It should result in cost savings by lowering the investment in energy storage systems. If there are not enough massive buildings on the ports, why not integrate the building stock behind the port fence.

Furthermore, where there is a lack of inertia in building structures, it would be interesting to address the energy needs of heavy industry, present in port area and requiring large cold or hot storage, using the properties of Phase Change Material (PCM). Cold or hot stores can help provide inertia and shift loads, then a large amount of flexibility. Nevertheless, heat and cold storages are slightly apart of Magpie framework.

For all these reasons, buildings can become active players in the port decarbonization process, intrinsically and by providing flexibility services in line with the energy matching objectives of the MAGPIE project.

2.2.3 Deep-dive on MAGPIE ports

2.2.3.1 *Transport modalities*

In order to deep-dive into the MAGPIE ports, a questionnaire was circulated among port partners (Annex A). Currently, rail transportation is one of the major consumers of electricity at the Port of Rotterdam and its consumption levels are expected to growth in the coming years as more trains and shunting locomotives are put into operation, while just a few e-trucks recharge their batteries at the port. Additionally, inland shipping with exchange of battery packs can be a reality (with a pilot ongoing), barges and road transportation, especially trucks, are foreseen as future electrical consumers in the Port of Rotterdam and might rely almost entirely on the port's capacity to cover their needs. Regarding maritime shipping, this transport modality may only rely on shore power when moored and so, no electric sea going vessels are expected to be deployed. Additionally, different technologies can be responsible for the recharging process. On-shore power supply for inland barges is already used in the port of Rotterdam and plans to extend it to sea going vessels are underway[23][24]. Although still uncertain, the demand for this technology could reach 150 MVA spread around the port. E-charging stations and overhead lines to power hybrid-electric shunting locomotives are also used as recharging options while for inland shipping and road transportation e-charging stations to charge swappable batteries and trucks are planned to be part of the recharging process in the future. Demos 3, 7, 8, and 9 address these technological options within the context of MAGPIE's project.

The electrical consumption status in the DeltaPort is quite different from the one observed in the Port of Rotterdam for the transport sector as there is no relevant consumer of electricity. In fact, the DeltaPort authorities are focused on a strategy based on hydrogen propulsion for inland shipping and rail. Given that Rotterdam and DeltaPort are situated on

[23] https://www.portofrotterdam.com/en/port-future/edition-february-2022/the-port-of-rotterdam-is-working-on-shore-power

[24] https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/shore-based-power-rotterdam/research-on-shore-based

the same corridor but have divergent focuses on energy carriers for inland waterway transport, there may be some operational issues arising from this strategic variation. This suggests that decarbonizing this transport modality does not have a straightforward solution, but it is crucial for ports, particularly those in the same corridors, to coordinate their efforts and, it is also urgent for the sector to reach a consensus on the matter.

Only road transportation is a future consumer of electricity in the transport sector where it is expected that all trucks may completely rely on electricity by 2040 and able to provide vehicle-to-grid (V2G) services to increase flexibility in the system overnight. Moreover, it is foreseen by the port authorities that nearly 30% of the trucks arriving at DeltaPort will need to power their batteries and so, an investment of four e-charging stations will be necessary to fulfil their needs. Besides this investment to trigger the electrification of road transportation in DeltaPort, the authorities do not exclude the possibility to electrify some other transport modalities, but there are still some barriers to overcome, and some drivers must be addressed to upscale the electrification of such transport modalities and creating a viable business model.

Overall, the current status on MAGPIE ports is quite similar to what generally happens in other ports where the transport sector has a significant share of electricity consumption. Transport modalities like rail are among the ones that have been electrified for a long time and so, their technological maturity and infrastructure is well-established followed by road (i.e., trucks) as many truck manufactures are steadily replacing their conventional heavy-duty vehicles with greener options. Regarding the latter, as with other ports, MAGPIE ports seek to endow their ports with the necessary recharging infrastructure to keep up with the current attempt to decarbonize ports and other logistic hubs as recharging stations are not so well-established as electric railways.

2.2.3.2 *Industries*

As previously mentioned, industrial activities account for a significant portion of electricity consumption in ports. By examining the replies provided by the MAGPIE ports to the questionary, it is evident that DeltaPort does not register a significant consumption of electricity for industrial activities while the situation in the Port of Rotterdam mirrors the global scenario described in section 2.3.1. Port of Rotterdam has active electricity consumers in fuel refining, power generation, heating industries, and steam production.

Currently, the existing industrial activities at the Ports of Rotterdam and Moerdijk (a small port near Rotterdam) are responsible for approximately 5.7 TWh of annual electricity consumption. Naturally, a high share of this aggregated consumption concerns to the Port of Rotterdam. Authorities forecast that this consumption will rise to 26 TWh by 2030 and 37.6 TWh by 2040 (stabilizing until 2050). It is worth noting that the projection of almost fivefold increase in electricity demand for industrial activities, including electricity generation, high-temperature heat processes, and steam production at Port of Rotterdam by 2030, aligns with the global trend towards electrification of industries. This emphasizes the importance of electrifying the industry sector to reduce overall GHG emissions.

2.2.3.3 *Buildings*

Ports are usually seen as vast open spaces. Their assets embrace endless storage areas, warehouses, boarding and shipping terminals, docks covered by hundreds of stacks of containers in a row. They also contain buildings that can be dedicated to some of the following uses:

- Captaincy
- Warehouses (air-conditioned or not)
- Customs offices

- Office buildings (generally speaking)
- Boarding or shipping terminals
- Dockers' quarters
- Others (cafeterias, police stations, medical or rescue posts, laboratories)

The electricity consumption associated with buildings and operations involved in port activities is considerable, as many equipment and facilities, such as cranes, forklifts, shore power, lighting, and cooling systems, rely on electricity. This trend is also observed in the ports of Portugal, Germany, Netherlands, and France, which are the focus of the MAGPIE project. The Port of Rotterdam is not an exception, as it hosts many warehouses, especially around the railway station, and including large buildings (e.g., Odin warehousing 490 m x 144 m). Additionally, there is a workshop near the railway station that is dedicated to locomotive repair and maintenance. The size of buildings associated with port activities can vary greatly and can be quite substantial, reaching up to 70,000 square meters on a single terminal, such as the "DOCKSEINE" terminal at HAROPA port in Rouen. Consequently, heating such a large space could result in a significant energy consumption, exceeding 100 kW. A consulting company in France, TL&A, has forecasted an average energy consumption of under 50 kWh/m²/year for warehouses heated under 12°C in typical winter conditions.

To set-up and calibrate the buildings model (section 3.5), some information concerning the port buildings will be required, namely the date of construction or last renovation, surface area and composition of outer walls and roof, surface area and exposure of openings, surface area and thickness of concrete floor, energy consumption indices per month/week, schedules (activity, occupancy, lighting, set point temperature). Port authorities have already pointed out that energy-related data belongs to different operators and is hardly available and sensible due to contractual issues. Nevertheless, part of the information relating to the dimensions of the buildings is publicly accessible via satellite imagery.

Shore power, which is becoming an increasingly important solution for reducing the carbon footprint of port-related activities, is also a significant consumer of electricity in the Port of Rotterdam when ships are docked. This is also the case in DeltaPort, where all of the electricity demand streams mentioned earlier are expected to be fully electrified by 2040, especially if besides the port authority terminal operators invest in their own infrastructures. In reality, the current status and the electrification plans for buildings and terminal operations in both ports are consistent with the general picture mentioned in a previous section of this report. Not only cargo handling equipment such as cranes, conveyors and other ground support equipment used for moving containers and other cargo, but also the refrigeration of warehouses and the ventilation of buildings are commonly electrified to improve efficiency and reduce emissions.

2.3 Production

2.3.1 Context

The energy supply mix of ports can vary depending on location, available resources, and economic factors. Historically, ports have relied on conventional energy sources such as coal, natural gas, and oil for electricity and heat supply. They have also depended heavily on oil products for cargo handling operations and transport to and from the port. Due to their role as gateways for conventional fuels, ports have been prime locations for electricity and heat generation plants using coal and natural gas. In fact, 46% of respondents in the most recent

ESPO survey[25] on governance in EU ports reported that electricity production industries are located within the port. Examples of this can be found in two MAGPIE ports, in Rotterdam, which over the years has housed several coal and natural gas generation units, and Sines, that until 2021 was the site of one of Portugal's few coals power plants. Renewable electricity generation still represents a minor share of the total electricity production within ports, and an even smaller share of the total energy consumption in ports. This is particularly noteworthy in industrial ports due to the high energy demand and load profiles associated with the industrial activities. For example, in the Port of Rotterdam, the renewable generation, from approximately 300 MW of wind capacity, accounts for less than 10% of the total installed electrical capacity in the port, which is currently dominated by gas plants.

As part of the effort to transition to more sustainable operations in line with climate mitigation goals and policies, ports worldwide are increasingly deploying new renewable capacity. According to the European Sea Ports Organisation (ESPO) survey, solar, biomass and wind were the top three sources of electricity present in the power systems of EU ports in 2022, reported by 58%, 36%, and 33% of the ports, respectively. Some ports are also exploring electricity supply from geothermal sources[26] (e.g., Ports of Antwerp and Hamburg) and from tidal or wave energy (e.g., Port of Antwerp Hydroturbine tidal project). Waste-to-power units also represent a significant source of electricity and heat in some ports. For example, in the Port of Hamburg, the Eurogate container terminal meets 20 to 50% of electricity needs from onshore wind and the wastewater treatment plant located in the port is sourcing most of its heat and power needs from a waste-to-energy CHP unit[27]. The electricity produced via the current power systems in ports is not limited to providing for port-related activities. Once injected into the public grid, it can be consumed throughout the system. Moreover, for many ports with limited technical potential for the installation of renewable sources, power purchase agreements from guaranteed renewable origin are an option.

With the increasing adoption of renewable energy sources, ports are implementing storage solutions and looking for options to incentivize local production and consumption. This is particularly important in ports located in areas with limited capacity to connect additional generation to the grid, as is already happening in some ports, e.g., in the Port of Amsterdam[28]. Some ports are exploring the implementation of microgrids and smart grids to deal with some of these issues[29], while also investing in electrification of cargo handling operations and onshore power connections side-by-side with new renewable capacity and local storage. These hybrid systems are becoming increasingly popular in ports, as they provide the benefits of diversity and resilience and help address the challenges of increased shares of non-dispatchable and variable generation. Further examples for electricity supply in port

[25] https://www.espo.be/media/ESPO%20Trends%20in%20EU%20ports%20governance%202022.pdf
[26] Alamoush, A.S. et al. (2020) Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review. Marine Pollution Bulletin. 160, 111508. DOI: 10.1016/j.marpolbul.2020.111508
[27] https://marketing.hamburg.de/energy-transition-in-hamburgs-port.html
[28] https://www.entrnce.com/customer-stories/port-of-amsterdam
[29] Roy, A., Auger, F., Olivier, J.-C., Schaeffer, E., & Auvity, B. (2020). Design, sizing, and energy management of microgrids in harbor areas: a review. Energies, 13(20), 5314.

ecosystems, such as grid-connected power, on-site generation, battery storage, and hybrid systems in ports are reported in the literature[30][31][32][33][34].

While the energy supply mix varies across ports, port authorities are increasingly working alongside supply chain partners, governments, and the public to adopt sustainable electricity generation alternatives, joining a collective effort to minimize the carbon footprint in logistics and shipping. Furthermore, economic, and technological factors are driving this energy transition, as renewable energy sources such as solar and wind become more affordable, contrasting with the rising costs of carbon emission penalties. Additionally, technological innovations are enhancing the efficiency of solar and wind production enabling the ports to install these solutions on-site paving the way for more sustainable ports.

2.3.2 The pathway towards decarbonization

The energy transition in ports is partly driven by climate mitigation policies and associated legislation (e.g., European Green Deal (EGD)[35] and Fit for 55 legislative packages[36]) implemented at the national and regional level, covering the hinterland side of the port, which demands specific targets for GHG emissions reductions by 2030 and 2050. And partly by the ongoing efforts to decarbonize shipping (e.g., International Maritime Organization (IMO) targets for 2050[37]; FuelEU Maritime[38], initiatives for zero-carbon shipping in 2050[39]) covering the shore side connections of the port to the global trade and the role of ports as energy hubs. Ports are thus considering different strategies for full decarbonization or reaching carbon neutrality by 2050, including electrification of transport modalities and port operations and systems, shifting to low-carbon energy vectors (e.g., green hydrogen, e-ammonia), use of renewable energy sources, efficiency measures, implementation of carbon capture and storage, and carbon offsetting. Ultimately the change in supply will depend on the evolution of the demand and the degree and pace of electrification and decarbonization of ports, transport modalities and the industrial sector.

Electrification of port operations involves using electric or hydrogen-powered cargo handling equipment, vessels, and other mobile and stationary systems and infrastructure. Recent industry reports show increasing projections of electrification of port operations in the

[30] Iris, Ç., & Lam, J. S. L. (2019). A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. Renewable and Sustainable Energy Reviews, 112, 170–182.
[31] Hoang, A. T., Foley, A. M., Nižetić, S., Huang, Z., Ong, H. C., Ölçer, A. I., & Nguyen, X. P. (2022). Energy-related approach for reduction of CO2 emissions: A strategic review on the port-to-ship pathway. Journal of Cleaner Production, 131772.
[32] Zhang, Y., Liang, C., Shi, J., Lim, G., & Wu, Y. (2022). Optimal port microgrid scheduling incorporating onshore power supply and berth allocation under uncertainty. Applied Energy, 313, 118856.
[33] Li, S., Ning, K., & Zhang, T. (2021). Sentiment-aware jump forecasting. Knowledge-based systems, 228. https://doi.org/10.1016/j.knosys.2021.107292
[34] Herrero, A., Ortega Piris, A., Diaz-Ruiz-Navamuel, E., Gutierrez, M. A., & Lopez-Diaz, A.-I. (2022). Influence of the Implantation of the Onshore Power Supply (OPS) System in Spanish Medium-Sized Ports on the Reduction in CO2 Emissions: The Case of the Port of Santander (Spain). Journal of Marine Science and Engineering, 10(10), 1446.
[35] https://www.consilium.europa.eu/en/policies/green-deal/
[36] https://www.consilium.europa.eu/en/press/press-releases/2022/06/02/fit-for-55-package-council-adopts-its-position-on-three-texts-relating-to-the-transport-sector/
[37] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx
[38] As adopted on the 19th of October 2022 by the European Parliament: https://www.europarl.europa.eu/doceo/document/TA-9-2022-10-19_EN.html
[39] https://explore.mission-innovation.net/mission/zero-emissions-shipping/

coming decades[40]. In addition to reducing GHG emissions associated with the use of fossil fuels and improving energy efficiency, electrification can also result in major reduction of emissions air pollutants. For example, electric or hydrogen-powered cranes, reach stackers, and terminal tractors can handle cargo, reducing emissions from diesel engines. Electric or hydrogen-powered vessels can also reduce shipping operation emissions. In the short to medium term, ports will also continue to invest and deploy additional OPS connections. This could lead to a very significant increase in the total electricity demand of ports on one side. On the other, in many ports the grid will have to be expanded to deal with the total additional demand and technical requirements in specific points of the grid, e.g., those providing OPS connections. An example of the implementation of the electrification of ports may be found in[41].

In terms of the decarbonization of the electricity supply in ports[42], port stakeholders and authorities are expected to keep investing and facilitating investments in onshore wind and solar PV, where possible, while also exploring geothermal and bioenergy sources for power generation. Some ports are also opting to pilot new carbon capture and storage (CCS) and carbon capture, utilisation, and storage (CCUS) infrastructure, to potentially retrofit existing fossil capacity (e.g., Ports of Rotterdam and Gothenburg) or as the current fleet of power plants ages, replace with new fossil capacity with CC(U)S. However, the most significant increase, for ports is likely to come from the expansion of offshore wind, with 60GW of new EU offshore capacity foreseen for 2030 and 300GW by 2050. Ports can have an important role as sites for part of this new generation – where technically and economically viable, and as facilitators of the assembly, transport, and installation of the turbines. In the first case, siting and connecting the new offshore capacity through the existing port grids may require expansion or upgrade of the public grid.

One of the typical problems associated with using renewable energy sources in ports is the variable nature and non-dispatchability of the renewable energy sources. Flexibility and local storage, both short term and seasonal, can help mitigate some of the challenges in management of the port power systems with increasing penetration of renewable generation. To maximize energy flexibility, ports must have access to real-time energy data and be able to control energy consumption and generation remotely. This requires the implementation of advanced technologies such as Internet of Things (IoT) devices, artificial intelligence (AI), and advanced energy management software[43]. Hybrid systems allow the system to adjust to changes in energy demand and availability by drawing power from the most suitable source in real-time while also helping optimization of energy use, by using the most efficient energy source for the given demand and reducing dependence on fossil fuels.

When the resources allow, ports have the potential to work as energy communities with flexible trading markets to address the non-dispatchability of renewable energy sources and

[40] Blonsky, M., Nagarajan, A., Ghosh, S., McKenna, K., Veda, S., & Kroposki, B. (2019). Potential impacts of transportation and building electrification on the grid: A review of electrification projections and their effects on grid infrastructure, operation, and planning. Current Sustainable/Renewable Energy Reports, 6, 169–176.
[41] Jonathan, Y. C. E., & Kader, S. B. A. (2018). Prospect of emission reduction standard for sustainable port equipment electrification. International Journal of Engineering, 31(8), 1347–1355.
[42] ESPO (2022), The new energy landscape. https://www.espo.be/media/The%20new%20energy%20landscape.pdf
[43] M. Sadiq et al., "Future Greener Seaports: A Review of New Infrastructure, Challenges, and Energy Efficiency Measures," in IEEE Access, vol. 9, pp. 75568-75587, 2021, DOI: 10.1109/ACCESS.2021.3081430.

improve energy security[44]. The concept of an energy community is based on local energy systems, where energy is produced, consumed, and traded locally. In this context, ports can generate, consume, and trade energy among their stakeholders, such as ships, cargo handling equipment, and port buildings. Flexibility trading markets can be established to facilitate the trading of energy flexibility among different energy consumers and producers. Flexibility trading markets can be used to match the supply of renewable energy with the demand for energy by different energy consumers. For example, a ship docked at a port can use its onboard energy storage system to store excess energy generated by the port's solar panels, and then use that stored energy when it departs. Similarly, cargo handling equipment can be charged with excess energy generated by the port's wind turbines, using that stored energy to handle cargo during periods of low wind.

2.3.3 Deep-dive on MAGPIE ports

As stated before, depending on the particular nature of each port, there might be a wide variety of electrical suppliers in it. Deep diving on MAGPIE ports, the current electrical energy supply mix in the Port of Rotterdam is constituted by solar, onshore wind, combined heat, and power (CHP), combined cycle gas turbine (CCGT) and coal. Although not present within the port's area, offshore wind from the North Sea also contributes to the generation mix. Contrarily, in DeltaPort solar is the only electrical energy source within the port.

Table 2 depicts the current and forecasted installed capacity per technology concerning the electricity supply within MAGPIE ports. A questionary was circulated among the port partners (Annex A) which led to the following data provided by the Port of Rotterdam and DeltaPort authorities, now presented in this table.

Table 2 - Present & future scenarios for installed capacity per technology in MAGPIE ports

		Present Installed Capacity (MW)	Installed Capacity in 2030 (MW)	Installed Capacity in 2040 (MW)	Installed Capacity in 2050 (MW)
Solar	PoR	11	110	130-150	130-150
	DeltaPort	2	10	15	15
Onshore wind	PoR	250-300	250-300	250-300	250-300
	DeltaPort	-	-	-	-
Offshore wind	PoR	-	7400	7400	7400
	DeltaPort	-	-	-	-
Biomass	PoR	NA	NA	NA	NA
	DeltaPort	-	-	-	-
CHP	PoR	3600	3600	NA	NA
	DeltaPort	-	-	-	-
CCGT	PoR	2100	2100	2100	2100
	DeltaPort	-	-	-	-
Coal	PoR	2900	0	0	0
	DeltaPort	-	-	-	-

Regarding solar installed capacity, both ports have set ambitious plans to deploy more solar panels within the port's area. DeltaPort aims to fivefold the actual installed capacity by 2030 reaching 10 MW and then, 15 MW by 2040 and 2050, while other renewable energy sources

[44] Hentschel M., Ketter W., Collins J. Renewable energy cooperatives: Facilitating the energy transition at the Port of Rotterdam (2018). Energy Policy, 121, 61-69. https://doi.org/10.1016/j.enpol.2018.06.014.

are not being considered by DeltaPort authorities due to lack of available land to install onshore wind and biomass is not a viable option due to proximity to residential areas which may arise some issues related to smell. In Rotterdam, a significant increase in solar installed capacity is planned where the authorities expect a tenfold increase in solar by 2030, moving from the actual 11 MW to 110 MW of installed capacity. In 2040 and 2050, between 20 MW to 40 MW of installed capacity may be added reaching a total capacity of 130 to 150 MW of solar.

Contrarily, onshore wind may keep the actual range of 250-300 MW of installed capacity as result of lack of space in port to install new wind generators. Although not present within the port's area, offshore wind from the North Sea is expected to provide 7.4 GW by 2030 onwards. In opposite, coal is expected to be decommissioned by 2030 as a measure to decarbonize port's activity while some uncertainties may arise regarding the future role of CHP and CCGT in the generation mix as CCGT may be used only as backup for renewables and plans about the future of CHP are still being discussed by its owners.

Overall, there is a main trend to supply the port actors with renewable energy, but not compulsory from local production as verified in the case of offshore wind production in Rotterdam and, in some cases, electricity can also be supplied by the electrical grid. Additionally, some companies are leading some local renewable energy production projects. For instance, CMA CGM, a French container shipping company which operates more than 700 warehouses and 50 port terminals, aims to cover 100% their electricity needs and, CEVA Logistics, a CMA CGM subsidiary, aims to install about 1.8 million square meters of solar panels in all warehouses[45].

2.4 Energy Storage

2.4.1 Context

Energy storage is of high importance for future energy systems with a high share of renewables and a significant decarbonization process going on through especially larger use of electricity and hydrogen. Deploying flexibility solutions is required particularly for balancing supply and demand in the electricity supply chain. Storage system for electricity is one of this flexibility but not the only one; demand-side management (DSM) for buildings or industrial applications or electrical vehicles charging, dynamic line rating (DLR) and tuned electrical grid management, power generation derating, short term local markets, etc., are powerful solutions to offer the required flexibility for the electricity supply chain. Storing electricity is another one.

Several vectors and technologies exist for storing electricity:

- it can be stored through mechanical energies for instance with Pumped Hydropower Storage (PHS), with Flywheels (low and high rotational speed) and with classical and adiabatic Compressed Air Energy Storage (CAES)
- by using electrostatic energy with supercapacitors,
- by using thermal means through power-to-heat technologies and heat storages (sensible heat storage, aqueous salt solution, thermochemical heat storage),
- by using chemical carriers (Power-to-gas: hydrogen thanks to electrolysis, and CH_4 thanks to methanation)
- and through electrochemical vector with batteries' technologies.

