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Spatial Feasibility and Infrastructure Requirements for E-Fuel Supply Chains in Ports

Master's thesis within Department of Environmental and Energy Sciences

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Abstract

Ports are expected to play a central role in maritime decarbonisation by receiving, producing, storing, and supplying low-carbon marine fuels. However, limited port land, competing activities, and the safety requirements associated with hazardous fuels may constrain the development of these supply chains. A systematic understanding of their infrastructure and land requirements is therefore essential for early-stage port planning. This thesis aims to quantify the infrastructure requirements of e-methanol and e-ammonia supply chains and assess whether they can be spatially accommodated within the Port of Gothenburg.

A demand-based spatial sizing framework was developed and implemented in MATLAB to connect the port's annual fuel demand with the sizing of storage tanks, transfer and bunkering facilities, synthesis plants, electrolyzers, renewable electricity supply, and hydrogen storage. Four scenarios were evaluated, combining e-methanol and e-ammonia with 25% and 100% energy-equivalent replacement of the port's conventional marine-fuel demand. Each scenario was assessed as either an import and distribution hub or an on-site production hub, using engineering calculations, hourly wind-generation and terminal-inventory data, spatial analysis of available port land, and sensitivity analysis.

The import hubs require 13.44 to 33.18 hectares of net land, or 18.14 to 44.79 hectares after accounting for supporting infrastructure, and all four scenarios can fit within the existing or near-term expanded port area. The production hubs require substantially more land, ranging from 69.36 to 316.61 hectares net and from 93.64 to 427.42 hectares with the supporting-infrastructure allowance; the electrolyser is the largest onshore component in every production scenario. Methanol is more spatially efficient for import hubs, whereas ammonia is more compact for production hubs because it does not require a carbon-capture facility. The results show that large-scale e-fuel import, distribution, and bunkering are spatially feasible at the Port of Gothenburg, while fully integrated on-site production generally requires land-intensive components, particularly electrolyzers, to be located outside the port and connected by pipeline. Neither fuel has a universal spatial advantage, because the preferred option depends on the hub configuration, demand level, safety requirements, and feedstock pathway. The framework provides a transparent and adaptable method for screening e-fuel infrastructure needs in other ports, while detailed investment decisions will require site-specific safety assessments, land-use planning, and cost analysis.

Keywords: e-fuels, e-methanol, e-ammonia, port infrastructure, bunkering, spatial feasibility, land use, infrastructure sizing, maritime decarbonisation, Port of Gothenburg.

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Acronyms

Below is a list of acronyms used throughout the thesis listed in alphabetical order:

AEGL	Acute Exposure Guideline Levels
AEL	Alkaline Electrolyzer (Pressurized Alkaline Electrolyzers)
AET	Acoustic Emission Testing
ALARP	As Low As Reasonably Practicable
ASU	Air Separation Unit
BOG	Boil-Off Gas
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
DWDI	Double-Wall, Double-Integrity
EIGA	European Industrial Gases Association
ESD	Emergency Shutdown
FEED	Front-End Engineering Design
FR	Fully Refrigerated
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IDLH	Immediately Dangerous to Life or Health
IEA	International Energy Agency
LFL	Lower Flammability Limit
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LRC	Lined Rock Caverns
LTCS	Low Temperature Carbon Steel
MGO	Marine Gas Oil
MSD	Methanol Synthesis and Distillation
NDT	Non-Destructive Testing
NFL	National Fertilizers Limited
NR	Non-Refrigerated
OSHA	Occupational Safety and Health Administration
OTS	Onshore-to-Ship
PDIL	Projects and Development India Ltd
PEM	Proton Exchange Membrane

PSA	Pressure Swing Adsorption
PV	Photovoltaic
QRA	Quantitative Risk Assessment
RBI	Risk-Based Inspection
RWGS	Reverse Water-Gas Shift
SCC	Stress Corrosion Cracking
SIMOPS	Simultaneous Operations
SOEC	Solid Oxide Electrolyser Cell
SR	Semi-Refrigerated
STS	Ship-to-Ship
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
TTS	Truck-to-Ship
VLGC	Very Large Gas Carrier
WTW	Well-to-Wake

Nomenclature

Below is the nomenclature of parameters used throughout this thesis.

Parameters

Demand Characterisation

m_{mgo}	Annual MGO demand [ton/yr]
h_{total}	Temporal baseline / hours per year [hr/yr]
t_{buffer}	Safety buffer duration, e-fuel [days]
$t_{\text{buffer,H2}}$	Safety buffer duration, hydrogen [days]
f_{heel}	Tank heel fraction [-]
f_{amm}	Ammonia mix fraction (future fuel mix) [-]
f_{meth}	Methanol mix fraction (future fuel mix) [-]
f_i	Fuel-specific mix fraction for fuel i [-]
M_i	Volumetric multiplier for fuel i relative to MGO [-]
$V_{\text{annual},i}$	Annual volume of fuel i [m ³ /yr]
ρ_i	Density of fuel i [kg/m ³]
LHV_i	Lower heating value of fuel i [MJ/kg]
ρ_{mgo}	MGO density [kg/m ³]
LHV_{mgo}	MGO lower heating value [MJ/kg]
ρ_{meth}	Methanol density [kg/m ³]
LHV_{meth}	Methanol lower heating value [MJ/kg]
$\rho_{\text{amm,FR}}$	Ammonia density, refrigerated [kg/m ³]
LHV_{amm}	Ammonia lower heating value [MJ/kg]
$\rho_{\text{amm,pipe}}$	Ammonia density, pressurised (pipeline) [kg/m ³]

Asset Inventory and Daily Reactant Demands

M_{meth}	Molecular weight of methanol (CH ₃ OH) [g/mol]
M_{amm}	Molecular weight of ammonia (NH ₃) [g/mol]
M_{H2}	Molecular weight of hydrogen (H ₂) [g/mol]
M_{CO2}	Molecular weight of carbon dioxide (CO ₂) [g/mol]
M_{N2}	Molecular weight of nitrogen (N ₂) [g/mol]
M_{H2O}	Molecular weight of water (H ₂ O) [g/mol]
M_{O2}	Molecular weight of oxygen (O ₂) [g/mol]
ΔH_{298K}	Standard reaction enthalpy at 298 K [kJ/mol]

$\eta_{\text{yield, meth}}$	Methanol yield factor [-]
$\eta_{\text{yield, amm}}$	Ammonia yield factor [-]
$\dot{m}_{\text{fuel, daily}}$	Daily fuel production mass flow [kg/day]
$\dot{m}_{\text{reactant}}$	Daily mass flow of a reactant feed stream [kg/day]
$r_{\text{reactant, fuel}}$	Stoichiometric reactant-to-fuel mass ratio [kg/kg]
$r_{\text{CO}_2, \text{meth}}$	Stoichiometric CO ₂ -to-methanol mass ratio [kg CO ₂ /kg MeOH]
$r_{\text{H}_2, \text{meth}}$	Stoichiometric H ₂ -to-methanol mass ratio [kg H ₂ /kg MeOH]
$r_{\text{H}_2, \text{amm}}$	Stoichiometric H ₂ -to-ammonia mass ratio [kg H ₂ /kg NH ₃]
$r_{\text{N}_2, \text{amm}}$	Stoichiometric N ₂ -to-ammonia mass ratio [kg N ₂ /kg NH ₃]
$r_{\text{H}_2\text{O}, \text{H}_2}$	Stoichiometric H ₂ O-to-H ₂ mass ratio (electrolysis) [kg H ₂ O/kg H ₂]
$r_{\text{O}_2, \text{H}_2}$	Stoichiometric O ₂ -to-H ₂ mass ratio (electrolysis) [kg O ₂ /kg H ₂]
Fuel Storage and Tank Sizing	
V_{working}	Working tank volume [m ³]
V_{pkt}	Nominal vessel packet volume [m ³]
$V_{\text{pkt, amm}}$	Ammonia VLGC packet volume [m ³]
$V_{\text{pkt, meth}}$	Methanol carrier packet volume [m ³]
$V_{\text{pkt, mgo}}$	MGO carrier packet volume [m ³]
$f_{\text{max, mgo}}$	MGO maximum tank fill fraction [-]
$f_{\text{max, meth}}$	Methanol maximum tank fill fraction [-]
$f_{\text{max, amm}}$	Ammonia maximum tank fill fraction [-]
f_{eff}	Effective usable tank volume fraction [-]
V_{max}	Maximum single-tank volume, MGO/methanol [m ³]
$V_{\text{max, amm}}$	Maximum single-tank volume, ammonia (FR) [m ³]
$V_{\text{geom, tot}}$	Total geometric tank volume required [m ³]
n_{tanks}	Number of tanks required [-]
V_{req}	Required working volume per tank [m ³]
V_{geom}	Geometric volume of a single tank [m ³]
$R(V)$	Empirical height-to-diameter (H/D) ratio as a function of volume [-]
R_{roof}	H/D ratio, fixed-roof tanks (MGO/methanol) [-]
R_{flat}	H/D ratio, flat-bottom refrigerated tanks (ammonia DWDI) [-]
a, b	Fuel-specific empirical regression coefficients (H/D fit) [-]
D_{inner}	Tank inner diameter [m]
D_{out}	Tank outer diameter [m]
H_{tank}	Tank height [m]
t_{insul}	Annular insulation thickness, ammonia DWDI tanks [m]
h_{bund}	Bund wall height [m]
δ_{shell}	MGO/methanol shell-to-shell gap [m]
$\delta_{\text{shell, amm}}$	Ammonia shell-to-shell gap [m]
δ_{btw}	Between-group spacing [m]
$n_{\text{pg, max}}$	Maximum tanks per containment group [-]
n_{grp}	Number of containment groups [-]
n_t	Number of tanks in a group [-]
$n_{\text{col}, i}, n_{\text{row}, i}$	Number of columns / rows in the layout of group i [-]
c_c	Centre-to-centre tank pitch [m]
$W_{\text{grp}, g}, H_{\text{grp}, g}$	Width / height of containment group g [m]
$W_{\text{farm}}, H_{\text{farm}}$	Width / height of the tank farm hardware envelope (Layer 1) [m]
A_{tanks}	Combined base area of the tanks in a group [m ²]

$V_{\text{liq,req}}$	Required bund containment volume [m ³]
$A_{\text{bund,grp}}$	Bund floor area per containment group [m ²]
$W_{\text{bund,grp}}, H_{\text{bund,grp}}$	Width / height of the bund per containment group [m]
W_{bund}	Total bund width across groups [m]
AR	Bund aspect ratio [-]
s_{bldg}	MGO/methanol safety setback [m]
$s_{\text{bldg,amm}}$	Ammonia (DWDI) safety setback [m]
A_{safety}	Total spatial footprint, safety exclusion (Layer 3) [m ²]
$W_{\text{safety}}, H_{\text{safety}}$	Width / height of safety exclusion envelope (Layer 3) [m]
Distribution: Import Terminal, Bunkering, and Pipeline	
f_{mode}	Share of the annual volume carried by a transport mode [-]
f_{pipe}	Pipeline share of modal split [%]
f_{rail}	Rail share of modal split [%]
f_{truck}	Truck share of modal split [%]
m_{mode}	Annual mass carried by a transport mode [kg]
m_{rail}	Annual mass allocated to rail delivery [kg]
m_{parcel}	Mass of a single delivery parcel [kg]
$V_{\text{parcel,mode}}$	Delivery parcel volume by transport mode [m ³]
$V_{j,\text{store}}$	Volume delivered by mode j , in the stored state [m ³]
ρ_{store}	Fuel density in the stored state [kg/m ³]
ρ_{mode}	Fuel density in the state carried by a given transport mode [kg/m ³]
ρ_{rail}	Fuel density in the state carried by rail [kg/m ³]
d_{op}	Operating days per year [days]
D_{op}	Set of operating days [-]
$t_{\text{hr}}(h)$	Hour of the day at hour h [-]
$d_{\text{day}}(h)$	Calendar day at hour h [-]
n_{trains}	Trains per year [-]
$n_{\text{trains,base}}$	Baseline block-train frequency [1/yr]
V_{truck}	Truck capacity [t/truck]
V_{cart}	Usable volume per rail tank wagon [m ³]
$\dot{V}_{\text{pipe}}$	Continuous pipeline inflow [m ³ /hr]
$\dot{V}_{\text{train}}$	Rail delivery flow rate [m ³ /hr]
$\dot{V}_{\text{truck,hr}}$	Truck delivery flow rate [m ³ /hr]
$V_{\text{rail}}(h), V_{\text{truck}}(h)$	Hourly rail / truck delivery inflow [m ³]
$\kappa(h)$	Accumulated fractional train credit at hour h [-]
$V_{\text{out}}(h)$	Hourly terminal outflow (vessel packet or bunker offtake) [m ³]
$\text{Inv}(h)$	Hourly terminal inventory level [m ³]
V_{shift}	Inventory trajectory shift term [m ³]
$\text{Inv}_{\text{shifted}}(h)$	Shifted (safety-buffer-adjusted) inventory trajectory [m ³]
V_{buffer}	Mandatory e-fuel safety buffer volume [m ³]
$V_{\text{work,req}}$	Required working volume from the simulated trajectory [m ³]
$V_{\text{nom,dynamic}}$	Nominal gross tank volume implied by the simulation [m ³]
$\dot{V}_{\text{daily}}$	Average daily bunker volume [m ³ /day]
Q_{bkr}	Sustained transfer rate at one bunkering position [m ³ /hr]
t_{win}	Daily bunkering operating window [hr]
f_{conn}	Fraction of occupied time spent on connection, purging, documentation and disconnection [-]

$k_{\text{peak,bkr}}$	Non-uniform vessel arrival allowance, bunkering [-]
N_{berth}	Number of bunkering transfer positions [-]
$A_{\text{bunker,hard}}$	Bunkering hardware (manifold) footprint [m ²]
$L_{\text{bunker}}, W_{\text{bunker}}$	Length / width of bunkering hardware footprint [m]
$A_{\text{bunker,safety}}$	Bunkering safety exclusion footprint [m ²]
L_{quay}	Minimum quay frontage [m]
$L_{\text{vessel,max}}$	Length overall of the largest vessel per transfer position [m]
$R_{i,\text{haz}}$	Regulatory hazard separation radius for fuel i [m]
$N_{\text{truck,max}}$	Maximum daily truck handling capacity [-]
N_{bays}	Number of active truck handling bays [-]
t_{ops}	Daily operational window [min]
τ_{truck}	Vehicle handling turnaround time [min]
$L_{\text{truck}}, W_{\text{truck}}$	Length / width of the truck loading bay [m]
$A_{\text{truck,hard}}$	Truck reception bay footprint [m ²]
$A_{\text{truck,safety}}$	Truck reception safety exclusion footprint [m ²]
L_{cart}	Rail tank wagon (cart) length [m]
m_{cart}	Payload of one rail tank wagon [kg]
n_{cart}	Wagons per block train [-]
$n_{\text{cart,max}}$	Maximum wagons per train under the length limit [-]
$L_{\text{train,max}}$	Maximum permitted train length [m]
c_{max}	Loading cycles one siding can complete per operating day [-]
n_{platform}	Number of parallel loading platforms [-]
$L_{\text{rail,wide}}$	Length of the widened rail corridor at the loading platform [m]
$L_{\text{rail,total}}$	Total railway siding length [m]
$W_{\text{rail,base}}, W_{\text{rail,wide}}$	Rail corridor width, baseline / widened at platform [m]
$A_{\text{rail,hard}}$	Rail siding hardware footprint [m ²]
$A_{\text{rail,safety}}$	Rail reception safety exclusion footprint [m ²]
$\dot{m}_{j,\text{daily}}$	Daily mass flow in fluid stream j [kg/day]
$\dot{m}_{\text{nom},j}$	Nominal mass flow in fluid stream j [kg/s]
$\dot{m}_{\text{max},j}$	Peak mass flow in fluid stream j [kg/s]
k_{peak}	Intermittent peak flow factor [-]
$Q_{\text{max},j}$	Peak volumetric flow in pipeline j [m ³ /s]
$A_{\text{req},j}$	Required cross-sectional area of pipeline j [m ²]
$D_{\text{pipe},j}$	Diameter of pipeline j [m]
v_{amm}	Ammonia (pressurised liquid) pipeline design velocity [m/s]
v_{meth}	Methanol (liquid) pipeline design velocity [m/s]
v_{water}	Water (liquid) pipeline design velocity [m/s]
v_{H2}	Hydrogen (compressed gas) pipeline design velocity [m/s]
ρ_{water}	Water density [kg/m ³]
$\rho_{\text{H2,pipe}}$	Hydrogen density at pipeline conditions [kg/m ³]

Synthesis Plant Sizing

s_{dac}	DAC space requirement [m ² /(t CO ₂ /yr)]
E_{dac}	DAC specific energy demand [kWh/t CO ₂]
A_{dac}	DAC unit spatial footprint [ha]
P_{dac}	DAC unit power demand [GW]
$s_{\text{meth,plant}}$	Methanol synthesis plant space factor [m ² /tph]
$E_{\text{meth,plant}}$	Methanol synthesis plant specific energy [MWh/t]

$A_{\text{meth,plant}}$	Methanol synthesis plant spatial footprint [ha]
$P_{\text{meth,plant}}$	Methanol synthesis plant power demand [MW]
$s_{\text{amm,plant}}$	Haber–Bosch plant space demand [m ² /tph]
$E_{\text{amm,plant}}$	Haber–Bosch specific energy, synthesis loop only [MWh/t]
$A_{\text{amm,plant}}$	Haber–Bosch plant spatial footprint [ha]
$P_{\text{amm,plant}}$	Haber–Bosch plant power demand [MW]
E_{ASU}	ASU specific energy demand [MWh/t NH ₃]
P_{ASU}	ASU power demand [MW]
Renewable Production: Wind and Electrolyser Sizing	
η_{Alk}	Alkaline electrolyser specific energy [kWh/kg H ₂]
s_{Alk}	Alkaline electrolyser footprint ratio [m ² /(kg/day)]
η_{PEM}	PEM electrolyser specific energy [kWh/kg H ₂]
s_{PEM}	PEM electrolyser footprint ratio [m ² /(kg/day)]
η_{SOEC}	SOEC electrolyser specific energy [kWh/kg H ₂]
s_{SOEC}	SOEC electrolyser footprint ratio [m ² /(kg/day)]
η_e	Electrolyser specific energy demand [kWh/kg H ₂]
E_{min}	Thermodynamic minimum specific energy, electrolysis [kWh/kg H ₂]
$P_{\text{wind}}(h)$	Hourly wind farm output [MW]
$P_{\text{norm}}(h)$	Hourly output normalised to peak capacity [%]
P_{sort}	Hourly output sorted in descending order (duration curve) [MW]
C_{peak}	Maximum measured wind farm output, adopted here in place of rated capacity [MW]
E_{annual}	Annual wind energy yield [MWh]
CF	Wind resource annual capacity factor [–]
f_{usable}	Usable fraction of the generation series at the capacity ratio [–]
r	Electrolyser-to-wind capacity ratio, $C_{\text{elyz}}/C_{\text{wind}}$ [–]
r_{base}	Selected baseline electrolyser-to-wind capacity ratio [–]
$P_{\text{limit}}(r)$	Electrolyser absorption ceiling at ratio r [GW]
$E_{\text{usable}}(r)$	Usable fraction of annual wind energy absorbed by the electrolyser [GWh]
$E_{\text{export}}(r)$	Excess wind energy available for grid export [GWh]
E_{req}	Required annual electrolyser energy input [GWh]
$E_{\text{req},f,e}$	Required annual energy input for fuel f , electrolyser e [GWh]
C_{elyz}	Electrolyser nameplate capacity [GW]
$C_{\text{elyz},f,e}$	Electrolyser capacity for fuel f , technology e [GW]
C_{wind}	Wind farm nameplate capacity [GW]
$C_{\text{wind},f,e}$	Wind farm capacity for fuel f , electrolyser e [GW]
A_{elyz}	Electrolyser spatial footprint [ha]
Hydrogen Buffer Storage	
$P_{\text{H2}}(d)$	Daily hydrogen mass production at capacity ratio r [kg/day]
$\dot{m}_{\text{H2,daily}}$	Daily hydrogen mass demand (synthesis plant) [kg/day]
$\dot{n}(d)$	Net daily hydrogen flow (production minus demand) [kg/day]
$C(d)$	Cumulative net hydrogen flow trajectory [kg]
$S(d)$	Shifted (buffer-adjusted) cumulative flow trajectory [kg]
V_{buf}	Minimum mandatory hydrogen buffer volume [kg]
$t_{\text{min,buf}}$	Minimum buffer duration [days]
V_{tank}	Required hydrogen buffer tank capacity [kg]
M_{onsite}	Hydrogen mass held on site at the terminal [kg]

$M_{\text{sphere,max}}$	Maximum commercially viable LH ₂ sphere capacity [t]
N_{sphere}	Number of LH ₂ spheres [-]
ρ_{LH2}	Liquid hydrogen density [kg/m ³]
t_{wall}	LH ₂ sphere wall thickness [m]
V_{sphere}	LH ₂ sphere volume [m ³]
N_{grp}	Number of LH ₂ sphere groups [-]
$W_{\text{grp},i}, L_{\text{grp},i}$	Width / length of LH ₂ sphere group i [m]
$W_{\text{pad}}, L_{\text{pad}}$	Width / length of consolidated hardware pad [m]
$d_{\text{inter}}, d_{\text{intra}}$	LH ₂ tank spacing, between- / within-group [m]
S_{LH2}	LH ₂ safety setback distance [m]
S_{GH2}	GH ₂ safety setback distance [m]
$A_{\text{sphere,hard}}$	LH ₂ sphere hardware footprint [m ²]
$A_{\text{sphere,safety}}$	LH ₂ sphere safety exclusion footprint [m ²]
λ_{pipe}	GH ₂ pipeline linear storage capacity [t/km]
D_{pipe}	GH ₂ pipeline diameter [m]
L_{pipe}	GH ₂ pipeline length, local storage option [km]
$A_{\text{pipe,hard}}$	GH ₂ pipeline hardware footprint [m ²]
$A_{\text{pipe,safety}}$	GH ₂ pipeline safety exclusion footprint [m ²]
Footprint Aggregation and Spatial Assessment	
$A_{\text{safety},j}$	Safety exclusion footprint of asset j [m ²]
f_{pack}	Gross-to-net packing factor [-]
A_{gross}	Gross site area after the packing factor [m ²]

AI Assistance Statement

Generative AI technologies, namely Claude, ChatGPT, and Gemini, served solely as linguistic aids during the preparation of this thesis. They were applied exclusively to improve grammar, spelling, and sentence flow. The core technical research, data analysis, and conclusions are my own intellectual property. All AI-supported phrasing was rigorously reviewed and edited before submission.

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1

Introduction

The maritime sector is undergoing a major transition as it works to reduce greenhouse gas emissions and meet increasingly strict global climate targets. One of the primary strategies for deep decarbonisation within the industry is the large-scale adoption of sustainable alternative fuels. These alternatives, often referred to as e-fuels, include e-methanol, e-ammonia, synthetic methane and hydrogen-based derivatives. Because they are produced using renewable electricity, they are expected to play a critical role in enabling low-carbon shipping operations.¹

There are several strategic reasons to supply e-fuels at ports. The shipping industry itself represents a significant potential demand for sustainable fuels, so a port equipped to handle fuel exports while also offering bunkering services creates dual-purpose infrastructure. Because sustainable fuels have a lower energy density than conventional options, ships will need to refuel more frequently or carry more fuel, which opens opportunities for new port regions to gain a foothold in the future bunkering market. And because cheap renewable energy is often produced in regions remote from global demand centres, international trade in sustainable fuels will rely heavily on ports acting as import and export facilities.²

Ports are therefore expected to move from logistics and cargo handling nodes to integrated energy hubs that receive, produce, store, transfer and bunker alternative fuels. Implementing such systems introduces significant new challenges. Ports operate within limited land areas, face strict spatial constraints, and must adhere to rigorous safety regulations on the handling of hazardous materials. These new infrastructure requirements must also be integrated without disrupting existing logistics operations.³

Despite the growing consensus on the necessity of e-fuels, there remains a limited understanding of the physical infrastructure requirements and spatial implications of implementing these supply chains within active port environments. The studies reviewed in Chapter 2 either size individual components without aggregating them into a port-level land demand, or report a single facility footprint without exposing the parameters behind it, and none tests an aggregated requirement against the land a specific port actually has. This thesis addresses that gap by evaluating whether ports can spatially accommodate future e-fuel demand.

The purpose of this thesis is to quantify and dimension the infrastructure requirements for enabling e-fuel supply chains within port environments. The study addresses the following research questions:

RQ1. How much physical infrastructure (facilities, equipment, land, and space) is required to support different e-fuel supply chains in port environments?

RQ2. What are the associated infrastructure sizing requirements for key components such as the synthesis plant, storage tanks, transfer systems, and bunkering facilities?

RQ3. To what extent can the Port of Gothenburg spatially accommodate the infrastructure required for e-fuel production, storage, transfer, and bunkering operations?

The framework developed to answer these questions is applied to the Port of Gothenburg as a reference case. Four demand scenarios are evaluated, combining two fuels, e-methanol and e-ammonia, with two market-penetration levels, and each is assessed under two hub configurations: an import and distribution hub that receives fuel produced elsewhere, and an integrated hub that produces it on site from renewable electricity. The resulting footprints are tested against the undeveloped land parcels the port actually holds.

The system boundary for this thesis is strictly limited to the port level. The study evaluates the port's potential as an energy hub, particularly with regard to shipping demand, analysing the spatial and physical requirements of key internal infrastructure components. These components include fuel production facilities (where applicable), onsite storage tank farms, internal transfer infrastructure, safety zoning, and bunkering equipment. The modelling relies on static engineering calculations and spatial feasibility assessments to determine infrastructure sizing. The underlying calculations rely on specifications and operational assumptions obtained from current literature and publicly available industry sources. These values are subject to variation depending on future technological developments and site-specific conditions. With the improvement of data accuracy, this approach allows for the development of a standardized calculation framework that can be adapted and applied to evaluate e-fuel infrastructure feasibility in different ports globally. By providing a framework to support the implementation of e-fuel infrastructure, the project directly contributes to enabling low-carbon maritime systems and reducing greenhouse gas emissions from global shipping.

The remainder of the thesis is structured as follows. Chapter 2 reviews the fuels, the infrastructure components and the existing spatial studies. Chapter 3 defines the sizing framework. Chapter 4 applies it to the Port of Gothenburg and bounds the parameter uncertainty. Chapter 5 answers the research questions, and Chapter 6 interprets the results and states what they can support.

2

Literature Review

2.1 Maritime Decarbonization and E-fuels

Maritime decarbonization will require a portfolio of low-carbon energy options, including biofuels, renewable electricity, hydrogen, and electricity-based fuels. Among these options, e-fuels are particularly relevant for long-distance shipping because they can provide high-energy-density alternatives where direct electrification is difficult. E-fuels are synthesized using renewable electricity, typically through water electrolysis to produce green hydrogen, followed by a synthesis step that yields the final energy carrier, such as e-methanol, e-ammonia, e-diesel, or synthetic methane.⁴ This thesis focuses on e-methanol and e-ammonia because their large-scale adoption would require substantial new production, storage, transfer, and bunkering infrastructure in ports.

Producing these fuels at a port requires more than the synthesis plant itself. Each pathway draws on three feedstock streams, and each stream carries its own infrastructure. Green hydrogen is produced on site by water electrolysis, which requires a dedicated renewable electricity supply, a water supply and treatment train, and intermediate hydrogen storage to bridge variable production to continuous synthesis demand. Carbon dioxide for the methanol pathway is captured either from the atmosphere by direct air capture or from a nearby point source, the latter adding a transport link and receiving facilities at the port. Nitrogen for the ammonia pathway is separated from air by a cryogenic air separation unit, which is normally integrated with the synthesis loop. Oxygen is produced as a co-product of electrolysis and requires either an offtake or a vent system.

Currently, E-LNG/bio-LNG and biodiesel/e-diesel are the most prominent alternatives, with dual-fuel Liquefied Natural Gas (LNG) engine technology now considered a fully mature option. With 1 539 LNG-capable ships currently in operation and another 966 on order as of August 2025, the industry has already solved many of the technical hurdles for these fuels.⁵

In contrast, technologies for E-Methanol and E-Ammonia represent potential pathways toward a carbon-neutral fleet but remain in the development or early trial phases. While the methanol-capable fleet is growing rapidly with 70 vessels in operation and 336 on order, ammonia-fuelled technology is still under development with only 3 vessels currently

in operation and a single dedicated bunkering facility globally.⁵

Scaling these options is time-critical because of asset lifetimes. Infrastructure and vessels in shipping typically remain in operation for 30 to 70 years, so the investment decisions taken in this decade determine whether capital is redirected toward low-emission technologies or locked into assets that risk becoming stranded.⁶

In a future global energy market, e-fuels are expected to act as carriers that move renewable electricity between regions in molecular form, converting it into transportable synthetic molecules that can be shipped over long-distance routes. This changes the pattern of global energy trade, allowing resource-rich areas such as South America, sub-Saharan Africa, and the MENA region to emerge as primary energy exporters, while densely populated, industrialized regions such as Europe and Japan become the major importers.⁷

2.2 Supplying E-fuels for Shipping at Ports

Supplying hydrogen and e-fuels at port areas is a strategic imperative for the clean energy transition, primarily because ports serve as a point where offshore renewable energy, electricity grids, and diverse transport sectors converge. By hosting electrolysis and e-fuel conversion infrastructure, ports can transform volatile renewable electricity into stable, transportable energy carriers such as hydrogen, ammonia, and methanol.⁸

This role is further strengthened by the high concentration of marine fuel demand and bunkering activities at ports, and by their function as multi-modal hubs connecting sea, rail, road, and industrial hinterlands. Industrial clustering within ports also provides opportunities for industrial symbiosis, where waste heat, carbon capture, and fuel distribution can be shared among port tenants.⁸

The physical and chemical properties of alternative fuels dictate the infrastructure requirements for port energy hubs. Marine Gas Oil (MGO) is adopted throughout this thesis as the reference fuel against which all e-fuel volumes, footprints, and emissions reductions are benchmarked, as its 0.10% sulfur content aligns with modern environmental standards and provides a more future-proof conventional baseline than Heavy Fuel Oil (HFO) (3.45% sulfur), whose continued use increasingly depends on scrubber technology facing tightening geographical restrictions^{9,10}.

Table 2.1 compares the primary e-fuels under consideration against this MGO baseline, highlighting the differences in energy density, storage conditions, and safety profiles that drive the infrastructure requirements developed in the remainder of this chapter. The table is the single numerical reference for fuel properties in this thesis; the process chemistry, feed-stock routes, and detailed hazard descriptions behind each fuel are given in Appendix A.1

to Appendix A.3.

Table 2.1: Comparative characteristics of E-fuels and MGO baseline.

Parameter	E-Methanol	E-Ammonia	E-LNG	Hydrogen	MGO
WTW Power (MJ/MJ)	6.5	4.2	6.1–6.2	5.0	2.4
LHV (MJ/kg)	19.9	18.6	49.2	120	42.7
Ambient density (kg/m ³)	786.3	0.6943	–	0.0824	810 – 890
Liquid density (kg/m ³)	786.3	602.8, 681.97	410–500	70.8	810 – 890
Storage temp (°C)	25	25, –33	–161	–253	15
Storage pressure (bar)	1	10, 1	1	1	1
Storage BOG (%/day)	0.00032	0.01	0.076	0.2	–
Loading BOG (%/day)	0.01667	0.022	0.170	1.3	–
GHG reduction vs. MGO (%)	99	94	88–98	100	–
Safety Class	Toxic / Corrosive / Flammable	Toxic / Corrosive	Cryogenic / Flammable	Cryogenic / Flammable / Explosive	–

Sources: Well-to-Wake (WTW) power, LHV and GHG reduction for all fuels, and hydrogen density and storage conditions [1, 11]; E-LNG density and storage conditions [12]; MGO density and storage conditions [13]; methanol density [14] and storage conditions [15]; ammonia densities and storage conditions [16–18]; all storage and loading boil-off values [19]; safety classes [20, 21]. Ammonia is listed at both its pressurised (10 bar, ambient) and fully refrigerated (–33°C, atmospheric) conditions.

Hydrogen. E-Hydrogen is both a high-potential zero-emission fuel and the fundamental chemical feedstock for e-methanol and e-ammonia, offering up to 100% WTW GHG reduction as a standalone fuel^{1,22}. However, its low volumetric density requires cryogenic liquefaction (Table 2.1), which is markedly more energy-intensive than e-ammonia synthesis and demands entirely new vessel designs, bunkering infrastructure, and crew training¹. Its extreme volatility and flammability compound these logistical hurdles^{20,21}. For these reasons, while hydrogen’s role as a precursor to the other e-fuels is central to this thesis, its direct use as a marine propulsion fuel is not further investigated (Appendix A.1).

E-Methanol. E-Methanol can be stored and bunkered much like conventional diesel, allowing much existing infrastructure to be converted rather than replaced¹. It delivers a 99% WTW GHG reduction versus MGO and the lowest boil-off rates of the fuels considered (Table 2.1), at the cost of high renewable-electricity intensity (6.5 units of electricity per unit of propeller energy on a WTW basis)^{1,19}. E-methanol is produced by

hydrogenating captured CO_2 with green hydrogen, most simply via the direct reaction $\text{CO}_2 + 3\text{H}_2 \rightleftharpoons \text{CH}_3\text{OH} + \text{H}_2\text{O}$ ($\Delta H_{298\text{K}} = -49.16 \text{ kJ/mol}$), at an overall process efficiency of 69–89%²². It is classified as highly flammable and acutely toxic, and is corrosive to standard fuel-system metals and elastomers, requiring dedicated material compatibility and ignition-control measures²⁰. The full reaction set and the associated hazard detail are given in Appendix A.2.

E-Ammonia. E-Ammonia forms no CO_2 on combustion and yields a 94% WTW GHG reduction versus MGO, with a higher volumetric energy density than liquid hydrogen¹. It requires storage volumes roughly three times, and weights roughly twice, those of an equivalent MGO cargo, and can be held either pressurised (~ 8 bar, ambient temperature) or fully refrigerated (-33°C)^{1,17}. It is synthesised via the Haber–Bosch reaction, $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$ ($\Delta H_{298\text{K}} = -92.28 \text{ kJ/mol}$), at an overall efficiency of 61–79%²². Ammonia’s high reactivity and acute toxicity mean its marine use is strictly governed by the IGC Code, though dedicated ISO/IMO safety codes for ammonia-burning engines remain under development²⁰. Because ammonia is listed at two densities in Table 2.1, the convention applied in the sizing chain is stated explicitly in Appendix A.3: the refrigerated density is used for all bulk storage, and the pressurised density only for non-refrigerated road and rail containment.

Synthetic Methane (E-LNG). E-LNG is fully blendable with fossil LNG and usable in existing vessels and infrastructure without modification, offering 88–98% GHG reduction depending on engine type, but it suffers the highest boil-off rates of the fuels considered and retains the same methane-slip challenge as fossil LNG^{1,12,19}. Given its high degree of infrastructure readiness and regulatory maturity relative to methanol and ammonia, E-LNG is excluded from further analysis, as this thesis focuses on the less-developed alternative fuel pathways.

Beyond the spatial drivers introduced above, estimating the infrastructure footprint of these fuels at a port is challenging for two compounding reasons: port land is inherently limited and contested among existing tenants, and the different e-fuels imply markedly different material flows, storage conditions, safety requirements, and land footprints because of their differing physical and chemical properties (Table 2.1). This combination of scarce land and fuel-specific spatial penalties motivates the systematic spatial feasibility methodology developed in Chapter 3.

2.2.1 Global Bunkering Volumes and E-fuel Targets

Understanding current global bunkering volumes is essential for assessing the feasibility of e-fuel implementation in ports, as these figures establish the baseline volumes and energy demand that sustainable alternatives must eventually offset (Table 2.2). Because e-fuels possess significantly lower energy densities than MGO, replacing existing fossil volumes

will require substantially larger storage capacities, directly impacting the sizing of on-site tanks, transfer systems, and safety zones.

Table 2.2: 2024 Global Top 10 Bunkering Ports by Volume²³

Rank	Port Name	2024 Volume (T)	Strategic Region
1	Singapore	54.92×10^6	Asia-Pacific
2	Rotterdam	9.80×10^6	Europe
3	Fujairah	7.50×10^6	Middle East
4	Zhoushan	7.26×10^6	Asia-Pacific
5	Antwerp-Bruges	6.51×10^6	Europe
6	Busan	6.24×10^6	Asia-Pacific
7	Hong Kong	5.70×10^6	Asia-Pacific
8	Panama	5.10×10^6	Americas
9	Gibraltar	4.77×10^6	Europe
10	Shanghai	4.13×10^6	Asia-Pacific

Against this baseline, several ports and maritime regions have announced concrete e-fuel targets. The Port of Gothenburg, the reference port modelled in this thesis with a conventional bunkering volume of 1.7 million tonnes annually, has ambitions to become the primary Northern European hub for renewable methanol bunkering²⁴. Broader market projections indicate a methanol share of approximately 13.4%²⁵, while ammonia is expected to constitute 25–45% of the future marine fuel mix^{25–27}. Comparable ambitions elsewhere, including Rotterdam’s target of 4.6 Mtpa of hydrogen handling by 2030, Singapore’s push to secure over 1 Mtpa of low-carbon methanol supply by 2030, and Antwerp-Bruges’s target of importing 1 Mtpa of hydrogen equivalents by 2030, illustrate that the scale modelled here is representative of a broader industry trend rather than a Gothenburg-specific outlier^{28–30}. The composition of these targets and the corresponding 2050 ambitions are set out in Appendix A.4.

The feasibility of supplying these volumes of e-fuels at ports is not purely techno-economic but also spatial: the required infrastructure must physically fit within the port’s land parcel, operate within mandatory safety setbacks, and integrate without disrupting existing cargo and vessel operations.

2.2.2 Infrastructure System Configuration

The study evaluates two port-based e-fuel supply configurations. Scenario I represents an e-fuel import and distribution hub, where imported e-fuel is stored and bunkered. Scenario II represents an integrated Power-to-X (PtX) production hub that additionally includes renewable electricity supply, electrolysis, hydrogen buffering, and CO₂ or N₂ feedstock production, and e-fuel synthesis. Both configurations include fuel storage, internal transfer,

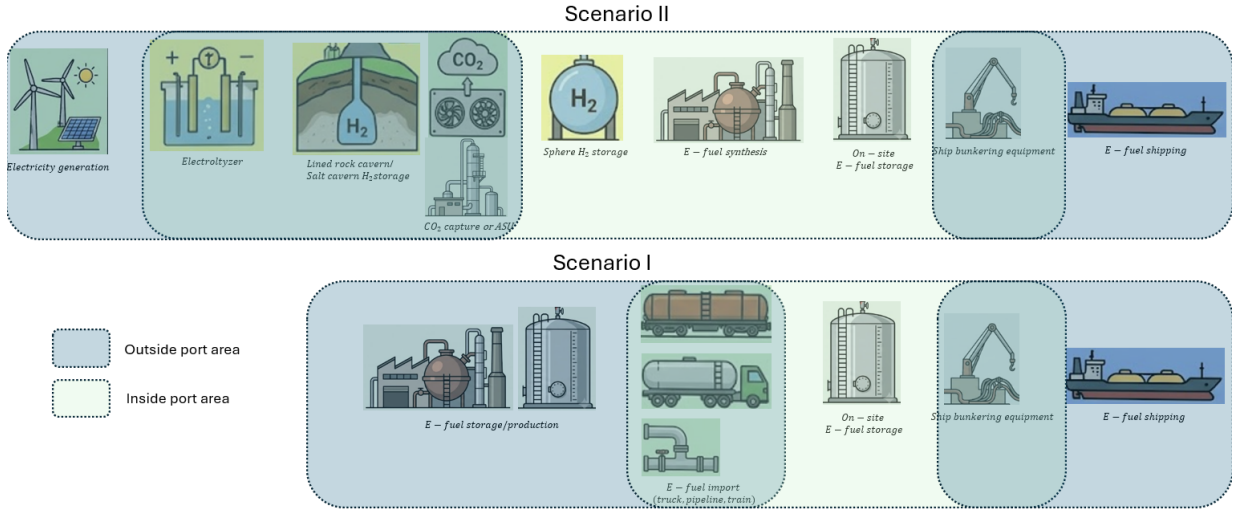


Figure 2.1: Overview of the port e-fuel supply chain and the two hub configurations evaluated in this thesis.

and shore-side bunkering infrastructure. Figure 2.1 shows the location of each component relative to the port boundary. Electrolysers, H_2 storage cavern and DAC units may be located inside or outside the port, depending on land availability.

E-Fuel Import and Distribution Hub. This scenario evaluates the port functioning as a distribution and refuelling node for fuel produced off-site. The configuration includes receiving terminals, storage tank farms, internal transfer systems, and the final bunkering interfaces, but excludes hydrogen and e-fuel production, and e-fuel dehydrogenation.

On-site H_2 and E-Fuel Production Hub. Hydrogen is produced from renewable electricity and converted on site into e-methanol or e-ammonia. The configuration includes electrolysis, hydrogen buffering, CO_2 or N_2 supply, fuel synthesis, storage, internal transfer, and bunkering.

Infrastructure outside the boundary is sized and reported but excluded from the port-area calculation described in Section 3.2, and the infrastructural assessment focuses on e-methanol and e-ammonia.

2.3 Infrastructure Inventory

The infrastructure components examined in this report are categorized based on their impact on spatial planning, energy demand, and safety requirements within a port environment. Components were identified as key parameters if they occupy large physical

footprints, require strict safety exclusion zones, or represent the primary energy-consuming processes of the supply chain.

- **Receiving and Unloading Terminals:** Evaluated across maritime (marine loading arms/hoses), rail (unloading gantries), road, and continuous pipeline modalities to account for the throughput requirements of the scenarios modelled here.
- **On-site Storage Facilities:** Dimensioned based on the distinct thermodynamic requirements of the fuels, including atmospheric tanks for e-methanol, and refrigerated flat-bottom tanks for e-ammonia (modelling focused on flat-bottom tanks given the volumes of fuel passing through the port).
- **Bunkering Systems:** Focused specifically on Onshore-to-Ship (OTS) systems, evaluated as the best operational interface for large-scale energy hubs.
- **Electrolysers:** Proton Exchange Membrane (PEM) technology is evaluated as the primary driver for green hydrogen due to its fast dynamic response for intermittent renewable energy integration^{31,32}.
- **Intermediate Hydrogen Storage and Pipelines:** Evaluated as a critical operational buffer (including liquid spheres and underground salt/lined rock caverns) to bridge intermittent renewable power with steady-state chemical synthesis.
- **Nitrogen Separation:** Cryogenic distillation via Air Separation Units (ASU) is evaluated as the sole viable technology for industrial-scale nitrogen feedstocks.
- **Carbon Dioxide Capture:** Evaluated primarily through DAC and Point-Source CCUS to provide the necessary carbon feedstock for e-methanol.
- **Chemical Synthesis Plants:** The physical footprints and energy demands of the Haber-Bosch reactors (for e-ammonia) and Methanol Synthesis and Distillation units.

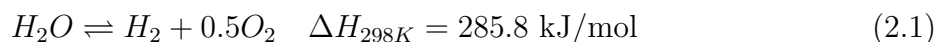
Several supporting systems and alternative technologies were identified during system-boundary definition but are excluded from detailed spatial and energy evaluation, because they are integrated into other processes, are negligible relative to other components, or fall outside the analytical focus of hazardous chemical handling:

- **Desalination Plants:** Consume only ~0.1% of the total electrolysis energy and are negligible in footprint compared to the downstream electrolysers³³.
- **Heat Exchangers, Pumps, and Compressors:** Categorised as Balance of Plant (BoP) and assumed integrated into the aggregated footprint metrics of the reference facilities used in this study (e.g. the Siemens Energy Elyzer and the *React* Bornholm synthesis plant)^{34–36}.
- **Electrical Grid Infrastructure:** Treated as a methodological boundary condition, sufficient electrical capacity is assumed delivered directly to the plant gate, to isolate the spatial footprint of chemical processing from general civil electrical engineering.
- **Alternative Bunkering Modalities (TTS and STS):** Excluded as they lack the capacity, safety scores, and economic viability of OTS at the fuel volumes modelled here³⁷.

- **Alternative Nitrogen Separation (Membrane/PSA):** Excluded as impractical at the gigawatt-scale nitrogen throughput required for a commercial e-fuel hub²².

2.3.1 Electrolyser

Selecting the optimal electrolyser for a port-scale hydrogen plant requires evaluating production capacity, spatial footprint, output pressure, and dynamic response against intermittent renewable supply, beyond just the underlying stack technology (Alkaline, PEM, or Solid Oxide Electrolyser Cell (SOEC)). Water electrolysis splits two water molecules into two hydrogen molecules and one oxygen molecule (Equation 2.1), with a water footprint of about 9 kg of water per kg of hydrogen produced and a reaction enthalpy of 285.8 kJ/mol hydrogen^{22,31}.



To avoid exacerbating freshwater scarcity, indirect seawater electrolysis (commercial desalination coupled with pure-water electrolysis) is the preferred feedstock pathway, as direct seawater electrolysis still faces technical barriers from chloride-induced corrosion and biofouling³³. Desalination energy demand is negligible relative to the downstream electrolysis load (~0.1% of total process energy) and is excluded from the primary sizing models³³. The water supply network feeding the electrolysers is dimensioned assuming a typical flow velocity of 0.9–2.4 m/s in standard steel pipes³⁸.

Ten commercial electrolyser systems spanning Alkaline, PEM, and SOEC architectures were surveyed for production capacity, energy efficiency, output pressure, and physical footprint; the full comparison is given in Appendix A.5, Table A.1. Reported footprint-per-output ratios vary by more than an order of magnitude (0.0075–0.509 m²/(kg/day)), reflecting differences in balance-of-plant integration as much as core stack technology: complete plant solutions (e.g. the Siemens Energy Elyzer, ITM Power ALPHA 50) report substantially larger footprints than isolated modular stacks reported without their balance-of-plant.

Beyond physical footprint and baseline stack specifications, the operational viability and overall efficiency of the hydrogen plant are fundamentally tied to its electrical integration. Because water electrolysis is a highly energy-intensive process, an electrolyser’s dynamic operation must be coupled with the incoming electrical load. When relying on variable renewable energy, the availability, intermittency, and quality of the power supply directly dictate how the electrolyser capacity must be scaled to maximize both hydrogen yield and capital efficiency.

Electricity

For the hydrogen to be officially classified as renewable under European Union frameworks, the electricity used to drive the electrolysis process must come exclusively from renewable

sources³⁹. Furthermore, EU regulations emphasize the principle of additionality, which dictates that large-scale hydrogen production should ideally be paired with the deployment of new renewable energy generation capacity, ensuring that existing green electricity is not simply diverted from the grid³⁹. To achieve this necessary expansion of new capacity, wind and solar power are the two most critical sources. Although hydropower is an essential part of the renewable energy mix in regions such as Sweden, it is largely considered a "built-out" resource; capacity has remained largely unchanged for more than a decade and there is very limited potential for the construction of new plants due to geographical constraints and strict environmental protections⁴⁰. Consequently, building out new wind and solar installations remains the most viable, scalable, and environmentally permissible pathway to secure the massive, newly added electricity supply required for green hydrogen production.

The most cost-effective sizing approach targets an electrolyser capturing at least 80% of available surplus energy, rather than 100% of peak generation, since matching peak output leaves substantial capacity under-utilised⁴¹. Because wind resources are faster, more stable, and have a higher capacity factor (40–50%) than solar, off-grid wind systems can support a substantially higher electrolyser-to-peak-capacity ratio (~60–89.3%) than solar PV (~45–57.7%)⁴¹.

2.3.2 Transportation

Under Scenario I, fuel may arrive and leave a port terminal via four primary modalities: maritime delivery by specialized tanker vessel, inland delivery by rail or road tankers, or continuous supply via pipeline. The applicable modality depends on the geographic situation of the port, its connection to industrial production regions, and terminal volume requirements. The following subsections summarise the representative infrastructure and operational parameters for each mode and fuel; the full underlying reference-fleet survey (vessel classes, railcar and truck specifications by manufacturer, and pipeline throughput benchmarks) is provided in Appendix A.6 to Appendix A.9.

Maritime Delivery

The primary interface between onshore storage and the vessel is typically a marine loading arm or heavy-duty flexible hose system (Figure 2.2).

Ammonia. Ocean-going ammonia deliveries commonly range from 6,300 m³ (mini carriers) up to 80,000 m³ (large Type 2G carriers), with Midsize Gas Carriers (MGCs) typically transporting ~37,000 m³^{343–45}. The DNV pre-feasibility reference vessel of 87,000 m³, which the DNV study uses to size ammonia storage facilities reports an unloading time of approximately three days for a 25,000 ton tanker³⁸.

Methanol. Large-scale ocean transport in vessels of up to 120,000 m³ has been established for over two decades, and the DNV study confirms this as the practical current upper limit, with capacities up to 200,000 m³ considered technically feasible^{38,46}. Smaller



Figure 2.2: A DockReel marine loading hose installation in use. Image sourced from [42].

coastal chemical tankers (1,200–7,000 m³) remain relevant for regional distribution.⁴⁷

Rail Transport

For high-volume inland distribution, bulk liquid commodities are well suited to unit trains, continuously coupled trains moving a single commodity without intermediate switching⁴⁸ (Figure 2.3).



Figure 2.3: A train loading/offloading system. Image sourced from [42].

The dimensioning of rail sidings and train length constraints is anchored in the European Union's Trans-European Transport Network (TEN-T) policy⁴⁹ which establishes standard-

ized infrastructure requirements and mandates that freight transshipment terminals be expanded to accommodate 740-meter long trains. Within terminal infrastructure planning, this TEN-T standard defines the 740-meter operational maximum length for incoming unit trains, which consequently requires that transshipment terminals on the core network be capable of receiving trains of that length. It does not require every receiving siding to be constructed at 740 m. The model therefore builds the siding to the consignment length actually required (Equation 3.50), capped at 740 m to process these trains without creating bottlenecks or missing links in the network.

Ammonia. A DNV pre-feasibility study modelling 200,000 t/yr of ammonia via rail derives a standard 12-car train configuration ($\sim 50\text{--}69$ t payload per car), amounting to approximately 238 trains annually, roughly one per weekday over a 48-week operating year, with each train processed within a single 12-hour shift^{38,50}.

Methanol. High-capacity methanol railcars carry payloads of ~ 73 t (~ 88 m³ usable volume)⁵¹.

Road Transport

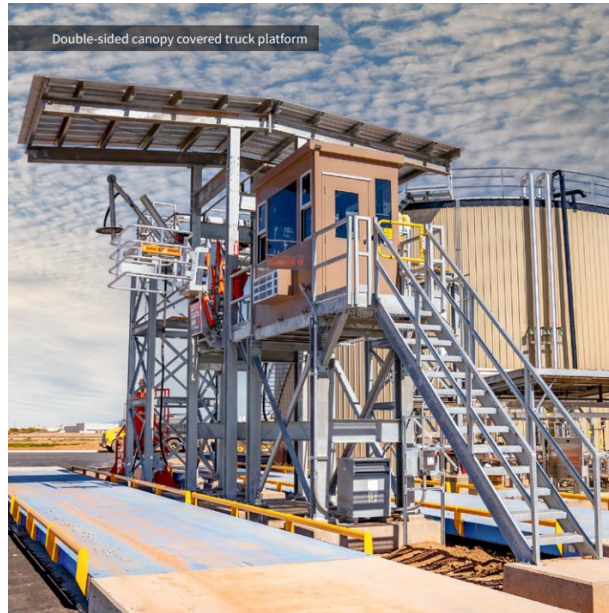


Figure 2.4: A truck loading/offloading system. Image sourced from [42].

Ammonia. A DNV pre-feasibility model handling 100,000 t/yr by road requires $\sim 4,184$ tanker deliveries annually at a standard payload of 23.9 t/vehicle, implying up to 18 trucks per 12-hour shift given a 60–90 minute unloading window per vehicle³⁸.

Methanol. A practical baseline capacity is 30 m³ per trailer⁵², though in practice European gross-vehicle-weight limits (40 t) typically constrain loading before tank volume

does⁵³.

Pipeline Transport

For continuous, high-volume inland distribution, pipelines are the preferred carrier, minimising transport cost and product loss while maximising supply stability⁵⁴.

Ammonia. Existing pipeline networks already move up to 1.5 Mtpa of liquid ammonia, and proposed European projects (Rotterdam–Germany, UK Humber cluster) demonstrate feasible scale-up to 6–7 Mtpa^{44,55}. The DNV design methodology adopts a design velocity of 1.8 m/s at 30 barg / 50°C (564 kg/m³), which keeps the flow safely below the cavitation-risk threshold³⁸.

Methanol. Dedicated long-distance methanol pipelines remain scarce, but the demonstrated feasibility of transporting methanol through conventional oil pipelines (which routinely move hundreds of thousands of m³/day) establishes oil-pipeline practice as a valid engineering reference^{54,56}.

For the dimensioning of the methanol pipeline, there is an upper fluid velocity limit of 5 m/s for single-phase liquid transport specifically to minimize flashing ahead of control valves⁵⁷. This is an upper bound rather than a design target. The design velocity of 2 m/s reflects normal practice for long transmission and pump-suction lines where pressure loss and erosion governs rather than flashing⁵⁸.

Hydrogen Pipelines. Hydrogen transmission pipelines typically operate at 80–100 bar^{59,60}. A velocity of 20 m/s is standard³⁸, well below the erosional velocity limits of 71–95 m/s implied by API RP 14E guidelines for large-diameter transmission lines⁵⁹. The diameter and capacity benchmarking behind these limits is given in Appendix A.15.

2.3.3 On-site Storage

In the absence of dedicated, fuel-specific spatial regulations, this assessment utilizes the AXA XL Risk Consulting Guidelines to establish a safe terminal layout (Table 2.3). As a widely applied industry standard for property loss prevention in oil and chemical terminals, these spacing rules give a consistent basis for layout that mitigates severe process hazards and guarantees adequate emergency access. They are insurer loss-prevention recommendations for the protection of the installation itself, not land-use planning distances.

The terminal layout also adheres to the following structural and safety principles⁶¹: pumps, valve manifolds, and transfer piping are located outside dikes or impounding areas; horizontal pressurised storage (bullets) is oriented so vessel ends do not point toward process areas; each pressurised or refrigerated tank group is limited to a maximum of six vessels, with at least 30 m or one tank diameter between groups; tanks are arranged in rows no more than two deep so that road access is preserved for firefighting; and storage tanks are located at a lower elevation and downwind of essential buildings and ignition sources.

Table 2.3: Consolidated minimum spacing recommendations (distances in metres)⁶¹

Exposure / facility type	Atmospheric tanks (floating/cone)	Pressure storage (spheres)	Pressure storage (bullets)	Refrigerated tanks (dome roof)
Intra-unit spacing				
Same tank type (self-exposure)	$0.5-1 \times D$ (min. 30 m)	$1 \times D$ (min. 30 m)	$1 \times D$	$1 \times D$ (min. 30 m)
Inter-unit spacing				
Service buildings / offices	76 m	106 m	106 m	106 m
Control rooms (central)	76 m	106 m	106 m	106 m
Process units (high hazard)	61 m	61 m	61 m	61 m
Compressor buildings	30.5 m	61 m	61 m	61 m
Large pump houses	30.5 m	76 m	76 m	76 m
Flares	106 m	106 m	106 m	106 m

Note: D denotes the largest tank diameter.

Under the International Energy Agency (IEA) regulations, member countries that are net oil importers must maintain emergency oil reserves equivalent to at least 90 days of average daily net imports⁶². Whether e-fuels will eventually fall under a comparable obligation is unresolved, and the distinction is not incidental: at full replacement, a 90-day buffer implies a working volume multiple times current storage volumes. This thesis assumes current IEA obligations do not yet extend to Power-to-X marine e-fuels, and that future strategic reserves will be managed nationally rather than localised at individual bunkering ports. The spatial methodology therefore applies a 7-day operational safety buffer, consistent with the DNV pre-feasibility methodology for alternative marine fuel terminals³⁸.

Most international standards (NFPA, HSG, CSCA) require a bund to hold at least 110% of the largest single tank's volume, which is the secondary containment; where regulations additionally require coverage of a partial multi-tank release (Australia, New Zealand, Ireland), the bund must also hold at least 25% of the total tank-farm volume. Minimum bund wall heights generally start at 0.5 m; maximum heights are capped at 1.8 m (NFPA) or 1.5 m (Ireland, UK) to preserve safe personnel egress and firefighting access⁶³.

Ammonia Storage

Ammonia storage technique is primarily determined by inventory scale: small-scale (<100 MT) storage uses pressurised cylindrical bullets at ambient temperature; intermediate scale (500–3,000 MT) uses semi-refrigerated Horton spheres; and large-scale storage (>3,000 MT) uses fully refrigerated flat-bottom tanks at -33°C and atmospheric pressure^{64–66} (Ta-

ble 2.4). For ammonia storage, filling densities must be maintained between 82% and 87.5% by volume for non-refrigerated containers⁶⁷. No equivalent filling limit for atmospheric refrigerated tanks was identified in the reviewed standards, and the transfer of this range to refrigerated storage in the sizing model is treated as an assumption rather than a regulatory requirement. The Occupational Safety and Health Administration (OSHA) state that refrigerated containers must not become entirely liquid-full at the temperature corresponding to the relief valve’s start-to-discharge setting⁶⁷.

Table 2.4: Ammonia storage regimes by scale^{64–66}

Storage Scale	Tank Type	Typical Operating Conditions
Small (<100 MT)	Cylindrical Bullet	Ambient temp / High pressure
Intermediate (500–3000 MT)	Horton Sphere	0°C to –30°C / Moderate pressure
Large (>3000 MT)	Flat-Bottom Tank	–33°C / Atmospheric

Given the terminal-scale volumes modelled in this thesis (Chapter 4), only the large-scale, fully refrigerated Double-Wall Double-Integrity (DWDI) flat-bottom tank design is carried forward into the sizing methodology, explicitly excluding pressurised Horton spheres and bullet tanks: matching terminal-scale volumes with pressurised vessels would require a very large number of vessels, inflating both land footprint and capital cost. DWDI construction, an inner vessel suspended within a larger insulated outer tank, achieves a failure rate nearly one-hundredth that of older single-wall designs⁶⁸, and current commercial capacity is practically limited to 40,000–50,000 t per tank, since larger vessels require steel plates thick enough to trigger impractical post-weld heat treatment requirements⁶⁹. This upper limit governs the maximum tank volume applied in the sizing model. Reference dimensions for the excluded storage regimes, the prototype designs proposed to break the 50,000 t ceiling, and the inspection practice associated with each vessel type are given in Appendix A.10.

Methanol Storage

Methanol remains stable as a liquid at standard atmospheric pressure and ambient temperature, making its storage simpler and less costly than ammonia’s, with negligible long-term storage or transport energy losses¹⁵. It is typically stored in standard single-wall steel tanks built to the API 650 standard, similar to conventional crude oil floating-roof tanks⁷⁰; a typical 100,000 m³ floating-roof tank (the current industry-standard scale) requires an internal diameter of 80 m and a wall height of 21.8 m⁷¹. For atmospheric above-ground storage, 20% of the tank’s working volume is reserved for liquid expansion, limiting the maximum fill level to 80%⁷². Active re-liquefaction systems used to manage ammonia boil-off are not required for methanol, whose modest vapour losses arise instead from standing and working losses during thermal breathing and liquid displacement^{73,74}.

Intermediate Hydrogen Storage

Hydrogen can be stored as a compressed gas, a cryogenic liquid, a high-pressure solid,

within sorbents, or as metal/chemical hydrides¹⁵. Its low volumetric density ($\sim 11 \text{ m}^3/\text{kg}$ at ambient conditions) means that storage phase choice has an outsized impact on footprint: storing 30 t of liquid hydrogen requires $\sim 10 \text{ m}^2$ of ground footprint, versus $\sim 500 \text{ m}^2$ for the same mass as 700-bar compressed gas^{75,76}. This large contrast is the basis for adopting cryogenic spherical storage as the on-site buffer configuration in the case study.

The primary operational challenge in green e-fuel production is bridging intermittent renewable generation with the steady-state requirements of the downstream synthesis loop: unplanned power loss risks ASU freezing, and forcing Haber–Bosch reactors through frequent shutdown-restart cycles can shorten catalyst lifespan from ten years to as little as three⁷⁷. To size the required buffer, an analysis of 40 years of German onshore wind data provides critical baseline statistics: a Power-to-X facility should expect ~ 5 consecutive days per year with average wind capacity factor below 10%, with decadal extremes reaching ~ 8 consecutive low-wind days (maximum ~ 10 days)⁷⁸.