[45] https://www.cmacgm-group.com/en/fund-for-energies

However, not all the technologies have the same degree of maturity as illustrated by the table hereafter containing data from IEA's ETP Clean Energy Technology Guide database[46].

Table 3 - Technology readiness levels of electricity storage technologies

Technology		Technology Readiness Level (TRL)
Battery storage	Redox flow	Demonstration: first of a kind commercial
	Lithium-ion	Early adoption: commercial operation in relevant environment
Mechanical storage	Flywheel	Early adoption: commercial operation in relevant environment
	Pumped storage	Mature: proof of stability reached
	Compressed air energy storage	Demonstration: first of a kind commercial
	Liquid air energy storage	Early adoption: commercial operation in relevant environment
Latent heat storage	Aqueous salt solution	Early adoption: commercial operation in relevant environment
	High temperature	Demonstration: first of a kind commercial
Sensible heat storage	Sensible heat storage	Large prototype: full prototype at scale
Thermochemical heat storage	Chemical reaction	Concept: concept needs validation
	Sorption process	Large prototype: full prototype at scale

Based on DOE Global Energy Storage Database and IEA statistics, PHS is by far the most used technology to store electricity for electrical grid management with about 140 GW of installed power and 600 MWh of installed energy. PHS accounts for about 85% of total installed power of storage for electricity. It is also the most mature storage technology, but it is not adapted to all locations (it requires a minimum head between lower and upper reservoirs).

Stationary Battery Energy Storage System (BESS) is gaining more and more interest in such applications. Historically stationary battery storage systems were dominated with water-based electrolyte technologies such as lead-acid batteries and to a lesser extent, nickel based (Ni-Cd and Ni-MH) and with high temperature sodium based (Na-S and Na-NiCl2) technologies. Lead-acid batteries are still leading the stationary battery market (especially for industrial applications as telecom and uninterruptible power supply (UPS) application) but are also installed as stationary storage for grid-related applications (about 4 GWh of global cumulative energy[47] and likely less in installed power). Lithium-ion stationary storage systems are growing very fast thanks to their fast adoption for mobility (x-EV) and nomad applications (leading to fast costs' decrease). Almost all the large BESS for grid-related applications (i.e., supplying flexibilities to electricity supply chain) are currently using lithium-ion batteries. Figure 7 depicts the global cumulative energy (from 2018 to 2020) of BESS installed for grid applications, and the 2021-2030 forecasts.

[46] https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedCCTag=Storage&selectedVCStep=Storage&selectedSector=Heat
[47] Energy Storage Grand Challenge: Energy Storage Market Report, US DOE, December 2020

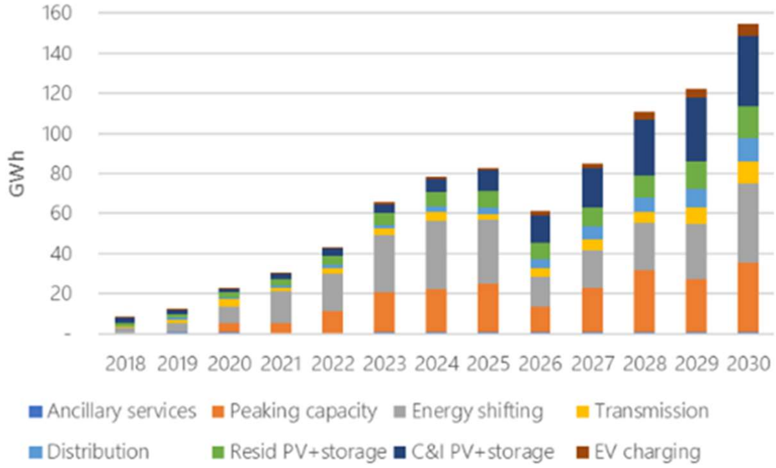

Figure 7 - Global BESS energy capacity and forecasts for grid applications

Many electrochemical technologies exist for storing electricity in batteries, but they do not all have the same technical performances (efficiencies, energy density, power/energy ratio, ageing), maturity level and costs. Figure 8 establishes a comparison between different battery technologies.

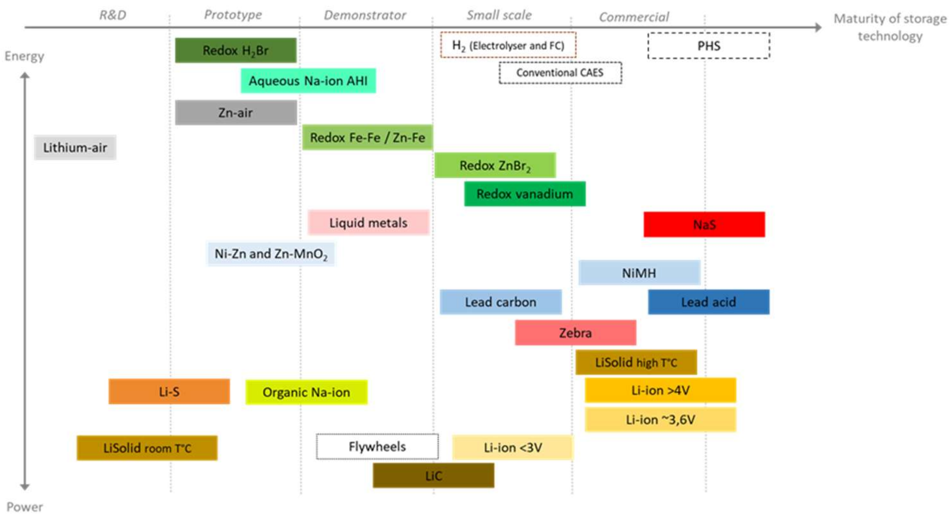

Figure 8 - Power/Energy and maturity of main battery technologies compared to PHS, CAES and Electrolysis

Lithium-ion is of high density and with a high level of maturity (20 to 30 years from first developments) explaining its recent fast growth in terms of manufacturing capabilities and market size. However, the size of the lithium-ion market for the next decade is difficult to foresee (as illustrated in Figure 9) but stationary storage would account for about 10% of it. Additionally, experts do not expect a change in stationary battery leading technologies (i.e., lithium-ion and lead-acid) in the next 8 to 10 years.

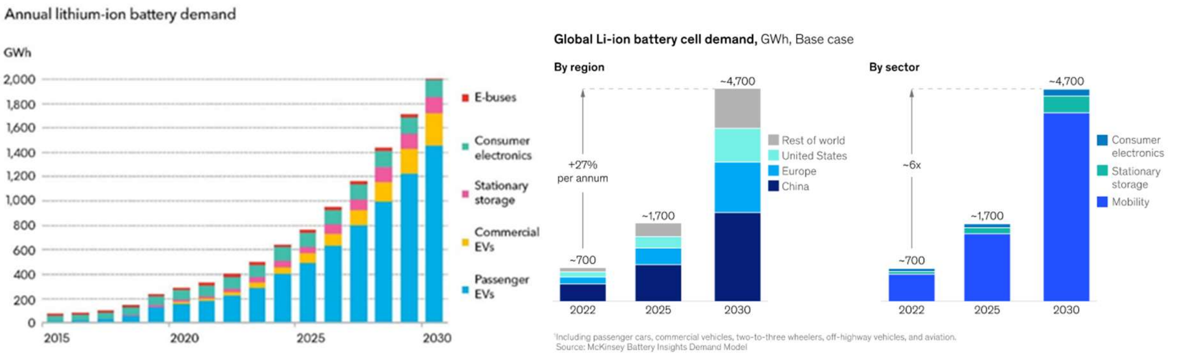

Figure 9 - Past, current, and future size of lithium-ion battery market stated in BNEF EV Outlook 2020[48] (left) and by McKinsey at the beginning of 2023[49] (right)

Nevertheless, whatever the technology used, battery is always an expensive way to provide flexibilities and its environmental impact has to be weighted; it is often advised to couple different flexibility services, to correctly defined the needs and to get a flexible and tunable system.

It is out of the scope of this deliverable to detail the characteristics of every battery technology, and so, more depicted information regarding this topic can be found in part 1.3 of public deliverable 2.1 of H2020 DRES2Market project, where concise information on 16 battery technologies is offered, or in literature. Only a short overview of lithium-ion technologies is discussed in this document.

Batteries, by design, are protected from abnormal operating conditions, especially regarding voltage and temperature, with redundant barriers considering the first barrier failures mentioned above. It is of high importance for lithium-ion batteries that could not operate outside the specified voltage and temperature ranges. In addition, to reinforce the safety of the container after some BESS fires were reported, the battery container is generally equipped with an automatic extinguishing system called Primary Fire Suppression System (PFSS) based on gas agent release (NOVEC 1230 fluid or N2 gas or argonite gas according to the local regulation and/or option). Nevertheless, a feared and critical major incident due to a generalized fire in a container due to PFSS failure or fire restart after its operation and end of its efficiency's duration, internal module propagation, etc., is considered in safety analysis. This propagation has a slow kinetics at first (propagation within the battery takes several minutes at the beginning of the incident for propagation between the abused module and the nearby modules mainly by radiation). During the first hour after fire triggering, several modules will have started their own propagation with fire, this is the reason for which the first responder must be on site in less than an appropriate duration (1 hour for some battery providers recommendation) and enforce the adapted process (see hereunder). Otherwise, a faster phenomenon may occur when the ambient temperature of the container reaches critical values (150°C) because the propagation will mainly occur by convection.

Assuming that all safety barrier redundancies have been inoperative, and all the energy of the batteries is released during a full fire at the container, an estimation of the intensity of the thermal effects and their duration outside the container would be as follows:

[48] BNEF EV Outlook 2020

[49] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

- Flames through pressure relief vent on the lateral door and potentially also on the roof through open frangible panels (see figure below);
- Temperature of flames > 1100°C;
- Duration of spread/fire > 8 h.

In order to stop the phenomenon of full fire in the container, the battery container is generally equipped with a Second Fire Suppression System (SFSS) allowing direct water injection on all modules in the container. A water snoot, located at the external side of container, permits the first responder to connect to a fire pipe or water reservoir once his arrival on site. If the fire continues, fire brigade intervention is required to apply water to the container to cool it down and stop the fire spreading and the heat radiation to the adjacent container. This let-it-burn strategy without propagation to neighbourhood tends to be more and more adapted, but some countries have a more restrictive strategy with fire extinguishing approach.

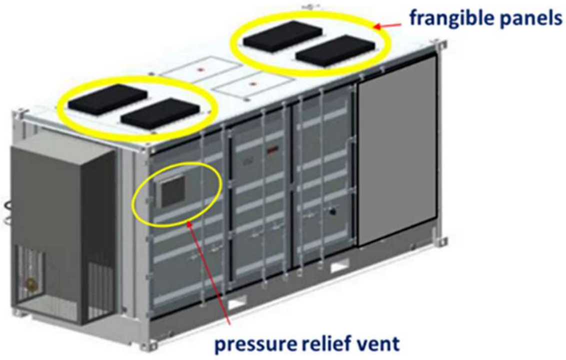

Figure 10 - Overview of different fire safety devices

Since the battery is classified as a dangerous and risk good, several standards and norms related to the safety and installation requirements have been created and updated according to the evolution of the energy storage applications and depending on each country authority.

- NFPA 855, Standard on the Installation of Energy Storage Systems for USA, created by the National Fire Protection Association
- PGS37-1, guideline on Energy Storage Systems (EOS or Energie Opslag Systemen in Dutch), containing of the most important risks concerning environmental and fire safety and describing of the measures that can be taken to increase safety and reduce risks of incidents and their consequences.
- IEC 62485-5, Safety requirements for secondary batteries and battery installations - Part 5: safe operation of stationary lithium-ion batteries.
- UL 9540, the Standard for Safety of Energy Storage Systems and Equipment.
- UL 9540A, the Test Method for Evaluating Thermal Runaway Fire Propagation in BESS Standard.

Regarding the implementation of a BESS on a port, the different international and national standards and regulations should be applied.

For instance, safety distance from a BESS must be considered as the BESS is a fire source. When designing the safety distance, the possibility of the spread of fire due to heat convection transfer of embers from the BESS must also be considered. The BESS location must be easily reached for firefighters' services with enough water available. The BESS has to get advanced monitored data to understand the situation of emergency, and an emergency stop to reduce the risk.

Large ports do not especially exploit BESS options except for very specific electrical grid needs such as grid congestion. BESS projects for port energy management are not especially reported in literature and none of the MAGPIE ports have a BESS in operation. Only a pilot project is being developed in the Port of Rotterdam and HAROPA is thinking on BESS for peak shaving. In smaller ports, there are more needs for BESS, for instance helping to manage high-required power for charging of electrical ferries without leading to grid reinforcement (peak load reduction flexibility service) and it is for instance one of the use cases of H2020 Hypobatt project[50]. More and more ports also installed equipment (or planned to do it) for OPS where electrical chargers on docks are responsible for powering ship's essential services in order to reduce GHG emissions and to respect air regulation. As stated in Deliverable 9.1, almost all ports interviewed have developed or are in the process of developing facilities for OPS. For European ports this is in line with the measures and OPS obligations, included in the "Fit for 55" package and in the FuelEU Maritime. For instance, HAROPA PORT is developing an integrated OPS strategy along the Seine Axis by 2024 with 3 connections in Le Havre, 2 in Rouen and 1 in Honfleur. Additionally, to the electrical chargers, it could be coupled to local renewable production and a stationary BESS for power peak-shaving. It is the case for the ferry terminal (ferries and cruise ships) of Toulon ports in France (and in short term of Marseille and Nice ports) with three electrical chargers coupled to a PV-shade house, a BESS for peak shaving and an energy management system (EMS). The solution is provided by ABB and is already in service in more than 50 ports in the world.

Ports will likely play an important role in the battery supply chain as they host imports and exports of batteries components and some battery manufacturing facilities (for instance the Verkor project in Dunkirk port in France), and for participating in battery recycling process (for instance the Eramet-Suez project of a refinery for battery's materials from battery recycling process in the port of Dunkirk in France). Ports will also have more and more electric vehicles to operate in or from (trucks, boats, cranes, train, etc.) and these 'mobile' batteries could be used smartly as 'stationary storage system' for electrical flexibility requirements when plugged at charging point.

2.4.2 The pathway towards decarbonization

In recent years, many studies at European or national levels evaluate the needs for flexibility for electrical grid management considering the electrical interconnections between countries and the coupling of different energy vectors. They make assumptions of 100% renewable Distributed Energy Resources (DER) scenarios[51] or of a compilation of national renewable scenarios to respect Paris agreement on climate[52].

Needs for flexibility vary from one study to another but they always increase. As one of the flexibility technologies for grid decarbonization, stationary BESS will be used more and more for electrical grid management and to a wider extent for optimal energy management. It is the main trend given by the figure on lithium-ion battery market forecast in the previous subpart; about 10% of the lithium-ion market in 2030 will be for stationary BESS. Ports will be a place among others for such BESS installations: they could be useful for peak-shaving

[50] https://www.hypobatt.eu/about

[51] Breyer C., Khalili S., Bogdanov D., Ram M. Oyewo A.S. and al. 'On the History and Future of 100% Renewable Energy Systems Research', IEEE, July 2022

[52] Deliverables of WP1 H2020 Osmose project, and especially D1.3

application, local flexibility needs, increasing self-consumption rates of buildings and activities or providing ancillary services for grid operators (Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), etc.). Battery will also be present on a port as mobile storage devices (e-trucks, e-trains, e-boats, e-tugboats, cranes, etc.). Smart charging management or even more V2G management could afford many storage capabilities on ports and supply numerous flexibility services.

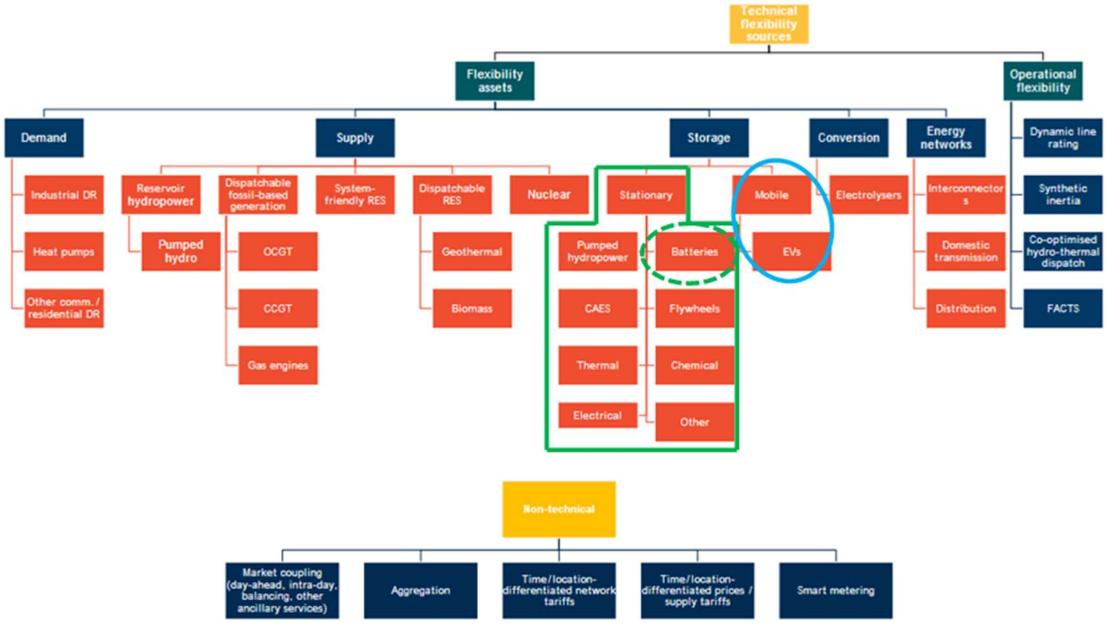

Figure 11 - Stationary storage (in green), stationary BESS (in green dashed line) and mobile battery (in blue) among all the flexibility sources[53]

As discussed previously, lithium-ion batteries should remain the main battery technology up to 2030 and even the main decentralized storage for electricity (i.e., excepting PHS) up to 2030. Lithium-ion batteries fit well the storage needs for 30 minutes to 4-5 hours applications in terms of technical characteristics and costs. Among lithium-ion batteries, the trend will be toward NMC technology with a lower content of cobalt and manganese (mainly driven by EV requirements) and LFP technology (likely more than last year's forecasts due to the use of less critical materials).

[53] 'Study on flexibility options to support decarbonization in the Energy Community', Trinomics and Artelys, July 2022

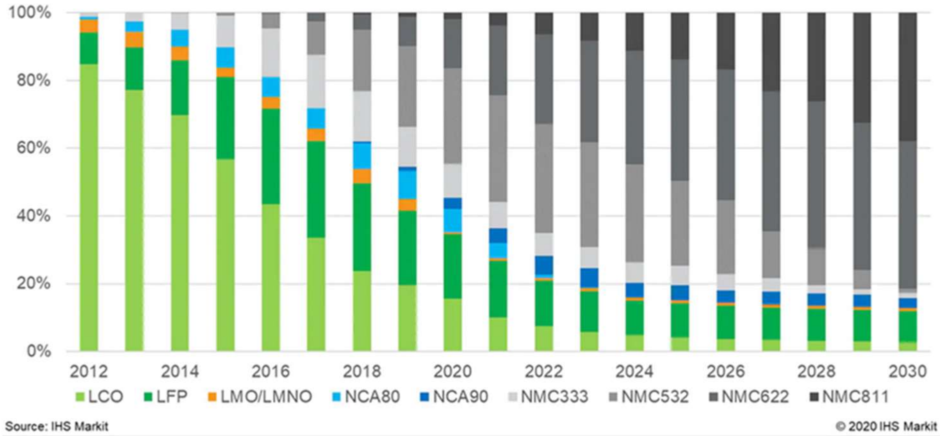

Figure 12 - Positive electrode shares among lithium-ion battery markets based on installed GWh[54]

Several studies are ongoing to setup all solid lithium batteries (i.e., the negative electrode is made of lithium metal) working at ambient temperature in order to increase energy density but also to improve safety and to likely decrease costs; most of the industrials and researchers working on it agree that it would not be ready before 2030 for mass production. Other battery technologies may be used as stationary storage at a lesser extent for specific needs (for instance larger storage durations) as redox flow batteries (vanadium redox flow, Zn-Br hybrid redox flow, Iron-iron redox flow) or as zinc-based batteries.

2.4.3 Deep-dive on MAGPIE ports

As already stated, developing a suitable storage system is of utmost importance as any effective energy system must be able to ensure security of supply and resilience. On MAGPIE ports some storage technologies are already in use, such as ammonia and natural gas. Others like BESS and hydrogen are not in operation today; however, they are planned to be deployed in Port of Rotterdam and HAROPA as already mentioned on a previous section.

In fact, some demonstrators in the MAGPIE project aim to demonstrate and validate the effectiveness of some electricity-based solutions as a contribution to the electrification process of ports, meaning that some electricity storage options are being studied and, possibly they could be deployed in some of these ports in the future. The demonstrators within the MAGPIE project's scope related to electricity power and storage are:

- Demo 3: Shore power peak shaving – aims to increase the utilization of a shore power hub facility to reduce costs by shaving the peaks using stored energy.
- Demo 7: Green container – demonstrates the use of containerized li-ion energy packs to provide electricity from renewables to an e-barge under real life port operations.
- Demo 8: Hybrid shunting locomotive – demonstrate the battery performance of a hybrid shunting locomotive during its in-port and last-mile operations within the Port of Rotterdam and DeltaPort.
- Demo 9: Green connected trucking – demonstrates the effectiveness of full electric heavy-duty trucks for short and medium distances in the Port of Rotterdam.

Onshore power supply (also known as cold ironing or shore-to-ship power (SSP)) and peak reduction strategies have attracted much interest from port authorities and decision-makers as a way to reduce the port's carbon footprint and increase its electrification levels. In fact,

[54] IHS Markit in 2020

cold ironing has a non-neglectable impact on reducing fuel consumption by ships while docked and on local air pollution and noise reduction.

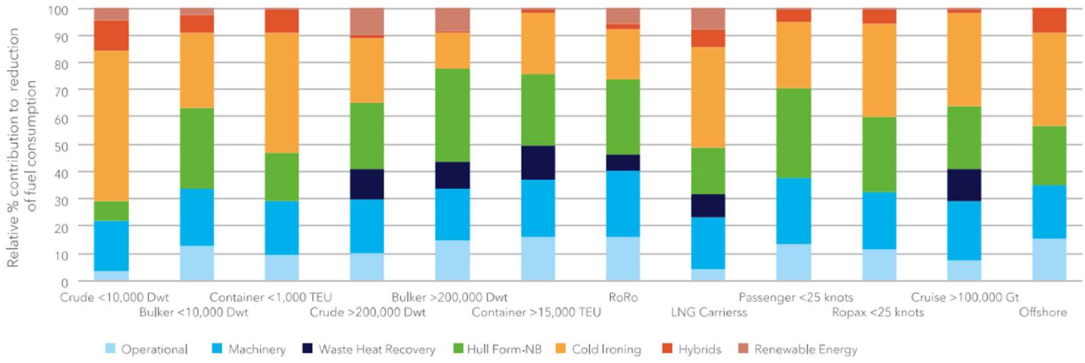

Figure 13 - Cold ironing contribution for fuel consumption reduction[55]

As shown in Figure 13, onshore power supply based on batteries can contribute to a future low carbon shipping industry and port-connected activities, while contributing to increase energy efficiency and avoiding unnecessary investments on electrical infrastructure by applying peak shaving strategies. For that reason, some ports have started making some investments and participating in pilot projects, pushing this technological solution forward. In MAGPIE ports some efforts have been made. For instance, a new 20 MW green shore power installation has been commissioned within the Port of Rotterdam and it has been used by offshore ships[56][57]. Moreover, the Dutch government has allocated 150 million euro in the 2022 budget for the installation of shore power in Dutch seaports. This decision helps the ambition of the Port of Rotterdam to have completed 8 to 10 new shore power projects by 2025, together with terminal company owners and, therefore, helping the port's authorities to get closer to objective of getting almost all moored container ships and passenger ships plugged in by 2030[56][57]. Concerning the DeltaPort, the necessary technical equipment is in place in the City Port of Wesel to supply barges with renewable shore power[58] and HAROPA installed high-voltage equipment (main substation, underground cables, and supply substation) within the port of Le Havre enabling ships to connect to onshore electricity supply[59].

Swappable containerized lithium-ion batteries for waterborne transport are another emerging strategy under analysis to provide a zero-emission source of electricity for vessel's propulsion and auxiliary power. The Port of Rotterdam is participating (is the demo site) in an EU funded project called Current Direct whose main purpose is to evaluate the feasibility of a swappable solution to enable vessels electrification along the inland waterways and coastal shipping transport network. If proved effective, this battery storage solution may become a reality not only in the Port of Rotterdam, but also in other ports like HAROPA and DeltaPort.

[55] Low Carbon Shipping Towards 2050, DNV GL, 2017
[56] https://www.portofrotterdam.com/en/port-future/edition-february-2022/the-port-of-rotterdam-is-working-on-shore-power
[57] https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/shore-based-power-rotterdam/research-on-shore-based
[58] https://www.deltaport.de/en/ecoports/
[59] https://www.HAROPAport.com/sites/default/files/media/files/HAROPA_PORT_installs_equipment_to_supply_power_to_ships_at_berth_reducing_their_environmental_footprint.pdf

Although substantial advancements have been made, the electrical storage and supply between ports and ships has not yet reached technological maturity and standardization. Nevertheless, as pilot projects progress and demonstrate the effectiveness of these novel solutions, MAGPIE ports might make early investments in BESS and electricity-based power supply infrastructures, boosting the electrification of the shipping sector and port operations. This decision could come with some risk because the infrastructures might not be fully exploited at first because most ships are still not ready; the technology might not be compatible with developments of a possible future standard; and because it might decrease the port's competitive advantage over other ports. Nonetheless, MAGPIE ports may decide to take this action in response to ambition and local emission targets.

2.5 Distribution grid

2.5.1 Context

Historically, electrical distribution networks were responsible for delivering electricity from large power plants to end-users such as households and medium/large size businesses. The rapid introduction of distributed energy resources on the generation (e.g., PV and Wind) and storage (e.g., electric transportation, large-scale batteries) sides together with an increased demand, is changing the way DSOs plan and operate their distribution networks. Furthermore, due to the expected large number of flexible resources, distribution grids will play a more active role in the operation of national power systems. While all these changes are critical to ensure a sustainable and reliable electrical grid, they also entail significant challenges: 1) guarantee security of supply when incorporating more volatile resources (due to their weather or human behaviour dependent features); 2) deal with power quality issues, including voltage magnitude quality and congestion events. Although the precise definition of a congestion event changes from DSO to DSO, this can be generally defined as when the demand for electricity (or the local generation) exceeds the network's capacity to deliver it, measured in terms of the maximum capacity of assets such as MV transformers and/or cables. DSOs are used to deal with these types of technical problems, but their increasing frequency and volatile nature demand for new solutions. Typical grid reinforcements will still be required, but other options namely all those capable to provide a fast response will be needed. Network reconfiguration actions, flexibility provision (e.g., demand response services) and smart control of BESS are among them.

This contextualization is not port specific. Indeed, distribution grids are national assets that are being impacted by the energy transition process. However, the aforementioned problems might be even more challenging in certain areas of the distribution grid, namely when large consumption hubs are concentrated in small geographic regions e.g., ports. That is the case in highly densely populated centres of the Netherlands where DSOs are currently facing several challenges. The most critical issue is the increasing frequency of congestion events reaching medium voltage (MV) and high voltage (HV) substations in important economic centers[60].

2.5.2 The pathway towards decarbonization

Flexibility can be defined as the ability of customers to adjust their operating point (increase/reduce their consumption and/or generation) in a timely and harmonized manner to accommodate expected and unexpected changes in the operating conditions of the

[60] Congestion announcement in the Noord-Papaverweg HV substation, Amsterdam: https://www.liander.nl/sites/default/files/20211209%20Vooraankondiging%20verwachte%20congestie%20Noord%20Papaverweg%20v1.2.pdf

network[61]. Exploit the flexibility shown by many distributed energy resources is technically feasible and has great potential to avoid grid technical problems and consequently reduce the need to anticipate planned network investments[62]. Currently, DSOs procure and contract this type of services from large industrial customers primarily because of their potential to significantly impact system load conditions. However, small, and medium size customers will also play an important role in the future. This is particularly relevant in the context of the MAGPIE project. Its centrepiece – the transport sector – will see a major shift towards electrification. A significant part of the road, rail and inland shipping fleet will be equipped with small/medium size batteries, which can become important assets for flexibility provision. Although the logistics sector is associated with tight schedules, the possibility of time-shift the battery recharging operations needs to be studied. Port buildings, depending on their inertia, may also shift or shed their loads without compromising the comfort set points and thus become important sources of flexibility. Recognizing this, the Dutch Authority for Consumers and Markets together with the DSOs developed a new congestion management regulation code that will allow DSOs to contract services from customers with lower capacities, reducing the original value from 1 MW to 100 kW[63]. This reduction in the minimum amount of power to provide congestion support services will surely increase the number of customers that can offer flexibility services, giving space for new revenue streams for these customers while enabling more efficient use of the currently available electricity infrastructure. Many other initiatives are being carried to promote the active participation of distributed energy resources in grid management services. As an example, the H2020 DRES2Market project[64] demonstrated the value of local flexibility markets (coupled to a national ancillary services market platform).

Concerning implementation, flexibility can be deployed through two main approaches: either by establishing a direct flexibility provision contract or by developing a network tariff program. The main difference between these two is the level of uncertainty regarding the customer's provision of flexibility. In the case of a direct contract, there is a mandatory flexibility dispatch order that customers must meet. Otherwise, they may face large penalties. In the case of network tariffs, the costumer response will depend on price incentives. From the DSOs' perspective, contracting flexibility in advance is a safer instrument.

As ports are sites quite susceptible to the arising of grid problems, they are also suited to exploit flexibility resources. To ensure that port ecosystems efficiently use these options, the following topics need to be studied:

- Impact of logistic constraints on the provision of flexibility services by the transport sector. Demo 7 (Green Energy Container), Demo 8 (Hybrid Shunting Locomotive) and Demo 9 (Green Connected Trucking) should be important information sources on this matter since they will demonstrate electrified vehicle options for the inland shipping, rail and road sectors.

[61] B. Mohandes, M. S. E. Moursi, N. Hatziargyriou and S. E. Khatib, "A Review of Power System Flexibility With High Penetration of Renewables," in IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 3140-3155, July 2019.

[62] Solutions for congestion in medium-voltage grids: The Buiksloterham-Zuid/Overhoeks Amsterdam case https://openresearch.amsterdam/nl/page/83648/oplossingsrichtingen-voor-congestie-in-middenspanningsnetten

[63] Congestion Management Code Decree: https://www.acm.nl/nl/publicaties/codebesluit-congestiemanagement

[64] https://cordis.europa.eu/project/id/952851

- Concrete role of the port authorities in promoting the usage of flexibility services. Many different stakeholders co-exist in a port environment (e.g., electricity suppliers, grid operators, manager of recharging infrastructures, etc) and their role sometimes differs between ports. As an example, APS (Administração dos Portos de Sines e do Algarve) is the owner of the port electrical grid while the Port of Rotterdam is not.

- Cost-effective management of flexibility options and their role in postponing grid investments (check the modelling work of section 3.7).

2.5.3 Deep-dive on MAGPIE ports

The electrical grid is at the heart of the energy transition process. Investing in it and efficiently managing it will be crucial to handle the growing electrification requirements. Grid upgrades, BESS, demand-side flexibility, energy management systems are different vectors that will be part of the same solution. The MAGPIE ports are aligned with this vision, and this can be proved by the work being carried in the project. Electric vehicles (Demos 7, 8 and 9) may show flexible charging profiles thus providing relevant demand response services to the grid operator. Similarly, BESS (Demo 3) can support the grid during peak demand periods or be used as a backup in power outage situations. On the industrial sector, large-scale consumers may also adjust their typical demand patterns thus contributing to a safer integration of renewables in the distribution grid (section 3.4). Buildings, depending on their inertia, can also become important flexibility providers (section 3.5).

The alignment of the MAGPIE ports with the transition pathway described in the previous section can also be observed in other initiatives. As an example, the Port of Rotterdam together with Stedin and Tennet (Dutch DSO and TSO) conducted a study to assess the impact of ongoing electrification processes to the local distribution grid[65]. The study concluded that the existing grid will not be able to accommodate the future power demand while keeping reasonable quality standards. Splitting the 150 kV network was one of the solutions pointed out. Such a measure would require a larger number of substations but would result in fewer power lines in the pipeline corridors and shorter connecting lines to feed clients in different locations. On another note, coordination between DSO and TSO while handling grid connection applications will be of utmost importance to avoid unnecessary power lines construction. Additionally, the study provides three recommendations to ensure that the necessary investments are met in due time and at a lower cost: 1) reserve space within the port area for the installation of future electricity infrastructure; 2) development of suitable legislation and regulation so that the deployment of infrastructure is accomplished with minimal economic impact for society and minimal risk of this new infrastructure become temporarily or permanently underutilized; 3) selection of sites for large-scale conversion of electricity into hydrogen and other energy carriers as the transport of these require lower investments when compared with the electric power distribution.

2.6 State of Digitalization

2.6.1 Context

The digitalization of seaports has been an important focus in recent years, with the goal of promoting decarbonization and reducing the carbon footprint of seaports. The use of digital

[65] Port of Rotterdam's power grid can be reinforced more efficiently and at a lower cost | Port of Rotterdam

technologies and tools has been instrumental in promoting the use of renewable energy and cleaner fuels, improving electricity supply chain visibility, optimizing green and smart logistics, e-navigation systems, and introducing automation and unmanned vessels. However, this effort is still limited to individual systems, terminals, or specific operations, rather than entire port ecosystems. Additionally, while considerable efforts have been made to digitalize port logistics operations, this has not included widespread adoption of digitalization of processes related with emissions and energy consumption inventories and management[66]. With the increasing participation of ports in the decarbonization of the economy and introduction of their own commitments and plans to reach climate mitigation goals, the increasing share of renewable generation and electrification of port operations, real-time data availability and tools to manage energy use and emissions have become a pressing need.

2.6.2 The pathway towards decarbonization

The move from carbon-intensive energy sources to renewable energy sources with the aim of lowering greenhouse gas emissions and mitigating the impacts of climate change is a significant challenge that requires collaboration among various sectors, including seaports and transportation. Ports can substantially contribute to this transition by implementing digital technologies and innovative solutions to enhance energy efficiency, reduce emissions, and promote sustainable operations. These solutions include the use of IoT devices, sensors, and energy management systems that can provide real-time data and information on various aspects of port operations, including cargo flow, vehicle activity, and energy consumption. This data-driven approach can optimize energy usage and reduce emissions while improving operational efficiency.

To promote decarbonization, ports are developing innovative digital tools that can help optimize their electricity supply chains and reduce their carbon footprint. These tools include data analytics and simulation software, renewable energy management systems, and smart grid technologies. These digital tools can help different stakeholders in ports to monitor and control energy usage, promote the use of renewable energy sources, and make better-informed decisions about energy use and efficiency.

Port energy management systems are already used in some seaports (e.g., Port of Rotterdam, Port of Antwerp, Port of Los Angeles, Singapore Port, and JadeWeserPort) for real-time monitoring of energy consumption, generation, and distribution. This allows for improved communication between energy suppliers and users, and optimized energy distribution. However, this process is currently either not extended to the full port ecosystem or relies on manual introduction of all or part of the data by the port stakeholders. One example is the energy monitoring tool PECMT[67] used in the JadeWeserPort to track energy use of all port operations and stakeholders. However, in this case, while some data is automatically collected from smart meters, much of the consumption is still manually added to the platform by end users. Another example is the Fritzy & friends initiative[68] that provides an open-source software that aims to balance supply and demand automatically to ensure the security of supply. However, this is only a small pilot scale initiative. A similar initiative at the port of Amsterdam is the SEP tool, also open source, that incentivizes local PV electricity producers to connect to local users. Smart grids are also being used in seaports to manage parts of the energy system, including electricity supply for cargo handling equipment, ship-to-shore power

[66] Poulsen, R. T., Ponte, S., Sornn-Friese, H. (2018) Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. Geoforum, 89, 83-95. https://doi.org/10.1016/j.geoforum.2018.01.011.
[67] https://sustainableworldports.org/project/jadeweserport-port-energy-consumption-management-tool/
[68] https://sustainableworldports.org/project/port-of-amsterdam-fritzy-and-friends/

supply, and other operations, enabling ports to operate more efficiently and reduce their carbon footprint.

Some projects are using innovative digital technologies to improve port management, data exchange between different port stakeholders, efficiency of operations and ensure safety and environmental sustainability. Examples include the Port Management Information System (PMİS[69]) developed by the Port of Baku in Azerbaijan to connect multiple systems operated by the variety of organizations that constitute the seaport community and the 5G-MoNArch[70] project, led by the Port of Hamburg, that is exploring the capabilities of 5G and network slicing to enhance traffic, infrastructure control and environmental monitoring within the port area. The INTER-IoT[71] project, aims to achieve inter-operability between different systems of different companies to exchange data. The STEAM[72] project, coordinated by the Port of Limassol in Cyprus, aims to manage sea traffic in Eastern Mediterranean Sea with a hub adopting modern digital technologies and enhanced services based on standardized ship and port connectivity, to ensure safety and environmental sustainability.

Another focus area is the development and use of unmanned vessels and vehicles in seaports to increase automation. The use of autonomous vessels and vehicles has the potential to reduce emissions and improve energy efficiency through optimized speed, real-time data analysis, and energy management systems. As most of these systems will be powered by electricity, this could have a significant impact on the port electricity infrastructure but also improve availability of data on energy use of vehicles, cargo handling equipment, and piloting assets. The real time communication from and to these systems could also allow for flexibility and demand side management strategies to be implemented.

One example of ongoing projects and pilots focusing on the introduction of autonomous systems in port is ABB development of an autonomous electric vehicle for seaports and the Kongsberg Maritime development of unmanned surface vessels (USVs) for port operations such as monitoring, surveillance, cargo handling, and environmental monitoring. Autonomous vessels and pilotage are also on the radar for Rolls-Royce that is currently working on autonomous cargo ships and tugboats for ports. Additionally, autonomous ships are being implemented for offshore wind farm maintenance, promoting sustainability in the maritime industry. Finally, Royal Vopak is developing autonomous barges to transport goods within seaports expected to be more energy-efficient than traditional vessels, reducing emissions and improving efficiency.

Projects focused on the development of models and platforms focused on speed optimization of autonomous vehicles in ports are also under development. In these projects, real-time data analysis of the vehicle's operating conditions and surrounding environment optimizes speed based on terrain, weather, traffic patterns, and energy consumption patterns. Some ongoing projects in this space include the Port of Rotterdam and the Maersk group use of IoT sensors to monitor and track energy consumption, improving energy efficiency and reducing emissions via optimization of speed of autonomous vehicles in ports.

Finally, the development of "e-navigation systems," particularly for autonomous and unmanned vessels, integrates data from multiple sources for real-time information to ships and stakeholders. E-navigation optimizes routes, speeds, and fuel consumption, leading to reduced emissions and improved energy efficiency. Ongoing projects in the Port of Hamburg, Port of Antwerp, and Port of Rotterdam improve ship-to-ship communication, increase

[69] https://sustainableworldports.org/project/port-of-baku-port-management-information-system-pmis/
[70] https://5g-monarch.eu/
[71] https://inter-iot.eu/
[72] https://steam.cut.ac.cy/the-project/

situational awareness, optimize vessel traffic management, reduce congestion, and improve safety. An example of is the e-Navigation Underway (ENU) project that is developing innovative e-navigation solutions to improve safety, efficiency, and sustainability in maritime transport.

2.6.3 Deep-dive on MAGPIE ports

Most of the current digital systems implemented or under development by MAGPIE Port Authorities are focused on the management and efficiency improvement of the port logistics chains. Additionally, some already implement tools to manage and track emissions and energy use, including electricity, for at least some of the assets and systems under direct ownership and control of the port authorities. However, in many cases these data are not retrieved in real time.

For the wider port ecosystem, since most port authorities in MAGPIE adopted a landlord business model with no ownership of the electricity grid, real-time information about energy consumption is either unavailable, or not duly exploited, as they are usually recorded in paper or worksheets (e.g., Microsoft Excel). Given the urgent need for green transition, port authorities could exploit the available information and further promote digitalization to optimize operations, reduce emissions and energy consumption at the port level, and gain a better understanding about how ports may foster the transition to more sustainable energy vectors.

Other actors of the port's ecosystem, e.g., terminals, road transport operators, already work towards digitalization of logistics operations and data exchange between actors. However, data are often provided by systems according to non-standard representations, which may hinder their reuse by other platforms. Furthermore, the lack of a knowledge representation model hinders the integration of the several platforms that are used by all actors within the port ecosystem. As an example, fostering sustainable synchromodal operations might be difficult without real-time information made visible to all actors in the supply chain.

Some of the MAGPIE ports already utilize Port Community Systems and Logistics Single Window platforms to centralize data provided by shipping agents, transport operators, and the hinterland. Still, such platforms currently work as a data hub, in which most data are still provided through human input. Furthermore, such platforms incorporate limited functionalities for evaluating (or implementing) Key Performance Indicators, support decision-making by simulating different operational scenarios or optimizing within-port movements towards more efficient and greener operations.

The digital twin and tools under development in MAGPIE in WP4, and other projects currently under implementation in MAGPIE ports (e.g., the development of the HESP tool by the Port of Rotterdam Authority, or the NEXUS project in the Port of Sines) are thus an important initial step towards enabling the operational and strategic decision making within ports that considers climate mitigation goals as an integral part of decision making of port actors.

3. Modelling the electricity supply chain

3.1 Introduction

Chapter 2 relied on exogenous inputs (literature review and interviews) to investigate how the future electricity supply chain will look like. On Chapter 3, dedicated models are proposed to endogenously realize how the electricity supply chain will evolve in the coming decades. While some of these models are built from ground-zero, others depart from pre-existing studies that need to be adapted to the port context. Besides the three main blocks of the supply chain – supply, storage, distribution – the future demand requirements are also analysed thus extending the work of D3.1[1]. Figure 14 shows a high-level vision of the links that will need to be established between the models to reach the final target.

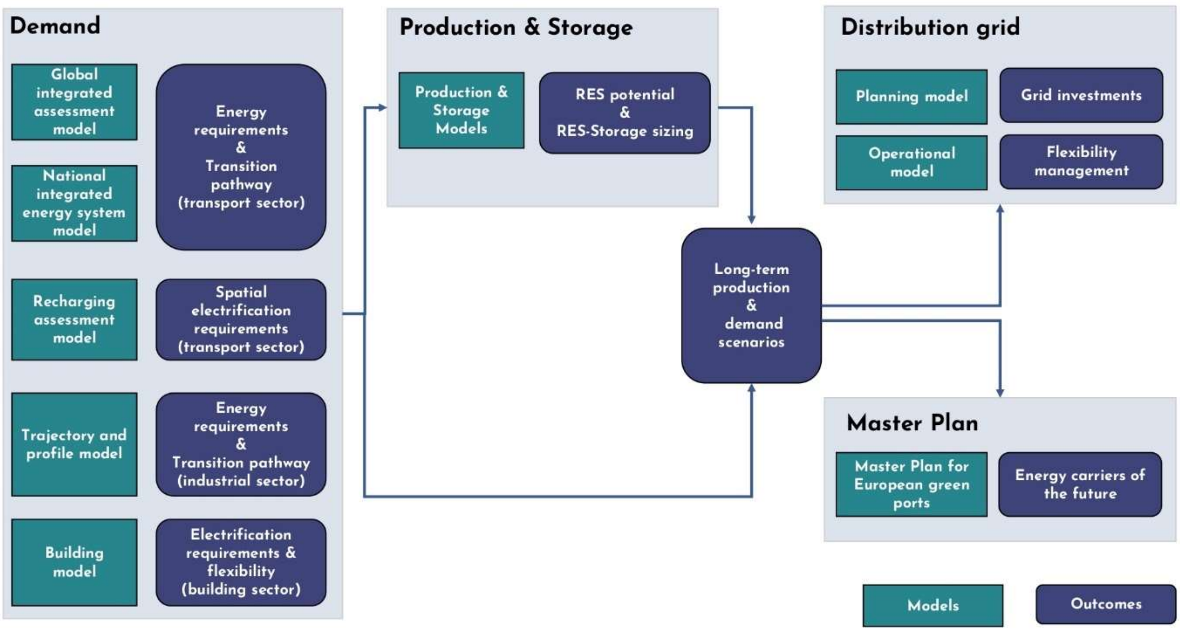

Figure 14 - High-level vision of modelling architecture

3.2 Demand side Transport

Having a clear understanding of the future electrification needs is crucial for an accurate modelling of the electricity supply chain. D3.1[1] started this work, but its focus was on the estimation of the energy requirements associated with the transport sector. Foresee how these requirements will increase and at what extent they will turn into electrification needs was also analysed but just using literature inputs. On the other hand, D3.1[1] only analysed the transport sector. Although it is the main topic of the MAGPIE project, the impact of other sectors (industries, buildings) for the electricity supply chain cannot be disregarded. This chapter will thus provide a deeper assessment on these two topics.