Given the very large multi-day buffer implied by intermittent operation, this thesis assumes the bulk hydrogen inventory is held off-site in geological storage (salt caverns or Lined Rock Caverns), with only a 1-day portion of that buffer retained on-site at the terminal. Both salt caverns and LRCs are proven, low-footprint solutions at the hundreds-of-GWh scale, with the LRC pathway specifically being demonstrated for pure hydrogen by the HYBRIT project in Sweden^{79,80}. Gothenburg has no salt formations, so LRC is the only geological route available at this location, and it is the less mature of the two. For the on-site local buffer, this thesis adopts NASA’s 1.25-million-gallon liquid hydrogen sphere at Cape Canaveral as the geometric reference: a nominal 20.8 m internal diameter grows to a 25.3 m external diameter once the insulation gap and structural jacket are included, which corresponds to 2.25 m added radially, at a working capacity of 270 t^{76,81}. Above-ground large-diameter pipeline storage is also evaluated as an alternative on-site configuration, at a nominal capacity of $\sim 12 \text{ t H}_2$ per km of 1.4 m-diameter, 100-bar pipeline⁷⁶. The geology, cavern dimensioning, and the reconciliation of the NASA sphere’s nominal and working capacities are set out in Appendix A.14.

2.3.4 Bunkering Systems

Bunkering, refuelling a ship following standardized procedures, is presently executed through three predominant methods: Truck-to-Ship (TTS), Ship-to-Ship (STS), and Onshore-to-Ship (OTS)³⁷. TTS is constrained by truck tank size to minor operations, while STS offers higher capacity but is weather-dependent and carries the highest spill risk; both are therefore excluded from the primary sizing model. OTS, linking onshore storage directly to vessels via pipelines and flexible hoses, requires the highest upfront capital investment but provides the greatest capacity, highest transfer efficiency, and weather independence³⁷, and is adopted as the primary bunkering modality throughout this thesis.

Ammonia can be handled Fully Refrigerated (FR, -33°C), Semi-Refrigerated (SR, -10 to 4°C), or Non-Refrigerated/Pressurized (up to 45°C)^{82,83} (Table 2.5); bunkering between mismatched storage states requires additional temperature/pressure regulation to manage boil-off and prevent over-pressurisation.

Table 2.5: Typical storage and transfer conditions of ammonia in maritime applications⁸²

Parameter	Fully Refrigerated (FR)	Semi-Refrigerated (SR)	Non-Refrigerated (NR)
IMO Type	Independent Type-A	Independent Type-B	Independent Type-C
Temperature	-33°C	-10 to 4°C	20 – 45°C
Pressure	~ 0 bar (Atmospheric)	3–4 bar	7–17 bar
Secondary Barrier	Complete	Partial	None

Methanol and ammonia bunkering share the same underlying safety logic, Emergency Shutdown (ESD) interconnection between vessel and shore, dry-break couplings, and electrical isolation, but differ in the size of the resulting exclusion zone and in regulatory maturity^{83–85}. Methanol bunkering is regulated locally: the Port of Gothenburg mandates a 25 m safety radius around the transfer point, within which Simultaneous Operations (SIMOPS) are generally prohibited⁸⁴. Ammonia bunkering safety zones instead depend on site-specific dispersion modelling; quantitative risk assessments (QRA) at operating terminals such as Rotterdam indicate zones as small as 50 m at berth, and this figure is adopted in the spatial model^{86,87}. Table 2.6 summarises the exclusion-zone values carried forward into Chapter 3.

Table 2.6: Bunkering safety zones adopted for spatial sizing.

Fuel	Bunkering exclusion radius	Basis
Methanol	25 m	Port of Gothenburg SIMOPS regulation ⁸⁴
Ammonia	50 m	QRA-based berth safety zone ⁸⁶

The size of an individual bunker parcel is set by the vessel being refuelled rather than by the terminal, and is smaller than the cargo packets handled. The number of transfer positions required at the quayside therefore follows from the daily bunkering throughput, the parcel size, and the turnaround time per operation, rather than from the dimensions of a single manifold. This relationship is developed in Chapter 3.

2.3.5 E-fuel Synthesis and Processing

Nitrogen Separation

Nitrogen for e-ammonia synthesis can be isolated from air via cryogenic distillation, membrane separation, or Pressure Swing Adsorption (PSA), with the choice depending on required scale and purity²². Membrane separation and PSA are efficient at small-to-medium

scale but impractical at the nitrogen throughput required for a commercial e-fuel hub; cryogenic distillation, the most mature and cost-effective approach at industrial scale, is therefore adopted for the remainder of this study.

Steady-state operating data for a 1 GW ammonia plant indicates an ASU specific energy demand of 0.311 MWh per tonne of ammonia produced, with a 36–48-hour startup time that makes it a highly inflexible continuous load³⁴. A separate technical source reports 0.114 MWh/t-NH₃ for the same duty⁸⁸. The two values differ by a factor of 2.7, which reflects differences in plant configuration and in what is included within the ASU boundary rather than a genuine divergence.

Carbon Dioxide Capture

CO₂ is a foundational feedstock for e-methanol production, sourced either through Direct Air Capture (DAC) or point-source Carbon Capture and Storage (CCUS) retrofitted to existing industrial emitters²². Point-source capture is more economical where available (10–50% CO₂ concentration in flue gas), and its capture footprint is confined to the existing host facility rather than the port. It is not carried into the primary sizing model for that reason, but the exclusion rests on two conditions that are not tested here: that a host emitter of sufficient scale exists near the port, and that the transport link delivering the CO₂ to the port carries its own footprint inside the system boundary. Both are returned to in the discussion. A survey of contemporary point-source technologies and their energy penalties is retained in Appendix A.11 for reference⁸⁹.

DAC extracts CO₂ directly from ambient air (~400 ppm), which is significantly more energy- and space-intensive than point-source capture. Two technology families exist: Solid DAC (S-DAC), using solid adsorbents regenerated at 80–120°C, and Liquid DAC (L-DAC), using an aqueous solvent regenerated at 300–900°C. S-DAC requires 7.2 GJ of heat and 2.3 GJ of electricity per tonne of CO₂ captured, while L-DAC requires 5.3 GJ of heat and 1.3 GJ of electricity⁹⁰. Across the wider literature, combined thermal and electrical demand for both families spans 769–4,006 kWh/tCO₂⁹¹; this envelope is an outer bound formed from the extremes of both families rather than the operating range of any single facility, and its derivation is given in Appendix A.11.

DAC space requirements vary similarly widely, from highly compact designs (0.002 km²/Mt-CO₂/yr) to expansive layouts (up to 2.0 km²/Mt-CO₂/yr), excluding supporting renewable energy infrastructure⁹². The only directly measurable calibration points are the two operating Climeworks plants: Google-Earth-measured footprints of Orca and Mammoth give 0.56 and 1.33 km²/Mt-CO₂ respectively, based on actual net removal capacity rather than nameplate^{93,94}. The measurements behind the two Climeworks calibration points, an independent back-solved space factor from the Port of Vancouver concept, and the net-removal accounting that separates nameplate from delivered capacity are given in Appendix A.11.

E-Ammonia Synthesis

For the same 1 GW reference plant, the combined syngas compression and plant utilities load (excluding ASU) amounts to 0.934 MWh per tonne of ammonia³⁴; an independent source for a water-electrolysis-based plant reports a comparable 0.97 MWh/t-NH₃⁸⁸. The synthesis loop itself has a cold start-up time of 12 hours³⁴.

Spatial data for the synthesis loop and ASU combined (footprint per tonne-hour throughput) is drawn from planned commercial-scale ammonia projects rather than the Bornholm reference plant, since detailed component-level footprint data was not available for the latter. A planned facility at the Port of Ventspils, Latvia (550,000 tpa capacity, 10 ha plant area) implies a specific area demand of 1,593 m²/tph assuming continuous year-round operation⁹⁵. A comparable planned facility near Kokkola, Finland (760,000 tpa, 55 ha excluding the electrolyser) implies 6,339 m²/tph⁹⁶.

E-Methanol Synthesis

The Kassø e-methanol facility in Denmark, developed by European Energy, is the world's first large-scale e-methanol production site and serves as the primary spatial reference for methanol synthesis plant sizing in this thesis. Spatial analysis of publicly available imagery of the facility (capacity 42,000 tpa, ~4.79 tph) yields a core synthesis-plant footprint (including compressor units) of 11,925 m², corresponding to a specific space demand of 2,487 m²/tph. The component-by-component breakdown of the Kassø site, including the electrolyser block and the power supply arrangement, is given in Appendix A.12.

For specific energy demand, dynamic modelling of a 50 MW-electrolyser Power-to-Methanol facility (25,000 tpa) indicates the standalone Methanol Synthesis and Distillation (MSD) unit consumes approximately 0.71 MWh per tonne at full nominal load and continuous year-round operation, excluding upstream electrolysis, carbon capture, and primary feedstock compression⁹⁷.

Re-liquefaction and Boil-Off Management

Re-liquefaction units maintain ammonia in its liquid state in flat-bottom refrigerated tanks and Horton spheres, preventing pressure build-up and fuel loss⁹⁸. Because this thesis models only DWDI flat-bottom ammonia tanks and atmospheric methanol tanks (neither of which is assumed to require active re-liquefaction equipment within the system boundary), the underlying refrigeration-cycle engineering is not required for the sizing methodology and is summarised in Appendix A.17 for completeness.

2.3.6 Safety and Regulatory Framework

Seveso III Thresholds

Table 2.7 outlines the qualifying quantities that trigger Seveso III obligations for the key substances handled in this study. In complex industrial clusters, the Directive mandates a summation rule to calculate cumulative physical hazards across co-located substances⁹⁹.

Table 2.7: Seveso III Qualifying Quantities for Selected Dangerous Substances⁹⁹

Substance	Classification / CAS Number	Lower-Tier (t)	Upper-Tier (t)
Hydrogen	Section P2 Flammable Gas (Cat. 1)	5	50
Ammonia	CAS 7664-41-7 (Annex I, Part 2)	50	200
Methanol	CAS 67-56-1 (Annex I, Part 2)	500	5,000

Facilities meeting the lower threshold but remaining below the upper threshold are regulated as lower-tier establishments; those exceeding the upper threshold are subject to upper-tier obligations, including a full Safety Report, Internal and External Emergency Plans, and annual inspections⁹⁹.

The Directive further requires member states to ensure that appropriate safety distances are maintained between all establishments and residential areas, buildings of public use, and major transport routes⁹⁹. These land-use planning distances are established by site-specific consequence assessment rather than by tank spacing, and they are distinct from the loss-prevention setbacks of Table 2.3. The footprints computed in this thesis therefore represent the land occupied by the installation, not the land-use restrictions the installation would impose on its surroundings.

Substance Hazard Classifications and Exposure Limits

Table 2.8 consolidates the flammability, toxicity, and exposure parameters that determine the safety-zone sizing used in the spatial model.

Table 2.8: Key hazard classification parameters by substance.

Parameter	Methanol	Ammonia	Hydrogen
Flammability/explosive range	5.5–44 vol% ¹⁰⁰	15–28 vol% ^{83,85}	4–75 vol% (LFL 4%) ¹⁰¹
Auto-ignition temperature	455°C ¹⁰⁰	651°C ^{83,85}	–
Primary hazard	Toxic, flammable, corrosive when wet ^{100,102}	Toxic, corrosive, narrow flammability ^{83,85}	Asphyxiant, cryogenic ¹⁰¹
Key exposure threshold	STOT Cat. 1 (eye damage) ¹⁰⁰	IDLH 300 ppm; AEGL-3 2,700 ppm ^{82,85}	LFL 4% vol ¹⁰¹

Methanol storage tanks, transport vessels, and pipelines require corrosion monitoring because methanol becomes corrosive to carbon steel alloys when it absorbs moisture in the presence of inorganic salts¹⁰². Hydrogen’s high diffusivity and low ignition energy drive the OSHA¹⁰³ and European Industrial Gases Association (EIGA)¹⁰⁴ separation distances summarised in Table 2.9, which are adopted directly as the on-site hydrogen buffer safety setbacks in Chapter 3.

Table 2.9: Selected minimum hydrogen safety separation distances.

Standard	Exposure type	Distance
OSHA 1910.103 ¹⁰³	Liquefied H ₂ , other buildings (>56.78 m ³)	30.48 m
OSHA 1910.103 ¹⁰³	Gaseous H ₂ , buildings (>424.75 m ³)	15.24 m
EIGA Doc 15/21 ¹⁰⁴	Site boundary / areas where people congregate	8 m
EIGA Doc 15/21 ¹⁰⁴	Open flames and ignition sources	5 m

2.4 Existing Studies of Port E-Fuel Infrastructure

The sections above establish the properties, handling requirements and separation distances of the individual assets. Far less has been published on the question this thesis asks, which is how much land those assets occupy once assembled into a working port supply chain. A literature review identified four relevant studies that report physical infrastructure requirements or spatial footprints for e-fuel production, storage or bunkering at a port, compared in Table 2.10.

Table 2.10: Studies reporting port e-fuel infrastructure or spatial requirements.

Study	Pathway	Components and scale reported	Sizing method	Main limitation
DNV (2022), Chile export terminal ³⁸	Ammonia	Two 60 000 m ³ refrigerated tanks, 600 m jetty, road and rail unloading, compressor house, flares, substation and spill containment; approx. 49 ha (700 m × 700 m) at 1 Mtpa	Conceptual pre-feasibility layout at one capacity; storage set by a single 87 000 m ³ carrier parcel	Export terminal rather than bunkering; a single plot total with no component areas, so it cannot be rescaled, and safety distances are deferred to a later QRA
SmartPort and TNO (2020), Rotterdam e-fuels cluster ⁹²	E-methanol	Electrolysis, DAC, synthesis, desalination and buffer storage; approx. 600 ha of which 400 ha DAC	Area factors per unit of installed capacity, applied to national 2050 fuel demand	Sized on national fuel demand rather than port bunkering; no transfer or bunkering assets and no containment; total ranges 112–1 500 ha on electrolyser technology alone
Oceans North and Arup (2025), Port of Vancouver ¹⁰⁵	E-methanol	Electrolysis, DAC and synthesis; 28–34 ha and 432.4 MW at 200 000 tpa in four phases, plus 65 000 m ³ of storage	Phased conceptual design at four capacities, from representative vessel demand	Production land only, of which approx. 90% DAC; storage given as volume and bunkering as a method, neither converted to area
Gu and Lan (2025), Greater Bay Area ¹⁰⁶	Ammonia	72 MW wind, 63 MW PEM electrolyser, 3.6 MW Haber–Bosch and 3 205 t of ammonia in pressurised 16–18 bar tanks, for one vessel taking 687 t per fortnight	Hourly wind simulation with a priority-based capacity expansion loop minimising capital cost	Cost-optimised rather than space-constrained, with no land area reported; vessel-scale and pressurised, so not transferable to terminal-scale refrigerated storage

Three limitations recur across these studies. First, the components are sized separately. Production plant is sized without reference to the storage it feeds, and storage without the transfer and bunkering assets that connect it to a vessel, so no single demand figure propagates through a complete chain. The hardware is also reported on its own, without the secondary containment and exclusion zones implied by the separation distances reviewed above. Second, the footprints that are reported are single totals at a single capacity. The contribution of each asset to the total is not visible, so the figure cannot be rescaled to another demand level or transferred to a port with a different fuel mix. Third, the aggregated requirement is not set against the land actually available at a given port.

The Rotterdam estimate is sized on national fuel demand, the Vancouver and Greater Bay Area studies cover production assets alone, and the DNV layout is a plot total for a new export terminal rather than an accommodation test within an operating port.

The gap is therefore not an absence of data on individual assets but the absence of a method that assembles them and tests the result against a real site. This is what the research questions of Chapter 1 address: the first asks what physical infrastructure a port e-fuel supply chain requires in total, the second asks how each component of that chain is sized, and the third asks whether a real port can accommodate the result. Answering them requires a framework in which one demand figure propagates through every asset and each asset is translated into land including its containment and its setback, and the aggregate is compared with the land inventory of an actual port, which is what Chapter 3 develops.

All four studies are carried forward as reference facilities against which the modelled footprints are compared in Section 6.3: the DNV ammonia export terminal (Appendix A.18.1), the Port of Vancouver e-methanol facility (Appendix A.18.2), the Rotterdam e-fuels cluster (Appendix A.18.3) and the Greater Bay Area ammonia plant (Appendix A.18.4). The DNV layout serves as the principal reference for the ammonia import hub, with the caveat that its plot absorbs assets excluded from the model developed here, among them the jetty and marine works, internal roads, administration and control buildings, and inter-unit spacing. Expanded discussion of each facility is given in Appendix A.18.

One further step is left unstated in all four studies: how an asset sum is converted into a plot. None of them states a gross-to-net treatment, yet the DNV parcel plainly contains internal roads, buildings and inter-unit separation that no component list accounts for. The same step is handled explicitly in land-footprint analysis outside the port context: a solar farm design study sums arrays, service roads and buildings into a direct-impact area, adds 5% for boundary setback and a further 30% as a site contingency, giving a combined gross-to-net factor of 1.365 against which the reported plot is sized.¹⁰⁷ That direct-impact area already contains the roads and buildings, whereas an asset sum of the kind assembled in Chapter 3 contains neither, so an allowance of at least that size applies here. A packing factor of 1.35 is adopted on this basis and swept in Section 4.6.4.

3

Methodology

This chapter defines the sizing framework: the research design, the system boundary, the origin and selection of every input value, the governing equations of each sizing step, and the aggregation of the resulting footprints against a land inventory. Case-specific input values are assigned in Section 4.1 and all numerical outputs are reported in Chapter 4. Full parameter tables, the tank height-to-diameter curve fit derivations, the hydrogen buffer packing geometry and the hour-by-hour inventory simulation logic are given in Appendix B, cross-linked from the equations below.

3.1 Research Design

The study is quantitative and deterministic, built as a single-case embedded design: one reference port, four demand scenarios, and two hub configurations within each scenario. The unit of analysis is a physical asset, and the quantity of interest is the land area that asset occupies once its hardware, its containment and its safety setback are accounted for.

The calculation chain is demand-first: a fixed annual end-use energy demand, expressed as an MGO volume, is converted to fuel volumes, and the chain then works upstream to the renewable electricity supply that produces them, so each step's output defines the input requirement of the step that physically precedes it. Section 3.5 sets it out in full.

The model assumes two separate electrical supply pathways. The electrolyser array is powered entirely by a dedicated variable renewable asset, given the scale of the electrical demand of water electrolysis, while the synthesis plants and auxiliary systems draw continuous green electricity from the wider grid. Because coupling the electrolyser to an intermittent profile drives the sizing of both the electrolyser and the hydrogen buffer, a comparative baseline with continuous electrolyser supply is also evaluated to isolate the effect of intermittency.

The framework is implemented as a single MATLAB script that executes the whole chain at both demand levels in one pass, so every quantity reported in Chapter 4 derives from one parameter set. The sensitivity engine re-runs the identical chain with one input perturbed at a time across its documented range; the swept quantities and the sweep procedure are

stated in Section 4.6.

The chapter follows the order the script implements: the system boundary fixes which assets are in scope (Section 3.2), the input data and their selection convention are stated (Section 3.3), demand is characterised and converted to annual volumes (Section 3.4), the asset inventory is established (Section 3.5), each asset class is translated into a footprint (Section 3.6), and the footprints are aggregated and tested against port land (Section 3.6.5).

3.2 System Boundary Definition

The model covers the physical infrastructure required to receive, store and supply e-fuels at a port terminal, and to produce those fuels on site from renewable electricity. Figure 3.1 separates this port-internal infrastructure from the global supply chains, ship-side systems and secondary outputs outside the boundary, and distinguishes the two hub configurations: an import hub, in which e-fuels are produced externally and delivered to the port for storage and bunkering, and a production hub, in which they are produced on site from renewable electricity and feedstocks. Included are the fuel storage tanks with

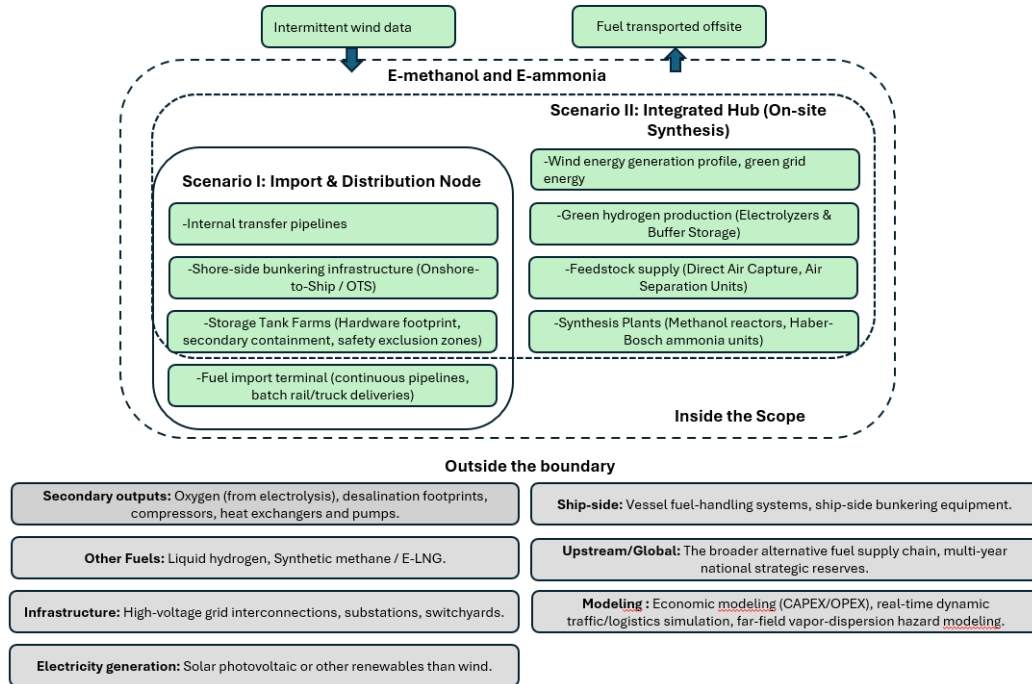


Figure 3.1: System boundary for the import hub and the integrated production hub.

their secondary containment and safety exclusion zones; the import terminal logistics of pipeline, ship, rail and truck delivery; the shore-side bunkering infrastructure of transfer stations, loading arms and local exclusion zones; the methanol and Haber–Bosch synthesis

plants; the Direct Air Capture and Air Separation feedstock units; the electrolyser plant; the hydrogen buffer between intermittent production and continuous synthesis demand; and the renewable electricity supply sized on a regional generation profile.

Excluded are grid interconnection and off-site transmission, ship-side bunkering equipment and vessel fuel-handling systems, oxygen handling and sale, multi-year strategic reserves, economic cost modelling, and far-field vapour-dispersion hazard assessment for ammonia. Water desalination for electrolysis is excluded because its footprint and energy penalty are small relative to the primary production processes.

Demand is scoped to ship bunkering only. The model input is the port’s annual bunkering volume expressed as a tonnage of MGO, and MGO is the reference fuel against which all e-fuel volumes are made energy-equivalent. Auxiliary port energy demand from terminal vehicles, cranes, tugboats, on-port industrial consumers and district heating is excluded as an independent, smaller and highly port-specific load that would not change the terminal-scale storage and synthesis footprints addressed here.

Two of the physically largest assets in the production hub are excluded from the onshore footprint: the generation asset is assumed to sit offshore or at a dedicated inland site, and the bulk hydrogen inventory in off-site geological storage. Both are reported at their computed scale alongside the onshore totals, so the size of the excluded asset is visible rather than implied.

3.3 Data Sources and Parameter Selection

3.3.1 Data Sources

Four classes of input are used, each treated differently.

Literature-sourced parameters. Densities, heating values, fill limits, spacing rules, setback distances, space factors, specific energies and vehicle capacities are taken from the sources reviewed in Chapter 2. Every value is recorded with its documented range where one exists, and those ranges are what the sensitivity analysis sweeps. The consolidated tables are given in Section B.1.

Reference facility measurements. Where no published space factor was available at the required scale, the footprint of an existing or announced facility was measured from satellite imagery and divided by its stated nameplate throughput. This applies to the methanol synthesis space factor and is identified as such at every point of use.

Industrial reference datasets. The tank height-to-diameter and insulation-thickness

relations are regressions fitted to a dataset of built and designed tanks compiled from vendor and operator sources. The dataset, the regression procedure and the fit diagnostics are given in Section B.2.

Hourly generation time series. The renewable supply is an 8 760-point hourly series at megawatt resolution published by the national transmission system operator¹⁰⁸. It enters the model as a profile rather than a scalar, so alternative profiles are run as separate cases through the full chain rather than swept as a parameter.

3.3.2 Parameter Selection Convention

Where a single measured or reported reference facility is available at a scale representative of the one modelled here, that value is adopted and the wider literature range is carried into the sensitivity analysis. Where no such reference exists and the literature offers only a range, the midpoint is adopted and both bounds are swept. Deviations from this convention are stated at the point of use, with the reason and the direction of the resulting bias.

The value adopted for every parameter carrying a literature range, its position within that range and the direction of its bias on the aggregated footprint are recorded in Table C.11. The directions are mixed rather than uniform, so the totals in Chapter 4 are a point estimate whose bias differs by component, and Section 4.6 is what bounds that mixture.

3.4 Demand Characterisation

The model anchors on a baseline annual bunker demand m_{mgo} in tonnes per year. This energy demand is a fixed boundary condition across all fuel types and synthesis pathways, so every e-fuel volume derived below delivers service equivalent to the baseline fuel.

The year is modelled as 8 760 hr with no leap-year correction. A safety buffer of duration t_{buffer} is maintained as the minimum inventory at all times, and a heel fraction f_{heel} is applied to all tank types for the residual volume that cannot be evacuated in normal operation due to pump submergence³⁸. A fuel-specific mix fraction f_i scales the MGO-equivalent demand to the projected share of each e-fuel in the future bunkering market. The operational boundary conditions and mix fractions are listed in Table B.1.

Because methanol and ammonia have lower volumetric energy densities than MGO, larger volumes are required to provide the same energy. The multiplier M_i calculates the energy-equivalent volume from fuel density and lower heating value. Engine efficiency is held constant to isolate infrastructure differences rather than vessel-specific performance.

$$M_i = \frac{\rho_{\text{mgo}} \times \text{LHV}_{\text{mgo}}}{\rho_i \times \text{LHV}_i} \quad [-] \quad (3.1)$$

Where ρ_{mgo} and LHV_{mgo} are the density and lower heating value of MGO, and ρ_i and LHV_i the corresponding properties of alternative fuel i . The total annual volume of each alternative fuel is then:

$$V_{\text{annual},i} = \frac{m_{\text{mgo}}}{\rho_{\text{mgo}}} \times M_i \times f_i = \frac{m_{\text{mgo}} \text{LHV}_{\text{mgo}}}{\rho_i \text{LHV}_i} \times f_i \quad [\text{m}^3/\text{yr}] \quad (3.2)$$

In which ρ_{mgo} cancels exactly, so the reference density affects the reported multiplier and the size of an MGO baseline tank farm, but not the e-fuel volumes or anything derived from them. $V_{\text{annual},i}$ is the top-level boundary condition propagated through all subsequent sizing steps. The fuel physical properties used in the conversion are listed in Table B.2.

3.5 Asset Inventory and Calculation Chain

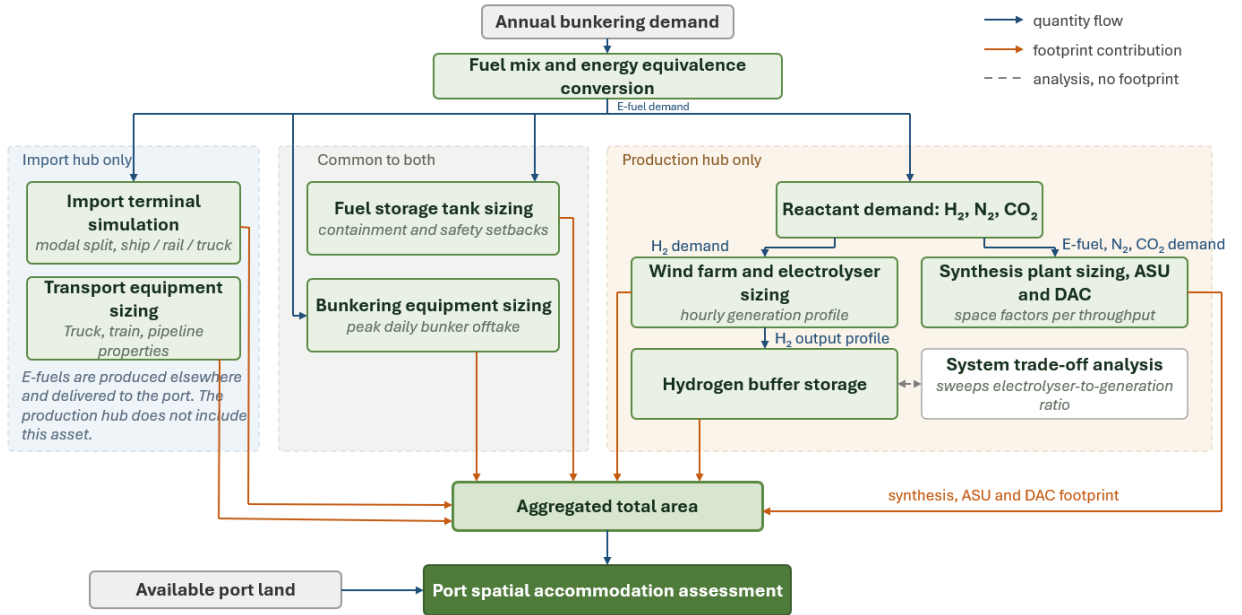


Figure 3.2: Demand-first sequential calculation logic.

Figure 3.2 sets out the chain the script implements, and Table 3.1 lists each component with its primary input and the section that defines it. Blue arrows carry quantities and orange arrows carry footprint contributions, and the italicised line beneath each heading gives the principal input to that step, or its role where no input is named. Grey blocks are inputs and parameters and green blocks are calculation steps. The chain begins with the

annual bunkering demand of Section 3.4 and converts it to an e-fuel volume. From that volume the assets are grouped by the configuration that requires them: the import terminal, needed only by the import hub; the storage tanks and bunkering equipment, needed by both; and the reactant, synthesis, electrolysis and generation capacity the production hub adds to manufacture the fuel on site rather than receive it.