3.2.1 Maritime shipping – Energy requirements model (Present & Future)

The current maritime energy requirements in the Port of Rotterdam (2018 used as reference year) were computed in D3.1[1] using 1) a bottom-up approach based on vessel movement information; 2) a top-down approach based on bunker sales and fixing a bunker amount per visit[73]. The application of both methods allowed to define a min-max range for the energy requirements of this sector. The focus is now on developing a more comprehensive method capable to define the actual maritime energy requirements (instead of a range) between different regions. To do so, the following steps will be carried out:

- Definition of ship/cargo categories (inputs used in D3.1[1] will be re-assessed)
- Assessment of bilateral trade data between different regions grouped by ship/cargo types for years up to 2020 [tons/year]
- Definition of one or more ports as proxies of the geographical transportation hubs. The average haul between ports [miles] can be obtained through relevant databases

By multiplying trade [tons/year] by the average shipping haul of the trip [miles], total shipping activity demand is captured [ton. miles/year]. Then, using average fuel consumption values, the maritime energy requirements can be easily computed. This process can be repeated for each pair of regions and for each ship/cargo category. An assumption concerning which region/port is responsible to fulfil the energy requirements will be established. By having trade amount between regions for the base-year from available databases, the model (still under development) equations follow:

$$T_{ij}(t,\, c) \propto T_{ij}(t_0,\, c)\,.\, Function(GDP,\, Fprice) \quad (1)$$

$$D(t,\, n,\, c)\left[\frac{ton.miles}{year}\right] = \frac{\left(T_{ij}(t,\, n,\, c)\left[\frac{ton}{year}\right] \times Haul_{ij}[miles]\right)}{2} \quad (2)$$

$$D(t,\, n,\, c)\left[\frac{ton.miles}{year}\right] < K(t,\, n,\, jship)[dwt].\, P(t,\, n,\, jship)\left[\frac{ton.miles}{dwt.year}\right] \quad (3)$$

$$EN(t,n)\left[\frac{kWh}{year}\right] = \sum_{jship} K(t,n,jship)[dwt]\,.\, P(t,\, n,jship)\left[\frac{ton.miles}{dwt.year}\right].\, FC(t,n,\, jship)\left[\frac{kWh}{ton.miles}\right] \quad (4)$$

Table 4 shows the meaning of symbols used in the above equations.

Table 4 – Symbols

Symbol	Type	Definition	Units
T	Variable	Trade amount	[ton/year]
D	Variable	Shipping activity demand	[ton.miles/year]

73 MAGPIE Deliverable 3.1 – Transport Energy Demand

Haul	Parameter	Average haul between regions	[miles]
K	Variable	Quantity of vessels	[dwt]
P	Parameter	Productivity of vessels	[ton,miles/dwt.year]
FC	Parameter	Fuel consumption of vessels	[kWh/ton.miles]
EN	Variable	Energy requirement	[kWh/year]
t	Index	Time step	-
c	Index	Cargo type	-
i,j,n	Index	Region	-
jship	Index	Vessel type	-

Contrary to what has been done in D3.1[1], projecting the future's maritime demand will be carried endogenously by using the elasticities of fuel prices and Gross Domestic Product (GDP) of each region. In economics, elasticity measures the percentage change of one economic variable in response to a percentage change in another. For this specific case, a higher GDP will increase the trade activity/energy requirements while a higher fuel price will lead to the opposite effect.

The aforementioned upgrades to the maritime energy requirements model will be implemented and tested in T3.6.

3.2.2 Inland shipping – Energy requirements model (Present & Future)

The current energy requirements for inland shipping in the Port of Rotterdam (2020 used as reference year) were computed in D3.1[74]. First, several vessel categories were defined (e.g., push boats, motor vessels). Then, for each vessel category, the model considered their specific consumption [MJ/tkm], the distance per route [km] and the weight transported in each journey [tons]. The product of these three elements corresponds to the inland shipping energy requirements per vessel type [MJ]. Although the model was tested using representative data of trips in the Rhine[75], its application is not constrained to any specific route/journey. In the specific test case carried in D3.1[1], the vessels were assumed to travel at 100% capacity and the energy use of empty returns was not considered.

The tests carried with this model showed that the transport of petroleum products is a major contributor for the total energy requirements of the inland shipping sector. For motor vessels of 80 to 109m length transporting liquid cargo, 67% of the final energy use is associated with the transport of these products. This is particularly relevant given the expected reduction in use of fossil fuels in the transport and industrial sectors. Another aspect to be considered is the foreseen increase of extreme weather events (e.g., droughts) which will naturally impact on the business-as-usual of inland shipping activities. Still, the EU has wide plans to shift an increasing share of freight activity to this modality.

Given all these uncertainties, projecting the future energy demand of the inland shipping sector is an exercise that should consider several different scenarios. D3.1[1] used three different scenarios (business-as-usual, conservative, and innovative), but these were more focused on

[74] MAGPIE Deliverable 3.1 – Transport Energy Demand
[75] 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).

the introduction of greener technologies than on accessing how the energy requirements will evolve.

3.2.3 Truck/Rail – Energy requirements model (Present & Future)

The current energy requirements for road transport in the Port of Rotterdam (2021 used as reference year) were computed in D3.1[1]. First, several cargo categories were defined (e.g., containers, liquid bulk) and an average payload weight was assigned to each of them[76]. Also, two different route types were considered: regional corresponding to trips within the Rotterdam area and long-haul illustrating trips within the Netherlands or abroad. Then, thanks to the VECTO tool[77], it was possible to define specific consumption values [MJ/km] per payload weight and type of route. Multiplying this by the number of trucks required to transport the 2021 cargo throughput and by the distance travelled [km], the energy requirements of road transport are calculated [MJ].

Projecting the future demand for HDV was also carried in D3.1[1] using exogenous information. Three aspects were considered: 1) improvements in vehicle efficiency, which translates into lower specific consumption values; 2) modal shift towards more efficient and less polluting modalities; 3) cargo growth and variation trends. Following the methodology proposed for maritime shipping, the dependency between cargo growth and the GDP of each region should also be modelled[78].

$$Number\ of\ HDV\ (t+1,n) = Number\ of\ HDV\ (t,n) \times \left(GDP(t+1,n)\right)/\left(GDP(t,n)\right) \quad (5)$$

Note that t refers to the time step and n to the region under analysis. For the refence year of 2021 ($t=0$), the vehicle fleet was assumed to be fully diesel-powered. For $t>0$, a competition among different fuel technologies needs to take place. This topic is addressed in sections 0 and 0.

The current energy requirements for rail transport in the Port of Rotterdam (2021 used as reference year) were also computed in D3.1[1]. Important to highlight that the focus was just on shunting locomotives that operate in the port area. As for the road transport, different cargo categories were first defined (e.g., containers, liquid bulk). For each of them, the corresponding energy requirements [MJ] were then computed. The model used to calculate these requirements is more complex than the one used for road transport since the operating pattern of a shunting locomotive is characterized by three different moments: 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. Each operational moment has therefore different specific consumption values, which are typically measured in [kg/h]. Thus, estimating the energy requirements per shunting locomotive also depends on the average time spent in idling, shunting, and travelling [h]. The latter is associated with the type of cargo being transported since it influences the departure/arrival locations. Finally, and to convert kg of fuel into MJ of energy, a conversion factor can be applied.

Projecting the future demand for shunting locomotives was also carried in D3.1[1] and considered the same aspects used for HDV. However, no efficiency improvements for diesel

[76] Cost Figures for Freight Transport (Netherlands Institute for Transport Policy Analysis)
[77] JEC Tank-to-Wheels Report v5: Heavy duty vehicles (European Commision)
[78] Fulton, Lew, and George Eads. "IEA/SMP model documentation and reference case projection." Auxilliary material to: Mobility 2030 (2004).

engines were considered. The reasoning is related with the fact that majority of shunting locomotives are decades old and will probably be replaced in coming years. Concerning the influence of cargo growth, exogenous inputs from the Wuppertal report[79] were the main information source. However, and since this study was oriented to the rail transport in general, it might be worth to study if the results continue valid when just focusing on shunting locomotives. In case not, the creation of dedicated growth scenarios might be necessary.

Models to estimate the present/future energy requirements of the transport modalities that co-exist in a port ecosystem were therefore presented. Some of them had already been conceived during D3.1[1], while others have now been proposed. Nevertheless, there is something that is common to all of them: a temporal resolution ≥ 1 year. While this time step may be suitable for some applications, some of WP4's digital tools need a lower resolution. As an example, the Energy Matching Tool (EMT) will require hourly demand and supply values to optimally manage the port electrical system. In that sense, a joint effort between T3.6 (Long-term energy supply and demand development) and T4.4 (Modelling and Intelligence) will be needed to fulfil this need.

3.2.4 Transition pathways & Future fuel mix

The models detailed in the previous section are fuel-agnostic. Indeed, they do not define which fuel type will be responsible to fulfil the estimated energy requirements. In other words, these models do not assess which will be the best fuel mix. D3.1[1] addressed this topic but relied on exogenous information that most of the times looked only to specific technical constraints of new green fuels (e.g., energy density). However, to properly understand how these fuels will compete against each other for the market share, many other factors need to be considered. The following sections propose two models whose goal is to provide an optimal fuel mix portfolio for transport modes. Although with the same objective, their geographical zoom differs. While one focuses on the impact of global dynamics on fuel choice, the other tries to capture the influence of regional driving forces. The global model is/will be prepared to define the best fuel mix for road and maritime transport sectors. In the regional model, inland shipping will also be a possibility. Concerning rail transport and following what was described in D3.1[1], its transition pathway is expected to be fully oriented to electrification. This is justified by the operational profile of a shunting locomotives which indicates that batteries will be the most promising technology. Establishing synergies between the global and regional models is a topic that still needs to be discussed in upcoming tasks.

Global Model (WITCH)

The WITCH[80] model is a non-linear optimization model that captures the dynamics of long-term economic growth and links them to the evolution of the energy sector in which transportation is included. The model foundations are associated to the Utility theory, a branch of economics that studies how individuals make choices and allocate their resources. The central idea behind it is that people make decisions based on the satisfaction or "utility" they derive from consuming goods and services. Therefore, people seek to maximize their utility subject to their constraints (e.g., budget) and to their preferences over different goods and services. In WITCH, these principles are implemented using a Power or Constant Relative Risk Aversion (CRRA) utility function derived from consumption per capita. This function is a mathematical representation of an individual's preferences over consumption. It is used in microeconomics to model the trade-off that individuals face between consuming now and

[79] Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam (Wuppertal Institute)
[80] Bosetti, Valentina, Emanuele Massetti, and Massimo Tavoni. "The WITCH model: structure, baseline, solutions." (2007).

consuming in the future, and it reflects the risk aversion of the individual. Currently, the WITCH model can compute the utility function (W) for 17 world regions (n) such as Europe or USA and considers a 5 years' time-step (t).

$$W(n) = \sum_{t}^{l}(t,n)\frac{\left(\frac{C(t,n)}{l(t,n)}\right) - 1}{1-\eta}\theta^{t} \tag{6}$$

This intertemporal utility function thus links the consumption of goods and services (C) to the population (l) and to the already mentioned relative risk of aversion (η). θ is a pure time preference discount factor given by the following geometric discounting rule:

$$\theta = (1+\rho)^{\Delta t} \tag{7}$$

where Δt corresponds to the 5 years' time-step and ρ is the discount rate. The maximization of W is obviously subject to constraints.

$$C(t,n) = Y(t,n) - I_{FG} - I_{RD} - I_{EXT} - I_{Grid} - I_n \tag{8}$$

The consumption of goods and services (C) is the single variable in the utility function. It depends on the available budget, which is linked with the region net output (Y) and the investment expenses (I). I_{FG},I_{RD}, I_{EXT}, I_{Grid} and I_n, stand for investments of a region in final goods, research & development, extraction sector, grid, and any other investments, respectively.

The production side of the economy is very aggregated. Each region produces one single commodity that can be used for consumption or investments. The net output Y is produced via a nested CES function that combines capital(K), labour (L) and energy services (ES). Capital and lobar are aggregated using a Cobb-Douglas production function. The computation of Y can be carried through the following expression:

$$Y(t,n) = \frac{tfp0\Big([\alpha(n).\big(tfpy(t,n).K_{FG}(t,n)^{\beta}.l(t,n)^{1-\beta}\big]^{\rho} + \big(1-\alpha(n)\big).ES^{\rho}(t,n)\big)\Big)^{1/\rho}}{\Omega(t,n)} \tag{9}$$

where $tfp0$ is the Total Factor Productivity in the base year. It is therefore calibrated to match GDP in year 0. $tfpy$ has the same meaning, but it evolves exogenously throughout the optimization time horizon. l corresponds to labor and is assumed to be equal to population (i.e., no unemployment). β illustrates the Cobb-Douglas coefficient of the capital-labor aggregate. α & ρ are CES production function's parameters. The parameter ρ is computed such that $\rho = \frac{\zeta-1}{\zeta}$, where ζ is the elasticity of substitution. Lastly, the capital stock in the final good sector (K_{FG}) is calculated using the standard capital accumulation rule with exponential depreciation:

$$K_{FG}(t+1,n) = K_{FG}(t,n) \times (1-\delta_{FG})^{\Delta t} + \Delta t \times I_{FG}(t,n) \tag{10}$$

Within the MAGPIE project, the WITCH model will seek to maximize the satisfaction related with the consumption of fuels in the transport sector. Each fuel type will have its own capital (K) and related investments (I) as variables. According to the previous formulation, this will affect their consumption patterns. The exact approach of modelling each fuel is yet to be determined. However, there are some factors that will clearly impact on the composition of the fuel mix: carbon policies, CAPEX & OPEX related with each fuel's production, available feedstock, range limitation of each fuel, available refuelling locations. At the end of the optimization process, and independently from the fuel mix, supply needs to match demand.

Figure 15 shows a preliminary list of fuels ("Final Products") capable to supply the energy requirements associated with the maritime shipping sector. Each of them is characterized by a diverse production process, which translates into different CAPEX & OPEX as well as GHG emissions.

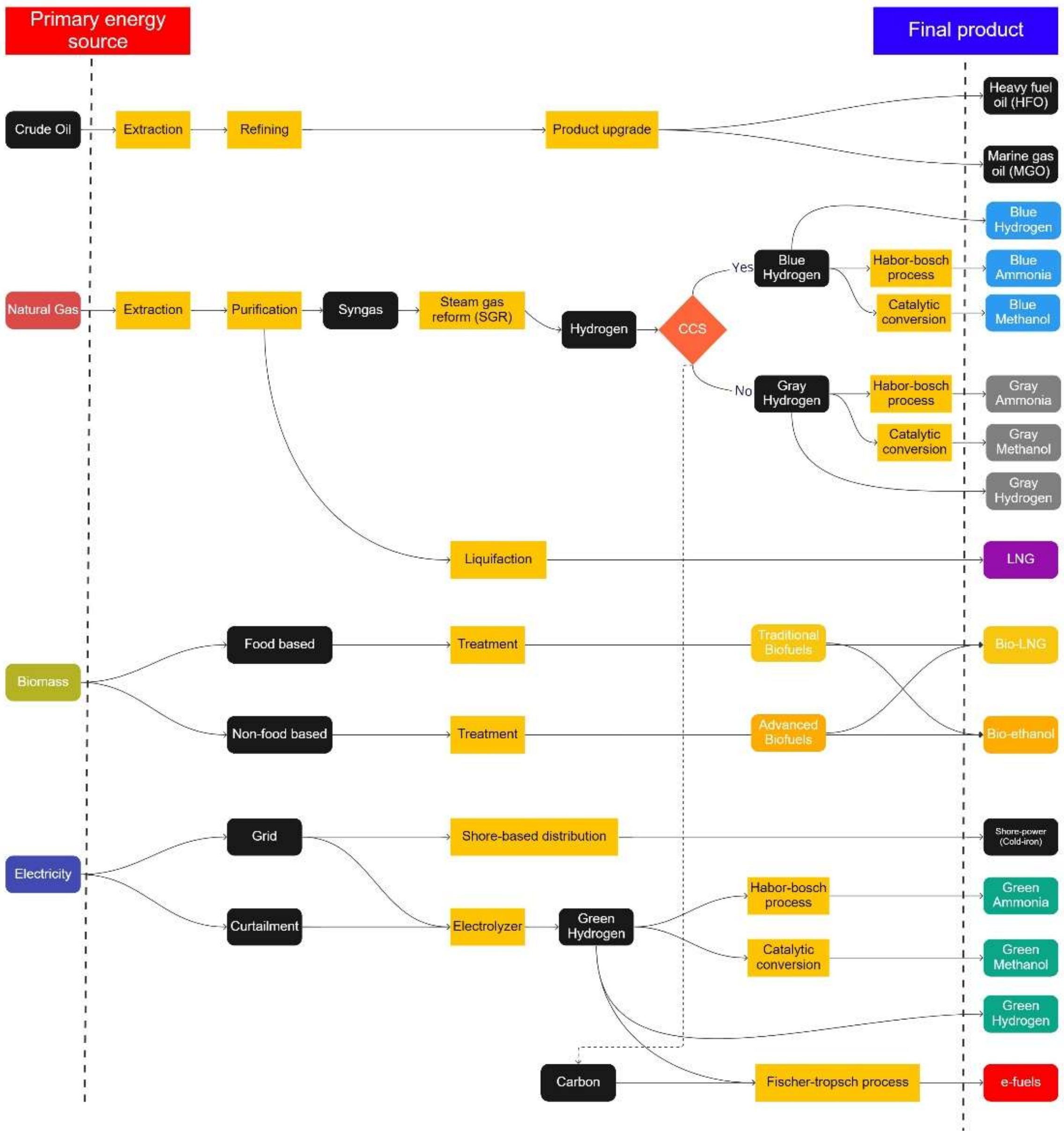

Figure 15 – Pre-list of fuels for the maritime shipping sector

When applying the optimization model to the road transport, five different fuel options are available: traditional diesel, hybrid, plug-in hybrid, electric and fuel cell.

Regional Model (OPERA)

The OPERA[81] model is an optimization model focused on minimizing the societal costs of the Dutch energy system. Part of these costs are associated with the fuels used to fulfil the consumption requirements of the system. Therefore, and in line with the objectives of the MAGPIE project, OPERA will search for an optimal fuel mix portfolio for the transport sector. Although OPERA shares the same general goal as WITCH, their methodologies have significant differences. Contrary to the global vision of the former, the latter focus on a national level. By geographically zooming in, different considerations come into play, namely all those that are particular to the country under analysis. A very specific but illustrative example relates with natural gas pipelines that can be retrofitted to transport hydrogen. Their availability might reduce the overall system costs thus placing hydrogen as a central player in the transition pathway. Thanks to OPERA, a model that makes use of distribution and transmission networks to couple supply and demand, this type of assessments is possible. On the other hand, OPERA has a high time-resolution. Being a model oriented to national planning, it is important to ensure that supply and demand constantly match. By doing so, it is also possible to capture and integrate their variability along the pre-defined time-horizon[82].

OPERA allows the regionalization of the nation under analysis. This does not mean that the optimization is carried per region. Instead, it means that a regional analysis of the national optimization results can be performed[83]. In the MAGPIE project, the Rotterdam Area, including the port of Rotterdam, will be divided into several sub regions and the rest of the Netherlands will have a coarser representation. The exact regionalization will be worked out in T3.6, but an illustrative example is provided in Figure 16.

Figure 16 – Regionalization of POR area (illustrative example)

[81] van Stralen, J. N., Dalla Longa, F., Daniëls, B. W., Smekens, K. E., & van der Zwaan, B. (2021). Opera: a new high-resolution energy system model for sector integration research. Environmental Modelling & Assessment, 26, 873-889.
[82] https://doi.org/10.1007/s10666-020-09741-7
[83] https://doi.org/10.1016/j.enconman.2022.116599

OPERA has so far only been applied to the Dutch context. Nevertheless, the model can in theory be used for any nation, provided that the necessary input data is available.

The driving force of the model is energy demand, which is mainly handled via service demand. In the transport sector, this is represented by the number of kilometres travelled by the different modalities. When demand is difficult to represent via service demand or is too small to be represented individually, a final energy consumption value is used. Table 5 shows the transport-related service demand currently available in OPERA and of interest for the MAGPIE project.

Table 5 - Transport related service demand

Sector	Service demand	Unit
Transport	Road heavy-duty vehicles	Billion vehicle km
Transport	Inland navigation freight	Billion-ton km
Transport	Trains - freighta	Billion-ton km
Industry	Mobile machinery	PJ
Services	Mobile machinery	PJ
Bunkers	Maritime	PJ fuel equivalent

[a]To be included

Estimating the present/future service demand requirements in the transport sector is exogenous to OPERA. The modelling work presented in the previous sections (together with the outcomes of D3.1[1]) may provide important insights on this topic.

On an annual basis the following equation needs to fulfil:

$$\sum_{r,o} AY_{r,o} C_{s,o} \geq SD_s \quad (11)$$

In which AY is the activity level of technology o in region r and SD corresponds to the annual consumption of service demand s. C is the coupling parameter and it defines if a technology o is suitable to fulfil de consumption associated with service demand s. In other words, this constraint ensures that enough supply is available for the service demand requirements. While ensuring it, the optimization model will choose the fuel mix that minimizes the total energy system costs. This model will run for each individual year. In other words, there is no single optimization over the entire time horizon, but a sequence of individual optimizations. Nevertheless, the results of individual years will be linked. So, the system will not start from a green field situation every year.

Table 6 shows all the technologies o (and corresponding fuels) that are currently available to fulfil the total transport-related service demand. This means, for example, that all truck types mentioned below can be used to cover the kilometres associated with heavy-duty transport.

Table 6 - Technologies and fuels/energy carriers for the transport sector

Service demand	Technologies	Fuels/energy carrier
Road heavy duty vehicles	ICE truck	Diesel[a]

	ICE truck with 8% efficiency improvement	Diesel[a]
	ICE truck with 13% efficiency improvement	Diesel[a]
	ICE truck with 18% efficiency improvement	Diesel[a]
	LNG truck	LNG[a]
	LNG truck with 13% efficiency improvement	LNG[a]
	DME truck	Bio-DME
	DME truck with 18% efficiency improvement	Bio-DME
	Electric truck	Electricity
	Electric truck with efficiency improvement	Electricity
	H2 truck	Hydrogen[b]
	H2 truck with efficiency improvement	Hydrogen[b]
Inland navigation freight	ICE inland navigation	Diesel[a]
	ICE inland navigation with 15% efficiency improvement	Diesel[a]
	Bio-diesel inland navigation	Bio-dieselc
	LNG inland navigation	LNG[a]
	Battery electric inland navigation	Electricity
	Fuel cell inland navigation	Hydrogen[b]
	Methanol inland navigation	Methanol[a]
Mobile machinery	ICE mobile machinery	Diesel[a]
	Hybrid mobile machinery	Diesel[a]
	Electric mobile machinery	Diesel[a]
Maritime	Marine fuel vessel	Fossil HFO, Bio-HFO, Diesel[a]
	LNG vessel	LNG[a]
	Methanol vessel	Methanol[a]
	Ammonia vesselc	Ammonia
	Battery electric vesselc	Electricity
	Hydrogen-powered vessel	Hydrogen[c]

[a]Fossil, biogenic and synthetic
[b]On the demand side the different types of hydrogen can't be discerned
[c]To be included if dimmed necessary

From the long list of fuels displayed in Table 6, most of them can be produced in many ways (e.g., hydrogen can be produced through electrolysis, steam methane reforming, etc). This is important since different production options result in different costs. For some energy carriers (i.e., hydrogen and ammonia) representing the explicit type (i.e., green hydrogen, grey hydrogen, etc) is possible, but not straightforward because, the production options connect to the same network. Nevertheless, and picking on the hydrogen example, an electrolyser can be directly coupled to the consumption side. By doing so, the model will know that there is a green hydrogen consumption on that location.

3.3 Recharging Requirements Assessment

So far in this chapter models to estimate the energy requirements of each transport modality were presented. However, it has not been assessed which share of these requirements fall under the port responsibility. To investigate this topic, the case of road transport will be analysed. This is because trucks can refuel at nearly any location across Europe, while, for example, maritime ships can only refuel at ports. Growing availability of charging locations for road transport increases the uncertainty of how the energy demand will be distributed across Europe and, consequently, the demand that will exist in the ports.

A model to simulate the operation of an electric fleet of trucks is hereby described. This type of models[84] intend to analyse the spatio-temporal demand of electrical vehicles. It will consider technical and operational characteristics of the trucks (the range, consumption, and recharge times), existing regulations, (e.g., how many hours a truck driver can drive) and the port's recharging infrastructure. With this information, the model will create a heat map showing where the recharging actions will occur (at the port or in the hinterland). The results will also serve to evaluate the occupancy of the charging infrastructure at the port throughout the day.

Figure 17 presents a flow scheme of the model's operation.

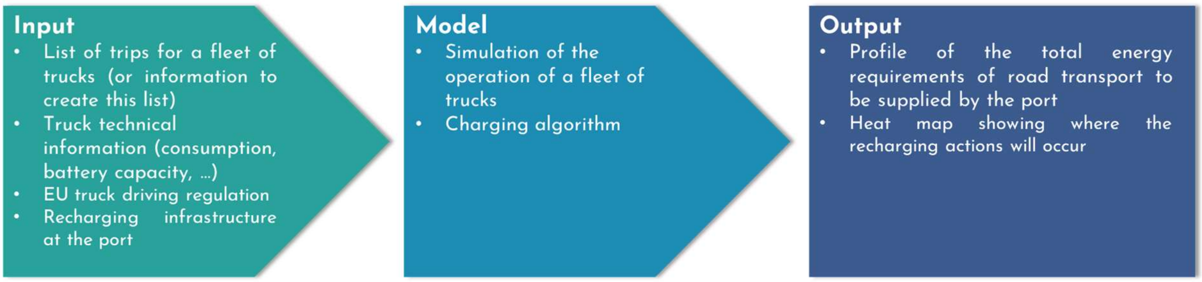

Figure 17 - Recharging infrastructure model overview

Model input

As input, the model will require historical information on truck trips containing the following information: the origin, the destination, the distance, and the average speed, which when combined with the remaining inputs enables the model to calculate the battery State-of-Charge (SOC) at each time step. Due to computational time reasons, the model would not be able to process the huge trip dataset that would represent e.g., one year of historical information. This means that this historic needs first to be treated and condensed so that the model can rely on realistic samples of truck trips. This topic is addressed in next subsection – Trip Distribution.

Then, inputs regarding the technical characteristics of the electrical trucks are also required. These inputs are the truck's specific consumption in kWh/km, its battery capacity and the charging curve.

[84] A. E. Trippe, P. López Hidalgo, M. Lienkamp and T. Hamacher, "Mobility Model for the Estimation of the Spatiotemporal Energy Demand of Battery Electric Vehicles in Singapore," 2015 IEEE 18th International Conference on Intelligent Transportation Systems, Gran Canaria, Spain, 2015, pp. 578-583, doi: 10.1109/ITSC.2015.101.

In order to properly model the trucks' operation, regulation governing truck driving will also be considered. The summary of the main regulations surrounding road transport workers is the following:

- Average weekly working time of 48 hours.
- Drive up to a maximum of 9 hours per day. However, the daily driving time can be extended to maximum 10 hours and not more than twice a week.
- Drivers cannot drive more than 56 hours per week
- Total fortnightly driving time cannot exceed 90 hours.
- After driving period of 4.5 hours, drivers must take an uninterrupted break of at least 45 minutes, unless they take a rest period. Alternatively, this can be split into a 30 minute and 15-minute break.
- Regular daily rest period of at least 11 consecutive hours. The rest period can be reduced to 9 hours for a maximum of 3 times between any two weekly rest periods. The driver can split a regular daily rest period into two parts: the first part must be of at least 3 hours, the second part of at least 9 hours, so that the sum of the two parts must be of at least 12 hours.
- Drivers should have an uninterrupted rest period of 45 hours per week, which can be reduced to 24 hours every second week.
- Drivers must have 45 continuous hours of rest after 6 days of driving and at least 24 hours every second week.

Lastly, the model will also receive the available recharging infrastructure at the port (number of chargers and respective power), which will be a deciding factor when determining whether to charge the truck or not. While the model will not optimize the recharging infrastructure, it can create a profile for the energy the port must supply, along with an analysis of the occupancy rate of the infrastructure that is (or will be) installed in the port.

Trip distribution

As previously mentioned, computational time issues constrain the use of a large trip dataset. In that sense, probability distribution curves will be built using the original dataset. Figure 18 and Figure 19 presents examples for two inputs that are required by the model: trip length and daily distance travelled. The distributions were plotted based on real dataset, however, they had to be modified due to confidentiality reasons. To do so, the shape of the curve was altered slightly and the entire data was normalized, meaning that for both figures the horizontal axis represents normalized values from 0 to 1.

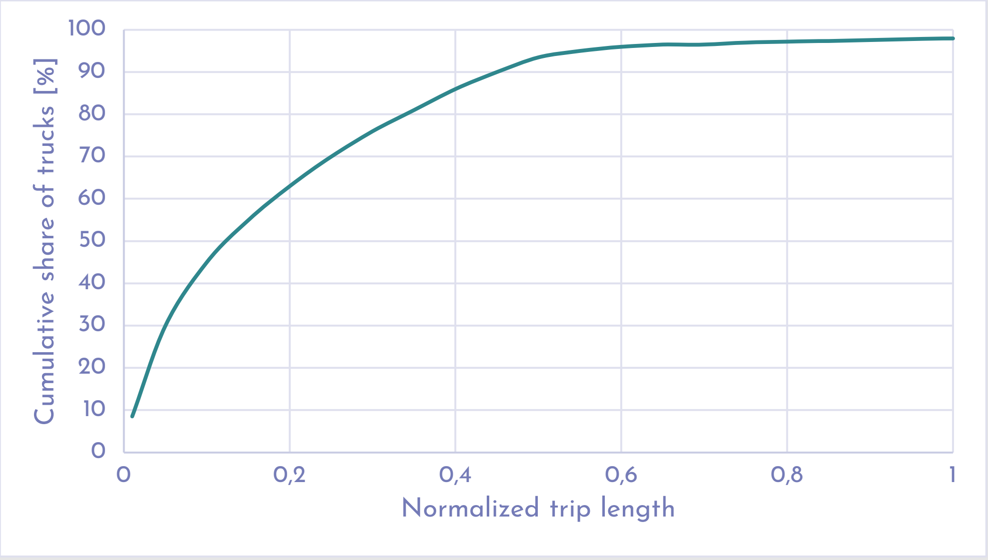

Figure *18* Normalized trip length distribution by tractor-trailers

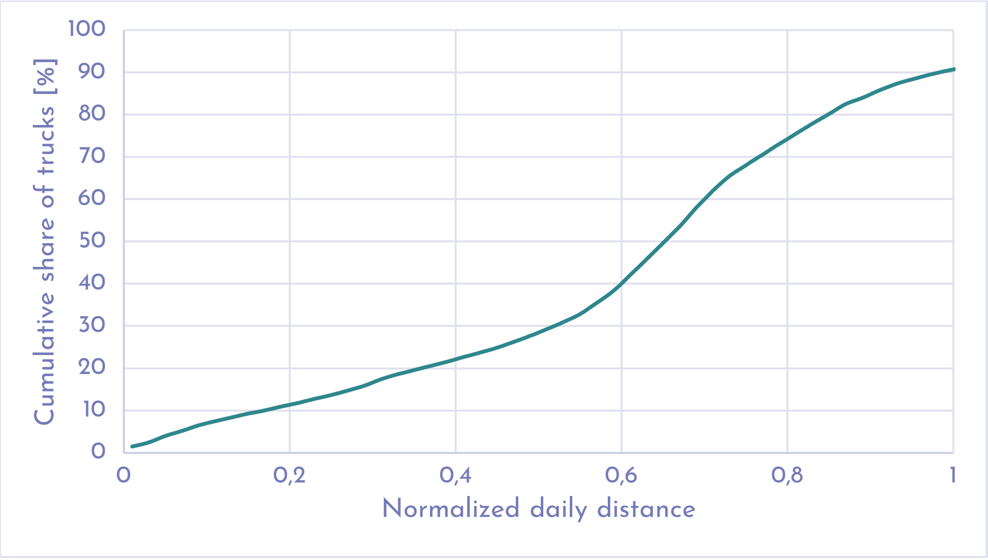

Figure *19* Normalized distribution of daily distance driven by a tractor-trailer

A sample list of trips is thus created from the distribution presented in Figure 18. The trips are then attributed to a fleet of trucks to ensure the daily driven distance of the fleet matches the one presented in Figure 19. To do so, after creating the list of trips, several combinations of schedules for each truck are tested to ensure both distributions are fulfilled.

For the creation of the heat map, information regarding the origin and destination of the trips also needs to be provided. According to the desired detail in the map, this information can be passed as the number of yearly trips (or percentage of total) from the port to each region and vice-versa, along with the driving distance between them. This will then be combined with the distribution curves to slightly adjust the distance values for trips within each region, creating a list of trips consistent with the distribution curves and to take into account trip origin and destination.

Methodology (Truck Charging algorithm)

From analysing the EU regulation on truck driving, it can be seen that this regulation creates plenty of room for truck drivers to adjust their schedule to their needs, which also significantly increases the difficulty of modelling the typical driving schedule of a truck. As a simplification, a decision was made to create a profile that is constant for every day and fulfils all the regulations listed. On a yearly basis, the driving time of the trucks is roughly the same regardless of the flexibility that the truck driver has to adjust its driving schedule, thus this assumption doesn't affect the distance travelled and trips performed by each truck.

The developed profile consists of 5 driving days and 2 full rest days, where the driving days are structured as follows:

1. Driving/working time (4.5h)
2. Break (0.75h)
3. Driving/working time (4.5h)
4. Daily Rest (14.25h)

Another aspect to consider is the initial state in the driving profile for the trucks. If all trucks were considered to start, for example, at the beginning of the driving period, then all trucks would take their breaks and resting periods at the same time, which leads to roughly the same charging periods for all trucks. While the total value of energy to be supplied by the port for road transport is the same regardless of the initial state, from a supply chain perspective the profile of energy to be supplied by the port is even more relevant than the total energy. Therefore, and to avoid using a random initial state, dedicated interviews with MAGPIE partners experienced in the transport sector will be conducted. The objective is to gather reliable information on how to model this initial state.

With the truck schedule and driving profile modelling defined, the model can simulate the operation of each truck according to the specified time step. This involves calculating the distance travelled per time step, from which the energy consumption per time step can be calculated as well. Combining the energy consumption per time step with the initial SOC and capacity of the battery, the SOC of the battery can be calculated for each time step.

The SOC at each time step is then used to estimate the energy requirements for road transport and, ultimately, plan location and charging amount for each truck. The method for defining the initial SOC at the starting point of the simulation for each truck will depend on the initial state in the driving profile, therefore the development of both these model conditions will be performed conjointly.

Regarding the decision of when to charge and how much is charged, this will be controlled by a charging algorithm that will calculate a probability for the truck to charge based on specific conditions. The conditions that the model will analyse are unique for each driving situation: overnight/weekend resting, mandatory break and driving. For overnight/weekend resting its considered that the trucks will ideally fully charge to take advantage of the time the truck is stopped. However, the power of the chargers might not be able to guarantee that the truck is fully charged when the rest period ends. For the remaining driving situations (mandatory break and driving), the following conditions will be considered:

- Distance to be travelled until the overnight/weekend rest period.
- SOC of the battery
- Occupancy rate of the recharging infrastructure (if the truck is in the port)

Only the infrastructure for the port of Rotterdam will be modelled, which is why the final condition mentioned above is only appliable when the truck is at the port. Nonetheless, when the conditions weigh more towards benefiting charging (higher distance to be travelled until the rest period, lower SOC, and low occupancy of recharging infrastructures), the probability of charging will be higher.

Mathematically, the SOC decreases according to the average speed of truck at that specific time ($\bar{v}_{v,h}$) multiplied by the specific consumption of the truck ($c_{sp,tr}$). When charging, the SOC increases by the maximum between the power of the charger (P_{ch}) and the maximum power at which the battery can charge given its SOC at the previous time step ($BC(SOC_{h-1})$).

$$SOC_{v,h} = SOC_{v,h-1} - \bar{v}_{v,h} \cdot c_{sp,tr} \tag{12}$$

$$SOC_{v,h} = SOC_{v,h-1} + Max(P_{ch}, BC(SOC_{h-1})) \tag{13}$$

Model output

The model will generate a profile of the total energy requirements for electric trucks that need to be supplied by the port while taking into account the existing/planned recharging infrastructure in the port. This profile can assist in several planning tasks for the port's adaptation towards the decarbonization of road transport, such as the planning of additional recharging infrastructure, the analysis of the better suited clean energy sources to supply the required energy, and the identification of congestion points when the energy demand is much higher than the average.

In addition to the profile of energy supplied, the model will create a heat map showing where the recharging actions will occur (at the port or in the hinterland). The port area and the hinterland regions will be illustrated by different shades of a colour, where a region with a higher energy demand for road transport has a darker shade.

One factor not considered by the model is the cost of recharging across different locations, which in the future of road transport will be a deciding factor for planning the charging of a truck. This cost was not considered due to several reasons, including the difficulty in assessing what the cost is across different locations, which will depend on cost of producing and transporting electricity, cost of building the recharging infrastructure and the profit margin of its operator. Moreover, considering that the ideal operation of a truck is dependent on the recharging sessions, savings on the recharging costs can come at the expense of a less efficient truck operation, leading to lower operating revenue. The balance between recharging costs and efficient operation is dependent on a number of external factors (e.g., revenue per load and costs of recharging at each location) and will be different on a case-by-case basis.

On the other hand, the profile of the energy supplied for road transport calculated by the model, along with the occupancy rate of the recharging infrastructure and the heat map can provide a valuable assessment metric to help determine competitive prices to be set at the recharging stations.

Current status and next steps

The overall structure of the model has been developed, albeit with several simplifications regarding some aspects of the model. In the coming MAGPIE task 3.6, focus will be given to develop all the features presented in this subsection. The current simplifications are the following:

- Dummy data for the considered fleet and respective trips

- Randomized initial state of driving profile and battery SOC
- Trucks always charge at resting periods and breaks, only charge to reach the next resting period or break

These simplifications were made to facilitate the development of the model, which can now be modularly upgraded to implement the features described above. The feature with the highest impact will be the charging algorithm, as it will not impose hard constraints on when and how much to charge. In the port ecosystem, the current and planned recharging infrastructure will also be included to assess how well suited it is to supply the required energy for road transport to and from the hinterland.

3.4 Demand side Industries

3.4.1 Energy requirements model (Present & Future)

Industries are not the focus of the MAGPIE project. However, the evolution of some port infrastructures cannot be dissociated from the way the transition will take place in the industrial sector. In particular, the electrification of many industrial processes will have a large impact on the electrical grid. Indeed, a significant percentage of worldwide ports is characterized by having strong industrial clusters (e.g., Port of Rotterdam), particularly in the field of chemical products. In such cases, a major share of the global energy demand of the port belongs to the industrial sector. Figure 20 shows the seven industrial branches and associated products whose energy requirements can be investigated.

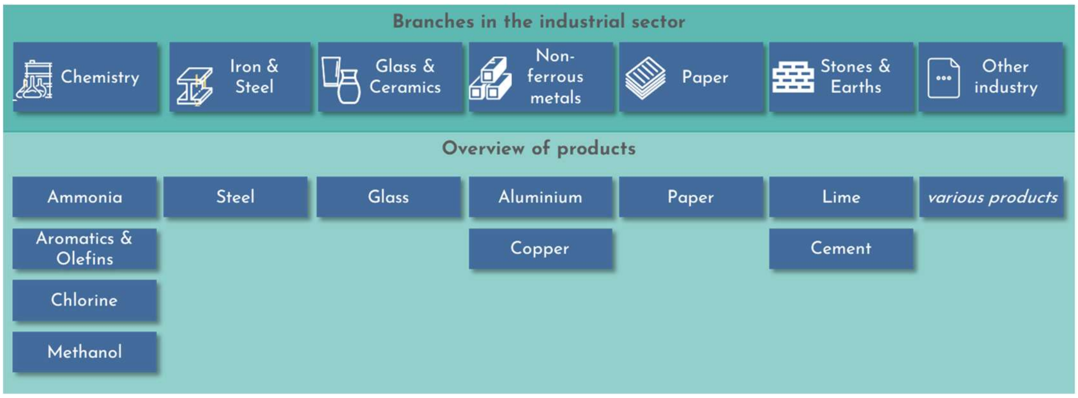

Figure 20 – Industrial branches and associated products

As companies adapt to emission reduction targets, traditional production processes change. Consequently, the requirements in terms of energy carriers also change. Table 7 shows exactly this for a sub-set of chemical products.

Table 7 – Traditional and innovative production processes for chemical products

Product	Processes	Energy carrier
Ammonia	Haber-Bosch, Steam Methane Reforming	Electricity, natural gas (material)
	Haber-Bosch, Electrolysis	Electricity, hydrogen(material)

Aromatics & Olefins	Steam cracking	Naphtha (material)
	Methanol-to-Aromatics/Olefins, Steam cracking	Electricity, green Naphtha (material)
Methanol	Partial oxidation, methanol synthesis, Steam Methane Reforming	Heavy oil, natural gas (material)
	Electrolysis-hydrogen, Methanol synthesis, Biomass gasification	Hydrogen (material), Biomass (material)

To properly understand how these changes will take place, it is essential to have: 1) short-term representations of the present/future demand profiles; 2) long-term transition pathways of underlying structural changes in the industrial energy demand. The former facilitates informed operational decisions while the latter is important for investment planning.

Focusing on 1), a model capable to compute industrial electricity demand profiles with an hourly time resolution is proposed. Building demand profiles for other energy sources such as hydrogen is also a possibility. Figure 21 shows the general structure of the model including the central inputs and outputs.

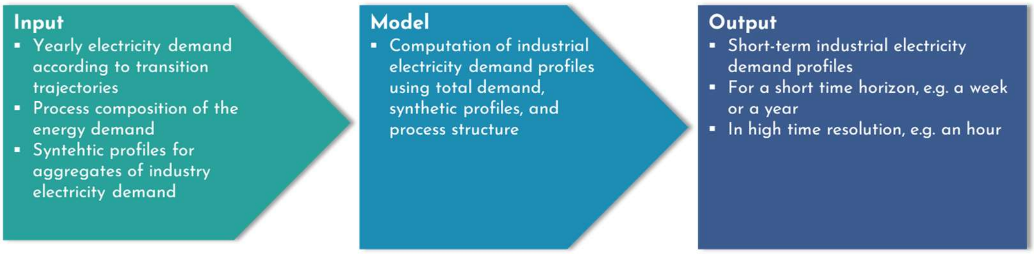

Figure *21* – Computing short-term industrial electricity demand profiles

The model builds on pre-established transition pathways (section 3.2.4), which provide yearly electricity demands and details on the industrial processes structure. Additionally, synthetic profiles of the industrial processes are needed. A potential source of these profiles is the Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA)[85]. The model then combines the yearly demand and the synthetic profiles to obtain a reliable representation of the electricity requirements within the industrial sector. The synthetic profile is deconstructed in sub profiles, e.g., a base load profile $\alpha_{i,t,h}$ and a peak load profile $\beta_{i,t,h}$. Each factor ($\alpha_{i,t,h}$, $\beta_{i,t,h}$) defines which share of the yearly energy consumption $E_{i,t}$ is consumed in which time step h of the year ($E_{i,t,h}$). These time steps can be, e.g., hours. Therefore, the sum of these factors equals 1.

$$\sum_{h}^{H}(\alpha_{i,t,h} + \beta_{i,t,h}) = 1 \; \forall i \; in \; I \; \forall t \; in \; T \tag{14}$$

$$E_{i,t,h} = E_{i,t} \cdot (\alpha_{i,t,h} + \beta_{i,t,h}) \tag{15}$$

[85] https://joint-research-centre.ec.europa.eu/potencia_en

With such an output (i.e., hourly industrial demand profiles), operational decisions can be taken and potential gaps on the supply side can be detected.

3.4.2 Transition pathways & Future fuel mix

The long-term transition pathways model is presented in Figure 22. Its main goal is to capture how the energy requirements of an industrial cluster will be fulfilled in the coming decades. In other words, the future fuel mix of several industrial processes will be defined.

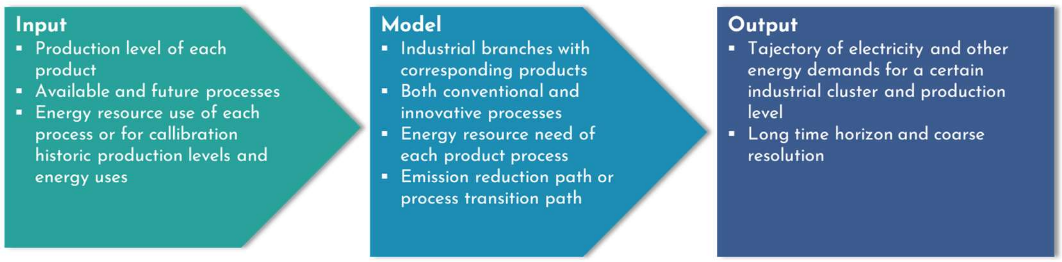

Figure 22 - Long-term transition pathways model (industries)

The model has three main inputs, the first of which is responsible for defining the industrial products g to be analysed, as well as the processes p available to produce them. Then, the present/future demand for each product g in time step t needs to be known ($S_{g,t}$). This will strongly depend on the future role of the port as an industrial cluster. Likewise, the energy requirements associated with each production process p, carrier i are needed ($d_{p,g,i,t}$). Historical consumption information on this would be enough to calibrate the model[86]. Departing from these inputs, the model will then determine which share of the production is served by which process ($\lambda_{p,g,t}$). This can be set either according to industrial plans or following a yearly GHG emission limit $\overline{E}_t$.

$$E_{p,g,i,t} = \left(d_{p,g,i,t} * e_{p,g,i}\right) * S_{g,t} * \lambda_{p,g,t} \quad (16)$$

$$E_t^{\text{Total}} = \sum_{p}^{P} \sum_{g}^{G} \sum_{i}^{I} E_{p,g,i,t} \quad (17)$$

$$E_t^{\text{Total}} \leq \overline{E}_t \quad (18)$$

$e_{p,g,i}$ represents the GHG emissions associated with producing one unit of g through method p (which consequently uses energy carrier i).

Figure 23 illustrates potential results of the model: a trajectory path for a specific industrial product over the next decades. Thanks to it, the demand for electricity and other energy carriers becomes available. As the focus of the model concerns to long-term trajectories, the time horizon is significant e.g., 2050 as the destination year for Europe's climate neutrality. In addition, and since structural changes are part of a gradual transition process, the resolution of output data is low, e.g., 5 years with yearly interpolation.