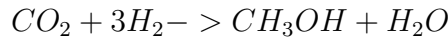
Table 3.1: Asset Inventory: Model Components and Corresponding Sections

Step	Component	Primary input	Section
1	Annual MGO demand (boundary condition)	Fixed assumption	3.4
2	Energy equivalence conversion	MGO volume	3.4
3	Daily reactant demands (H ₂ , CO ₂ , N ₂)	Fuel mass flows	3.5.1
4	Fuel storage tank sizing	Annual fuel volumes	3.6.1
5	Import terminal simulation	Annual fuel volume	3.6.2
6	Shore-side bunkering sizing	Peak daily bunker offtake	3.6.2
7	Pipeline dimensioning	Peak mass flows	3.6.2
8	Synthesis plant sizing	Daily reactant demands	3.6.3
9	Generation and electrolyser sizing	Daily H ₂ demand	3.6.4
10	H ₂ buffer storage	Generation profile and ratio	3.6.4
11	System trade-off analysis	All upstream outputs	3.6.4
12	Port spatial accommodation assessment	Total calculated footprints	3.6.5

3.5.1 Daily Reactant Demands

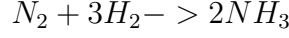
Volumetric fuel flows are translated into daily mass feedstock requirements using fixed stoichiometric mass ratios from the balanced reactions. Stoichiometric ratios are used rather than empirical yield factors because they give thermodynamically consistent lower bounds independent of the reactor technology assumed. A daily basis is adopted because the synthesis plants are assumed to run at continuous steady-state load, so the daily average describes throughput without introducing spurious intra-day variation.

E-methanol via CO₂ hydrogenation.



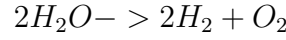
$$r_{H_2, \text{meth}} = \frac{3 \times M_{H_2}}{M_{\text{meth}}} = \frac{3 \times 2}{32} = 0.1875 \quad [\text{kg } H_2 / \text{kg MeOH}] \quad (3.3)$$

$$r_{CO_2, \text{meth}} = \frac{M_{CO_2}}{M_{\text{meth}}} = \frac{44}{32} = 1.375 \quad [\text{kg } CO_2 / \text{kg MeOH}] \quad (3.4)$$

E-ammonia via Haber–Bosch.

$$r_{H_2,amm} = \frac{(3/2) M_{H_2}}{M_{amm}} = \frac{3}{17} \approx 0.1765 \quad [\text{kg } H_2 / \text{kg } NH_3] \quad (3.5)$$

$$r_{N_2,amm} = \frac{(1/2) M_{N_2}}{M_{amm}} = \frac{14}{17} \approx 0.8235 \quad [\text{kg } N_2 / \text{kg } NH_3] \quad (3.6)$$

Green hydrogen via water electrolysis.

$$r_{H_2O,H_2} = \frac{2 M_{H_2O}}{2 M_{H_2}} = 9 \quad [\text{kg} / \text{kg } H_2] \quad (3.7)$$

$$r_{O_2,H_2} = \frac{M_{O_2}}{2 M_{H_2}} = 8 \quad [\text{kg} / \text{kg } H_2] \quad (3.8)$$

Oxygen handling lies outside the system boundary. At the flows derived in Chapter 4 the stream would require either a dedicated offtake or a vent system, and venting an oxygen-enriched stream near hydrogen and ammonia inventories is a design constraint in its own right.

The daily mass production target and the daily mass flow of any reactant feed stream are:

$$\dot{m}_{\text{fuel,daily}} = \left(\frac{V_{\text{annual},i}}{365} \right) \times \rho_i \quad [\text{kg/day}] \quad (3.9)$$

$$\dot{m}_{\text{reactant}} = \frac{\dot{m}_{\text{fuel,daily}} \times r_{\text{reactant,fuel}}}{\eta_{\text{yield},i}} \quad [\text{kg/day}] \quad (3.10)$$

Where $\eta_{\text{yield},i}$ is the overall process yield efficiency for synthesis pathway i . The baseline value is unity, so all ratios above are theoretical limits at 100% single-pass conversion and the reported feedstock flows are stoichiometric minima. A realistic single-pass yield would increase every upstream quantity in proportion, and the yield is swept in Section 4.6. Molecular weights and yield factors are listed in Table B.3.

3.6 Spatial Footprint Modelling

The modelling proceeds outward from the demand-facing end of the chain through distribution and synthesis to the upstream renewable production assets, mirroring the calculation order of Table 3.1.

3.6.1 Fuel Storage and Tank Sizing

The tank inventory is translated into land through a three-layer construction. Layer 1 is the hardware footprint, the bounding box of the equipment itself including the spacing required between units. Layer 2 is the secondary containment footprint, the area required to retain a spill, which for some tank types exceeds Layer 1 and for others coincides with it. Layer 3 is the safety exclusion zone, obtained by applying a setback radially to the Layer 1 hardware.

Working Volume and Tank Count

The working volume is the sum of a mandatory safety buffer and one full ship-packet delivery:

$$V_{\text{working}} = \left(\frac{V_{\text{annual}}}{365} \right) \times t_{\text{buffer}} + V_{\text{pkt}} \quad [\text{m}^3] \quad (3.11)$$

Where V_{pkt} is the nominal vessel packet volume. The model assumes sufficient working volume to receive one full vessel parcel while maintaining the minimum safety inventory, or to load one while the tank is at its maximum. The result depends strongly on the assumed parcel size, so the packet is swept in Section 4.6 and the assumption is tested against the dynamic inventory simulation of Section 3.6.2.

Maximum fill fractions differ by fuel and reflect distinct regulatory regimes. The methanol limit of 80 % is prescribed by storage safety guidelines and accounts for the vapour-space requirement at ambient temperature⁷². Ammonia fill limits of 82–87.5 % are governed by pressure vessel codes⁶⁷ that mandate a minimum ullage for thermal expansion.

That ammonia range applies to non-refrigerated containment. No equivalent published limit for atmospheric refrigerated flat-bottom tanks was identified, so it is transferred to refrigerated storage as a stated assumption rather than a requirement. The upper bound is adopted, giving the smallest tank count, and the full span is carried into Section 4.6. The effective usable fraction subtracts the heel from whichever fill limit applies, and grossing up the working volume gives the geometric volume that must be installed:

$$f_{\text{eff}} = f_{\text{max}} - f_{\text{heel}} \quad [-] \quad (3.12)$$

$$V_{\text{geom,tot}} = \frac{V_{\text{working}}}{f_{\text{eff}}} \quad [\text{m}^3] \quad (3.13)$$

The minimum number of tanks follows from the maximum permitted single-tank volume V_{max} , and the per-tank volumes from an equal distribution:

$$n_{\text{tanks}} = \left\lceil \frac{V_{\text{geom,tot}}}{V_{\text{max}}} \right\rceil \quad [-] \quad (3.14)$$

$$V_{\text{req}} = \frac{V_{\text{working}}}{n_{\text{tanks}}} \quad [\text{m}^3] \quad (3.15)$$

$$V_{\text{geom}} = \frac{V_{\text{req}}}{f_{\text{eff}}} \quad [\text{m}^3] \quad (3.16)$$

For refrigerated ammonia, V_{max} is set from the commercial ceiling imposed by post-weld heat treatment limits (Section 2.3.3). Larger single-tank volumes reported in the literature relate to prototype construction methods that are not commercially available.

Because n_{tanks} is an integer, the storage footprint is a stepped rather than a smooth function of the working volume. Crossing a tank-count boundary reduces the per-tank diameter and can also change the shape of the array, and since Layer 3 applies a fixed setback to the array perimeter, a squarer array of smaller tanks can occupy less land than a longer array of larger ones. The footprint is therefore not monotonic in the storage duty, and the sweeps in Section 4.6 step accordingly. Fill limits, maximum tank volumes and vessel packet sizes are listed in Table B.4.

Tank Geometry

Physical dimensions are derived from empirical height-to-diameter ratios fitted to industrial tank design data. Separate fits are used for fixed-roof atmospheric tanks and for flat-bottom refrigerated tanks, since the two are designed under different structural codes, API 650⁷⁰ and API 620⁶⁸ respectively, and exhibit different proportions.

Refrigerated ammonia tanks are constructed on the Double-Wall Double-Integrity principle, in which an inner vessel is suspended within a larger outer tank with the annular space filled with insulation. The insulation thickness grows with tank volume to manage the heat leak through the larger surface area, so the outer diameter exceeds the inner by twice that thickness. For ammonia the model evaluates fully refrigerated DWDI tanks only. Matching the required capacity with pressurised spheres or bullet tanks at the volumes modelled here would require a vessel count several times larger, inflating both land footprint and capital cost.

The resulting closed-form expressions for the height-to-diameter ratio are, for fixed-roof tanks,

$$R_{\text{roof}}(V_{\text{geom}}) = 0.7661 \exp(-1.18 \times 10^{-5} V_{\text{geom}}) \quad [-] \quad (3.17)$$

and, for flat-bottom refrigerated tanks,

$$R_{\text{flat}}(V_{\text{geom}}) = 0.7012 \exp(-1.48 \times 10^{-6} V_{\text{geom}}) \quad [-] \quad (3.18)$$

The two fits differ in quality. The fixed-roof regression is supported by its data; the refrigerated regression behaves as a constant close to the mean of the surveyed population

rather than as a volume-dependent relationship. It is retained on that basis, as a central value drawn from built tanks, since tank proportions in practice reflect site, contractor and vintage rather than capacity alone. The reference dataset, the regression procedure and the fit diagnostics are given in Section B.2.

Substituting $H = R \cdot D$ into $V = \frac{\pi}{4} D^2 H$ gives the inner diameter, with $H_{\text{tank}} = R \cdot D_{\text{inner}}$:

$$D_{\text{inner}} = \left(\frac{4 V_{\text{geom}}}{\pi R} \right)^{1/3} \quad [\text{m}] \quad (3.19)$$

For DWDI tanks the annular insulation thickness and the outer envelope diameter that governs the footprint are:

$$t_{\text{insul}}(V_{\text{geom}}) = 6.197 \times 10^{-6} V_{\text{geom}} + 0.7127 \quad [\text{m}] \quad (3.20)$$

$$D_{\text{outer}} = D_{\text{inner}} + 2 t_{\text{insul}} \quad [\text{m}] \quad (3.21)$$

For single-walled tanks, $D_{\text{outer}} = D_{\text{inner}}$.

Three-Layer Spatial Model

Layer 1, hardware footprint. Tanks are distributed into containment groups subject to the insurer-prescribed maximum of six tanks per group⁶¹:

$$n_{\text{grp}} = \left\lceil \frac{n_{\text{tanks}}}{n_{\text{pg,max}}} \right\rceil \quad [-] \quad (3.22)$$

Within each group, tanks are arranged in a rectangular grid, with the number of rows the integer square root of the group's vessel count:

$$n_{\text{row}} = \lfloor \sqrt{n_t} \rfloor \quad [-] \quad (3.23)$$

The number of columns is calculated by dividing the total number of tanks in the group by the number of rows and rounding up to the nearest integer:

$$n_{\text{col}} = \left\lceil \frac{n_t}{n_{\text{row}}} \right\rceil \quad [-] \quad (3.24)$$

The six-tank cap limits the rule to at most three columns and two rows, giving the arrangements shown in Figure 3.3. The rule is a fixed layout convention rather than an area optimisation: for a group of three it yields a single row, which for wide fixed-roof tanks occupies more land at Layer 3 than a two-by-two grid with one position vacant. It is retained because the arrangement that minimises Layer 3 is fuel-dependent, the row being more compact for refrigerated ammonia under its larger shell gap and setback, and because the resulting bias overstates rather than understates the footprint.

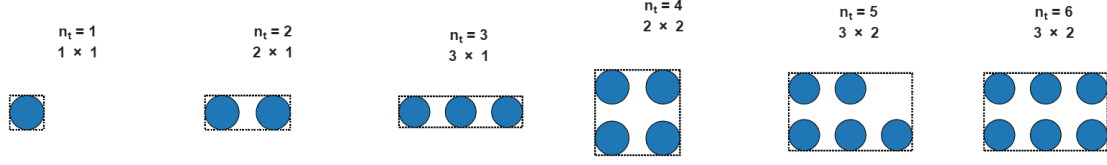


Figure 3.3: In-group tank arrangements produced by Equation 3.24 and 3.23 for group sizes of one to six vessels.

The centre-to-centre pitch is:

$$c_c = D_{\text{out}} + \delta_{\text{shell}} \quad [\text{m}] \quad (3.25)$$

With δ_{shell} the tank-specific shell-to-shell gap. For MGO and methanol tanks $\delta_{\text{shell}} = \max(30 \text{ m}, 0.5 D_{\text{out}})$; for ammonia DWDI tanks $\delta_{\text{shell}} = \max(30 \text{ m}, D_{\text{out}})$, reflecting the greater consequence of an ammonia release and the corresponding requirement for emergency access and dispersion clearance. The bounding box of a single group, and the overall hardware footprint with between-group spacing $\delta_{\text{btw}} = \max(30 \text{ m}, D_{\text{out}})$, are:

$$W_{\text{grp}} = (n_{\text{col}} - 1) c_c + D_{\text{out}} \quad [\text{m}] \quad (3.26)$$

$$H_{\text{grp}} = (n_{\text{row}} - 1) c_c + D_{\text{out}} \quad [\text{m}] \quad (3.27)$$

$$W_{\text{farm}} = \sum_{g=1}^{n_{\text{grp}}} W_{\text{grp},g} + (n_{\text{grp}} - 1) \delta_{\text{btw}} \quad [\text{m}] \quad (3.28)$$

$$H_{\text{farm}} = \max_g (H_{\text{grp},g}) \quad [\text{m}] \quad (3.29)$$

$$A_{\text{tanks}} = W_{\text{farm}} \times H_{\text{farm}} \quad [\text{m}^2] \quad (3.30)$$

The resulting hardware envelope is shown in Figure 3.4.

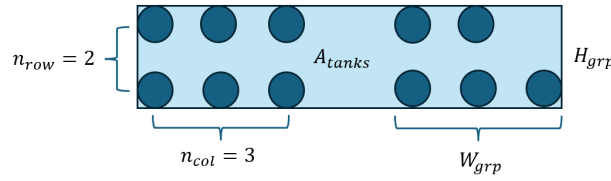


Figure 3.4: Layer 1: the physical bounding box of the tank array, including intra-group spacing and group segregation limits.

Layer 2, secondary containment footprint. DWDI ammonia tanks provide integral secondary containment by construction, so $A_{\text{bund}} = A_{\text{tanks}}$ for ammonia. For single-walled tanks an earthen bund must retain the more demanding of 110 % of the largest individual

tank volume, covering a catastrophic single-tank failure including firewater and foam, or 25 % of the combined group volume, covering a partial release across multiple tanks:

$$V_{\text{liq,req}} = \max(1.10 V_{\text{geom}}, 0.25 n_t V_{\text{geom}}) \quad [\text{m}^3] \quad (3.31)$$

The 25 % criterion is applied per containment group rather than across the whole tank farm, on the basis that a bund is a group-level structure. For four or fewer tanks per group the 110 % rule governs regardless, so the distinction affects only groups of five or six.

The required bund floor area per group, corrected for the base area displaced by the tanks, and its dimensions at preserved aspect ratio $\text{AR} = W_{\text{grp}}/H_{\text{grp}}$, are:

$$A_{\text{bund,grp}} = \max\left(\frac{V_{\text{liq,req}}}{h_{\text{bund}}} + n_t \frac{\pi D_{\text{out}}^2}{4}, W_{\text{grp}} H_{\text{grp}}\right) \quad [\text{m}^2] \quad (3.32)$$

$$W_{\text{bund,grp}} = \sqrt{A_{\text{bund,grp}} \cdot \text{AR}} \quad [\text{m}] \quad (3.33)$$

$$H_{\text{bund,grp}} = \sqrt{\frac{A_{\text{bund,grp}}}{\text{AR}}} \quad [\text{m}] \quad (3.34)$$

The resulting containment envelope is shown in Figure 3.5.

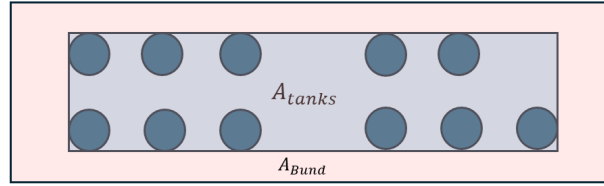


Figure 3.5: Layer 2: the scaled earthen bund area required to meet volumetric spill-retention mandates while preserving the group aspect ratio.

Layer 3, safety exclusion zone. A uniform recommended setback s_{bldg} is applied radially from the edge of the Layer 1 hardware footprint rather than from Layer 2, because the hazardous source of radiation, blast or toxic release is the tank itself: the bund retains liquid but does not reduce the radiant heat or vapour cloud boundary. The values used are insurer loss-prevention separation distances for the protection of adjacent structures⁶¹, and are referred to throughout as loss-prevention setbacks rather than regulatory distances. The governing outer envelope, shown in Figure 3.6, is the larger of the hardware-plus-setback rectangle and the secondary containment rectangle:

$$W_{\text{safety}} = \max(W_{\text{farm}} + 2 s_{\text{bldg}}, W_{\text{bund}}) \quad [\text{m}] \quad (3.35)$$

$$H_{\text{safety}} = \max(H_{\text{farm}} + 2 s_{\text{bldg}}, H_{\text{bund}}) \quad [\text{m}] \quad (3.36)$$

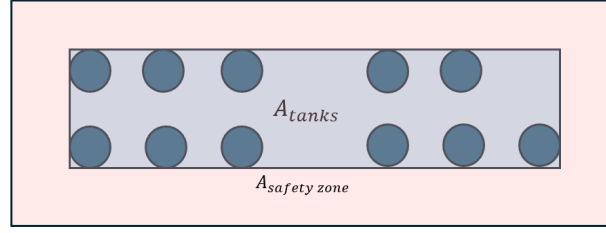


Figure 3.6: Layer 3: the final land-use boundary, generated by applying loss-prevention setbacks radially from the hardware footprint.

$$A_{\text{safety}} = W_{\text{safety}} \times H_{\text{safety}} \quad [\text{m}^2] \quad (3.37)$$

Layer 3 captures the intra-terminal structural boundary only: it is the land occupied by the installation, not the land-use restriction the installation imposes on its surroundings. For ammonia, far-field vapour-dispersion hazard radii must be assessed independently through site-specific dispersion modelling during site selection, and where a configuration exceeds the Seveso III upper-tier qualifying quantities of Table 2.7, land-use planning consultation distances are set by consequence modelling rather than by tank spacing. The Layer 3 envelope is therefore a lower bound on the true exclusion envelope, and every ammonia feasibility verdict in Chapter 4 is conditional on those consultation distances not exceeding it.

Spacing, containment and setback parameters are consolidated in Table B.6.

3.6.2 Distribution: Import Terminal, Bunkering, and Pipeline Footprints

Carried-State Density Convention

Ammonia is handled in different thermodynamic states along the chain, so a single density is not sufficient. Bulk storage and the reference carrier are fully refrigerated, rail tank cars and road tankers carry ammonia as an ambient-temperature pressurised liquid, and the pipeline design basis is a third state. Vehicle and wagon capacities are therefore expressed as a mass, or equivalently as a vessel volume at the carried density, and every inbound stream is converted to mass before being converted into the storage volume basis:

$$m_{\text{mode}} = f_{\text{mode}} \times V_{\text{annual}} \times \rho_{\text{store}} \quad [\text{kg}] \quad (3.38)$$

$$V_{\text{parcel,mode}} = \frac{m_{\text{parcel}}}{\rho_{\text{mode}}} \quad [\text{m}^3] \quad (3.39)$$

This closes the annual mass balance across all four modes regardless of the state in which each transports the fuel. Applying a vehicle capacity directly to a refrigerated volume allocation would make the delivered mass differ from the mass allocated by the modal split. For methanol the question does not arise, since it is handled as an ambient liquid throughout.

Fuel Import Terminal Simulation

The static working-volume formula provides a lower bound based on single-packet buffer logic. A full 8760-hour inventory simulation is run alongside it, following the DNV pre-feasibility methodology³⁸, to resolve the interplay between continuous inflows, discrete batch deliveries and instantaneous export events. Import streams are allocated across transport modes to represent a multi-modal hub, pipeline flows are modelled as continuous, and rail and truck deliveries arrive as discrete impulses within shifted schedules that reflect working hours.

Two terminal operating modes are implemented, and the labels are introduced for this study rather than taken from the literature. In the *batch-export* mode inland deliveries accumulate and the terminal discharges one full vessel packet whenever the inventory reaches the packet volume, representing the terminal as a bulk transshipment node; this is the configuration used for the primary results. In the *continuous-offtake* mode inland deliveries accumulate against a continuous offtake at the demand rate with no packet export, representing bunkering as a continuous draw on the inventory.

The two modes are read differently. In batch-export the trajectory oscillates between approximately zero and one packet volume, and the subsequent shift places its minimum at the safety buffer, so the peak of the shifted trajectory necessarily equals the buffer plus one packet. The simulation therefore reproduces Equation 3.11 by construction and is not an independent test of it; its value lies in resolving the sawtooth structure produced by discrete arrivals against continuous pipeline inflow, and in confirming that no intermediate state violates the buffer floor under the modelled delivery schedule. In continuous-offtake the outflow is decoupled from the inventory level, so the peak is an independent result. Both modes are reported in Section 4.6.

The hour-by-hour inflow, delivery and export logic, together with the inventory-shift procedure, is given in Section B.4. The two outputs carried forward are the required working volume $V_{\text{work,req}}$, the peak of the shifted inventory trajectory, and the implied nominal gross tank volume obtained by grossing it up with f_{eff} . Terminal delivery and modal split parameters are listed in Table B.7.

Shore-Side Bunkering and Transfer Infrastructure

A bunker parcel is set by the vessel being refuelled and is smaller than a cargo packet by two

to three orders of magnitude, so the quayside interface cannot be dimensioned from V_{pkt} . The number of onshore-to-ship transfer positions follows instead from the daily bunker offtake, the transfer rate and the turnaround time per operation. With $\dot{V}_{\text{daily}} = V_{\text{annual}}/365$ the average daily bunker volume, Q_{bkr} the sustained transfer rate at one position, t_{win} the daily operating window, and f_{conn} the fraction of occupied time consumed by connection, purging, documentation and disconnection rather than by pumping:

$$N_{\text{berth}} = \left\lceil \frac{k_{\text{peak,bkr}} \cdot \dot{V}_{\text{daily}}}{Q_{\text{bkr}} \cdot t_{\text{win}} \cdot (1 - f_{\text{conn}})} \right\rceil \quad [-] \quad (3.40)$$

Where $k_{\text{peak,bkr}}$ accounts for non-uniform vessel arrivals. The transfer rate is bounded by the cargo-pump data for the reference vessels of Section 2.3.2. Bunkering transfers are smaller and more frequently interrupted than cargo discharge, so the lower end of that envelope governs the baseline and the full range is carried into Section 4.6.

A single fuel-specific hazard separation radius $R_{i,\text{haz}}$ governs every transfer interface in this subsection: the port SIMOPS exclusion zone for methanol⁸⁴, and for ammonia the minimum baseline indicated by quantitative risk assessment at operating terminals⁸⁶, where the required zone depends on site-specific dispersion simulation. The same radius is applied to ship bunkering, truck reception and rail reception, and it rather than the manifold hardware governs the resulting footprints.

The land-side footprint of a single transfer position is estimated from the dimensions of standard marine loading equipment (Figure 2.2). The water-surface area occupied by the vessel is excluded. Positions are assumed to be separated sufficiently that their exclusion zones do not overlap, so the totals are sums over positions:

$$A_{\text{bunker,hard}} = N_{\text{berth}} \times L_{\text{bunker}} \times W_{\text{bunker}} \quad [\text{m}^2] \quad (3.41)$$

$$A_{\text{bunker,safety}} = N_{\text{berth}} \times (L_{\text{bunker}} + 2R_{i,\text{haz}}) \times (W_{\text{bunker}} + 2R_{i,\text{haz}}) \quad [\text{m}^2] \quad (3.42)$$

Because transfer positions must be distributed along the waterfront rather than stacked inland, the berth count also implies a minimum quay frontage:

$$L_{\text{quay}} = N_{\text{berth}} \times (L_{\text{vessel,max}} + 2R_{i,\text{haz}}) \quad [\text{m}] \quad (3.43)$$

Where $L_{\text{vessel,max}}$ is the length overall of the largest vessel expected to bunker at a single position. Quay frontage is reported alongside the area footprint, since a terminal may satisfy an area constraint while failing a frontage constraint.

Land-side reception. The maximum daily truck handling capacity of the reception station is:

$$N_{\text{truck,max}} = N_{\text{bays}} \times 2 \times \left\lfloor \frac{t_{\text{ops}}}{\tau_{\text{truck}}} \right\rfloor \quad [-] \quad (3.44)$$

Where N_{bays} is the number of active double-sided handling bays, t_{ops} the daily operational window applied in the inventory simulation, and τ_{truck} the turnaround time encompassing positioning, connection, active transfer and clearance. Truck reception is modelled using dedicated loading platforms (Figure 2.4), which fix the hardware and exclusion footprints:

$$A_{\text{truck,hard}} = N_{\text{bays}} \times L_{\text{truck}} \times W_{\text{truck}} \quad [\text{m}^2] \quad (3.45)$$

$$A_{\text{truck,safety}} = (N_{\text{bays}} \times L_{\text{truck}} + 2R_{i,\text{haz}}) \times (W_{\text{truck}} + 2R_{i,\text{haz}}) \quad [\text{m}^2] \quad (3.46)$$

The bays are assumed to use access roads already required for the facility.

Rail reception and the train length cap. Rail throughput is delivered by block trains whose length is bounded by infrastructure rather than by demand. The maximum consignment is set by the TEN-T standard, at a wagon length over couplers L_{cart} :

$$n_{\text{cart,max}} = \left\lfloor \frac{L_{\text{train,max}}}{L_{\text{cart}}} \right\rfloor \quad [-] \quad (3.47)$$

The payload of one wagon is its usable volume at the carried density, $m_{\text{cart}} = V_{\text{cart}} \cdot \rho_{\text{rail}}$. Holding the baseline frequency $n_{\text{trains,base}}$ fixed, the required consignment length is:

$$n_{\text{cart}} = \left\lceil \frac{m_{\text{rail}}}{n_{\text{trains,base}} \cdot m_{\text{cart}}} \right\rceil \quad [-] \quad (3.48)$$

Where this exceeds $n_{\text{cart,max}}$ the train is held at maximum length and the frequency is increased instead, reflecting operating practice for hazardous liquids:

$$n_{\text{trains}} = \left\lceil \frac{m_{\text{rail}}}{n_{\text{cart,max}} \cdot m_{\text{cart}}} \right\rceil \quad [-] \quad (3.49)$$

The siding is built to the required consignment length, and a total length allowance σ accounts for run-in, run-out and clearance beyond the transfer zone:

$$L_{\text{rail,wide}} = n_{\text{cart}} \times L_{\text{cart}}, \quad [\text{m}] \quad (3.50)$$

$$L_{\text{rail,total}} = \sigma L_{\text{rail,wide}} \quad [\text{m}] \quad (3.51)$$

Capping the train length converts a demand increase into an arrival-rate increase, which a single siding cannot absorb indefinitely. Where the arrival rate exceeds the number of loading cycles one siding can complete per operating day, c_{max} , parallel platforms are provided:

$$n_{\text{platform}} = \max\left(1, \left\lceil \frac{n_{\text{trains}}/d_{\text{op}}}{c_{\text{max}}} \right\rceil\right) \quad [-] \quad (3.52)$$

The structural footprint accounts for the clearance corridor along the whole siding and the lateral expansion at the offloading platform for gangways and fluid-handling skids (Figure 2.3), multiplied by the number of platforms:

$$A_{\text{rail,hard}} = n_{\text{platform}} [(L_{\text{rail,total}} - L_{\text{rail,wide}}) W_{\text{rail,base}} + L_{\text{rail,wide}} W_{\text{rail,wide}}] \quad [\text{m}^2] \quad (3.53)$$

$$A_{\text{rail,safety}} = n_{\text{platform}} \left[\max(0, L_{\text{rail,total}} - L_{\text{rail,wide}} - 2R_{i,\text{haz}}) W_{\text{rail,base}} + (L_{\text{rail,wide}} + 2R_{i,\text{haz}}) \times (W_{\text{rail,wide}} + 2R_{i,\text{haz}}) \right] \quad [\text{m}^2] \quad (3.54)$$

The first term is floored at zero because at short siding lengths the hazard corridor around the transfer zone extends beyond the siding itself, in which case the plain corridor contributes no additional area.

Pipeline Dimensioning

Pipelines are sized for an intermittent peak-demand scenario rather than the average daily flow. A universal peak factor k_{peak} is applied as an upper bound reflecting industrial batch-transfer schedules: a transfer nominally requiring 24 hours but executed in a four to five hour window demands a proportionally higher instantaneous flow rate. The factor also provides margin for unplanned acceleration of deliveries required to maintain buffer levels. For fluid stream j :

$$\dot{m}_{\text{nom},j} = \frac{\dot{m}_{j,\text{daily}}}{24 \times 3600} \quad [\text{kg/s}] \quad (3.55)$$

$$\dot{m}_{\text{max},j} = k_{\text{peak}} \times \dot{m}_{\text{nom},j} \quad [\text{kg/s}] \quad (3.56)$$

$$Q_{\text{max},j} = \frac{\dot{m}_{\text{max},j}}{\rho_j} \quad [\text{m}^3/\text{s}] \quad (3.57)$$

Applying continuity $Q = A \cdot v$ at the fluid-specific design velocity v_j yields the minimum required pipe diameter:

$$A_{\text{req},j} = \frac{Q_{\text{max},j}}{v_j}, \quad [\text{m}^2] \quad (3.58)$$

$$D_{\text{pipe},j} = \sqrt{\frac{4 A_{\text{req},j}}{\pi}} \quad [\text{m}] \quad (3.59)$$

Design velocities are set by pressure loss over a long transmission line rather than by the erosional limit, which is an upper bound the resulting design is checked against; both are

reported side by side in Table B.9. Gaseous hydrogen is transported at elevated pressure to maintain sufficient density for meaningful mass flow through a compact pipe⁷⁶, at a velocity taken from the lower end of the range published for compressed hydrogen lines³⁸.

3.6.3 Synthesis Plant Sizing

The physical footprints of the upstream production facilities follow from empirical space factors. The Direct Air Capture unit, the methanol synthesis plant and the Haber–Bosch plant including its Air Separation Unit are assumed to run continuously at constant load, so their footprints and power demands scale linearly with the respective daily mass flows.

Linear scaling is applied even though process plants ordinarily benefit from economies of scale in equipment size. No e-methanol or e-ammonia plant has yet been built at the throughputs modelled here, and sub-component sizes are bounded by fabrication and transport limits likely below those duties, so a plant of the required capacity would be constructed as several parallel trains and plot area would scale approximately with the number of trains. The alternative assumption, that such plants would be redesigned into a more space-efficient architecture, would require a reference footprint that does not exist. The assumption does not extend to capital cost, and it does not hold below the capacity at which a second train becomes necessary, so the space factors are applied only at or above the throughput of their reference facilities. Residual uncertainty in the space factors is carried through Section 4.6, where each is swept across its full literature range.

Direct Air Capture

The DAC space factor is expressed in m² per tonne of CO₂ captured per year, since DAC plant layouts in the literature are most consistently reported on an annual production basis³⁸. The literature range spans three orders of magnitude, reflecting the diversity of DAC technologies: liquid-solvent systems are compact but energy-intensive, while solid-sorbent systems require substantially more land per unit of captured CO₂⁹¹.

$$A_{\text{dac}} = \left(\dot{m}_{\text{CO}_2, \text{daily}} \times \frac{365}{1000} \right) \times s_{\text{dac}} \quad [\text{m}^2] \quad (3.60)$$

$$P_{\text{dac}} = \frac{\left(\frac{\dot{m}_{\text{CO}_2, \text{daily}}}{1000} \right) \times E_{\text{dac}}}{24 \times 10^6} \quad [\text{GW}] \quad (3.61)$$

Methanol Synthesis Plant

The methanol space factor is expressed on a tonnes-per-hour throughput basis and derived from direct spatial measurement of a reference e-methanol facility¹⁰⁹. The measured footprint includes the synthesis reactor, compressor unit and associated balance-of-plant,

giving an integrated rather than an equipment-only reference. The specific energy covers the synthesis loop only, excluding the upstream electrolysis and carbon capture steps accounted for separately.

$$A_{\text{meth,plant}} = s_{\text{meth,plant}} \times \left(\frac{\dot{m}_{\text{meth,daily}}}{24 \times 1000} \right) \quad [\text{m}^2] \quad (3.62)$$

$$P_{\text{meth,plant}} = \frac{E_{\text{meth,plant}} \times \left(\frac{\dot{m}_{\text{meth,daily}}}{1000} \right)}{24} \quad [\text{MW}] \quad (3.63)$$

Ammonia Synthesis Plant and Air Separation Unit

The Haber–Bosch space factor bundles the synthesis loop, the cryogenic Air Separation Unit and their balance-of-plant into a single footprint parameter, since industrial layouts integrate the nitrogen generation columns closely with the synthesis reactor. The ASU energy demand is calculated separately as a distinct electrical load, which allows the total site power demand to be disaggregated by sub-process. The adopted space factor is the lower of the two planned commercial facilities identified in Section 2.3.5, between which the range spans a factor of four.

$$A_{\text{amm,plant}} = s_{\text{amm,plant}} \times \left(\frac{\dot{m}_{\text{amm,daily}}}{24 \times 1000} \right) \quad [\text{m}^2] \quad (3.64)$$

$$P_{\text{amm,plant}} = \frac{E_{\text{amm,plant}} \times \left(\frac{\dot{m}_{\text{amm,daily}}}{1000} \right)}{24} \quad [\text{MW}] \quad (3.65)$$

$$P_{\text{ASU}} = \frac{E_{\text{ASU}} \times \left(\frac{\dot{m}_{\text{amm,daily}}}{1000} \right)}{24} \quad [\text{MW}] \quad (3.66)$$

Synthesis sizing parameters are listed in Table B.10.

3.6.4 Renewable Production, Electrolysis and Hydrogen Buffer Sizing

The wind-generation system and electrolyser are sized jointly to meet the annual hydrogen demand of each e-fuel pathway, using a capacity-ratio method. The electrolyser-to-generation capacity ratio r is taken from the literature as a design parameter, and the range reported for off-grid wind-coupled electrolysis is given in Chapter 2⁴¹; the sizing chain built on it is developed in this work. The method has two parts: an appropriate value of r is selected, and the trade-offs across a range of r values are quantified. For a given r , the ratio fixes the power ceiling the electrolyser can absorb and therefore the share of the generation profile that reaches the stacks; the generation fleet is then scaled

so that the absorbed share exactly covers the annual electrical energy the hydrogen demand requires; the electrolyser nameplate follows from the scaled fleet; and the resulting hourly hydrogen-production profile gives the surplus electricity and the buffer requirement.

An hourly profile is used because electrolyser utilization and buffer requirements depend on the timing and duration of generation deficits. A continuous-supply case is evaluated separately to isolate the additional capacity and storage associated with intermittency. Two features of the dataset shape the result in opposite directions: it aggregates generation across a large geographical area and is therefore smoother than the output of a single wind farm, which understates local variability and underestimates the buffer an isolated facility would need; and it is wind-only, so because the governing deficit occurs in summer, a wind-solar portfolio could reduce the cumulative deficit and the buffer sized here.

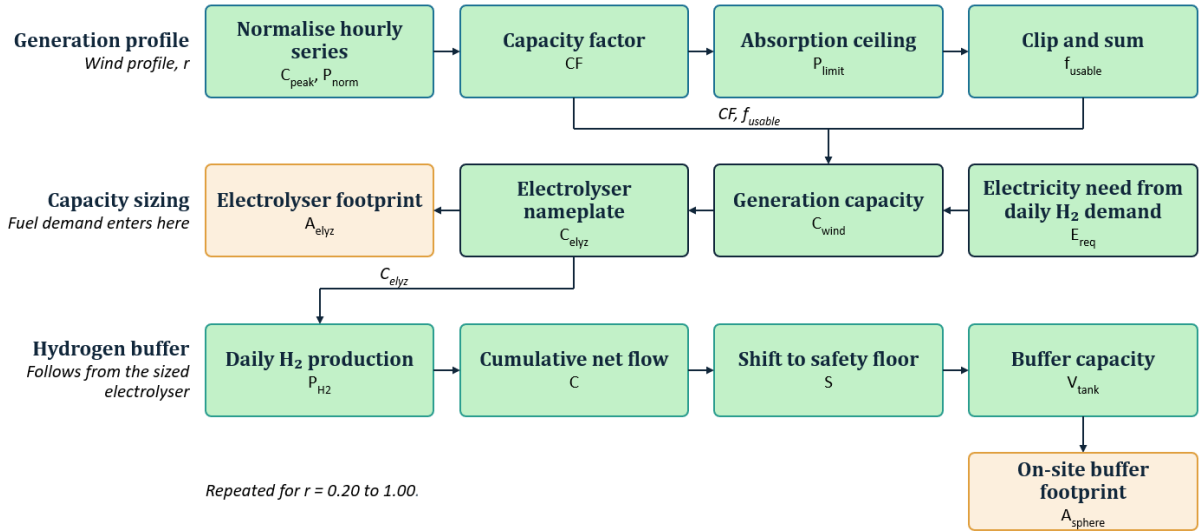


Figure 3.7: Sizing logic for the renewable generation, electrolyser capacity and hydrogen buffer, with the quantity produced at each step.

Figure 3.7 shows the order in which the quantities are established, with the two boxes shaded orange the footprints carried into the aggregated totals. The first band operates on the generation profile alone: the hourly series is normalised against its measured maximum output, the capacity ratio fixes the ceiling the electrolyser can absorb, and clipping the series at that ceiling gives the usable fraction f_{usable} . Fuel demand enters in the second band through the annual electrical requirement, and the generation capacity is sized to meet it once the clipped share is accounted for. The third band reuses the same ratio and the scaled profile to size the buffer. The whole chain is re-evaluated across the sweep of r reported in Section 4.4.1.

The hourly wind generation profile is normalised to the measured maximum output of

the series, giving $P_{\text{norm}}(h)$, the generation in each hour expressed as a percentage of that maximum. The normalised series is independent of the absolute installed capacity, which makes the shape of the profile transferable to any fleet size. The reference maximum C_{peak} is the largest hourly value in the series and is assumed to act as the installed capacity:

$$P_{\text{norm}}(h) = \frac{P_{\text{wind}}(h)}{C_{\text{peak}}} \times 100, \quad [\%] \quad (3.67)$$

$$C_{\text{peak}} = \max_h [P_{\text{wind}}(h)] \quad [\text{MW}] \quad (3.68)$$

$$E_{\text{annual}} = \sum_{h=1}^{8760} P_{\text{wind}}(h), \quad [\text{MWh}] \quad (3.69)$$

$$CF = \frac{E_{\text{annual}}}{C_{\text{peak}} \times 8760} \quad [-] \quad (3.70)$$

The capacity factor is conventionally defined as the annual energy yield divided by the energy the fleet's rated capacity would deliver running continuously for the same period. The rated capacity of the wind fleet behind the SE3 series is not published with the dataset, so this thesis substitutes the measured maximum hourly output, C_{peak} for the rated capacity. All capacities derived below are on a consistent peak-referenced basis, and a physical fleet delivering this profile would carry a nameplate rating above the stated capacity.

The Electrolyser-to-Generation Capacity Ratio

The central design variable is the dimensionless ratio $r = C_{\text{elyz}}/C_{\text{wind}}$. A low ratio combines a relatively small, highly utilized electrolyser with a larger wind fleet, producing comparatively stable hydrogen output and a smaller buffer but more surplus electricity. A high ratio lets the electrolyser absorb a larger share of generation peaks, reducing the required wind capacity and surplus, but hydrogen production then follows the variable wind profile more closely and the buffer grows.

The ratio enters the sizing through an absorption ceiling, above which the excess passes over and is exported rather than converted:

$$P_{\text{limit}} = r \times C_{\text{peak}} \quad [\text{MW}] \quad (3.71)$$

The fraction of the annual wind energy falling below the ceiling is obtained by clipping the hourly series at P_{limit} and summing:

$$E_{\text{usable}} = \sum_{h=1}^{8760} \min(P_{\text{wind}}(h), P_{\text{limit}}), \quad [\text{MWh}] \quad (3.72)$$

$$f_{\text{usable}} = \frac{E_{\text{usable}}}{E_{\text{annual}}} \quad [-] \quad (3.73)$$

f_{usable} is therefore fixed by the shape of the hourly profile and the value of r alone. The annual electrical energy requirement follows from the daily hydrogen demand and the electrolyser specific energy η_e , and is the energy that must reach the stacks rather than the energy the wind farm generates:

$$E_{\text{req},f,e} = \frac{\dot{m}_{\text{H}_2,\text{daily},f} \times \eta_e \times 365}{10^6} \quad [\text{GWh}] \quad (3.74)$$

The generation capacity is sized so that the absorbed part of its output equals E_{req} exactly. Dividing by $CF \times 8760$ converts the energy requirement into a capacity, and dividing by f_{usable} inflates the farm to compensate for what is clipped:

$$C_{\text{wind},f,e} = \frac{E_{\text{req},f,e}}{CF \times f_{\text{usable}} \times 8760} \quad [\text{GW}] \quad (3.75)$$

A smaller r therefore gives a lower ceiling, more clipping, and a larger farm for the same hydrogen output. The electrolyser nameplate follows from the farm capacity and the ratio, and its peak output and footprint from the nameplate:

$$C_{\text{elyz},f,e} = r \times C_{\text{wind},f,e} \quad [\text{GW}] \quad (3.76)$$

$$P_{\text{H}_2,\text{peak}} = \frac{C_{\text{elyz}} \times 24 \times 10^6}{\eta_e} \quad [\text{kg/day}] \quad (3.77)$$

$$A_{\text{elyz}} = P_{\text{H}_2,\text{peak}} \times s_e \quad [\text{m}^2] \quad (3.78)$$

The specific energy η_e cancels between Equations 3.76 and 3.77, so the electrolyser footprint depends on s_e and the hydrogen demand alone and not on the efficiency of the technology selected. A change of technology moves the footprint through s_e and the energy demand through η_e , and the two effects are reported separately in Section 4.6.

Energy generated in excess of the ceiling is assumed to be exported to the grid at no penalty, which is the most favourable assumption for surplus disposition; curtailment instructions or transmission constraints could reduce it:

$$E_{\text{export}} = C_{\text{wind}} \times CF \times 8760 - E_{\text{req}} \quad [\text{GWh}] \quad (3.79)$$

Electrolyser Technology Selection

Three technologies are compared: PEM, alkaline and solid oxide. PEM is selected as the baseline because its stacks ramp quickly between loads³², which an intermittent profile requires; because the reference PEM plant has a lower footprint ratio than the alkaline comparator; and because that reference is a complete industrial plant rather than an isolated stack, giving realistic balance-of-plant parameters³⁵.

The PEM footprint ratio spans a factor of about 47 across the surveyed systems, and the upper end is adopted, so the electrolyser footprint is reported at the high end of that range. The span reflects whether balance-of-plant is included in the reported footprint rather than a difference in stack technology, and the complete-plant figure is the appropriate basis for a land-use assessment. The ratio is swept separately from the comparison between the three technologies, because the two questions are distinct: the technology comparison covers three commercial products, while the ratio spans the reporting conventions applied to one.

Solid oxide offers the lowest specific energy and the most compact footprint but requires elevated steady-state operating temperatures³², limiting its suitability for dynamic renewable-coupled operation where thermal cycling would accelerate stack degradation. Alkaline is mature but responds more slowly to load changes and carries the largest footprint penalty. All three are retained in the comparative analysis. Parameters are listed in Table B.11.

Hydrogen Buffer Storage

The hydrogen buffer balances variable wind-driven electrolysis with the synthesis plant's constant hydrogen demand. Storage is sized from daily balances, assuming that in-line process inventory absorbs intra-day fluctuations and that underground bulk storage covers multi-day imbalances. For a given r , daily hydrogen production is calculated by summing the hourly wind power available to the electrolyser, capped at its nameplate capacity:

$$P_{\text{H}_2}(d) = \frac{1}{\eta_e} \sum_{h \in \text{day } d} \min\left(P_{\text{wind}}(h) \times \frac{C_{\text{wind}}}{C_{\text{peak}}}, C_{\text{elyz}}\right) \times 10^6 \quad [\text{kg/day}] \quad (3.80)$$

Where P_{wind} is scaled to the sized generation capacity. The net daily flow traces the trajectory of an idealised unbounded inventory:

$$\dot{n}(d) = P_{\text{H}_2}(d) - \dot{m}_{\text{H}_2, \text{daily}} \quad [\text{kg/day}] \quad (3.81)$$

$$C(d) = \sum_{k=1}^d \dot{n}(k) \quad [\text{kg}] \quad (3.82)$$

Because annual production equals annual demand by construction, $C(d)$ is cyclic and returns to its starting level at year-end with no multi-year drift. The trajectory is shifted upward so that its minimum coincides with the mandatory safety buffer, and the required capacity is the peak of the shifted trajectory:

$$S(d) = C(d) - \min_d[C(d)] + V_{\text{buf}} \quad [\text{kg}] \quad (3.83)$$

$$V_{\text{buf}} = \dot{m}_{\text{H}_2, \text{daily}} \times t_{\text{min, buf}} \quad [\text{kg}] \quad (3.84)$$

$$V_{\text{tank}} = \max_d[S(d)] \quad [\text{kg}] \quad (3.85)$$

At a given r the required buffer mass is independent of electrolyser technology, demand level and fuel. Efficiency scales the electrical energy consumed and the generation capacity but not the hydrogen mass balance, and the generation asset is scaled so that annual production equals annual demand regardless of η_e , so the shape of the net-flow trajectory depends only on the profile and on r . Expressed as a number of days of demand, the buffer is therefore invariant across all scenarios at a given r .

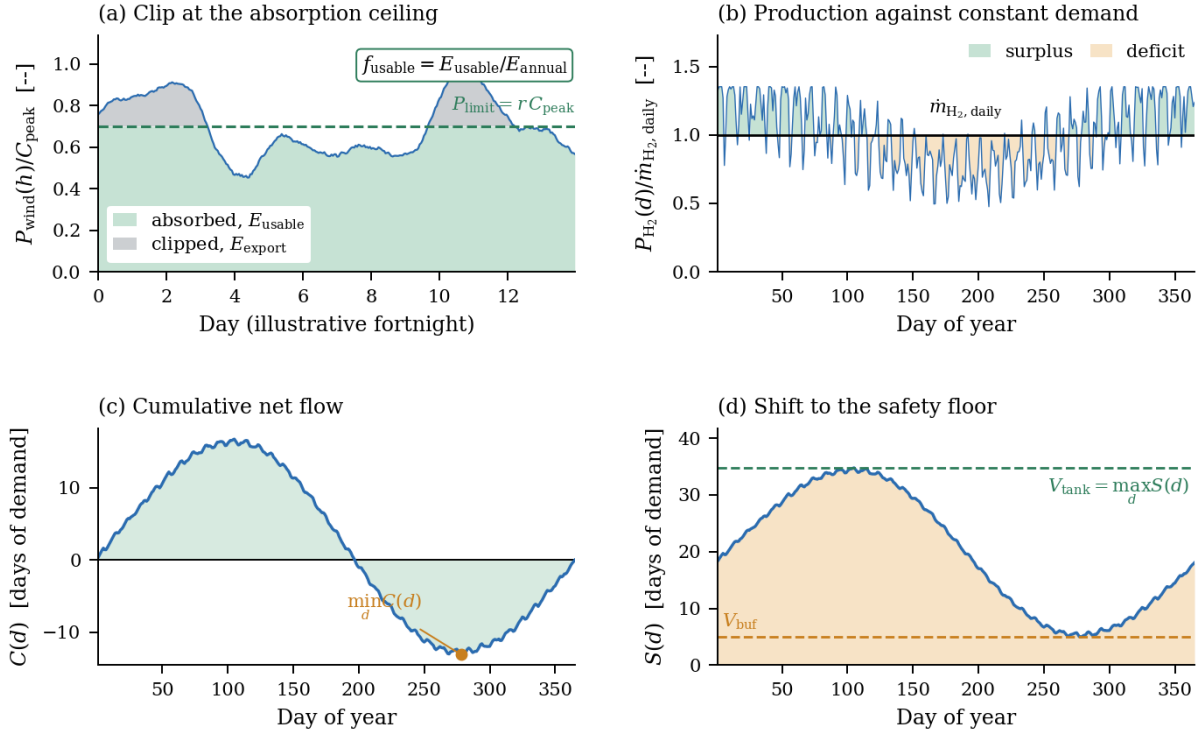


Figure 3.8: Illustration of the sizing chain at a given r . Series are synthetic and dimensionless.

Figure 3.8 shows the same chain graphically. Panel (a) is the clipping step of Equations 3.72 and 3.73, panel (b) the daily production of Equation 3.80 against the constant synthesis draw, and panels (c) and (d) the cumulative net flow of Equation 3.82 and its shift onto the safety floor in Equation 3.83, whose peak is the required capacity.

Given the scale of the multi-day buffer, the primary bulk inventory is assumed to be held off site in geological storage such as lined rock caverns. A one-day buffer is retained on site for operational redundancy, at the steady daily hydrogen demand of the synthesis plant:

$$M_{\text{onsite}} = \dot{m}_{\text{H}_2, \text{daily}} \times 1 \text{ day} \quad [\text{kg}] \quad (3.86)$$

Two options for local buffering of this on-site mass are considered, cryogenic spherical tanks and large-diameter pipeline storage. Both apply the grid-packing and setback logic of

Section 3.6.1, scaled to hydrogen-specific vessel geometry and OSHA separation distances; the geometric derivation is given in Section B.3. The two results carried into the aggregated totals are the safety-zone footprints:

$$A_{\text{sphere,safety}} = (W_{\text{pad}} + 2S_{\text{LH}_2}) \times (L_{\text{pad}} + 2S_{\text{LH}_2}) \quad [\text{m}^2] \quad (3.87)$$

$$A_{\text{pipe,safety}} = (L_{\text{pipe}} \times 1000 + 2S_{\text{GH}_2}) \times (D_{\text{pipe}} + 2S_{\text{GH}_2}) \quad [\text{m}^2] \quad (3.88)$$

Where S_{LH_2} and S_{GH_2} are the OSHA-derived separation distances for liquefied and gaseous hydrogen systems. Splitting the inventory this way accounts for the land use of an immediate local backup without forcing the multi-week seasonal buffer into above-ground containment.

Ratio Selection and Trade-off Sweep

The trade-off between generation capacity, electrolyser capacity, grid export and buffer storage is quantified by sweeping r from 0.20 to 1.00 in steps of 0.05, recalculating the power limit, usable fraction, generation capacity, electrolyser capacity, buffer size and surplus at each step.

The baseline ratio is selected from the energy capture curve. Ranking the normalised hourly values in descending order gives the power duration curve, which shows how little of the annual energy sits in the top of the distribution and therefore how much an electrolyser sized below peak generation can still absorb:

$$P_{\text{sort}}(k) = \text{sort}_{\downarrow}[P_{\text{norm}}(h)], \quad k = 1, \dots, 8760 \quad [\%] \quad (3.89)$$

The curve is used to read the trade-off rather than to compute it: the capture fraction at each candidate ratio is the usable fraction of Equation 3.73, which clips the series at the ceiling and is independent of the order in which the hours are taken,

$$f_{\text{capture}} = f_{\text{usable}} \times 100 \quad [\%] \quad (3.90)$$

3.6.5 Port Spatial Accommodation Assessment

The final research question is addressed by aggregating the Layer 3 footprints computed in Section 3.6 and comparing the total against the industrial land parcels of the reference port. The assessment establishes whether the architecture can be centralised at the quayside, or whether land constraints and risk-mitigation mandates force a decentralised approach that relocates land-intensive or hazardous utilities to inland industrial zones.

Gross-to-net allowance. Summing the Layer 3 rectangles of independently sized assets assumes complete packing efficiency: no internal roads, firewater loop, administration or control buildings, pipe racks, laydown area or separation between the units themselves.

A packing factor f_{pack} is therefore applied to the aggregated total, and both figures are reported:

$$A_{\text{gross}} = f_{\text{pack}} \times \sum_j A_{\text{safety},j} \quad [\text{m}^2] \quad (3.91)$$

The value of f_{pack} is assumed rather than derived, at 1.35, following the gross-to-net treatment introduced in Section 2.4. The net figures are retained as the primary results because they are what the model computes; the gross figures are the appropriate basis for comparison against a real land parcel.

Land inventory and verdict definitions.

The parcels are ordered into tiers by scale and planning confidence, and a verdict is assigned to each configuration against that ordering:

- *Feasible (acquisition threshold)*: fits within the confirmed near-term acquisition area.
- *Feasible (existing boundary)*: fits within an undeveloped parcel inside the current port boundary.
- *Feasible (opportunistic)*: fits only within the speculative land-reclamation scenario.
- *Conditionally feasible*: requires relocating large components off site to fit an existing boundary.
- *Not feasible*: exceeds all identified parcels, even with decentralisation.

Verdicts are assigned on the gross footprint wherever the gross-to-net allowance changes the applicable tier. The parcels themselves are presented in Section 4.5.1.

Code availability

The complete MATLAB implementation of the sizing model is described in Appendix D and is openly available at <https://github.com/ResearcherLXH/Master-thesis-on-e-fuel-infrastructure-in-ports>¹¹⁰.

4

Case Study and Results

This chapter applies the sizing framework of Chapter 3 to the Port of Gothenburg as a bunkering hub for e-methanol and e-ammonia. Section 4.1 fixes the case-specific input values. The remaining sections present the quantitative outputs in the same order as the calculation chain of Table 3.1, with each section’s outputs defining the boundary conditions for the section that follows. Parameter uncertainty is bounded separately in Section 4.6, and the interpretation of the results is deferred to Chapter 6.

Four demand scenarios are evaluated, distinguishing the two fuels and two market-penetration assumptions:

- **Scenario A (25 % methanol):** e-methanol is assigned a 25 % share of annual MGO demand to match the lower bound of the ammonia market projection and enable symmetric comparison between the two fuels at equivalent demand levels; the port’s expressed ambition to become the primary Northern European methanol bunkering hub provides further justification for this framing²⁴.
- **Scenario B (25 % ammonia):** e-ammonia satisfies 25 % of the annual MGO demand, aligned with a lower-range ammonia market share projection.
- **Scenario C (100 % methanol):** e-methanol replaces the port’s entire MGO-equivalent bunkering demand, an upper-bound scenario exploring the maximum spatial and energy requirement of a fully methanol-based supply chain.
- **Scenario D (100 % ammonia):** the equivalent full-replacement of annual MGO demand scenario for e-ammonia.

4.1 Case Study Parameter Selection

Tables 4.1 and 4.2 give the baseline value used for every parameter. The literature justification, competing-value reasoning and source for each entry are consolidated in Tables C.1–C.10, under the same thematic groupings used here. The selection convention is stated in Section 3.3.2, and the position of every ranged parameter within its range is given in Table C.11.

Table 4.1: Case Study Baseline Parameters I: Demand, Fuel Properties, Storage, and Distribution

Parameter	Symbol	Value used
<i>Demand and fuel mix</i>		
Annual MGO demand	m_{mgo}	1.7×10^6 t/yr
Methanol / ammonia mix fraction	$f_{\text{meth}} / f_{\text{amm}}$	0.25 or 1.00 (each)
Safety buffer (e-fuel / H ₂)	$t_{\text{buffer}} / t_{\text{buffer,H}_2}$	7 d / 5 d
Tank heel fraction	f_{heel}	0.05
<i>Fuel physical properties</i>		
MGO / methanol / ammonia (FR) density	ρ	850 / 786.3 / 681.97 kg/m ³
MGO / methanol / ammonia LHV	LHV	42.7 / 19.9 / 18.60 MJ/kg
Ammonia density, rail and road (pressurised)	$\rho_{\text{amm,NR}}$	602.8 kg/m ³
Ammonia density in pipeline (pressurised)	$\rho_{\text{amm,pipe}}$	564 kg/m ³
<i>Tank fill limits and spacing</i>		
MGO / methanol max fill fraction	f_{max}	0.95 / 0.80
Ammonia max fill fraction	$f_{\text{max,amm}}$	0.875
MGO/methanol max tank volume	V_{max}	100 000 m ³
Ammonia max tank volume (FR)	$V_{\text{max,amm}}$	60 000 m ³
Bund wall height	h_{bund}	1.5 m
MGO/methanol / ammonia safety setback	s_{bldg}	76 / 106 m
<i>Logistics and distribution</i>		
Ammonia VLGCC / methanol carrier packet	V_{pkt}	87 000 / 120 000 m ³
Pipeline / rail / truck share	$f_{\text{pipe/rail/truck}}$	70 / 20 / 10 %
Max block-train length	$L_{\text{train,max}}$	740 m
Sustained bunker transfer rate	Q_{bkr}	500 m ³ /hr
Peak flow factor	k_{peak}	5
Ammonia / Methanol / H ₂ design velocity	v	1.8 / 2.0 / 20 m/s
Bunkering hazard radius (methanol / ammonia)	$R_{i,\text{haz}}$	25 / 50 m
Gross-to-net packing factor	f_{pack}	1.35

Table 4.2: Case Study Baseline Parameters II: Synthesis, Renewable Production, and Hydrogen Buffer

Parameter	Symbol	Value used
DAC space / specific energy	$s_{\text{dac}} / E_{\text{dac}}$	0.10 m ² /(t CO ₂ /yr) / 2 639 kWh/t CO ₂
Methanol plant space / specific energy	$s_{\text{meth,plant}} / E_{\text{meth,plant}}$	2 487 m ² /tph / 0.71 MWh/t
Haber–Bosch plant space / specific energy	$s_{\text{amm,plant}} / E_{\text{amm,plant}}$	1 593 m ² /tph / 0.97 MWh/t
ASU specific energy	E_{ASU}	0.114 MWh/t _{NH₃}
Electrolyser technology	–	PEM (Siemens Elyzer)
PEM specific energy / footprint ratio	$\eta_{\text{PEM}} / s_{\text{PEM}}$	55.0 kWh/kg / 0.349 m ² /(kg/day)
Capacity ratio	r_{base}	0.70
Wind resource dataset	–	SE3 hourly (8 760 pts)
LH ₂ sphere max capacity / density	$M_{\text{sphere,max}} / \rho_{\text{LH}_2}$	270 t / 70 kg/m ³
Sphere wall thickness	t_{wall}	2.25 m
GH ₂ pipeline linear capacity / diameter	$\lambda_{\text{pipe}} / D_{\text{pipe}}$	12 t/km / 1.4 m
LH ₂ / GH ₂ safety setbacks	$S_{\text{LH}_2} / S_{\text{GH}_2}$	30.48 / 15.24 m

4.2 Demand Characterisation

4.2.1 Energy Equivalence and Annual Fuel Volumes

Substituting the fuel physical properties into Equation 3.1 gives:

$$M_{\text{meth}} = \frac{850 \times 42.7}{786.3 \times 19.9} = 2.3196, \quad M_{\text{amm}} = \frac{850 \times 42.7}{681.97 \times 18.6} = 2.8613$$

E-methanol therefore requires 2.32 times, and e-ammonia 2.86 times, the volumetric throughput of MGO for an equivalent energy service. Applying these multipliers to the port’s annual demand gives the fuel volumes of Table 4.3. The MGO baseline density enters only through the multipliers and cancels against the reference volume, so the annual fuel volumes and everything derived from them are independent of it.

4.2.2 Daily Reactant Demands

Table 4.4 converts the annual fuel volumes to daily mass flows and applies the stoichiometric ratios of Equations 3.3–3.8 at 100 % single-pass conversion. The two pathways have near-identical hydrogen demand at each demand level, differing by under 1 %. At the level of aggregate hydrogen demand, the two pathways require similar wind-generation and electrolyser capacities. However, fuel-specific requirements may limit the direct interchangeability of the associated infrastructure.