[86] https://energy.nl/tools/midden-database/

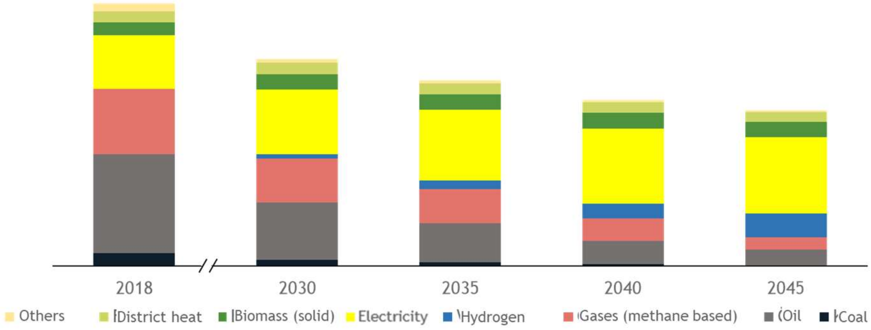

Figure 23 – Illustrative result of the long-term transition pathways model

3.5 Demand side Buildings

3.5.1 Energy requirements model (Present & Future)

The buildings sector is another relevant consumption stream. As shown in Figure 24, this sector represents between 30 to 50% of the total energy consumption of the EU-27 member states (2019 as reference year). In Germany and France - two countries represented in the MAGPIE project – the share of buildings consumption is above 40%. A significant part of this demand is associated with heating and cooling activities.

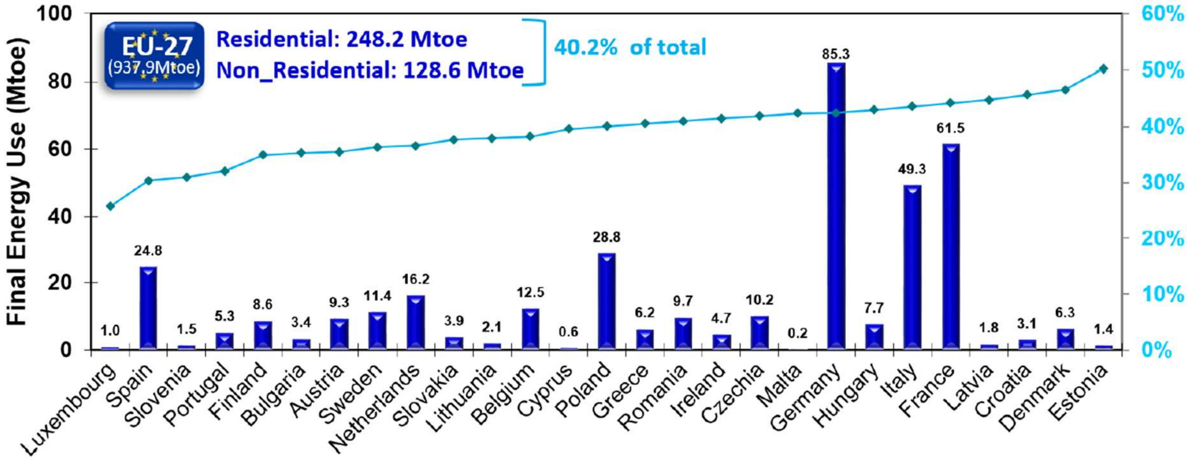

Figure 24 – Impact of the buildings sector for the national energy consumption (EU-27, 2019)[87]

In 2020, heating and cooling needs were largely fulfilled through non-renewable sources. Despite the technical and economic efficiency of renewable options (e.g., electrification, renewable based gases, direct use of solar heat) and the current interest in decreasing import dependency, their widespread use is not yet in place (Figure 25). The IEEE-European Public Policy Committee has also highlighted that renewable energy sources for heating and cooling

[87] C. A. Balaras, E. G. Dascalaki, I. Psarra, and T. Cholewa, 'Primary Energy Factors for Electricity Production in Europe', *Energies*, vol. 16, no. 1, p. 93, Dec. 2022, doi: 10.3390/en16010093

have largely been neglected[88]. However, a significant change is expected in the upcoming decades. The European Renewable Energy Council (EREC) assumed that renewable energy sources for heating and cooling could reach a share of more than half of the EU's heat demand by 2030.

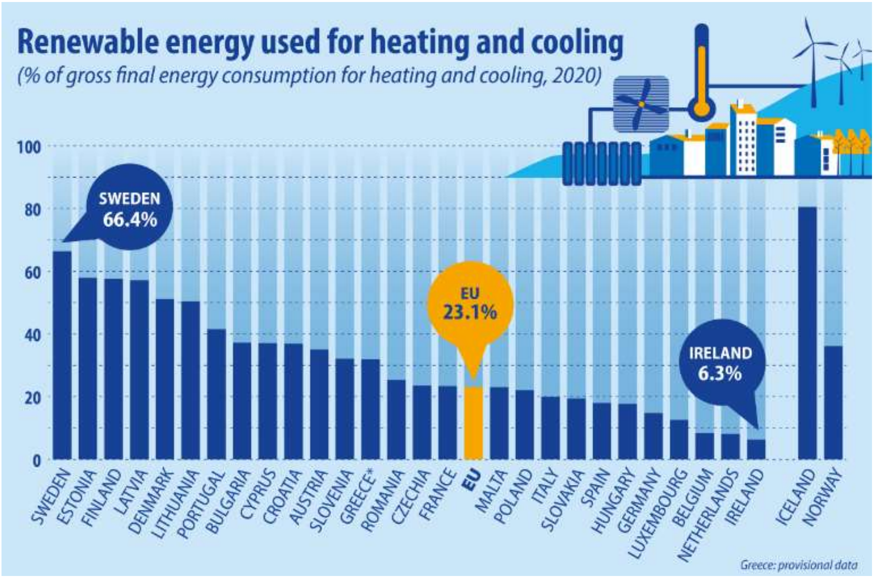

Figure *25* – Renewable energy in the heating/cooling sector[89]

When compared to the industrial/transport sector of a port, buildings may not possess the same share of the global energy requirements. However, and assuming that electrification of cooling/heating systems will ramp-up, the impacts for the electrical grid cannot be neglected. In this sense, realize what are the present/future energy requirements of port buildings is important.

There are different manners to model the thermal behaviour of buildings. Models for buildings are complex because of the huge number of implicated variables. The building energy model to be developed in the context of the MAGPIE project, is a thermal Building Model by Electric Analogy (BEAM), at the manner of the one described in the standard ISO 13790 March 2008. Although this international standard was aborted in 2017, the most recent French construction policies, such as RE2020[90], are still based on the same approach.

Departing from previous experience in this field[91], a model that enables to calculate either the temperature profile or the space heating/cooling needs of a given building at each time step is being developed. The energy demand of other building functionalities might also be

[88] IEEE-European Public Policy Committee - Heating and Cooling Future of Europe and Interactions with Electricity

[89] https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20220211-1

[90] French regulation : "Arrêté du 4 août 2021 relatif aux exigences de performance énergétique et environnementale des constructions de bâtiments en France métropolitaine et portant approbation de la méthode de calcul prevue à l'article R. 172-6 du code de la construction et de l'habitation" - Journal Officiel 15 août 2021 / N°189 - NOR : LOGL2107359A

[91] A. Foucquier, A. Brun, G. Antone, and F. Suard, 'Effect Of Wall Merging On A Simplified Building Energy Model: Accuracy Vs Number Of Equations', presented at the 2017 Building Simulation Conference, Aug. 2013. doi: 10.26868/25222708.2013.1316

integrated into the model. One example relates with buildings that offer charging stations services for individual cars.

As a first step, a spreadsheet for calculating the aggregated parameters to be put into the BEAM model from the actual characteristics of the building will be provided. This will allow to reduce the whole building, considered as a single group, to an equivalent space of one volume, one wall including all walls, floor, roof and one window area, based on the following assumptions:

- Addition of the extensive values, surfaces, solar and thermal irradiations. To be noticed that the addition of the solar radiations raises the question of the exposition of the wall
- Conservation of the thermo-physical values, properties of materials (conductivity, thermal volumetric capacity, and volumetric mass, transfer coefficients inside and outside, solar factor)

A user interface will be made available to facilitate this step. Still, items/information need to be filled in manually, e.g., the following dimensions of walls and floors of the studied case (Table 11).

Table 8 - Buildings dimensions information needed for the TBMEA model (ISO 13790:2008)

Dimensions	Length [m]	Width [m]	Height [m]	Conditioned floor area [m²]	Facade N/S [m²]	Facade E/W [m²]	Volume [m³]	Total internal surface [m²]
Floor 1	10	7	3	70	30	21	210	242
Floor 2	10	7	2.6	70	26	18.2	182	228.4
Sum	20	14	5.6	140	56	39.2	392	470.4

The user interface (Figure 26) will be composed by four items: 1) Class that will be dedicated to set the effective mass area (A_m) in accordance with ISO 13790:2008(E) §12.2.2 and the internal heat capacity of the building or zone (C_m) in accordance with ISO 13790:2008(E) §12.3.1.1; 2) Typology that will define the typology of the building as for energy performances. The terminology specifying the type of the buildings is based on the IEA Tasks 32 & 44[92]. SFH stands for "Single Family Houses; 3) the draught rate; 4) the width of the opening frame.

Choice	
Class	ISO 13786:2007
Typology	SFH45T44
Draught rate	0.4
Width of the opening frame	0.15

[92] IEA Tasks 32 & 44, Advanced Storage Concepts for Solar and Low energy Buildings, and Solar and Heat Pump Systems

Figure 26 – User Interface

Using the user preferences (Figure 26) and the information manually introduced (Table 8), the composition and thermal characteristics of the actual walls of the building will be automatically set-up. Table 9 exemplifies this for some typologies. Within the MAGPIE project, main types of buildings located in seaports will also be considered. Buildings typology within the port area are limited to two types: warehouses, which can be heated or cooled according to the requirements of the goods they house, and office buildings for the port owner or for the operators. Both types of buildings can be made of light or heavy structure.

Table 9 - Composition and thermal characteristics of the actual walls of the building

Typology	Uwall [W/m².K]	Uground [W/m².K]	Uroof [W/m².K]	Uwindow [W/m².K]	Uframe [W/m².K]	gvalue [-]	eroof [m]	eground [m]	ewall [m]
SFH15T44	0.18	0.00	0.16	0.59	2.27	0.584	0.2	0.2	0.2
SFH30T32	0.16	0.00	0.12	0.52	1.60	0.585	0.28	0.22	0.24
Choice	0.29	0.00	0.20	1.40	2.27	0.622	0.16	0.16	0.12

Then, the spreadsheet will be responsible to calculate the aggregated parameters to be put into the BEAM model. Table 10 lists some of these.

Table 10 - Inputs and aggregated parameters calculated from the actual buildings characteristics

Parameters 5893 – ISO 13790:2008		
Heat capacity of the building	C_{m}	45839600 J/K
Effective mass area	A_{m}	412 m²
Conditioned floor area	A_f	140 m²
Thermal transmission coefficient of doors, windows, curtains walls and glazed walls	$H_{\mathrm{tr,w}}$	35.20 W/K
Heat transfer coefficient between the air node and the star node	h_{is}	3.45 W/m²K
Heat transfer coefficient between the mass-related node and the star node	h_{ms}	9.10 W/m²K

Ratio between the internal surfaces area and the floor area	*xat*	3.84
Inputs 5893 – ISO 13790:2008		
Thermal transmission coefficient due to ventilation	H_{ve}	47.39 W/K
Thermal transmission coefficient of opaque (inertial) building elements	$H_{\mathrm{tr,op}}$	65.56 W/K

In Annex B, a complete list of parameters, inputs and outputs that make part of the BEAM model is presented.

Figure 25 presents the equivalent electric scheme that characterizes the model. Thanks to it, all heat transfers impacting the building temperature can be properly assessed. Based on these, the model can then estimate the active power ($\Phi_{HC,nd}$) that is needed to keep the temperature θ_{air} between the heating set point temperature and the cooling set point temperature.

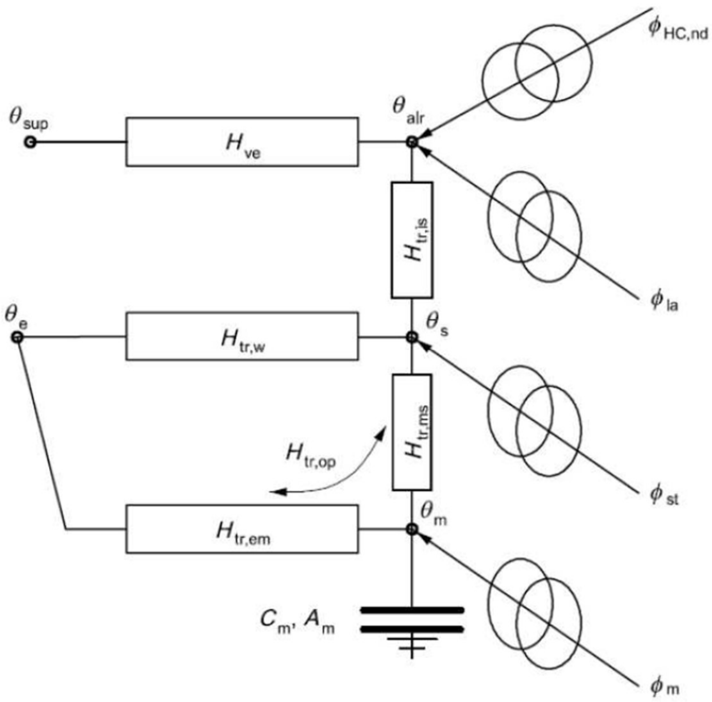

Figure 27 - Electric Analogy model extracted from ISO 13790:2008

One can distinguish in this model:

- Heat transfer by airflow through the building between the internal air node temperature θ_{air} and the supply air node temperature θ_{sup}, via the H_{ve} conductance.

- Conductive heat transfers through the walls of the buildings. Those are split in two elements:
  - Transfer in purely resistive elements (without thermal inertia, like windows). In the equivalent electrical model, these transfers occur between the star node θ_s and the ambient temperature node θ_e, via the $H_{\mathrm{tr,w}}$ conductance;
  - Transfer in resistive/capacitive elements (with thermal inertia). In the equivalent electrical model, these transfers occur between the mass-related temperature node θ_m and the ambient temperature node θ_e, via the $H_{\mathrm{tr,em}}$ conductance;

$H_{\mathrm{tr,op}}$ represents the thermal transmission coefficient of opaque (inertial) building elements. As already mentioned (and partially shown by Table 10), $H_{\mathrm{tr,w}}$, $H_{\mathrm{tr,em}}$, $H_{\mathrm{tr,ms}}$, $H_{\mathrm{tr,is}}$ conductances as well as C_{m} and A_{m} can be calculated from physical and architectural parameters of the building according to the ISO 13790.

Superficial exchanges by conduction and long wave radiation inside the buildings can be described by three conductances leading to a triangle between nodes (not represented in Figure 27). By means of the Kennelly theorem (also known as the Y-Δ transform[93]), the scheme is simplified with a central star temperature node θ_s. Supplementary resistance transformations and simplifications lead to the scheme depicted in Figure 27.

Temperature nodes are subjected to:

- $\Phi_{HC,nd}$ active power for heating (>0) or cooling (<0) the building;
- Φ_{int} and Φ_{sol}, internal and solar passive gains.

Below, the thermal balance equations that rule the model are defined.

$$C_m . \frac{d\theta_m}{dt} = H_{tr,em}(\theta_e - \theta_m) + H_{tr,ms}(\theta_s - \theta_m) + \Phi_m \quad (19)$$

$$H_{tr,ms}(\theta_s - \theta_m) + H_{tr,w}(\theta_s - \theta_e) + H_{tr,is}(\theta_s - \theta_{air}) = \Phi_{st} \quad (20)$$

$$H_{ve}\left(\theta_{air} - \theta_{sup}\right) + H_{tr,is}(\theta_{air} - \theta_s) = \Phi_{ia} + \Phi_{HC,nd} \quad (21)$$

As per the equations below, Φ_{sol} and Φ_{int} are split between the several nodes using intermediate powers: Φ_{ia}, Φ_{st} and Φ_{m}. Φ_{sol} is purely radiative and is applied to nodes θ_s and θ_m. The latter is considered half convective (applied to node θ_{air}) and half radiative (applied to θ_s and θ_m). Radiative gains are divided according to A_{m} and to the total internal surface A_{tot}.

[93] Kennelly, A. E. (1899). "Equivalence of triangles and three-pointed stars in conducting networks". *Electrical World and Engineer*. **34**: 413–414.

$$\Phi_{ia} = 0.5\Phi_{int} \quad (22)$$

$$\Phi_m = \frac{A_m}{A_{tot}}(0.5\Phi_{int} + \Phi_{sol}) \quad (23)$$

$$\Phi_{st} = \left(1 - \frac{A_m}{A_{tot}} - \frac{H_{tr,w}}{9.1A_{tot}}\right)(0.5\Phi_{int} + \Phi_{sol}) \quad (24)$$

At this stage, HVAC systems are assumed to be resistive. However, it is foreseen to integrate more complicated systems with their yields. The BEAM should entail the energy efficiency of heating and cooling systems and the consumptions for all uses, such as lighting and appliance consumption, which could be computed by rates per square meter.

As a conclusion, the building model allows to calculate the energy needs of buildings through the next 20 years. This can then be used as an input for the EMT under development in WP4.

3.6 Production & Storage

With the expected growth on the demand side, the electricity supply chain will have to adapt. Increasing the penetration of green energy sources coupled with energy storage systems is at the heart of the solution. To ensure this happens, there are some prior steps that need to be taken: 1) estimate the available renewable potential in the port area, namely for the technologies with highest maturity (i.e., solar photovoltaic and wind); 2) based on this potential and on future demand, size the optimal renewable energy system (including storage options). The availability of such outcomes will be extremely important for the definition of a long-term vision for demand and supply (main objective of T3.6).

3.6.1 Renewable Energy Sources potential

Multiple renewable energy options can be used in ports to generate electricity, including traditional sources such as solar photovoltaic and wind, as well as less traditional sources, such as tidal or wave. Solar photovoltaics are among the most popular, due to their ease of installation, low maintenance requirements, and high energy yield, while both onshore and offshore wind are widely used in ports.

There are different types of renewable energy potential, ranging from theoretical to market potential. The theoretical potential corresponds to the highest production level of a renewable energy source, limited only by natural and climatic conditions. Geographical potential considers the availability of resources (e.g., land) in specific locations, while the technical potential adds the feasibility of using existing technologies and the conversion efficiencies. Market potential is the amount of renewable energy that can realistically be implemented in the market, considering demand, competition from other technologies, costs, subsidies, and barriers.

In this section, a generic methodology to estimate the technical renewable energy potential is proposed (Figure 28Figure 28). The first step is to assess the available resources for each renewable energy option. This includes gathering data on weather patterns, climate conditions, and geographical conditions such as topography, land use, and accessibility. Based on this information and on technical details of each technology (e.g., efficacy rates), the proposed mathematical models can then estimate the technical potential of each renewable energy source. These models may also include impacts of technology trends, market conditions, regulations, and incentives.

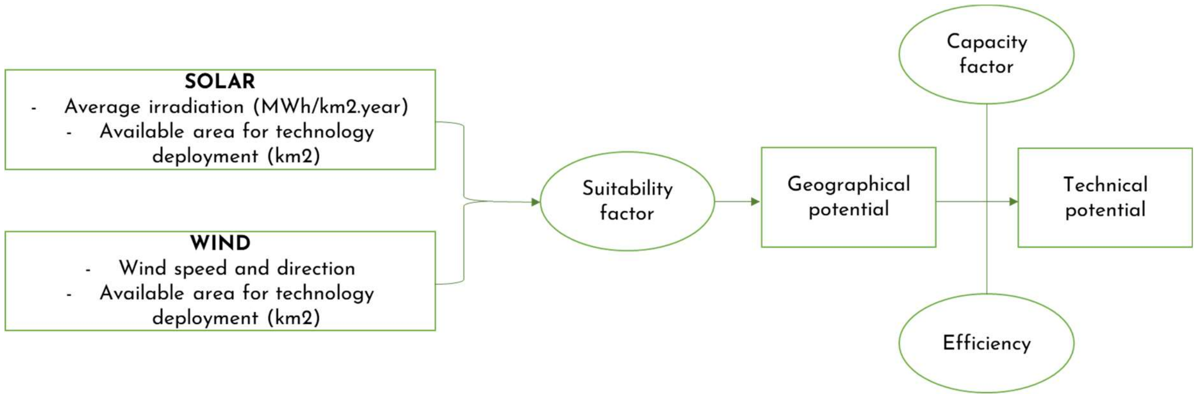

Figure 28 - General framework for solar and wind potential assessment

Generally representing, for renewable energy technologies, the geographical potential G_p (MWh) is the product of the unitary energy potential E_p (MWh/km²) by the resource availability R_a(km²) e.g., land, building rooftop and the suitability factor. The latter takes into account many factors and its implementation approach will vary according to the technology under assessment.

$$G_p = E_p * R_a * F \tag{25}$$

The technical potential T_p (MW, MWh) can then be generally determined by including the technology characteristics, as the capacity factor C_f (expressed as a fraction) and the efficiency rate η (%). However, for each technology, the technical potential formula may adopt different forms, according to the power calculation model selected.

$$T_p = G_p * C_f * \eta \tag{26}$$

The previous two equations represent a general approach to evaluate RES potential. Following these general expressions, the technical potential depends on the geographical potential and technology characteristics (that determine C_f and η). However, when a detailed assessment is possible, the technical potential adopts the mathematical form of the selected power output model and is related to the final geographical potential assessed given the specific characteristics of each location. The sections below describe detailed assessment methods for solar photovoltaic (PV) and wind energy, including the energy resource assessment and the power generated through the technology.

Solar PV potential

Assessing the solar energy resource at local scales in urban or industrial areas requires a combination of global/regional solar resource databases and analysis of the local conditions that impact on the actual availability of solar energy. These include influence of geographical conditions, weather conditions (e.g., cloud cover and clearness index), daily and seasonal variations, topography, surrounding infrastructure and vegetation, and any limitations to the optimal mounting of the panels.

Figure 29 shows a methodology for the assessment of the solar resource, representing the approach that will be followed for ports. The framework includes a three-step procedure. First, the solar profiles for various azimuth angles and tilt angles can be calculated based on hourly solar radiation data on a horizontal surface. This step produces a georeferenced map of available radiation. This information is then used in the second step to evaluate the loss of radiation caused by topography obstructions, surrounding infrastructure (e.g., buildings) and vegetation. This step can include the use of software and existing models such as Cercasol, URBES and ArcGIS[94][95]. The joint output of steps 1 and 2 is a map of the final local radiation with hourly resolution, reflecting also seasonal variations. Lastly, the orientation, slope, shading and surrounding conditions of each surface are analysed to determine the optimal mounting infrastructure, e.g., ground mounted, rooftop. In case irradiance time-series are not available, state-of-the art methodologies (e.g., numerical weather prediction models, measurement-based methods) can be applied.