Table 4.3: Annual Fuel Volumes and Volumetric Multipliers by Scenario

Scenario	Fuel	M_i	f_i	V_{annual} (m ³ /yr)	Daily mean (m ³ /day)
A (25 % methanol)	Methanol	2.3196	0.25	1 159 780	3 177
B (25 % ammonia)	Ammonia	2.8613	0.25	1 430 667	3 920
C (100 % methanol)	Methanol	2.3196	1.00	4 639 118	12 710
D (100 % ammonia)	Ammonia	2.8613	1.00	5 722 668	15 679
MGO (baseline reference)	MGO	1.000	–	2 000 000	5 479

Table 4.4: Daily Fuel Production Rates and Stoichiometric Reactant Demands

Stream	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
<i>Fuel product</i>				
Fuel production (t/day)	2 498	2 673	9 994	10 692
Fuel production (t/hr)	104.1	111.4	416.4	445.5
<i>Upstream reactants</i>				
H ₂ demand (t/day)	468	472	1 874	1 887
CO ₂ demand (t/day)	3 435	–	13 741	–
N ₂ demand (t/day)	–	2 201	–	8 805
H ₂ O consumed (t/day)	4 216	4 245	16 865	16 982
<i>Co-products</i>				
O ₂ produced (t/day)	3 748	3 774	14 991	15 095

CO_2 is the most spatially consequential reactant for the methanol pathway, since it drives the sizing of the DAC unit. The oxygen co-product, at roughly 3 800 t/day at the 25 % level and 15 100 t/day at full replacement, is a substantial industrial stream; it lies outside the system boundary but is reported as a design constraint in its own right.

4.3 Spatial Footprint Modelling

4.3.1 Fuel Storage Tank Sizing

Working Volume and Tank Count

The effective usable fractions are 0.75 for methanol and 0.825 for ammonia. Applying Equations 3.11–3.16 with the largest vessel packets and a 7-day safety buffer yields Table 4.5.

Table 4.5: Tank Sizing Results by Scenario

Parameter	Sc-A (25 % MeOH)	Sc-B (25 % NH_3)	Sc-C (100 % MeOH)	Sc-D (100 % NH_3)
Safety buffer volume (m^3)	22 242	27 437	88 969	109 750
Working volume V_{working} (m^3)	142 242	114 437	208 969	196 750
Total geometric volume (m^3)	189 656	138 712	278 626	238 485
Number of tanks n_{tanks} (–)	2	3	3	4

Scenario A requires a larger working volume than Scenario B despite the higher annual throughput of ammonia, because the methanol ship packet exceeds the ammonia VLGC packet and the packet dominates the working-volume formula at the 25 % level. At full replacement the buffer contribution grows proportionally and partially offsets this, leaving Scenario C above Scenario D by a much smaller margin.

Tank Geometry

Physical dimensions follow from the empirical H/D fits of Equations 3.17 and 3.18, and are given in Table 4.6.

Methanol tanks are wide and shallow in the API 650 fixed-roof regime, while ammonia DWDI tanks are taller and more cylindrical under the API 620 flat-bottom refrigerated regime.

Table 4.6: Tank Geometry Results

Parameter	Sc-A	Sc-B	Sc-C	Sc-D
Per-tank geometric volume (m^3)	94 828	46 237	92 875	59 621
H/D ratio R (-)	0.250	0.655	0.256	0.642
Inner diameter D_{inner} (m)	78.4	44.8	77.3	49.1
Tank height H_{tank} (m)	19.6	29.3	19.8	31.5
Insulation thickness t_{insul} (m)	–	1.00	–	1.08
Outer diameter D_{outer} (m)	78.4	46.8	77.3	51.2

Table 4.7 presents all three layers for each scenario. Layer 2 is substantially larger than Layer 1 for methanol, because the bund must hold the larger of 110 % of the single-tank volume or 25 % of the group volume, expanding the footprint to roughly five times the hardware core. For ammonia DWDI the two layers coincide. The Layer 3 exclusion zone then dominates both: the 106 m ammonia setback against 76 m for methanol almost equalises the final safety footprints at full replacement, despite the different containment requirements upstream of them. The resulting layouts at the 25 % level are shown in Figures 4.1 and 4.2.

The corresponding 100 % layouts follow the same structure at proportionally larger scale and are given in Figures C.1 and C.2.

Table 4.7: Three-Layer Storage Footprints by Scenario (all areas in hectares)

Layer	Dimension	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
L1 Hardware	$W \times H$ (m)	196×78	234×47	309×77	154×154
L1 Hardware	Area (ha)	1.54	1.09	2.39	2.36
L2 Bund/Containment	$W \times H$ (m)	445×178	234×47	573×143	154×154
L2 Bund/Containment	Area (ha)	7.92	1.09	8.22	2.36
L3 Safety zone	$W \times H$ (m)	445×230	446×259	573×229	366×366
L3 Safety zone	Area (ha)	10.25	11.54	13.15	13.38

4.3.2 Distribution: Import Terminal, Bunkering, and Pipeline Footprints

Import Terminal Inventory Simulation

The 8 760-hour simulation is executed for all four scenarios at the baseline modal split of 70 % pipeline, 20 % rail and 10 % truck, held constant across both fuels. Block-train length is capped at 740 m, and where the rail volume exceeds one capped train per operating

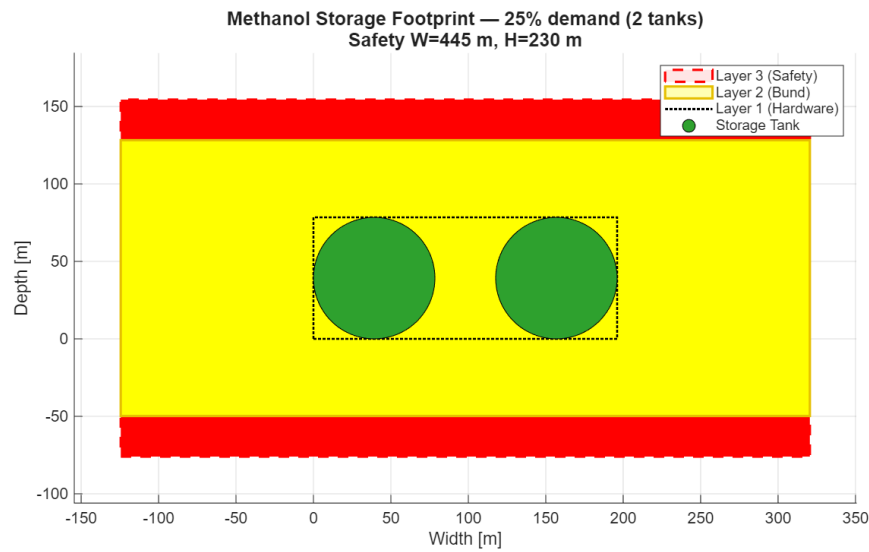


Figure 4.1: Three-layer spatial footprint for methanol storage under Scenario A (25 % demand, 2 tanks). The yellow zone indicates the earthen bund required for single-wall liquid containment.

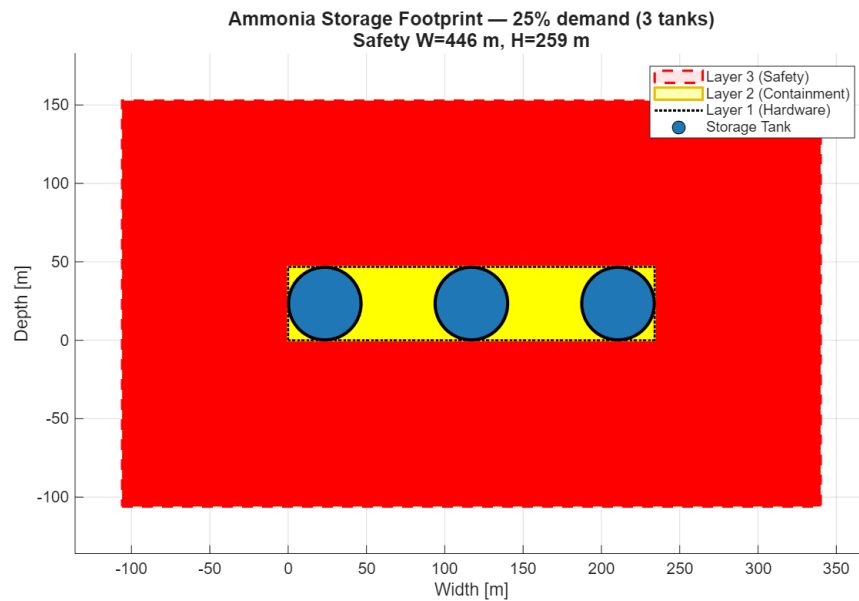


Figure 4.2: Three-layer spatial footprint for ammonia DWDI storage under Scenario B (25 % demand, 3 tanks). The secondary containment is structurally integral to the tanks, making Layer 2 identical to Layer 1.

weekday the throughput is met by increasing frequency rather than length. Table 4.8 gives the resulting delivery pattern and inventory requirement.

The simulated trajectory reproduces the static working-volume estimate of Equation 3.11 to within 1 %. As set out in Section 3.6.2, this agreement is structural rather than independent. What the simulation resolves is the shape of the trajectory, shown in Figures 4.3

Table 4.8: Inventory Simulation Results: All Scenarios

Stream	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
Annual throughput (m ³ /yr)	1 159 780	1 430 667	4 639 118	5 722 668
Pipeline inflow rate (m ³ /hr)	92.68	114.32	370.71	457.29
Rail: trains per year	238	238	296	412
Rail: volume per train (m ³)	974.6	1 202.2	3 134.5	2 778.0
Rail: wagons per train (-)	12	17	37	37
Truck: trips per year	3 816	4 082	15 263	16 329
Truck: daily (avg, 240 op. days)	15.9	17.0	63.6	68.0
Ship packet size (m ³)	120 000	87 000	120 000	87 000
Annual vessel calls (simulated)	~9	~16	~38	~65
7-day safety buffer (m ³)	22 242	27 437	88 969	109 750
Required working volume (m ³)	≈142 200	≈114 400	≈209 000	≈196 700
Dynamic nominal volume (m ³)	≈189 600	≈138 700	≈278 600	≈238 500

and 4.4: the sawtooth produced by discrete vessel calls against continuous pipeline inflow and batched rail impulses, and the confirmation that no intermediate state violates the buffer floor under the modelled delivery schedule.

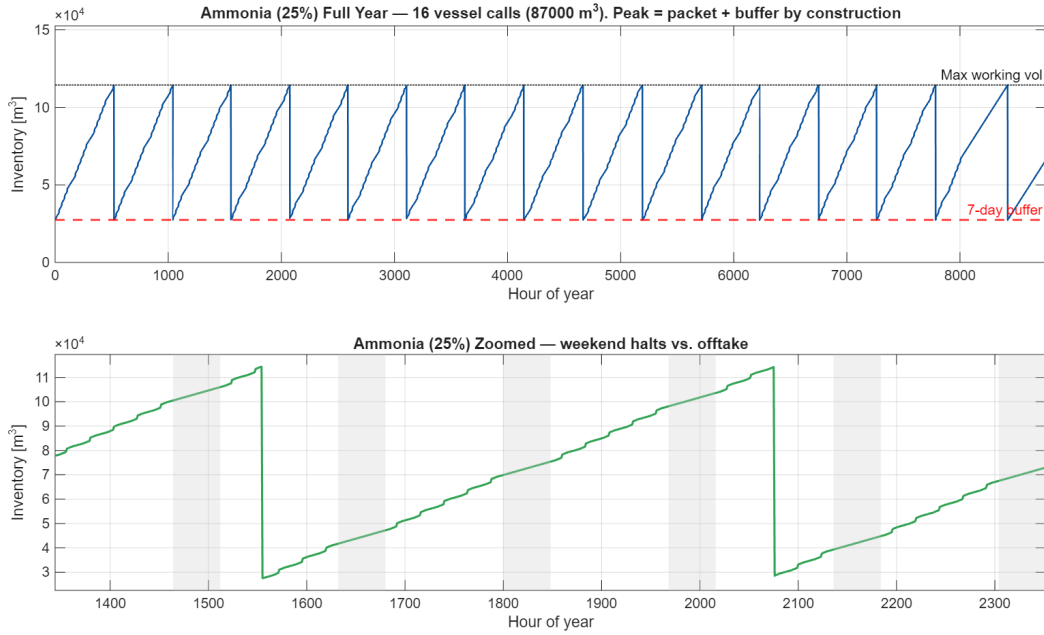


Figure 4.3: Simulated 8 760-hour inventory trajectory for the Scenario B ammonia import terminal. Upper panel: full operating year showing the sawtooth drawdown pattern from VLGC vessel calls at 87 000 m³. Lower panel: six-week zoom highlighting weekend pipeline-only accumulation (grey bands) and weekday rail impulses at noon.

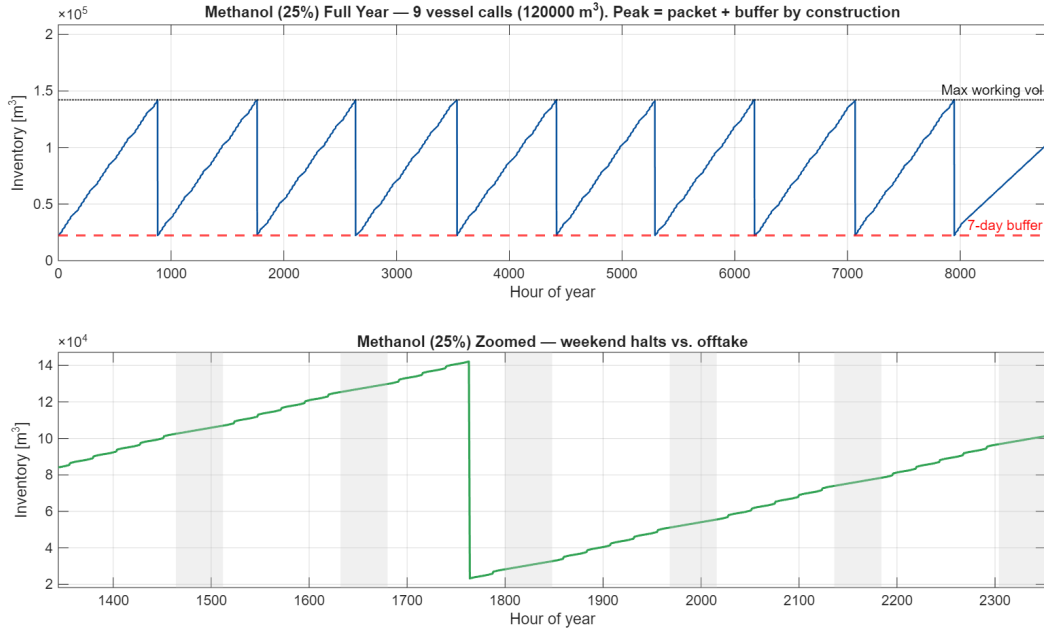


Figure 4.4: Simulated 8760-hour inventory trajectory for the Scenario A methanol import terminal. The larger ship packet of 120 000 m³ produces fewer but larger drawdown events, approximately 9 vessel calls per year against 16 for ammonia, and a slightly higher peak inventory.

The 100 % trajectories preserve the same structure with vessel call frequency increasing proportionally, and are given in Figures C.5 and C.6.

Pipeline Dimensioning

Table 4.9 gives the minimum pipe diameters at the peak flow factor $k_{\text{peak}} = 5$. They are reported for completeness of the asset inventory but contribute no land area to the aggregated totals, since transmission corridors lie outside the system boundary of Section 3.2.

Table 4.9: Minimum Pipeline Diameters at Peak Flow Factor $k_{\text{peak}} = 5$

Pathway	Line	Sc-A	Sc-B	Sc-C	Sc-D
Methanol	Product line	342 mm	—	684 mm	—
Ammonia	Product line	—	440 mm	—	881 mm
Both pathways	H ₂ feed line	470 mm	472 mm	941 mm	944 mm
Both pathways	Water supply line	455 mm	457 mm	910 mm	913 mm

Shore-Side Bunkering and Transfer Infrastructure

The number of transfer positions follows from the peak daily bunkering throughput and the per-operation turnaround, so the quayside footprint of Table 4.10 scales with demand in the same way as the land-side nodes.

Table 4.10: Quayside Bunkering Hardware and Safety Exclusion Footprints

Parameter	Sc-A (MeOH, 25 %)	Sc-B (NH ₃ , 25 %)	Sc-C (MeOH, 100 %)	Sc-D (NH ₃ , 100 %)
Daily bunker offtake (m ³ /day)	3 177	3 920	12 709	15 679
Transfer positions (–)	2	2	5	6
Quayside hardware area (m ²)	300	300	750	900
Hazard radius (m)	25	50	25	50
Active safety exclusion zone (ha)	0.78	2.53	1.95	7.59
Minimum quay frontage (m)	500	600	1 250	1 800

The physical quayside equipment remains compact, but the exclusion zone scales with the number of positions demand requires, and the fuel-specific hazard radius sets how steeply. At full replacement the ammonia pathway needs six positions at a 50 m dispersion baseline against five at 25 m for methanol, which is a difference of one position but almost four times the exclusion area, and 1 800 m of quay frontage against 1 250 m.

Table 4.11 gives the corresponding land-side reception requirements.

Table 4.11: Land-Side Transfer Infrastructure Requirements (Truck and Rail)

Parameter	Sc-A (MeOH, 25 %)	Sc-B (NH ₃ , 25 %)	Sc-C (MeOH, 100 %)	Sc-D (NH ₃ , 100 %)
<i>Truck transfer infrastructure</i>				
Daily truck arrivals (avg)	15.9	17.0	63.6	68.0
Required truck bays	1	1	4	4
Active safety footprint (ha)	0.52	1.50	1.10	2.53
<i>Rail siding infrastructure</i>				
Volume per train (m ³)	974.6	1 202.2	3 134.5	2 778.0
Wagons per block train	12	17	37	37
Block trains per year	238	238	296	412
Active siding platform length (m)	240	340	740	740
Platforms required	1	1	1	1
Active safety footprint (ha)	1.89	5.06	5.18	9.68

At the 25 % level the land-side footprint is modest: a single truck bay and block trains within standard European industrial siding lengths. At full replacement the 740 m cap

binds, so Scenario D meets its throughput through 412 trains per year rather than a longer consignment, giving a 9.68 ha safety corridor instead of the larger one an uncapped 57-wagon train would require. The ammonia road and rail streams are carried at the pressurised ambient density of 602.8 kg/m^3 under the carried-state convention, which is what sets the Scenario B truck count.

4.3.3 Synthesis Plant Sizing

Applying the space factors of Section 3.6.3 to the daily production rates gives the plant footprints of Table 4.12. The methanol pathway carries more than twice the synthesis and capture footprint of the ammonia pathway at both demand levels. The difference is dominated by the DAC unit, which has no counterpart in the nitrogen-based pathway.

Table 4.12: Synthesis Plant Footprints and Power Demands

Component	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
<i>Footprint (ha)</i>				
DAC unit	12.54	–	50.16	–
Methanol synthesis plant	25.89	–	103.56	–
Haber–Bosch plant (incl. ASU)	–	17.74	–	70.97
<i>Power demand (MW, grid-supplied except electrolyser)</i>				
DAC power	377.75	–	1 511.00	–
Methanol synthesis	73.91	–	295.65	–
HB synthesis loop	–	108.04	–	432.15
ASU	–	12.70	–	50.79

4.3.4 Wind Farm and Electrolyser Sizing

SE3 Wind Resource Characterisation

The SE3 regional dataset yields $CF = 0.326$. The 14-day smoothed profile of Figure 4.5 shows high-generation winters and low-generation summers, and this seasonal structure is the primary driver of the multi-week hydrogen buffer requirement.

Figure 4.6 recasts the same series as a duration curve and as the energy captured at each candidate capacity ratio. Generation exceeds 70 % of peak output for fewer than 1 000 hours per year, so the top of the duration curve contributes little annual energy. This is what makes the capture curve concave and allows an electrolyser sized well below peak generation to absorb almost all of it.

Wind Farm and Electrolyser Sizing

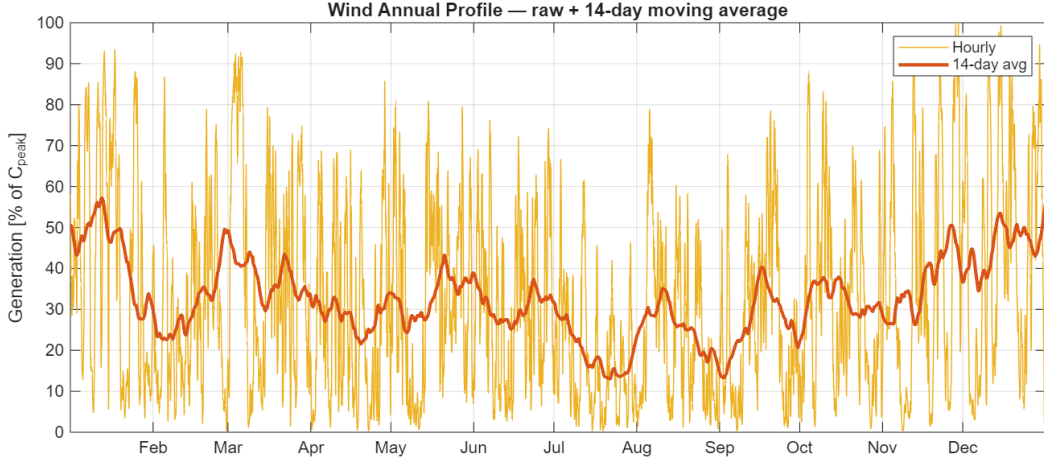


Figure 4.5: SE3 hourly generation profile with 14-day centred moving average. The summer wind drought visible in July and August is the binding constraint on hydrogen buffer sizing.

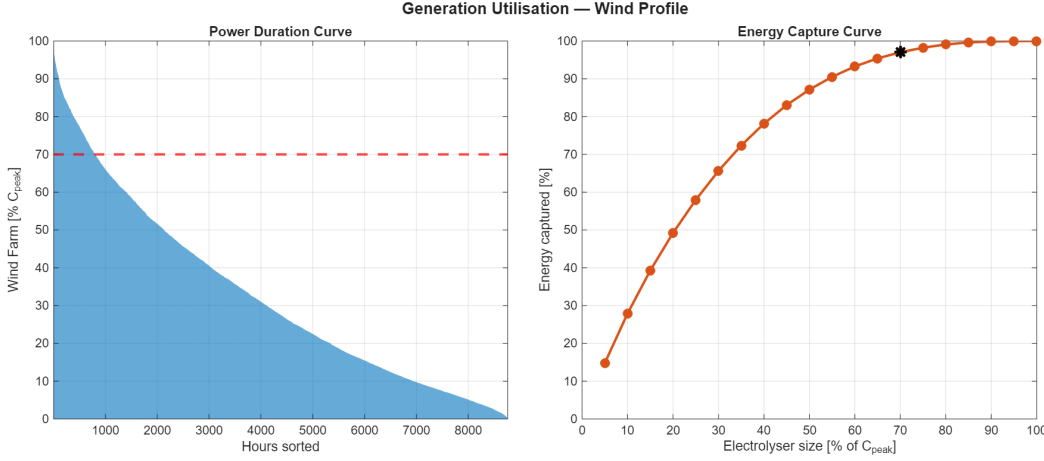


Figure 4.6: Left: SE3 power duration curve. Right: energy capture fraction as a function of the electrolyser capacity ratio r , with the selected operating point $r = 0.70$ marked.

With $r = 0.70$ and PEM technology, the wind farm and electrolyser are sized from Equations 3.75–3.78, giving the capacities of Table 4.13. The near-identical hydrogen demands of Table 4.4 translate directly into near-identical wind farm and electrolyser sizes, so the renewable supply asset is effectively the same in either pathway at a given demand level.

4.3.5 Hydrogen Buffer Storage

The required buffer mass is technology-independent at any given r (Section 3.6.4), so a single result applies across all three electrolyser technologies. Table 4.14 gives the requirement for all four scenarios at three capacity ratios, in tonnes of H_2 and in days of synthesis-plant demand covered.

Table 4.13: Wind Farm and Electrolyser Sizing at $r = 0.70$, PEM technology

Parameter	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
H ₂ electricity demand (GWh/yr)	9 404	9 470	37 617	37 879
Electrolyser capacity (GW)	2.37	2.39	9.50	9.57
Wind farm peak capacity (GW)	3.39	3.42	13.57	13.67
Electrolyser area (ha)	36.17	36.42	144.67	145.68

Table 4.14: Hydrogen Buffer Storage Requirements at Selected Capacity Ratios.

r	Sc-A (MeOH, 25 %)		Sc-B (NH ₃ , 25 %)		Sc-C (MeOH, 100 %)		Sc-D (NH ₃ , 100 %)	
	mass (t)	covered demand (days)	mass (t)	covered demand (days)	mass (t)	covered demand (days)	mass (t)	covered demand (days)
0.40	10 748	22.9	10 822	22.9	42 992	22.9	43 288	22.9
0.70	16 367	34.9	16 481	34.9	65 469	34.9	65 925	34.9
1.00	18 534	39.6	18 663	39.6	74 136	39.6	74 652	39.6

At $r = 0.70$ the buffer holds approximately 34.9 days of hydrogen demand in all four scenarios, against a mandatory 5-day floor, which reflects the extended summer wind drought in the SE3 profile. The requirement grows with r , consistent with the greater day-to-day production variability of an electrolyser sized closer to peak output. The invariance of the covered-demand figure across scenarios at each ratio is the behaviour predicted in Section 3.6.4. The annual trajectories are shown in Figures 4.7 and 4.8.

The methanol trajectories are near-identical and are given in Figures C.8 and C.9. A one-day operational buffer is retained on site and the balance assigned to off-site lined rock caverns; Table 4.15 gives the split.

Table 4.15: System Hydrogen Buffer Distribution at $r = 0.70$

Parameter	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
Total buffer mass (t)	16 367	16 481	65 469	65 925
Equivalent days of demand	34.9	34.9	34.9	34.9
Off-site LRC bulk (t)	15 899	16 010	63 596	64 038
On-site local terminal (t)	468	472	1 874	1 887

On-Site Local Terminal Spatial Footprint

Table 4.16 sizes the one-day on-site buffer under the two local containment options. The comparison rules out pipeline storage at terminal scale: holding one day of demand at the 25 % level requires roughly 39 km of linear pipe and a 125 ha exclusion corridor,

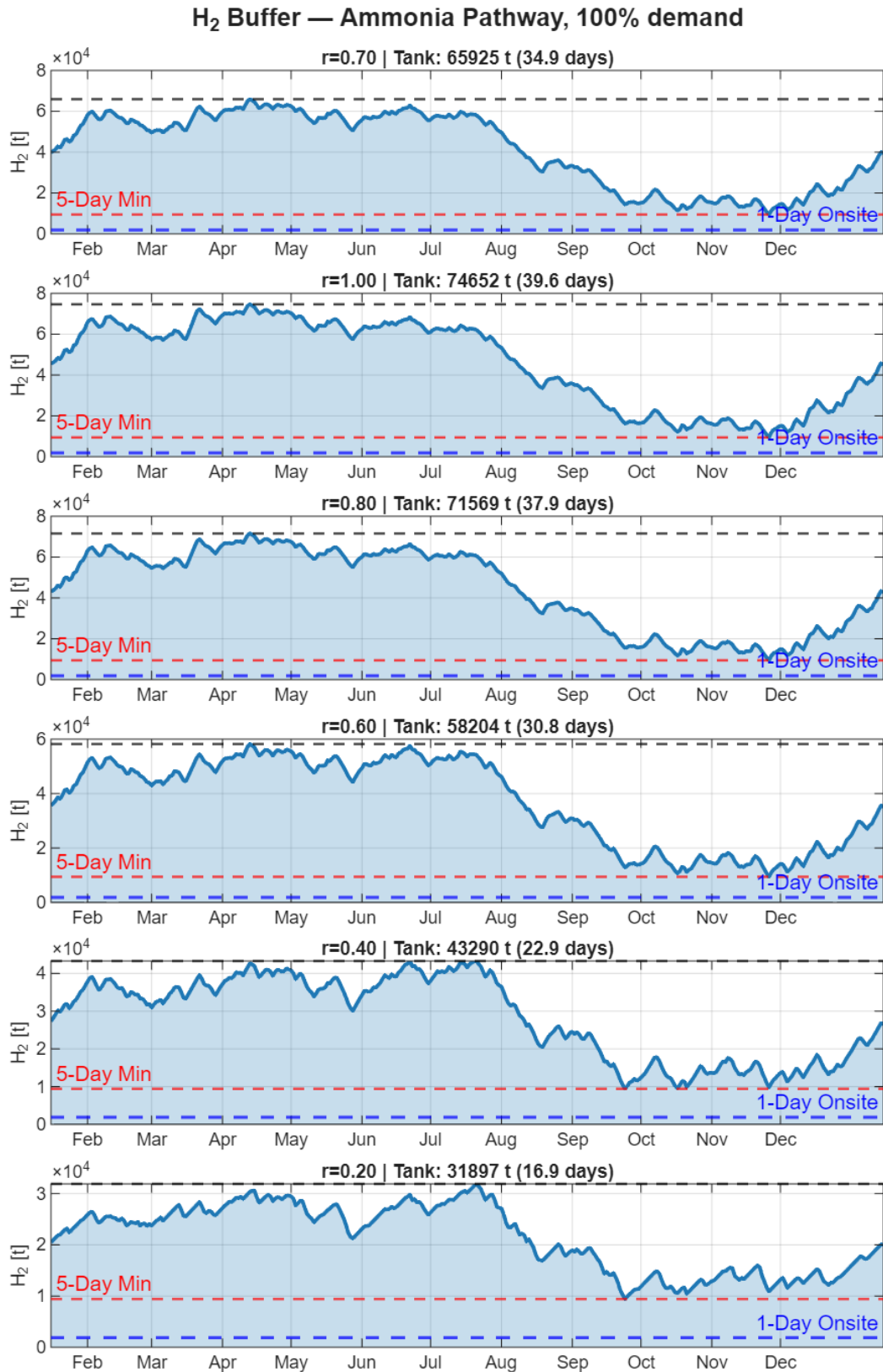


Figure 4.7: Annual hydrogen buffer tank level trajectories for Scenario D (100% ammonia) at six capacity ratios. The dashed red line marks the 5-day safety floor and the dashed black line the required tank capacity at each ratio.

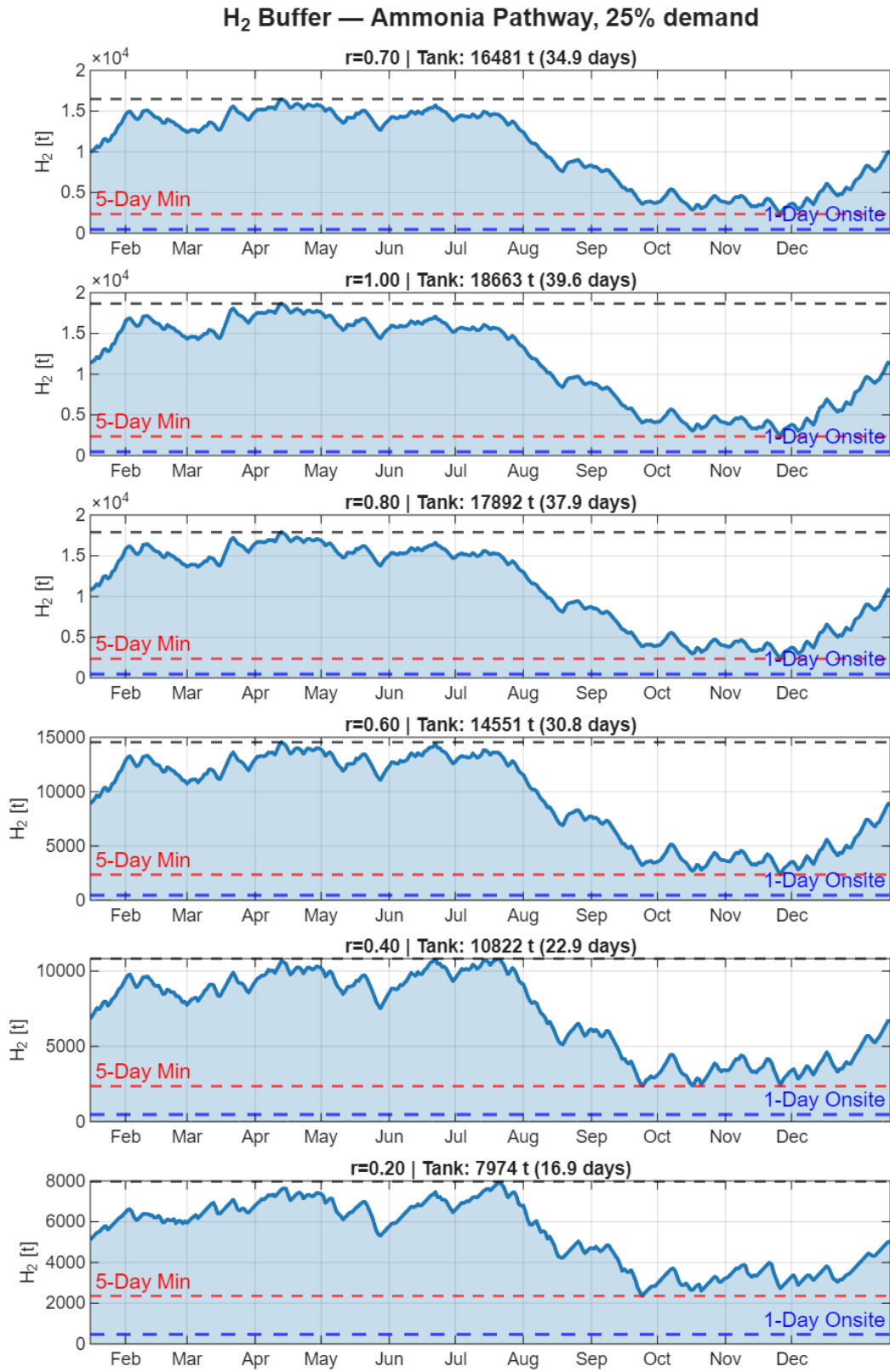
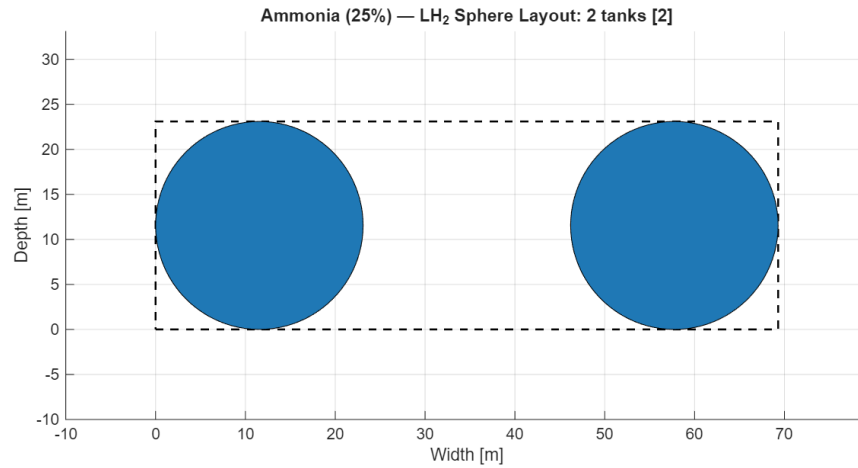


Figure 4.8: Annual hydrogen buffer tank level trajectories for Scenario B (25% ammonia) at six capacity ratios.

Table 4.16: On-Site Hydrogen Terminal Geometry and Spatial Footprint by Scenario

Parameter	Sc-A (MeOH, 25 %)	Sc-B (NH ₃ , 25 %)	Sc-C (MeOH, 100 %)	Sc-D (NH ₃ , 100 %)
<i>Local Option A: cryogenic spheres (LH₂)</i>				
Required vessels	2	2	7	7
Vessel capacity (t)	234	236	268	270
Outer diameter (m)	24.0	24.0	24.0	24.0
Layout (groups)	1 group	1 group	2 groups	2 groups
Layer 3 safety footprint (ha)	1.13	1.13	3.12	3.12
<i>Local Option B: large-diameter pipeline storage (GH₂)</i>				
Required length (km)	39.04	39.31	156.15	157.24
Layer 1 hardware footprint (ha)	5.47	5.50	21.86	22.01
Layer 3 safety footprint (ha)	124.55	125.42	497.91	501.38

while cryogenic spheres consolidate the identical mass into 1.13 ha, two orders of magnitude smaller. Spheres are therefore adopted as the baseline and their Layer 3 footprint carried into the aggregated totals; the resulting pads are shown in Figures 4.9 and 4.10. The methanol layouts are structurally identical and are given in Figures C.3 and C.4.

**Figure 4.9:** Hardware pad configuration (Layer 1) for the on-site LH₂ buffer supporting the ammonia pathway under Scenario B (25 % demand, 2 spheres).

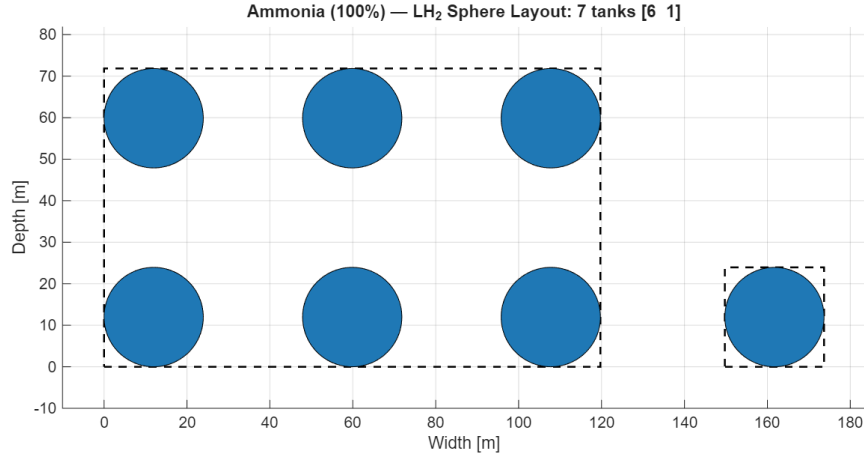


Figure 4.10: Hardware pad configuration (Layer 1) for the on-site LH₂ buffer supporting the ammonia pathway under Scenario D (100% demand, 7 spheres). The layout splits into two containment groups under the six-tank per-group limit.

4.4 Aggregation and Feasibility Analysis

4.4.1 System Trade-off Sweep

Figure 4.11 presents the sweep of r from 0.20 to 1.00 for Scenario C, giving the required wind farm capacity, the electrolyser nameplate, the surplus available for export and the hydrogen buffer.

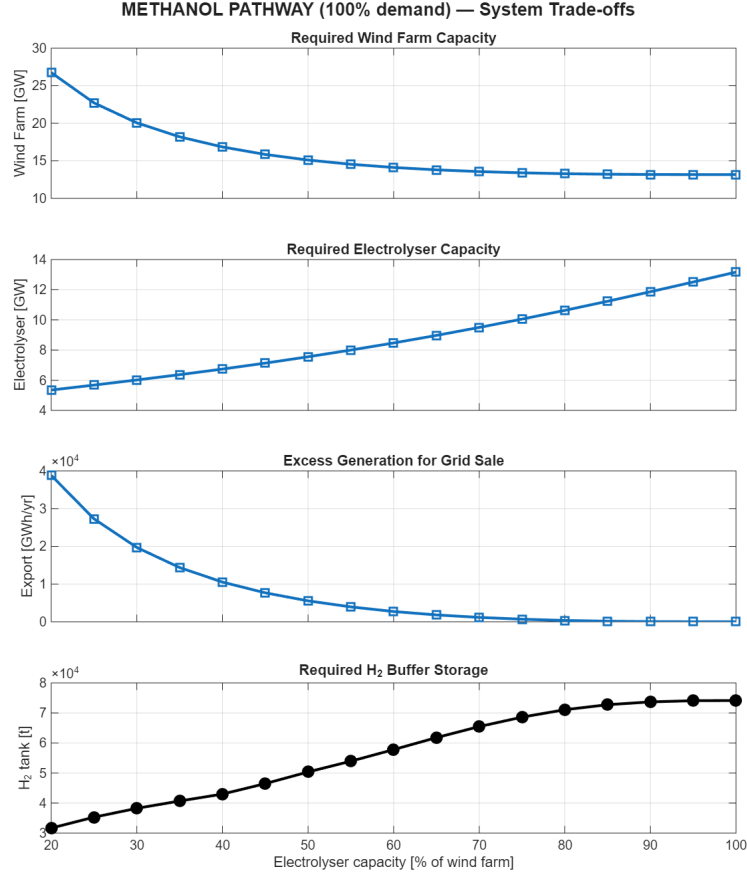


Figure 4.11: System trade-off sweep for Scenario C (100 % methanol): (1) required wind farm capacity, (2) electrolyser nameplate capacity, (3) surplus wind energy available for grid export, and (4) hydrogen buffer storage requirement, as functions of the capacity ratio $r \in [0.20, 1.00]$.

The two ends of the sweep bracket the design problem. At $r = 0.20$ the Scenario C methanol pathway requires a 26.7 GW wind farm to feed a 5.35 GW electrolyser, and the surplus exported, roughly 38.8 TWh/yr, exceeds the 37.6 TWh/yr the electrolyser absorbs. At $r = 1.00$ the wind farm falls to about 13.2 GW, export approaches zero, and the buffer grows by a further 13 %, reflecting the higher day-to-day production variability of an electrolyser sized close to peak output.

The energy-capture curve is strongly concave and flattens at $r \approx 0.70$, where 97.0 % of annual generation is absorbed and only 1.16 TWh/yr remains for export. The baseline is set at that point: further electrolyser capacity buys little additional absorption, while a lower ratio leaves a substantially larger share of the fleet’s output unconverted. The selected value also lies inside the range reported for wind-coupled systems in Chapter 2⁴¹, so the design point is consistent with systems built in practice.

The sweep has the same shape in all four scenarios, since the capture fraction, the wind-to-electrolyser ratio and the buffer expressed in days of demand are set by the generation

profile and by r alone (Section 3.6.4). The remaining sweeps therefore differ only in the absolute scale of the axes, and are given in Figures C.10, C.11 and C.12.

4.4.2 Aggregated Infrastructure Footprints

The two hub configurations differ in their spatial logic. The import hub receives e-fuel by pipeline, rail and truck and supplies it by ship, so its onshore footprint is dominated by fuel storage and active logistics. The production hub eliminates the inbound logistics chain but introduces the footprints of electrolysis, synthesis and hydrogen buffer storage. All values are the Layer 3 exclusion boundary of each asset, and both the net asset sum and the gross total at $f_{\text{pack}} = 1.35$ are reported. The wind farm and the bulk hydrogen inventory are off site and excluded from both. Figures 4.12 and 4.13 show the component composition of the two configurations across all four scenarios.

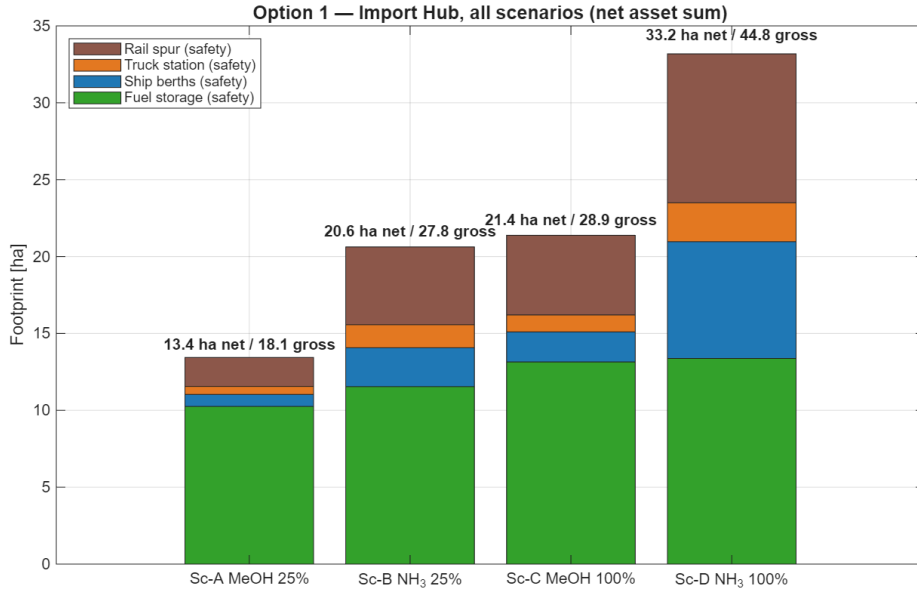


Figure 4.12: Aggregated onshore land-use footprints for the import hub across all four scenarios. Each bar is the stacked sum of the component Layer 3 areas; net and gross totals are annotated.

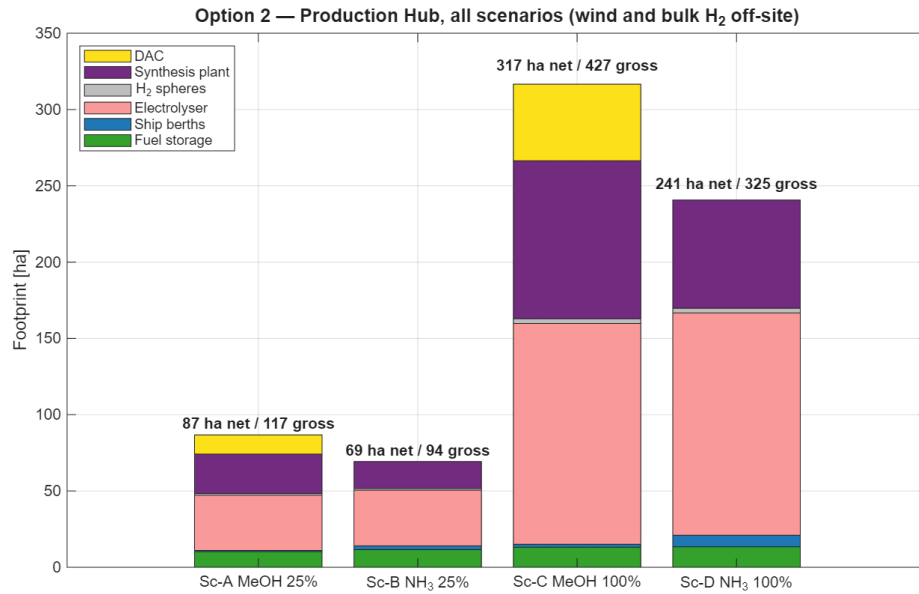


Figure 4.13: Aggregated onshore land-use footprints for the production hub across all four scenarios, with wind generation and bulk hydrogen storage excluded as off-site infrastructure. Net and gross totals are annotated.

Option 1: Import and Distribution Hub

Table 4.17: Aggregated Onshore Land-Use Footprints: Option 1 Import Hub (ha)

Component	Sc-A (MeOH, 25 %)	Sc-B (NH ₃ , 25 %)	Sc-C (MeOH, 100 %)	Sc-D (NH ₃ , 100 %)
Fuel storage (safety zone)	10.25	11.54	13.15	13.38
Ship berth (bunkering OTS, safety zone) [†]	0.78	2.53	1.95	7.59
Truck reception (safety zone)	0.52	1.50	1.10	2.53
Rail siding (safety zone)	1.89	5.06	5.18	9.68
Net total (asset sum)	13.44	20.63	21.39	33.18
Gross total (×1.35)	18.14	27.85	28.87	44.79

[†] Ammonia bunkering zones are based on a 50 m exclusion radius per transfer position; site-specific dispersion modelling is required. Methanol zones are based on a 25 m radius.

The import-hub footprints are compact across all four scenarios, spanning 13.44 to 33.18 ha net. The ammonia scenarios are the larger of each pair, because the 50 m setback widens the bunkering and rail-siding envelopes at both demand levels, and at full replacement those two logistics nodes together exceed the storage footprint they serve. The import hub layout at the 25% level is shown in Figure 4.14.

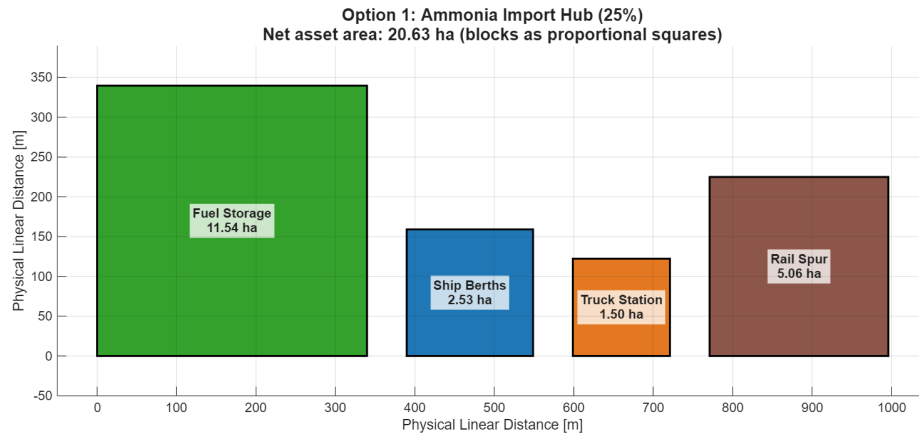


Figure 4.14: Schematic layout of the import hub configuration for Scenario B (25 % ammonia). Outer perimeter is approximately to scale.

Option 2: On-Site Production Hub

Table 4.18: Aggregated Onshore Land-Use Footprints: Option 2 Production Hub (ha)

Component	Sc-A (MeOH, 25 %)	Sc-B (NH ₃ , 25 %)	Sc-C (MeOH, 100 %)	Sc-D (NH ₃ , 100 %)
Fuel storage (safety zone)	10.25	11.54	13.15	13.38
Ship berth (bunkering OTS, safety zone) [†]	0.78	2.53	1.95	7.59
H ₂ buffer spheres (safety zone)	1.13	1.13	3.12	3.12
DAC unit (baseline $s_{\text{dac}} = 0.10 \text{ m}^2/\text{t/yr}$)	12.54	–	50.16	–
Methanol synthesis plant	25.89	–	103.56	–
Haber–Bosch plant (incl. ASU)	–	17.74	–	70.97
Electrolyser plant (PEM, Siemens Elyzer)	36.17	36.42	144.67	145.68
Net total (onshore, excl. wind)	86.76	69.36	316.61	240.74
Gross total ($\times 1.35$)	117.13	93.64	427.42	324.99
Wind farm (off site, indicative)	3.39 GW	3.42 GW	13.57 GW	13.67 GW

[†]Ammonia bunkering zones are based on a 50m exclusion radius per transfer position; site-specific dispersion modelling is required. Methanol zones are based on a 25m radius. The H₂ buffer footprint is the Layer 3 safety zone of the on-site cryogenic sphere pad.

The production hub is between three and fifteen times larger than its import equivalent, the ratio being 6.5 for Scenario A, 3.4 for Scenario B, 14.8 for Scenario C and 7.3 for Scenario D. The fuel ordering also reverses: the ammonia hub is the more compact of the pair here, because the Haber–Bosch plant is smaller than the methanol synthesis plant and

the nitrogen pathway carries no DAC unit at all. The electrolyser is effectively identical across both pathways, reflecting the near-identical hydrogen demands, and is the largest single onshore component in all four scenarios. The two production hub layouts at the 25 % level are shown in Figures 4.15 and 4.16.

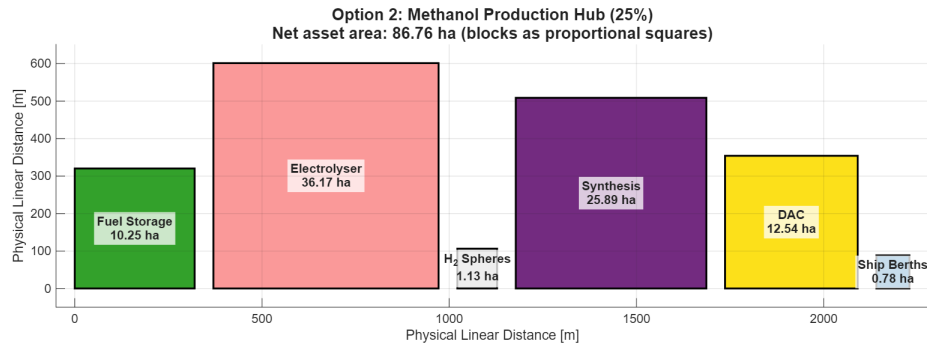


Figure 4.15: Schematic layout of the production hub configuration for Scenario A (25 % methanol). Outer perimeter is approximately to scale.

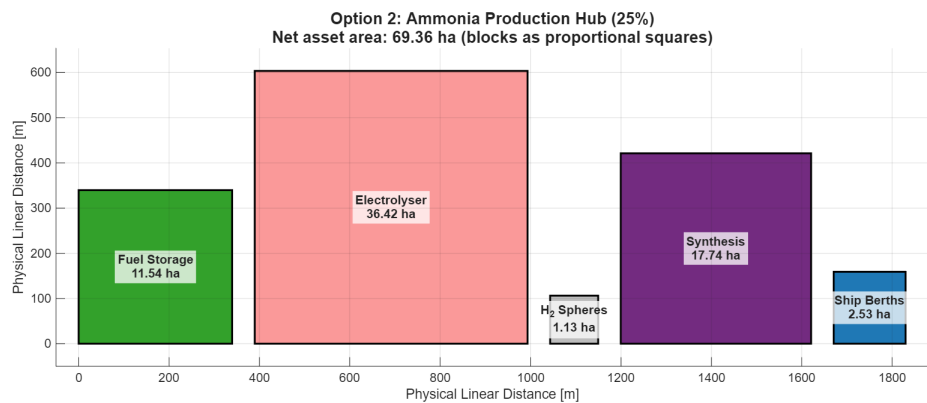


Figure 4.16: Schematic layout of the production hub configuration for Scenario B (25 % ammonia). Outer perimeter is approximately to scale.

4.4.3 System Electricity Demand

The spatial results are read alongside the electrical energy the same configurations require, given in Table 4.19 and shown by end use in Figure 4.17.

Electrolysis dominates the electrical demand in every scenario, and the methanol pathway is the more energy-intensive of the two at equal demand because DAC adds a continuous load the nitrogen pathway does not carry. The energy ordering therefore follows the same direction as the production-hub footprint ordering above, both being driven by the carbon supply step rather than by the synthesis reaction itself.

Table 4.19: Production-Hub Annual Electricity Demand by Scenario

End use	Sc-A (MeOH)	Sc-B (NH ₃)	Sc-C (MeOH)	Sc-D (NH ₃)
Electrolysis (GWh/yr)	9 404	9 470	37 617	37 879
DAC (GWh/yr)	3 309	–	13 236	–
Synthesis + ASU (GWh/yr)	647	1 058	2 590	4 231
Total (TWh/yr)	13.36	10.53	53.44	42.11
Dedicated wind capacity (GW)	3.39	3.42	13.57	13.67

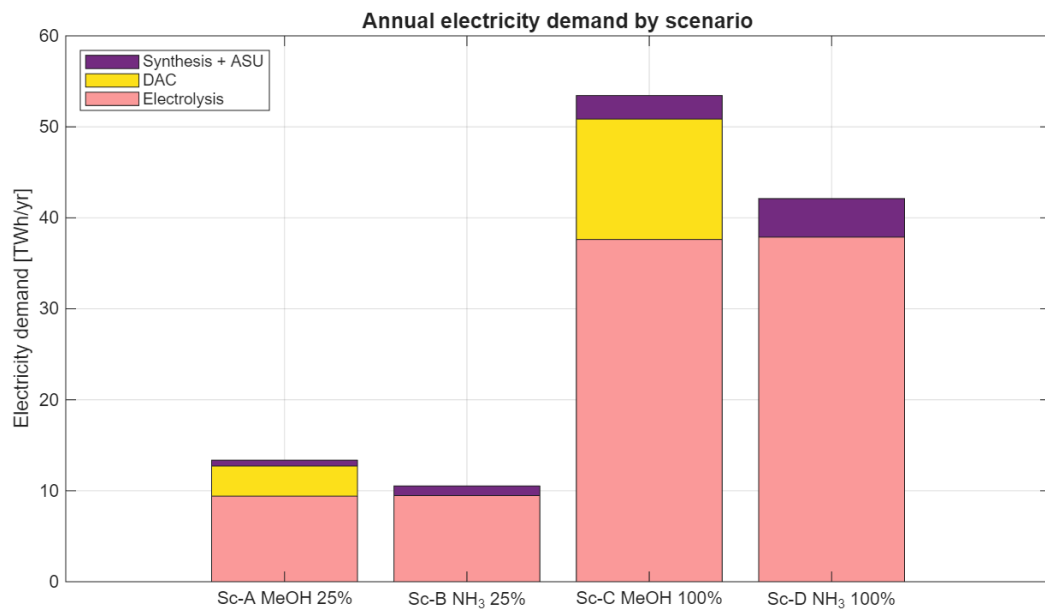
**Figure 4.17:** Annual electricity demand of the production hub across all four scenarios, split into electrolysis, DAC, and synthesis and ASU loads.



Figure 4.19: Port of Gothenburg’s westward expansion. The pink and blue markings indicate the land and water areas being acquired. Image credit: Port of Gothenburg [111].

The five-tier hierarchy of Section 3.6.5 is therefore populated as follows: opportunistic reclamation at approximately 287 ha; the Outer Quayside Parcel at 77 ha; the Central Quarry Parcel at 50 ha; the acquisition threshold at 21 ha; and the Integrated Fuel-Cluster Parcel at 20 ha.

4.5.2 Import Hub Feasibility

All import hub scenarios are spatially feasible within the existing port boundary, and none require land reclamation. Scenario A is the only configuration that fits the 21 ha acquisition threshold on both bases. Scenario B clears that threshold on its net footprint but requires an existing-boundary parcel once the gross allowance is applied, so the packing factor rather than the asset sum decides its tier. At full replacement both scenarios fit the 50 ha Central Quarry Parcel, with the 740 m train-length cap holding the Scenario D rail siding within that envelope. The per-scenario verdicts and siting rationale are given in Table 4.20 and Table C.12.

Non-spatial constraint for all ammonia scenarios. The modelled safety zones cover structural setbacks only. Under adverse weather, toxic ammonia vapour plumes could extend for kilometres, so site-specific atmospheric dispersion modelling is a mandatory prerequisite before finalising any ammonia layout.

4.5.3 Production Hub Feasibility

The production hub is tier-sensitive to the gross-to-net allowance in every scenario. At 25 % demand the ammonia hub fits the 77 ha Outer Quayside Parcel on its net footprint but crosses into the opportunistic tier at gross, while the methanol equivalent requires the opportunistic parcel unless the electrolyser, and optionally the DAC unit, is decentralised. At full replacement Scenario D fits the opportunistic parcel on its net footprint but exceeds every identified parcel at gross, and Scenario C exceeds all parcels on both bases. Decentralising the electrolyser alone removes roughly 36 ha at the 25 % level and 145 ha at full replacement in both pathways. Full verdicts, decentralisation pathways and residual footprints are given in Table 4.20 and Table C.12.

All four scenarios place the terminal well above the Seveso III upper-tier qualifying quantities of Table 2.7: Scenario D holds approximately 110 000 t of ammonia against a 200 t threshold, and up to 1887 t of hydrogen on site against a 50 t threshold. Every configuration modelled here is therefore an upper-tier establishment, and the land-use planning consultation distances that follow are set by site-specific consequence modelling rather than by tank spacing. The setbacks applied here are insurer loss-prevention distances for the protection of adjacent structures, not regulatory exclusion distances, so the footprints reported are the land the installation occupies rather than the restriction it imposes on its surroundings. Table 4.20 summarises the verdicts for both configurations against the parcel hierarchy.

4.6 Sensitivity Analysis

Because pre-feasibility sizing relies on literature-sourced parameters and assumed boundary conditions, the deterministic outputs carry significant uncertainty. The analysis employs a one-at-a-time sweep: each targeted variable is perturbed across its established literature range while all other inputs are held at baseline, and the full chain is re-run for every value. The method isolates the individual impact of each parameter but does not capture interactions, so a combined worst case would exceed the envelope of any individual sweep.

Twelve scalar parameters are swept continuously. Four further quantities are handled separately: the logistics modal split is a three-component allocation run as a set of bounding allocations, the electrolyser technology is a choice between three commercial systems, the renewable supply profile is an hourly series run as a separate case against a constant baseload comparator, and the packing factor is applied to the aggregated total rather than re-run through the chain.

Results are reported separately for the two aggregated outputs, land footprint and annual electricity demand, because several parameters enter only one of them. A parameter that

Table 4.20: Spatial Feasibility Summary for the Port of Gothenburg: Comparison of Option 1 (E-Fuel Import and Distribution Hub) and Option 2 (On-Site E-Fuel Production Hub) Net/Gross Footprint (ha) and Feasibility.