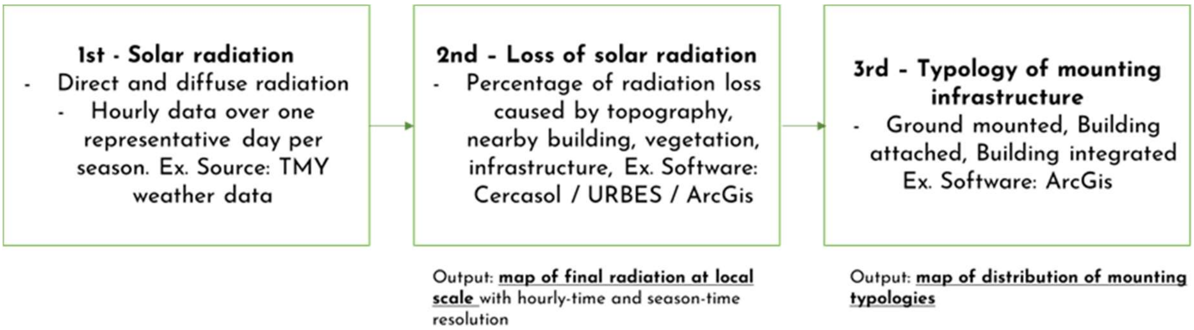

Figure *29* - General framework for the assessment of solar resource in urban or industrial areas

This framework is thus a detailed consideration on how to obtain the final geographical potential given the local characteristics. First, and for cases with limitations on the mounting angle of the PV structure, the angle of incidence θ_i (in radians) is calculated according to the following equation.

$$\theta_i = arccos(cos(\theta_z) \times cos(\varphi) \times cos(\beta) + sin(\theta_z) \times sin(\varphi)) \quad (27)$$

where θ_z is the solar zenith angle, φ the latitude of the location and β the tilt angle of the surface. Once θ_i is known, the irradiation I available on the surface can be obtained.

$$I = I_0 * \cos(\theta_i) \quad (28)$$

I_0 is the solar irradiation available on a horizontal surface. Based on the resource availability in year t, the geographical potential can finally be estimated. The suitability factor here is assessed in the corrections of the solar irradiance to the surface angle.

$$G_{p_t} = 365 * I * R_{a_t} \quad (29)$$

[94] Lobaccaro, G. et al. (2019) 'A methodological analysis approach to assess solar energy potential at the neighborhood scale', Energies, 12(18), p. 3554.
[95] Wegertseder, P. et al. (2016) 'Combining solar resource mapping and energy system integration methods for realistic valuation of urban solar energy potential', Solar Energy, 135, pp. 325-336.

Table 11 summarizes the inputs needed to calculate the geographic potential of solar PV resources.

Table 11 - Inputs to estimate the geographical potential of solar PV

Inputs	Description & sources
Geographical Location	Latitude and longitude of the location where the solar resource potential is being assessed. It can be obtained from maps, GPS data, or online geolocation tools.
Climate Data	Historical or simulated climate data, such as solar irradiation time-series, temperature, precipitation, humidity, and cloud cover. The sampling rate and data format will depend on the source of the data. E.g., meteorological data may be available at hourly, daily, or monthly intervals and in various data formats, such as CSV, NetCDF, or HDF5.
Topography	Elevation, slope, and similar aspects, needed to estimate impact of shading and terrain on available solar radiation. Can be derived from topographic maps, digital elevation models (DEMs) or remote sensing data.
Land Cover	Information on vegetation, buildings, and other obstructions. Needed to estimate the shading effects on the available solar radiation. This information can be obtained from land cover maps, satellite imagery, or LiDAR data.
Solar Models	If solar irradiation time-series are not available, these models can estimate the available solar radiation. Such models use the inputs described above to calculate the direct, diffuse, and reflected solar radiation. Examples of solar models include the HelioClim-3 database [96], and the National Renewable Energy Laboratory (NREL) Solar Prospecting Tools[97]. The data format and sampling rate will depend on the model used.

The next step of the model (Figure 30) regards to the estimation of the technical potential T_p. Several methods can be applied to assess the power potential of PV systems[98]. The main ones are the efficiency model, the single-diode model (SDM)[99], the two-diode model (TDM)[100], the multi-diode model (MDM)[101], the four-parameter model (4PM), the PVT model[102], and the system model. These methods are implemented in various simulation software packages and can be used to predict the performance of a PV system under diverse scenarios, such as different weather, shading, and load conditions. It's also worth mentioning that these models are not mutually exclusive, they can be combined to have a better representation of the system. For example, the PVT model can be linked with the SDM to provide more accurate results. Each model has its own advantages and limitations, and the choice of the model will depend on the specific requirements of the analysis, the available data, and the complexity of the PV system.

Wind potential

The proposed framework for wind resource assessment is shown in Figure 30. The first step includes the collection of time-series measurements of wind data for a given location, with

[96] https://www.soda-pro.com/help/helioclim/helioclim-3-overview
[97] https://www.nrel.gov/solar/data-tools.html
[98] Luque, A., Hegedus, S. (2011). Handbook of photovoltaic science and engineering. John Wiley & Sons.
[99] "Performance Analysis of Photovoltaic Systems Using the Single Diode Model" by M. A. Ali and M. A. R. Sharif, IEEE Transactions on Energy Conversion, vol. 25, no. 3, 2010.
[100] "Modelling of photovoltaic modules using the two-diode model" A.Luque, A. Hegedus, Solar Energy, vol. 47, no. 1, 1991.
[101] "A multi-diode model of photovoltaic modules" A. Luque, A. Hegedus, IEEE Transactions on Energy Conversion, vol. 12, no. 4, 1997.
[102] A review of temperature dependent models for photovoltaic modules" A. Luque, A. Hegedus, Progress in Photovoltaics: Research and Applications, vol. 19, no. 6, 2011.

appropriate spatial and time resolution. If large datasets of time-series are available, the next step relates to data treatment and quality check. Cleaning and filtering actions may be required to remove noise and smooth out the data e.g., through median, mean, or Kalman filtering[103]. Additionally, wind speed/direction correction should be performed, accounting for both measurements at a height above the ground and at the ground level. Lastly, statistical analysis of the wind data allows to determine the distribution of wind speeds, wind power, and other parameters. All these data treatment processes help to improve the accuracy and reliability of the wind data and make it suitable for wind energy assessments. In case time-series of wind measurements cannot be obtained, the following options are available: i) meteorological reanalysis high-resolution wind data, provided by national atmospheric centres; ii) openly available wind data from e.g., Wind Atlas Data[104], which provides wind resource information, including wind speeds and direction, at a specific location; iiii) mesoscale models, such as the Weather Research and Forecasting (WRF) model[105]; iv) remote sensing data e.g., from lidar and sodar, used to measure directly wind speed and direction at a specific location; v) empirical models that estimate resource availability considering factors such as topography, land use, historical wind measurements at nearby locations, and other relevant information. Independently if the wind time-series are directly available or not, the final outcome of the two first steps (Figure 30) should consist of a map of wind speed and direction for a given location. Additionally, when feasible, a validation/calibration step with data from local measurements or CFD simulations can be performed to further improve the quality of the data.

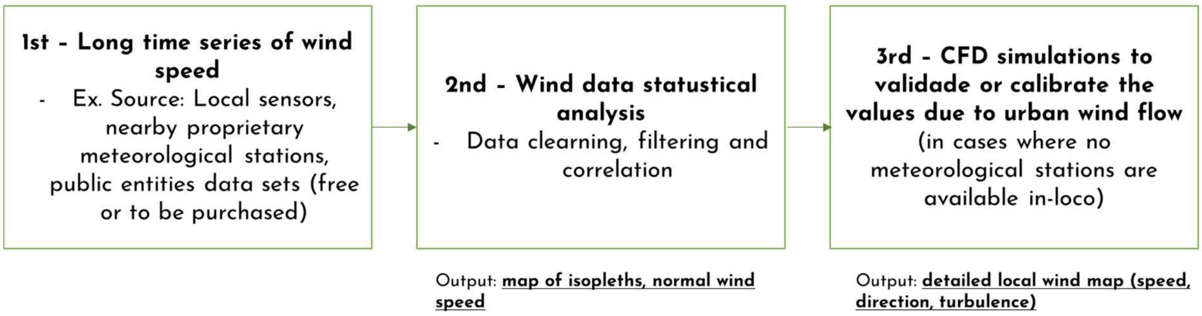

Figure 30 - Proposed wind resource assessment methodology for ports

After applying the proposed framework, the geographical potential of wind power in year t can be estimated as follows. Important to highlight that depending on the method adopted to the power calculation, G_{p_t} can be required only as an area unit (i.e., available suitable area for the installation of the turbines).

$$G_{p_t} = R_{a_t} * F \tag{30}$$

where R_{a_t} (kWh/m²/year) is the available resource of wind power (already accounting with R_{a_t} multiplied by the annual wind resource) and F (%) is a Suitability factor. In here, F represents the fraction of the resource that can be effectively harnessed by the wind turbine

[103] Brower, M. (2012) Wind resource assessment: a practical guide to developing a wind project. John Wiley & Sons.
[104] https://globalwindatlas.info/en
[105] https://ncar.ucar.edu/what-we-offer/models/weather-research-and-forecasting-model-wrf

technology under consideration. This factor takes into account factors such as wake effects, turbine spacing, turbulence intensity, and terrain complexity.

Once the geographical potential has been assessed, T_p can be estimated given the characteristics of the technology. Several different methodologies can be adopted, including the power curve model[106], the Betz limit model[107], the power coefficient model[108], the aerodynamic model, and the structural model. In general, models that incorporate more detailed information about the wind turbine, such as the aerodynamic model, can provide more accurate results, but may also require more data and computational resources. In contrast, models that rely on simpler assumptions, such as the power curve or the power coefficient model, may be more appropriate for preliminary assessments or for areas where data is limited.

3.6.2 Optimal RES sizing

The theoretical potential of solar PV and wind power production can be assessed using the models previously described. This section focuses on estimating how much of this potential actually needs to be realized. In that sense, an optimization framework for the sizing of a renewable energy system (solar PV + onshore wind) coupled with energy storage is proposed. Such sizing exercise will minimize the generation costs over a given time horizon while ensuring that security of supply is kept.

$$min \sum_t (c_t^g \times x_t^g + c_t^p \times x_t^p + c_t^w \times x_t^w + c_t^b \times |x_t^b|) \tag{31}$$

The decision variables to be considered are: x_t^p (power output of the PV system at time t, in kW), x_t^w (power output of the wind system at time t, in kW), x_t^b (power input/output of the battery storage system at time t, in kW), and E_t^b (energy level of the battery storage system at time t, in kWh). x_t^g represents the power input/output of the external grid connections. It is not a decision variable but ensures the match between supply and demand. To each power input/output variable, the corresponding generation/charging/discharging cost is associated ($c_t^g, c_t^p, c_t^w, c_t^b$). d_t illustrates the electricity demand at time t.

The objective function is subject to the following constraints:

- **Power balance** – Together, the power output from the PV, wind, and battery storage systems must be equal to the electricity demand at time t.

$$x_t^g + x_t^p + x_t^w + x_t^b = d_t \tag{32}$$

[106] "Wind turbine power performance prediction" by J.F. Manwell, J. G. McGowan and A. L. Rogers, Wind Energy Explained: Theory, Design and Application, John Wiley & Sons.
[107] "The Betz limit and its implications for modern wind turbine design" by J.F. Manwell, J. G. McGowan and A. L. Rogers, Renewable Energy, vol. 33, no. 2, 2008.
[108] "Wind turbine power coefficient" by J.F. Manwell, J. G. McGowan and A. L. Rogers, Wind Energy Explained: Theory, Design and Application, John Wiley & Sons, 2002.

- **PV/Wind power output constrains -** The power output of the PV/Wind systems at time t cannot exceed the maximum capacity of the PV/Wind systems (C_p, C_w). Such capacity limits can be established by the models proposed in 3.6.1.

$$x_t^p <= C_p \quad (33)$$

$$x_t^w <= C_w \quad (34)$$

- **Non-negativity constraints -** the power output of solar and wind systems and the energy level of the battery storage system must be non-negative.

$$x_t^p >= 0 \quad (35)$$

$$x_t^w >= 0 \quad (36)$$

$$E_t^b >= 0 \quad (37)$$

- **Battery power/energy constraint** – Section 3.6.3 carries a detailed discussion on possible BESS models

Thanks to this optimization framework, an effective sizing of the PV, wind and battery systems is possible (a valuable input for the Digital Tools of WP4). Electricity production and storage profiles (with an hourly resolution) are also outcomes of this model.

Table 12 summarizes the inputs required by the optimization framework.

Table *12* – Inputs for the optimal RES/Storage sizing

Inputs	Description & sources
Load data	Historical or projected load data for the location and time period of interest. This data can be obtained from energy utilities, directly from the port stakeholders and authorities, or from public national or regional energy statistics. The data should be available at high temporal resolution, such as hourly or 15-minute intervals.
System component data	Technical and economic data for the solar panels, wind turbines, and energy storage system. It can be obtained from manufacturers or from engineering databases. The data should include the performance characteristics of the components, such as efficiency, capacity, and lifetime, as well as the cost and other economic parameters.
System constraints	Constraints on the operation of the hybrid energy system, such as the maximum power output of the solar panels and wind turbines, the max/min SOC of the energy storage system, etc.

Solving non-linear optimization problems like this one often requires specialized techniques that can handle non-linear functions, such as gradient-based methods[109] (e.g., Newton-

[109] Jameson, A. (1995) 'Gradient based optimization methods', MAE Technical Report No, (2057).

Raphson), Nonlinear Programming (NLP) solvers[110] (for small to medium-sized optimization problems), Evolutionary algorithms[111] (e.g., genetic algorithms), Simulated annealing [112](metaheuristic), Constraint programming[113] (often used for scheduling and resource allocation) and Mixed-Integer Nonlinear Programming[114](MINLP) solvers (combination of NLP and MILP). During T3.6, the method that best suits the characteristics of this specific problem will be chosen.

3.6.3 BESS operational behaviour

BESS modelling is widely discussed in the literature and numerous models are proposed depending on the purpose[115]. This section analyses some of them and evaluates which one fits best to the MAGPIE objectives. To note that the BESS models will mainly be used for the optimal system sizing (section 3.6.2) and for the EMT to be developed in WP4.

The most accurate way to model BESS is based on a physical approach. It aims to model as close to the reality as possible all the internal electrochemical, and even mechanical, processes within a battery. Physical-based models require large amount of experimental data as well as in-depth cell analysis. Even if some ongoing research is assessing the use of this type of models for control purposes, most of the times they are only used to get a better understanding of the internal dynamics of the battery for improving its performance and ageing.

A second category for BESS modelling is based on building an electrical analogy of the physical dynamics of the cell. The equivalent circuits are usually composed by serial and parallel connections between resistances and capacitance (RC branches), and they can represent voltage, current and SOC dynamics. In the literature, models with one, two or three RC branches are the most used. The electrical analogy modelling is usually applied to control BESS, anticipating voltage behaviour or power limitations. They can also be useful to follow online the BESS performance and to detect any potential failures.

The last category is a global Energy/Power modelling approach. Here, the BESS is described as a power component. This model fits very well with energy balancing simulations that require a low time resolution (e.g., hourly-based). It is also suited to model all electricity storage technologies as it just relies on general parameters. Given these characteristics, it is proposed to use this type of modelling approach in the MAGPIE project.

Within the Energy/Power modelling category, several options are available in the literature. It is not an objective of the MAGPIE project to analyse each one of them. Having said that, the following one was chosen due to its interesting characteristics for energy simulation and BESS sizing purposes. It describes the evolution of the State-of-Energy (SOE) depending on the nominal energy (E_{nom}), the charging and discharging efficiencies (Eff_{ch} and Eff_{dis})and the charging and discharging powers (P_{ACch} and P_{ACdis}). The SOE metric is similar to SOC, but it considers the effect of voltage on charged/discharged energy. E_{nom} is given by the

---

110 Avriel, M. (2003) Nonlinear programming: analysis and methods. Courier Corporation.
111 Bäck, T. and Schwefel, H.-P. (1993) 'An overview of evolutionary algorithms for parameter optimization', Evolutionary computation, 1(1), pp. 1–23.
112 Brooks, S. P. and Morgan, B. J. T. (1995) 'Optimization using simulated annealing', Journal of the Royal Statistical Society: Series D (The Statistician), 44(2), pp. 241–257
113 Rossi, F., Van Beek, P. and Walsh, T. (2008) 'Constraint programming', Foundations of Artificial Intelligence, 3, pp. 181–211.
114 Lee, J. and Leyffer, S. (2011) Mixed integer nonlinear programming. Springer Science & Business Media.
115 https://www.osmose-h2020.eu/download/d7-5-methodology-report-for-application-specific-design-of-bess/

BESS manufacturer under nominal conditions of operation (of temperature and power) or under typical conditions of the use case. Eff_{ch} and Eff_{dis} depend on the current values for SOE, P_{ACc} and P_{ACdis}. Based on data provided by the BESS manufacturer concerning the electrical characterization of the system, empirical tables that link the efficiencies to the State-of-Energy and to the charging/discharging powers can be built.

$$SOE(i+1) = SOE(i) - \int_{i}^{i+1} \frac{P_{ACch}(t)}{3600 * E_{nom}} * Eff_{ch}\big(SOE(t), P_{ACch}(t)\big)dt, \quad \boldsymbol{charge} \tag{38}$$

$$SOE(i+1) = SOE(i) - \int_{i}^{i+1} \frac{P_{ACdis}(t)}{3600 * E_{nom}} * \frac{1}{Eff_{dis}\big(SOE(t), P_{ACdis}(t)\big)}dt, \quad \boldsymbol{discharge} \tag{39}$$

$$P_{ACch}(t) * P_{ACdis}(t) = 0 \tag{40}$$

$$P_{ACchmax}(SOE(t)) \leq P_{ACch}(t) \leq 0 \tag{41}$$

$$0 \leq P_{ACdch}(t) \leq P_{ACdismax}\,(SOE(t)) \tag{42}$$

$$SOE_{min} \leq SOE(i+1) \leq SOE_{\max} \tag{43}$$

t (seconds) is the simulation time while i represents the selected time step. The third equation of this model avoids the simultaneous occurrence of charging/discharging actions. Then, the fourth and fifth equations illustrate the limitations imposed on the charging/discharging power, which depend on the SOE. Empirical tables illustrating how this link takes place can also be built. Lastly, the SOE can be restricted to minimum/maximum values for slowing battery ageing or for energy management purposes (e.g., to keep ability to charge/discharge the battery in case of defined emergencies).

While this method suits well the project purposes, the fact that it would be applied in optimization problems (optimal system sizing and management of the electrical system) could constitute a problem. Indeed, the more complex the component models are, the harder it becomes to find the optimal solution of the problem. Even using powerful optimization solvers, convergence issues may arise when the complexity starts increasing. Therefore, simplified versions of the method previously proposed will be here discussed.

One of the simplest versions for optimal control and management is a 100 % efficiency model (i.e., efficiency = 1). The evolution of the SOE is determined as follows:

$$SOE(i+1) = SOE(i) - E(i)\ \forall i \in [1, TH-1] \tag{44}$$

where $E(i)$ is the energy charged (<0) or discharged (>0) from the BESS in time step i (belonging to time horizon TH). This energy is then limited considering the physical constraints of the battery (e.g., total energy of the battery, maximal currents in charging and discharging actions). The simplest way to model this is by imposing constant limits that do not depend on ageing, temperature or charge/discharge rates.

$$E_{min} \leq E(i) \leq E_{max} \; \forall i \in [1, TH] \quad (45)$$

As in the previous model, the SOE can also be restricted to minimum/maximum values.

$$SOE_{min} \leq SOE(i) \leq SOE_{\max} \; \forall i \in [1, TH] \quad (46)$$

Another simplified version to model the BESS is to consider constant charging/discharging efficiency rates. This means that a single efficiency value for charging and another for discharging are defined regardless of the temperature or the SOE. As the charging/discharging actions are treated separately in this model, $E(i)$ is now described by $E_{ch}(i)$ and $E_{dis}(i)$. The evolution of the SOE is determined as follows:

$$SOE(i+1) = SOE(i) - Eff_{ch} \times E_{ch}(i) - \frac{1}{Eff_{dis}} \times E_{dis}(i) \; \forall i \in [1, TH-1] \quad (47)$$

Since charging and discharging phases are not feasible at the same time, a logical constraint equation is defined as follows. All the remaining constraints of the 100% efficiency model can also be applied in this approach.

$$E_{ch}(i) \times E_{dis}(i) = 0 \; \forall i \in [1, TH] \quad (48)$$

This last equation turns the problem into a nonlinear one, which can be an obstacle for the optimization process. A possible alternative is to convert the problem into a mixed-linear by introducing a binary variable $\gamma(i)$. As this variable always assumes a 0 or 1 value, it automatically excludes the possibility of simultaneous charging and discharging actions. Therefore, the previous non-linear equation can be removed from the model.

$$SOE(i+1) = SOE(i) - \gamma(i) \times Eff_{ch} \times E_{ch}(i) - (1-\gamma(i)) \times \frac{1}{Eff_{dis}} \times E_{dis}(i)$$
$$\forall i \in [1, TH-1], \gamma(i) \in \{0,1\} \quad (49)$$

3.7 Distribution grid model

As the energy transition process gains pace, electricity needs start to grow. Indeed, all the demand sectors analysed in this report (transports, industries, buildings) will move (at least partially) towards the electrification of their processes. On the supply side, the ambitious decarbonization targets set by the EU will also lead to several changes. First, new energy sources will be needed as a direct response to the growing electricity requirements. Then, traditional sources based on fossil fuels will be phased-out and replaced by renewable-based systems, which are characterized by their uncertainty at the power production level. While the demand and supply sides are changing rapidly, the system that connects the two also needs to adapt[116]. It is therefore crucial to understand how the distribution grid needs to evolve to cope with all these new requirements. Two optimization models are hereby proposed:

- Investment planning model: Structural changes on the distribution network (e.g., grid upgrades) belong to the so-called planning time horizon. This type of models[117][118][119] looks to how the system will evolve in the next years and decides which is the best investment strategy to avoid the arising of technical problems (e.g., balancing issues).

- Operational model: Short-term changes on the distribution network (e.g., exploitation of flexibility resources) belong to the so-called operational time horizon. This type of models[120] focus on how the system will look like in the day-ahead and decides which flexibility options should be activated to avoid the arising of technical problems (e.g., branch overloads).

Important to mention that these models are not mutually exclusive. The short-term usage of flexibility options will be of utmost importance to keep the system stable and ensure power balance (it can even allow to postpone investment actions) but will not always solve structural problems of the electrical grid[121].

Although these models follow different objectives, they share the main principles. Both depart from the same grid infrastructure (i.e., same grid topology and electrical characteristics for all transmission lines, transformers, etc.). Likewise, time-series (with different time horizons) for each distributed energy resource and demand stream are needed. The two models then need to ensure grid stability. This is translated into: 1) ensure the power balance of the electrical grid. To do so, buy/sell energy supply from external grids is possible; 2) branch capacity limits are respected. These two constraints are mathematically formulated below:

$$P_n^G - P_n^D - P_n = 0, \forall n \in N \tag{50}$$

$$\left|P_{ij}^l\right| \leq P_{max}^l, \forall l \in TL \tag{51}$$

where P_n^G represents the active power operating point in network node n resulting from the market-clearing mechanism and P_n^D illustrates the net-load forecast in network node n. P_n is the active power flow in node n coming from the transmission lines. The active power flow in

[116] https://www.iea.org/reports/smart-grids
[117] Jannesar, M. R., Sedighi, A., Savaghebi, M., & Guerrero, J. M. (2018). Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration. *Applied energy*, *226*, 957-966
[118] Bozorgavari, S. A., Aghaei, J., Pirouzi, S., Nikoobakht, A., Farahmand, H., & Korpås, M. (2020). Robust planning of distributed battery energy storage systems in flexible smart distribution networks: A comprehensive study. *Renewable and Sustainable Energy Reviews*, *123*, 109739.
[119] Saboori, H., Hemmati, R., Ghiasi, S. M. S., & Dehghan, S. (2017). Energy storage planning in electric power distribution networks–A state-of-the-art review. *Renewable and sustainable energy reviews*, *79*, 1108-1121.
[120] Potenciano Menci, S., *et al.* Functional Scalability and Replicability Analysis for Smart Grid Functions: The InteGrid Project Approach. *Energies* 2021, *14*, 5685.
[121] InteGrid Project, D7.4 - CBA Methodology and Results. https://cordis.europa.eu/project/id/731218/results

each transmission line P_{ij}^{l} is constrained by the thermal capacity P_{max}^{l}. i and j correspond to the network nodes connected by transmission line l.

Table 13 shows the decision variables considered in the planning/operational models. To properly understand their role, the characteristics of each model are described below.

Table *13* - Decision variables of the planning/operational models

Decision Variables	Investment planning model	Operational model
BESS	x	x
Transmission lines (i.e., grid upgrades)	x	
EVs	x	x
Demand-side flexibility (rather than EVs)		x

The investment planning model is divided into two interlinked stages. First and while trying to minimize the investment costs, a one-time decision concerning the BESS and the grid upgrades (including size/capacity and location) is taken. Given the required time to install the BESS and upgrade the transmission lines, these decisions are typically made ahead of time and therefore, not likely to change over short time periods. Therefore, these are treated as here-and-now decision variables. Then, in the second stage, a multi-period problem focuses on matching the uncertain power supply with the uncertain demand for power while subject to the investment decisions previously made. To ensure this balance, the SOC of the BESS can be managed (see section 3.6.3 for storage modelling). Also, smart charging of EV's is possible. Within the MAGPIE project, the investment planning model will be applied in the context of an increasing penetration of EVs. The model development and testing will be carried under Demo 2 of WP3.

The operational model relates with the EMT to be developed under WP4. An optimization approach that will show the importance of flexibility options (e.g., BESS, V2G, demand response actions, etc) to ensure that the daily operation of a distribution grid remains stable, even with the foreseen demand growth and increase of renewable energy-based systems. The exploitation of the flexibility options will be carried while minimizing their activation costs.

4. Conclusions & Next steps

The work presented in this deliverable successfully complies with the main objectives that were settled. First, and thanks to a comprehensive literature review and dedicated interviews with port partners, the main challenges for the electricity supply chain were identified:

- Demand – Electrification requirements in the transport, industrial and building sectors will significantly grow in the coming years. Ambitious GHG emission reduction targets will dictate this transition to electrified processes, but to what extent this will happen has yet to be estimated with precision.

- Production and Storage – Fulfilling growing electrification needs while complying with ambitious decarbonization targets is possible, but only by relying on renewable energy sources. To effectively manage the non-dispatchable characteristics of many of these resources, BESS might need to be coupled. Therefore, realizing how production sites and storage assets need to evolve is of utmost importance.

- Distribution system – Changes on the usual patterns of demand, production and storage have a direct impact upon the distribution grid. Technical problems such as energy balancing issues will see a significant increase and to avoid them efficient solutions need to be studied (e.g., grid investments, flexibility management)

Then, dedicated models designed to support port stakeholders in overcoming these challenges were presented. They aim to build reliable long-term energy scenarios and based on them define the developments needed across the electricity supply chain.

Important to highlight that this deliverable (Chapter 3) served as a platform for the description of all models. However, their development is only now starting which explains why not all of them were presented with the same level of detail.

Next steps

Having the models well described, the following steps are:

- Fine-tune the links between each other to enable the definition of a comprehensive long-term vision of energy demands and availability. The construction of a scenario-based vision might be vital to serve as input for some of the tools being developed in WP4
- Develop and test them during T3.6 while providing important outcomes for the Master Plan
- Assess the current status of the port electrical grid through simulations. While doing so, explore the potential of flexibility options in the transport sector to ensure a stable operation of the distribution network. Important to mention that this will require the availability of real data from the port electrical grid.

Annex A

Electricity Supply Chain Questionnaire

1. **Are these electrical consumers reloevant in a port environment? Do they already exist in <u>your port</u> (present), just in a future scenario (future) or they are not a possibility (No)?**

		Relevant? **Yes/No**	**Present/Future/No**
Transport	Maritime		
	Inland Shipping		
	Rail		
	Road		
Industries	Fuel refining		
	Ammonia production		
Port/Terminal operations	Cranes		
	Forklifts		
	Buildings/Cooling warehouses		
	Lighting		
Energy production	H2 production		

2. **Please indicate other demand sectors that should be considered. Indicate also if they already exist in <u>your port</u> (present), just in a future scenario (future) or if they are not a possibility (No)?**

		Present/Future/No
Transport	***Type A***	
	....	
Industries	***Type A***	
	....	
Port/Terminal operations	***Type A***	
	....	

Energy production	***Type A***	
	….	
Sector A	***Type A***	
	….	

3. **<u>If yes & present/future</u>, what is the current/forecasted yearly consumption? If you do not have exact numbers, you can also provide growth %'s or just some forecasts (see examples below).**

		<u>Demand Present (MWh)</u>	**<u>Demand 2030 (MWh)</u>**	**<u>Demand 2040 (MWh)</u>**	**<u>Demand 2050 (MWh)</u>**
Transport	Maritime				
	Inland Shipping		e.g., inland shipping transport will represent x MWh of energy consumption by 2030		
	Rail				
	Road				
	Type A				
Industries	Fuel refining	e.g., fuel refining is currently responsible for x GWh of electricity needs			
	Ammonia production			e.g., Ammonia production is expected to increase by x% until 2040. This will lead to a	

				proportional increase of the current electricity needs	
	Type A				
Port/Terminal operations	Cranes			e.g., all port/terminal operations should completely rely on electricity by 2050	
	Forklifts				
	Buildings/Cooling warehouses				
	Lighting				
	Type A				
Energy production	H2 production			e.g., electricity needs will increase x% due to the expected demand growth for green H2	
	Type A				
Sector A	Type A				

4. **For each one of the identified sectors, which are the triggers to advance with their electrification (<u>General Drivers</u>)? Which characteristics might make a specific port more suitable/capable than other to start this transition (<u>Port Drivers</u>)?**

		General Drivers	**Port Drivers**
Transport	Maritime		e.g., the type of port defines the amount of time that a vessel stays anchored, that a truck stays in the port area, etc. This might lead to more recharging needs, which consequently contributes to a viable business model for the port recharging infrastructure
	Inland Shipping		
	Rail		
	Road		
	Type A		

Industries	Fuel refining		
	Ammonia production		
	Type A		
Port/Terminal operations	Cranes		
	Forklifts		
	Buildings/Cooling warehouses		
	Lighting		
	Type A		
Energy production	H2 production		e.g., ports in which local RES production is already in place are more likely to become H2 producers. Usually, ports with industrial hubs are more likely to have RES
	Type A		...
Sector A	Type A		...

5. **The electrification of these sectors might open possibilities for demand response services for the electrical grid (i.e., flexibility). Do you see this as a viable possibility? Please specify what kind of flexibility actions can occur (e.g., load shifting, load shedding, storage, etc).**

		<u>**Yes/No**</u>	<u>**How?**</u>
Transport	Maritime		
	Inland Shipping		e.g., not part of the business model. Using swappable batteries to provide grid services would lead to a fast wear and tear. Using the entire battery lifetime to power barges makes more sense from the economical point of view
	Rail		
	Road		e.g., makes part of the business model. In cases where trucks stay

			overnight in ports, they can provide V2G services
	Type A		...
Industries	Fuel refining		e.g., yes, high demand processes can be shifted to night periods
	Ammonia production		
	Type A		...
Port/Terminal operations	Cranes		e.g., yes, load shifting actions are possible
	Forklifts		e.g., no, the time schedules of forklifts are very tight and so there is no possibility for load shifting actions
	Buildings/Cooling warehouses		......
	Lighting		
	Type A		...
Energy production	H2 production		e.g., yes, Green H2 production allows to avoid RES curtailment
	Type A		...
Sector A	Type A		...

6. Focusing now on the **transport sector**. Although several different types of modalities operate in a port ecosystem, they do not rely entirely on the port to supply their own demand e.g., a diesel truck not always fuel its tank in the port (gas stations are spread throughout Europe). Having this in mind, what % of vehicles fuel their tanks in the port ecosystem?

		%	**Comment**
Transport	Maritime		e.g., electrification only to power the vessels while anchored
	Inland Shipping		e.g., electrical power to recharge swappable batteries
	Rail		....

	Road		e.g., electrical power to recharge trucks batteries
	Type A		....

7. **And if instead of diesel-powered vehicles, we are speaking of e-powered vehicles? Is the same situation expected?**

		Comment
Transport	Maritime	e.g., yes, all vessels will continue relying on the port's infrastructure. Nevertheless, electrification is only foreseen to power the vessels while anchored
	Inland Shipping	
	Rail	....
	Road	e.g., No. On a first moment we foresee an increase in the number of trucks recharging their batteries in the port (comparing to the number of trucks that nowadays fuel their tanks). This will be related with an initial lack of recharging infrastructures outside the port area
	Type A	....

8. **Different technologies can be responsible for the recharging process. Some of them are listed below (associated with the MAGPIE demonstrators). Any of these already exist in <u>your port (present)</u>? Does the port have plans to exploit them in the future (future)? If not, please provide a brief comment on why that is.**

		Type	**Present/Future/No**	**Comment**
Transport	Maritime	Offshore charging buoy		e.g., in our port, vessels do not have long waiting periods, **or** our growth plans do not foresee investments on offshore tech. Therefore, the offshore charging buoy is not expected to have a role in our port
		On-shore Power supply		e.g., in our port, vessels do not have long staying periods. Therefore, OPS

				is not expected to have a role on our port
	Inland Shipping	E-charging stations (e.g., to charge swappable batteries)		…
	Rail	E-charging stations/Over headlines (e.g., to power hybrid-electric shunting locomotives)		e.g., the number of shunting locomotives in our port is reduced. Having a recharging infrastructure would not lead to a viable business model
	Road	E-charging stations for truck		e.g., although e-trucks are foreseen, we do not expect that they will recharge their batteries in the port. So, no investments on recharging infrastructure are expected

9. **Please indicate other recharging technologies that should be considered. Indicate also if they already exist in <u>your port</u> or if they will just become a reality in the future.**

		Type	Present/Future
Transport	Maritime	Type A	
		…	
	Inland Shipping	Type A	
	Rail	Type A	
	Road	Type A	

10. **Concerning the technology in which your demo focuses on, which % of vehicles do you aim to impact? What investments would be necessary to achieve those targets?**

		Type	Targets	Investments
Transport	Maritime	Offshore charging buoy	e.g., 20% of the vessels arriving to Rotterdam need to wait offshore more than x hours. The offshore charging buoy solution should target all these vessels	e.g., To achieve this target, X offshore charging buoys (similar to the one demonstrated) would be needed
		On-shore Power supply		
	Inland Shipping	E-charging stations (e.g., to charge swappable batteries)	e.g., swappable batteries are expected to power just x% of the electric barges fleet by 2050	
	Rail	E-charging stations/Over headlines (e.g., to power hybrid-electric shunting locomotives)		
	Road	E-charging stations for truck	e.g., It is foreseen that x% of the trucks arriving to Rotterdam will need to power their batteries. E-charging stations should be available to fulfil this need.	e.g., To achieve this target, X e-charging stations would be necessary

11. **Concerning the following technologies, which are the main drivers/challenges that will allow its upscale (<u>General Drivers</u>)? Which characteristics might make a specific port more suitable than other to explore your technology (<u>Port Drivers</u>)?**

		Type	General drivers	Port drivers
Transport	Maritime	Offshore charging buoy	e.g., economic incentives, regulation	e.g., existence of a city nearby. The offshore charging buoy would allow vessels to be kept away while waiting for entrance permission. This would

				result for example in lower levels of noise pollution for the citizens
		On-shore Power supply		
	Inland Shipping	E-charging stations (e.g., to charge swappable batteries)		
	Rail	E-charging stations/Over headlines (e.g., to power hybrid-electric shunting locomotives)		
	Road	E-charging stations for truck		

12. **Concerning the offshore charging buoy, it is foreseen a connection to the electrical national grid? Or the power availability will just rely on the offshore wind park?**

		Type	Power supply	Comments
Transport	Maritime	Offshore charging buoy	Just offshore wind park or also connection to the grid?	

13. **Concerning the road transport, do you consider vital the availability of a recharging infrastructure in the port environment? Or since trucks can easily charge their batteries in other locations, this would not be crucial? Please provide a brief comment on why.**

Yes/No	**Comment**

14. **The availability of consumption time-series that characterize the operation of the aforementioned sectors is vital for the success of the MAGPIE project. Who owns this data? Please specify the entity and, if possible, a direct contact point.**

Note: In cases where electrification is not yet a reality, we would look to the current consumption patterns (i.e., fossil-fuel based)

		Contact points
Transport	Maritime	e.g., vessels manufacturers, terminal operators
	Inland Shipping	e.g., Demo 7 green Energy container
	Rail	e.g., Prorail
	Road	
Industries	Fuel refining	
	Ammonia production	
Port/Terminal operations	Cranes	e.g., NL distribution system operator
	Forklifts	
	Buildings/Cooling warehouses	
	Lighting	
Energy production	H2 production	

Supply sector

15. **Are these e-sources relevant in a port environment? Do they already exist in <u>your port</u> (present), just in a future scenario (future) or they are not a possibility (No)?**

		Relevant? **Yes/No**	**Present/Future/No**
RES	PV		if neither in present nor future, please do not fill the box
	Wind onshore		
	Wind offshore\		
	Tidal		
	Wave		
	Biomass		
Conventional Generation	CHP		
	CCGT		
	Coal		

16. **Please indicate other supply sources that should be considered. Indicate also if they already exist in <u>your port</u> (present), just in a future scenario (future) or if they are not a possibility (No)?**

		Present/Future/No
RES	***Type A***	if neither in present nor future, please do not fill the box
	….	
Conventional Generation	***Type A***	
	….	

17. **<u>If yes & present/future</u>, what is the current/forecasted installed capacity per technology? If you do not have exact numbers, you can also provide growth %'s or just some targets (based on your growth plans).**

		<u>Installed Capacity present (MW)</u>	**<u>Installed Capacity 2030 (MW)</u>**	**<u>Installed Capacity 2040 (MW)</u>**	**<u>Installed Capacity 2050 (MW)</u>**
RES	PV				
	Wind onshore				
	Wind offshore				
	Tidal				
	Wave				
	Biomass				
	Type A				
Conventional Generation	CHP				
	CCGT				
	Coal				
	Type A				

18. If you **<u>do not see</u>** a role to be played in the port ecosystem by some of the aforementioned supply options, please provide a brief comment why.

		<u>Comment</u>
RES	PV	
	Wind onshore	e.g., lack of land availability
	Wind offshore	e.g., lack of offshore wind potential
	Tidal	
	Wave	e.g., not a mature technology, difficult to anticipate its future role
	Biomass	
	Type A	

Conventional Generation	CHP	
	CCGT	e.g., no role for fossil production in 15-20 years
	Coal	
	Type A	

19. **Do you see power production assets as potential flexibility providers? Please specify what kind of flexibility actions can occur (e.g., power curtailment, power increase)?**

		Yes/No	How?
RES	PV		
	Wind onshore		
	Wind offshore		
	Tidal		
	Wave		
	Biomass		
	Type A		
Conventional Generation	CHP		
	CCGT		
	Coal		
	Type A		

20. **The availability of generation time-series is vital for the success of the MAGPIE project. Who owns this data? Please specify the entity and, if possible, a direct contact point.**

		Contact points
RES	PV	
	Wind onshore	
	Wind offshore	
	Tidal	
	Wave	
	Biomass	
	Type A	
Conventional Generation	CHP	
	CCGT	
	Coal	
	Type A	

21. **Is there any open-source access to find this information? (Particularly in the Netherlands/POR)**

Storage & Distribution

22. **Are these storage options relevant in a port environment? Do they already exist in your port (present), just in a future scenario (future) or they are not a possibility (No)? Please indicate other storage technologies that should be considered**

	Relevant? Yes/No	Present/Future/No
BESS	e.g., associated with the OPS system in Rotterdam	
Flywheel		
Type A		

23. **If yes & present/future, what is the current/forecasted storage capacity (power and energy)? If you do not have exact numbers, you can also provide growth % or just some targets (based on your growth plans).**

	Storage Capacity Present (MW/MWh)	Storage Capacity 2030 (MW/MWh)	Storage Capacity 2040 (MW/MWh))	Storage Capacity 2050 (MW/MWh)
BESS				
Flywheel				
Type A				

24. **In your opinion, storage technologies are relevant in all ports? Or there are some characteristics of a port that may better justify an investment on storage technologies?**

25. **Within the MAGPIE project, there will be three demonstrators that will test the full electrification of barges, shunting locomotives, and trucks. Considering this, will battery range limitations affect the charging patterns? And what investments will be needed in terms of recharging infrastructure?**

26. **Is the Port authority the owner of the grid within the port? If not, who is?**

	Grid owner
Electrical distribution grid	

27. **Has the port authority information on grid topology, grid measurements, etc? If not, who has?**

28. **Considering the expected increase in 1) E-demand; 2) RES penetration; 3) Electricity Storage, what are the expected plans in terms of grid expansion (in the port area)?**

Annex B

The BEAM model reduces a given building, considered as a single group, to an equivalent space of one volume, one wall (including all walls, floor, and roof) and one window area. While performing this, the following assumptions are followed:

- Addition of the extensive values, surfaces, solar and thermal irradiations. To be noticed that the addition of solar radiations raises the question of the exposition of the wall
- Conservation of the thermo-physical values, properties of materials (conductivity, thermal volumetric capacity, and volumetric mass, transfer coefficients inside and outside, solar factor…)

Table 11, Table 12 and Table 13 show a complete list of all parameters, inputs and outputs that make part of the BEAM model. Their meaning as well as the corresponding units are also presented.

Table *14* – Parameters of the BEAM model

Parameter ID	Description	Unit
Cm	Internal heat capacity of the building (see ISO 13790-2008 : 12.3)	$J.K^{-1}$
Am	Effective mass area (see ISO 13790-2008 : 12.2.2)	m^2
Af	Conditioned floor area (see ISO 13790-2008 : 6.4)	m^2
Htr_w	Thermal transmission coefficient of doors, windows, curtains walls and glazed walls (see ISO 13790-2008 : ANNEXE A)	$W.K^{-1}$
his	Heat transfer coefficient between the air node Tair and the star node Ts. (default : 3.45 W/m².K)	$W.m^{-2}.K^{-1}$
hms	Heat transfer coefficient between the mass-related node Tm and the star node Ts (default : 9.1 $W/m^{-2}.K^{-1}$)	$W.m^{-2}.K^{-1}$
xat	Ratio between the internal surfaces area and the floor area (Atot = xat*Af) (default : 4.5)	-
Nsurf	Number of surfaces to deal with for passive solar gains /!\ 15 max , restriction of the number of inputs	-
EmMode	0: default ISO original behavior 1: coupling with external radiant heating/cooling floor /!\ With 1, heat transfer between types still to be defined !	-
FreeMode	<True>: calculation of the building temperatures given Phc_nd as an input [Temperatures in outputs OUT(1) to OUT(4) correspond then to this kind of model]	-
AcMode	<True>: calculation of the required power for heating or cooling the building according to set point temperatures Tint_Hset and Tint_Cset (PAR(12) and PAR(13)) [Temperatures in outputs OUT(1) to OUT(4) correspond to this kind of model only if "FreeMode" mode PAR(10) is <False>]	-
Tini	Initial temperature of every nodes of the building	°C

Table *15* – Inputs of the BEAM model

Input ID	Description	Unit
Text	Ambient temperature	°C
Tsup	Temperature of the air supplied in the ventilation system	°C
Phc_nd	Power supplied to the building for heating (>0) or cooling (<0)	$kJ.hr^{-1}$
Pint	Internal passive gains (see ISO 13790-2008 : 10.2)	$kJ.hr^{-1}$
Tint_Hset	Set point temperature for heating the building (AcMode)	°C
Tint_Cset	Set point temperature for cooling the building (AcMode)	°C
Hve	Thermal transmission coefficient due to ventilation (see ISO 13790-2008 : ANNEXE A) /!\ Must be different than 0	$W.K^{-1}$
Htr_op	Thermal transmission coefficient of opaque (inertial) building elements (see ISO 13790-2008 : ANNEXE A)	$W.K^{-1}$
-	NOT TO BE USED YET → 0 (Maybe repartition of the power supplied…To be checked if necessary)	-
Isol	Solar irradiation on surface i	$kJ.hr^{-1}.m^{-2}$
xRad	Ratio of radiative power over total power emitted by space heating distribution component – TO BE CHECKED	-
Fsh_ob	Shading reduction factor from external obstacles for the solar effective collecting area of surface i	-
Asol	Effective collecting area of surface i (see ISO 13790-2008 : 11.3.3 et 11.3.4)	m^2
Ploss GLO	Heat flow due to thermal radiation to the sky from building element i (see ISO 13790-2008 : 11.3.5 et 11.4.6)	$kJ.hr^{-1}$

Table *16* - Outputs of the BEAM model

Output ID	Description	Unit
Tair	Internal air temperature	°C
Tm	Mass-related temperature	°C
Ts	Start temperature	°C
Top	Operative temperature	°C
Psol	Global Passive solar gains	$kJ.hr^{-1}$
Pia	Passive gains to the air node	$kJ.hr^{-1}$
Pm	Passive gains to the mass-related node	$kJ.hr^{-1}$
Pst	Passive gains to the star node	$kJ.hr^{-1}$

PstHF	Passive gains to the heating floor (only when HeatEmitterType=1) [This power is NOT withdrawn to the global heat balance of the building]	$kJ.hr^{-1}$
Phc_nd_ac	AcMode = <True>: Required heating (>0) and cooling (<0) power AcMode = <False>: Received heating (>0) and cooling (<0) power	$kJ.hr^{-1}$