Scenario	Option 1 Import Hub (ha)	Import Hub Feasibility	Option 2 Production Hub (ha)	Production Hub Feasibility [‡]
A (25 % MeOH)	13.44 / 18.14	<i>Feasible (acquisition threshold)</i>	86.76 / 117.13	<i>Feasible (opportunistic)</i> Decentralised: <i>Conditionally feasible</i>
B (25 % NH ₃)	20.63 / 27.85	<i>Feasible (acquisition threshold, net; existing boundary at gross)[§]</i>	69.36 / 93.64	<i>Feasible (existing boundary, net; opportunistic at gross)[§]</i> Decentralised: <i>Conditionally feasible</i>
C (100 % MeOH)	21.39 / 28.87	<i>Feasible (existing boundary)</i>	316.61 / 427.42	<i>Not feasible</i> Decentralised: <i>Cond. feasible (opportunistic)</i>
D (100 % NH ₃)	33.18 / 44.79	<i>Feasible (existing boundary)[§]</i>	240.74 / 324.99	<i>Feasible (opportunistic, net; exceeds all parcels at gross)[§]</i> . Decentralised: <i>Conditionally feasible</i>

[‡]The decentralised configuration relocates space-intensive components (electrolyser, DAC) off site.

[§]Ammonia scenarios: site-specific vapour-dispersion modelling is mandatory.

cannot reach a given output, such as the DAC space factor in the ammonia pathway or the ASU specific energy in any footprint total, is reported as having no effect rather than presented as a null result. The import hub is treated separately from the production hub for the same reason: it contains only storage, the quayside interface and the land-side reception nodes, so it responds to the buffer duration, the vessel packet, the modal split and the transfer rate alone.

The scalar sweeps are reported at the 25 % demand level. Every sweep passes through the two baselines of Table 4.18, the Scenario A production hub at 86.76 ha and the Scenario B production hub at 69.36 ha, and a parameter absent from a pathway leaves that pathway at its baseline for the whole sweep. Table 4.21 gives every swept quantity against both baselines; the complete numerical sweeps are given in Section C.9.

4.6.1 Direct Air Capture

The DAC space factor is the single most consequential parameter in the study, spanning a factor of more than four on the Scenario A net total across its documented range. The

Table 4.21: Swept Quantities Against Both Pathway Baselines (25 % demand)

Quantity	Range swept	Total affected	Sc-A (ha)	Sc-B (ha)	Verdict
<i>Baseline</i>			86.76	69.36	
DAC space factor	0.002–2 m ² /(t/yr)	Prod. net	74.47–325.00	–	yes
Haber–Bosch space	1 593–6 339 m ² /tph	Prod. net	–	69.36–122.22	yes
Electrolyser technology	Alkaline / PEM / SOEC	Prod. net	58.78–103.34	41.19–86.06	yes
Methanol synth. space	1 500–4 000 m ² /tph	Prod. net	76.49–102.51	–	yes
Renewable supply	SE3 wind / constant	Prod. net	66.94–86.76	49.41–69.36	yes
Yield factor	0.85–1.00	Prod. net	86.76–95.76	69.36–76.20	no
Vessel packet scale	0.072–1.00	Prod. net	80.51–86.76	64.42–69.36	no
Buffer duration	7–90 d	Prod. net	86.76–92.04	69.36–86.11	yes (import)
Max NH ₃ tank volume	60 000–181 458 m ³	Prod. net	–	65.82–69.36	no
NH ₃ fill fraction	0.82–0.875	Prod. net	–	69.36–69.56	no
MGO density	810–890 kg/m ³	Prod. net	no change	no change	no
Packing factor	1.00–2.50	Prod. gross	86.76–216.90	69.36–173.41	yes
Logistics modal split	five allocations	Import net	11.03–16.22	14.07–33.44	yes (100 %)
Bunker transfer rate	500–2 000 m ³ /hr	Import net	13.05–13.44	19.36–20.63	no
DAC specific energy	769–4 006 kWh/tCO ₂	Energy (TWh)	11.02–15.07	–	no
ASU specific energy	0.114–0.311 MWh/t	Energy (TWh)	–	10.53–10.72	no

baseline of 0.10 m²/(t CO₂/yr) sits well below the two operating reference plants: at the Orca value of 0.56 the total reaches 144.44 ha and at the Mammoth value of 1.33 it reaches 240.99 ha, both exceeding every identified parcel except the speculative reclamation scenario. The ammonia pathway is unaffected, since it carries no capture unit. The specific energy carries a comparable spread with no spatial consequence, moving the methanol pathway from 11.02 to 15.07 TWh/yr. Both sweeps are given in Tables C.13 and C.14.

4.6.2 Synthesis Plant Space Factors

The Haber–Bosch space factor is adopted at the lower and most optimistic bound of its documented range. At the midpoint the Scenario B production hub reaches 95.79 ha and at the upper bound 122.22 ha, both exceeding the 76.63 ha Outer Quayside Parcel, so the ammonia verdict rests on the optimistic end of the range being the representative one.

The methanol synthesis space factor is a single measured reference facility with no published range, so it is swept across a plausible band rather than a documented one. The lower end leaves the Scenario A net total just inside the 76.63 ha parcel and the upper end well outside it. Both sweeps are given in Table C.15.

4.6.3 Electrolyser Technology

The electrolyser is the largest single onshore component in both pathways at the 25 % demand level. Substituting the alkaline and solid oxide reference systems changes the footprint ratio and the specific energy together, so both aggregates move, as shown in Table 4.22.

Table 4.22: Production-Hub Footprint and Energy Demand by Electrolyser Technology (25 % demand)

Technology	Sc-A (ha)	Sc-B (ha)	Sc-A (TWh/yr)	Sc-B (TWh/yr)
Alkaline (Rely Clear100+)	103.34	86.06	12.80	9.96
PEM (Siemens Elyzer, baseline)	86.76	69.36	13.36	10.53
SOEC (FuelCell Energy)	58.78	41.19	11.45	8.60

The choice moves either total by nearly 45 ha, which in the ammonia case is the difference between fitting the 50 ha Central Quarry Parcel and requiring the 77 ha Outer Quayside Parcel. Footprint and energy do not move together: solid oxide is both the most compact and the least energy-intensive, while alkaline is the largest in area yet lower in energy demand than the PEM baseline, because the alkaline reference system reports a lower specific energy than the Siemens plant. Figures 4.20 and 4.21 place this result alongside the other swept parameters.

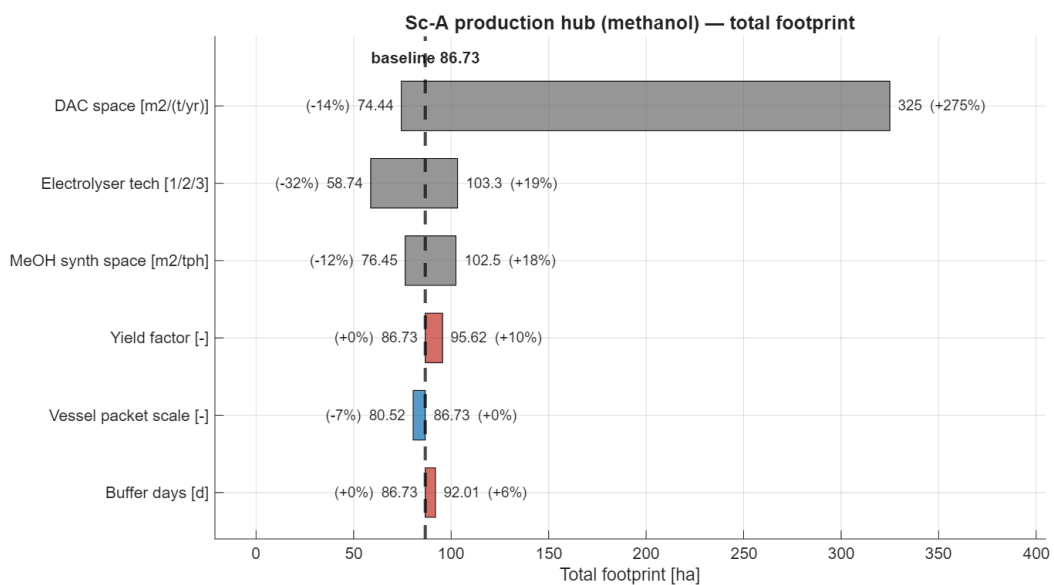


Figure 4.20: Tornado plot of the Scenario A production-hub net footprint, ordered by swing. Six of the twelve scalar parameters are plotted; the remainder are absent from the methanol pathway, do not enter any footprint term, or move the total by less than 0.5 %.

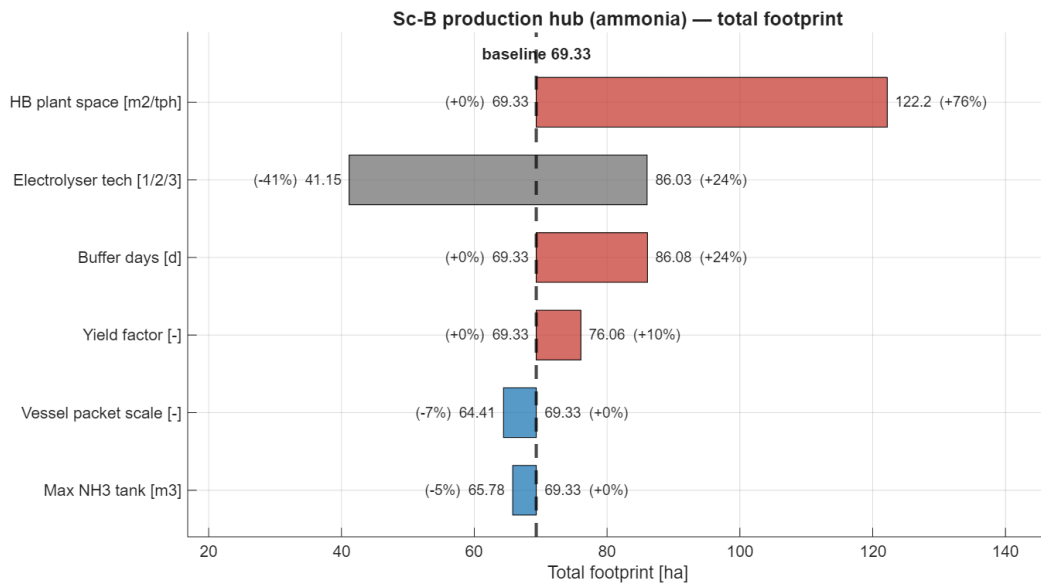


Figure 4.21: Tornado plot of the Scenario B production-hub net footprint, on the same basis. The Haber–Bosch space factor and the electrolyser technology are the only two quantities capable of moving the ammonia verdict.

4.6.4 Gross-to-Net Packing Allowance

The aggregated totals are asset sums and the gross figures follow by applying a single scalar, so this sweep is exact rather than a re-run of the chain. The import-hub verdicts are robust to it: Scenario A remains within the 21 ha acquisition threshold up to a factor of 1.56, and Scenario D moves from the Central Quarry Parcel to the Outer Quayside Parcel at 1.49 and exceeds both only above 2.31.

The production hub is considerably more exposed. The Scenario B existing-boundary verdict holds only below a factor of 1.10 and the Scenario D opportunistic verdict only below 1.19, so both are conditional on near-complete packing efficiency, and the adopted 1.35 sits above those thresholds. Scenario A remains inside the opportunistic envelope across the entire range, and Scenario C exceeds every identified parcel at all values including unity. The full sweep is given in Table C.16.

4.6.5 Renewable Supply Profile

All primary results couple the electrolyser to the intermittent SE3 profile. Substituting a continuous supply at full availability sizes the electrolyser precisely to average daily hydrogen demand and drops the buffer from 34.9 days to the 5-day operational floor. The production hub falls by 22.9% in Scenario A and 28.8% in Scenario B, entirely through the electrolyser and the off-site buffer, and by a comparable margin at full replacement.

The annual electricity demand is identical in both cases, since the hydrogen mass balance does not depend on how the power arrives. The full comparison is given in Table C.17.

4.6.6 Terminal Operating Mode

The primary results are produced in batch-export mode. Continuous-offtake mode replaces the packet discharge with a continuous draw at the demand rate, representing a terminal serving bunkering customers directly rather than transshipping cargo, and Table 4.23 compares the resulting peak inventories.

Table 4.23: Simulated Peak Inventory by Terminal Operating Mode (1 000 m³)

Basis	Sc-A	Sc-B	Sc-C	Sc-D
Simulated peak, batch-export mode (baseline)	142.2	114.4	208.9	196.7
Simulated peak, continuous-offtake mode	52.7	65.1	209.1	256.9
Continuous-offtake against batch-export (%)	−62.9	−43.1	+0.1	+30.6

The mode changes the simulated trajectory, not the tank farm. The aggregation takes the working volume from Equation 3.11 rather than from the simulation, so the storage footprints of Table 4.17 and the resulting verdicts are identical under both modes. The two peaks nonetheless diverge in opposite directions at the two demand levels, and the mechanism is set out in Section C.9.7.

4.6.7 Logistics Modal Split

The baseline allocates inbound volume 70 % to pipeline, 20 % to rail and 10 % to road. Because the allocation determines which reception infrastructure the terminal must build, it reaches the import hub directly and is the widest-swinging quantity in that total, as Table 4.24 shows.

Table 4.24: Import-Hub Net Footprint by Logistics Modal Split (ha)

Allocation (pipeline / rail / road)	Sc-A	Sc-B	Sc-C	Sc-D
70 / 20 / 10 (baseline)	13.44	20.63	21.39	33.18
100 / 0 / 0	11.03	14.07	15.10	20.97
50 / 25 / 25	14.22	22.24	22.36	44.93
0 / 100 / 0	16.22	33.44	35.83	69.39
0 / 0 / 100	13.11	18.67	22.44	35.23

Gross totals and the component breakdown are given in Table C.21.

The fuel storage and quayside components are invariant across every allocation, since neither the annual volume nor the bunkering duty depends on how the fuel arrives. The entire response is carried by the truck station and the rail spur, and pipeline-only delivery is the floor in every scenario, removing both land-side nodes.

Rail-only delivery is the ceiling, and the mechanism is the 740 m train length cap. Once the cap binds, throughput can only be met by frequency, and once the arrival rate exceeds what one siding can turn round in a day, parallel platforms are required. Scenario D under rail-only delivery requires 2059 block trains per year and 8.58 arrivals per operating day, which at two loading cycles per siding per day calls for five parallel platforms and a 48.42 ha corridor, 70 % of the scenario total. Scenario C requires four platforms and 20.74 ha on the same basis. This platform multiplication, rather than siding length, is what makes the rail-dominant case binding.

The allocation is capable of changing a verdict at the upper demand level. Under pipeline-only delivery the Scenario D import hub fits the 21 ha acquisition threshold on its net footprint and the Central Quarry Parcel at a gross footprint of 28.31 ha. Under rail-only delivery the gross footprint of 93.68 ha exceeds the Outer Quayside Parcel and requires the opportunistic tier, the only case in the study where an import hub does so. The land-side reception requirements behind these totals are given in Table C.22.

4.6.8 Remaining Swept Parameters

The remaining swept quantities move the totals by less than the parameters above, though the largest of them still crosses a parcel threshold. That is the storage buffer duration, which raises the Scenario D import hub from 33.18 to 85.12 ha between 7 and 90 days without reaching the next tier. Because the tank count is an integer, crossing a count boundary can reduce the array footprint even as the stored volume rises, so the Scenario A import hub falls from 16.64 ha at 30 days to 14.59 ha at 45 days before rising again, as anticipated in Section 3.6.1.

The vessel packet scale, the stoichiometric yield, the maximum ammonia tank volume, the ammonia fill fraction and the ASU specific energy all move their aggregate by a smaller margin. The bunker transfer rate is the only one of these to change an asset count rather than scale an area: raising it from 500 to 1000 m³/hr reduces the berth count at both demand levels, removing 5.06 ha from the Scenario D import hub across the full range. All are reported in full in Section C.9.

5

Conclusion

This thesis developed a demand-first spatial sizing framework for e-methanol and e-ammonia supply chain infrastructure in port environments, and applied it to the Port of Gothenburg across four demand scenarios and two hub configurations. The conclusions below address each research question in turn.

5.1 RQ1: How much physical infrastructure (facilities, equipment, land, and space) is required to support different e-fuel supply chains in port environments?

The requirement differs between the two hub configurations. The import-and-distribution hub, comprising fuel storage, OTS bunkering, truck reception and rail siding measured at the Layer 3 boundary, spans 13.44 to 33.18 ha net and 18.14 to 44.79 ha gross across the four scenarios, with fuel storage dominating at the 25 % demand level and the quayside and land-side reception nodes at full replacement. The on-site production hub spans 69.36 to 316.61 ha net and 93.64 to 427.42 ha gross, driven in every case by the PEM electrolyser array and, for the methanol pathway, by the DAC unit.

5.2 RQ2: What are the associated infrastructure sizing requirements for key components such as synthesis plant, storage tanks, transfer systems, and bunkering facilities?

Storage tanks. E-methanol requires wide, shallow API 650 fixed-roof tanks ($H/D \approx 0.25$) with large earthen secondary containment bunds, while e-ammonia requires taller DWDI flat-bottom refrigerated tanks ($H/D \approx 0.65$) whose integral containment eliminates the bund and makes Layer 2 coextensive with Layer 1. The two nevertheless converge at Layer 3, so the containment advantage of the refrigerated tank is cancelled by the wider

setback applied around it. Storage is also inelastic to demand: quadrupling throughput raises the Layer 3 envelope by a factor of 1.28 for methanol and 1.16 for ammonia, because the working volume is sized around one ship packet and does not scale with throughput.

Bunkering and transfer. The transfer hardware is compact and identical between the two pathways, and the land-use penalty arises entirely from the safety exclusion zone: a methanol radius of 25 m set by flammability against an ammonia radius of 50 m set by toxicity. Because the radius applies per position, the totals scale with berth count rather than with volume. Rail reception follows the same pattern but is governed by the TEN-T length cap: at full replacement the 740 m cap binds in both pathways and throughput is met by frequency instead until a certain point, and when exceeding that point, the corridor grows through parallel platforms rather than through siding length.

Synthesis plants. The methanol pathway carries more than twice the synthesis and capture footprint of the ammonia pathway at both demand levels, the difference resting on the dedicated capture plant that the carbon feedstock requires. Both scale linearly with throughput, so the gap widens in absolute terms at full replacement.

Hydrogen and renewable supply. At the baseline ratio $r = 0.70$ the SE3 wind profile requires a 34.9-day hydrogen buffer in all four scenarios, driven by the summer wind drought. The buffer is technology-independent, since the wind farm is sized to equalise annual production and demand regardless of electrolyser efficiency, and it is what places the bulk hydrogen inventory outside the port boundary. The electrolyser array is the largest single onshore component in every scenario, while the one-day on-site operational reserve in cryogenic LH₂ spheres is minor beside it; above-ground pipeline storage of the same inventory is not viable within any port parcel.

5.3 RQ3: To what extent can the Port of Gothenburg spatially accommodate the infrastructure required for e-fuel production, storage, transfer, and bunkering operations?

The assessment benchmarks the calculated footprints against four identified parcels at the Port of Gothenburg and a confirmed 21 ha near-term acquisition.

The import hub is spatially feasible at every demand level. All four scenarios fit within the existing or near-term acquired port boundary without land reclamation. Scenario A fits the acquisition threshold on both bases and Scenario B on its net footprint alone, the gross allowance pushing it into an existing-boundary parcel, while at full re-

placement both scenarios fit the Central Quarry Parcel. The binding constraint at full replacement is not storage but the reception and transfer nodes, and the delivery mode allocation governs them: pipeline-only delivery brings the Scenario D import hub inside the acquisition threshold, while rail-only delivery raises it to 93.68 ha gross, the only case in the study where an import hub requires the speculative reclamation tier.

The production hub requires decentralisation to be spatially viable. Only the 25 % ammonia configuration fits an identified parcel as a co-located facility, and only on its net footprint against the Outer Quayside Parcel; every other configuration requires the speculative reclamation tier or exceeds all identified parcels. Relocating the electrolyser off site is the single largest reduction available in every scenario. On-site e-fuel production is therefore not impossible at Gothenburg, but it is compatible with the port boundary only if the upstream energy conversion infrastructure is treated as a distributed system rather than a co-located one.

Set against the approximately 1 030 ha port boundary, the import hub is a marginal claim at every demand level, from 1.8 % of that area in Scenario A to 4.3 % in Scenario D, so converting the entire Gothenburg bunkering market to imported e-ammonia requires under 5 % of the land inside the boundary. The co-located production hub inverts the comparison, at 11.4 % in Scenario A and 41.5 % in Scenario C. Against the motivating problem that port land is a fixed resource competing with container, RoRo and bulk operations, the constraint binds on the energy conversion step rather than on the fuel handling step, and a port the size of Gothenburg can absorb the second without reorganising its land holdings.

5.4 Synthesis of Findings

Neither e-methanol nor e-ammonia holds a categorical spatial advantage at the Port of Gothenburg, and the more compact pathway reverses between the two hub configurations: methanol is smaller at the import hub and ammonia at the production hub. Land use therefore cannot be used to select a fuel independently of the hub configuration, and the selection should be driven by vessel uptake, feedstock availability, safety culture and economics rather than by onshore land constraints.

One caveat qualifies every result above: the ammonia verdicts rest on a structural setback rather than on a dispersion-modelled toxic hazard distance, and are therefore the more provisional of the two pathways. This and the remaining limitations are set out in Section 6.4.

6

Discussion

Table 6.1 collects the headline figures for both configurations. Net figures are the sum of the Layer 3 component footprints and gross figures apply the 1.35 packing allowance. Normalised areas are in hectares per Mt of fuel handled per year, and share is the gross footprint as a percentage of the 1 030 ha port boundary.

Table 6.1: Headline results by scenario and hub configuration.

		Throughput	Footprint (ha)		Normalised		Share
Scenario	Fuel and penetration	(Mt/yr)	Net	Gross	Net	Gross	(%)
<i>Import and distribution hub</i>							
A	E-methanol, 25 %	0.91	13.44	18.14	14.7	19.9	1.8
B	E-ammonia, 25 %	0.98	20.63	27.85	21.1	28.5	2.7
C	E-methanol, 100 %	3.65	21.39	28.87	5.9	7.9	2.8
D	E-ammonia, 100 %	3.90	33.18	44.79	8.5	11.5	4.3
<i>On-site production hub</i>							
A	E-methanol, 25 %	0.91	86.76	117.13	95.1	128.5	11.4
B	E-ammonia, 25 %	0.98	69.36	93.64	71.1	96.0	9.1
C	E-methanol, 100 %	3.65	316.61	427.42	86.8	117.2	41.5
D	E-ammonia, 100 %	3.90	240.74	324.99	61.7	83.3	31.6

6.1 Methanol Versus Ammonia

Neither fuel is uniformly more land-efficient. Three effects work in different directions.

Volume. Ammonia requires approximately 23 % more volume than methanol for the same energy service, which follows from the volumetric energy multipliers and increases its storage and transfer requirements.

Containment. This is partly offset by the integral secondary containment of refrigerated DWDI ammonia tanks. Methanol tanks require external bunding, which at the 25 % level expands the tank farm to roughly five times its hardware footprint, while the ammonia

containment area remains equal to the hardware it encloses.

Setback. Ammonia then incurs a larger penalty through its wider loss-prevention setbacks and transfer hazard zones, 106 m against 76 m at the tank farm and 50 m against 25 m at each transfer position. These distances are applied around the perimeter of the tank farm and around each berth or land-side node, so their effect depends not only on the volume handled but on the number of nodes. As demand grows and more transfer positions are required, the ammonia penalty grows faster than the methanol equivalent.

Which effect dominates depends on what else is on the site. At the import hub there is nothing but storage and transfer, so the setback governs; at the production hub the carbon capture unit is larger than the whole difference between the two fuels downstream, and it appears in only one of the pathways.

Not everything differentiates the pathways. Daily hydrogen demand differs by less than 1 %, because the mass-specific stoichiometric ratios are offset almost exactly by the production rates that follow from the volumetric multipliers. The dedicated wind capacity and the electrolyser footprint are therefore effectively interchangeable between the two pathways at a given demand level, which means the upstream hydrogen infrastructure could be developed before the choice between methanol and ammonia is made.

The pathways diverge once the downstream production energy is included. The methanol pathway is the more electricity-intensive, driven by DAC, which introduces a continuous electrical load with no equivalent in the ammonia pathway.

6.2 Import Hub Versus Production Hub

The gap between the two configurations has a practical reading. An import and distribution terminal is spatially a small part of this port. On-site production is a different commitment: it requires an order of magnitude more land, and in three of the four scenarios the verdict depends on relocating the electrolyser. That relocation is also the most straightforward available, since the electrolyser connects to the rest of the chain by a hydrogen pipeline rather than by any physical interface with the quayside.

This suggests a sequence rather than a choice: import first, with production capacity added inland and connected by pipeline, rather than a single integrated quayside facility.

The modal split reinforces the same point from the logistics side, being the widest-swinging quantity in the import-hub total. Under rail-only delivery the Scenario D import hub rises into the opportunistic tier. The driver is not siding length, which is capped, but the parallel platforms that frequency forces, each carrying its own safety distance. Pipeline connection

to an inland production site is therefore the compact option for both configurations.

6.3 Comparison With Published Studies

Published reference facilities differ substantially in throughput, technology and system boundary, so their absolute areas are not directly comparable with the configurations modelled here. Table 6.2 reports area per million tonnes of annual throughput and identifies the principal scope or design difference behind each comparison. Normalisation removes the effect of scale but not differences in what infrastructure is included or how components are sized.

Table 6.2: Modelled configurations against published reference facilities on a normalised area basis.

Facility or scenario	Type	Throughput (Mt/yr)	Normalised area (ha/Mt/yr)	Main reason for difference
DNV Chile terminal ³⁸	NH ₃ import	1.00	49.0	Includes jetty, roads, utilities, buildings and internal separation distances.
Scenario B import hub	NH ₃ import	0.98	21.1 / 28.5	Narrower system boundary.
Scenario D import hub	NH ₃ import	3.90	8.5 / 11.5	Higher throughput spreads fixed storage and setback requirements over more product.
Port of Vancouver ¹⁰⁵	MeOH production	0.20	140–170	Larger DAC footprint and lower throughput.
Scenario A production hub	MeOH production	0.91	95.1 / 128.5	Lower adopted DAC space factor.
Scenario C production hub	MeOH production	3.65	86.8 / 117.2	Similar configuration at larger throughput.
TNO Rotterdam cluster ^{92,112}	MeOH production	~42	~14	More compact assumptions for electrolysis and synthesis infrastructure.

Note: Modelled areas are reported as net / gross and their absolute values are given in Table 6.1. Reference facility areas are given in Table 2.10. Throughputs are derived from Table 4.4.

The closest comparison is the DNV ammonia terminal, whose throughput almost matches Scenario B. Its reported area exceeds both footprints estimated here, primarily because the DNV boundary includes jetty infrastructure, circulation space, buildings, utilities and internal separation distances excluded from the present model. The methanol production

references diverge for a different reason and in both directions: the Vancouver estimate is larger than Scenario A when normalised, mainly because DAC occupies a larger share of its site, while the Rotterdam estimate is substantially more compact than Scenario C despite a DAC assumption of similar order, which points to more compact electrolysis and synthesis assumptions.

Import-hub divergence is therefore explained mainly by system boundary and production-hub divergence mainly by technology and space-factor assumptions, particularly for DAC, electrolysis and synthesis. What the comparison does not do is validate the model: no terminal of this type has been built, none of the references shares the system boundary, and the estimates bracket the results rather than confirming them.

6.4 Limitations

Several limitations are capable of changing a feasibility verdict rather than only its magnitude.

The first is ammonia far-field dispersion. Layer 3 is an intra-terminal structural boundary built from insurer loss-prevention distances. Every configuration modelled here exceeds the Seveso III upper-tier qualifying quantities, so the applicable land-use planning consultation distances are set by site-specific consequence modelling and not by tank spacing. If those distances exceed the Layer 3 envelope, and under adverse weather a toxic plume can extend for kilometres, then every ammonia verdict in this study is optimistic by an amount the model cannot estimate. A site-specific dispersion study is the prerequisite for any ammonia verdict.

The second is the packing allowance. The model sizes each named asset and sums the areas. Items that serve the site, such as internal roads, pipe racks, control and administration buildings, laydown and the space between units, are not sized. A packing factor has to cover them. No site layout was drawn, so the value is assumed at 1.35: the Scenario B import hub drops from the acquisition threshold to an existing-boundary parcel, the Scenario B production hub from an existing-boundary parcel to the opportunistic tier, and the Scenario D production hub from opportunistic to not feasible. The other five verdicts are unchanged. The DNV comparison of Section 6.3 is the only matched-scope evidence on how large the gap really is, and it suggests 1.35 is low; a drawn layout at the level of internal roads, pipe racks and firewater loops would help refine the factor with a computed figure, and the narrow margins on the production-hub verdicts make this the most consequential of the aggregation assumptions.

The third is the land inventory itself. The parcels are identified visually from satellite imagery and carry no planning status. A verdict of feasible therefore means that land of

the required area appears undeveloped, not that it is available.

The fourth is the exclusion of cost. The current framework cannot evaluate trade-offs between land use and cost. A verdict of conditional feasibility therefore indicates only that sufficient land could be made available by relocating components, without determining whether relocating a 145 ha electrolyser and connecting it by a dedicated hydrogen pipeline is economically sensible. A cost layer would convert the conditional verdicts into decisions, and the electrolyser relocation trade-off provides the most immediate application.

The fifth is the treatment of the two excluded assets. The generation array and the bulk hydrogen inventory are placed outside the onshore boundary by assumption, which is defensible for offshore wind and for lined rock caverns in the Swedish geological context but removes 3.39 GW of dedicated wind capacity and 15 899 ton of cavern capacity from the Scenario A accounting. A port without access to either would face a materially different problem. The 34.9-day buffer that drives the cavern requirement is itself an artefact of the wind-only supply assumption: under a continuous supply at full availability the buffer falls to the 5-day operational floor and the production hub falls by 23 to 33 % across the four scenarios, concentrated entirely in the electrolyser and the off-site buffer. A blended wind and solar profile, or a partially firm supply, would replace the buffer duration with a design value rather than an upper bound.

The sixth is the carbon source assumption. Point-source capture was excluded from the sizing model on the ground that its footprint sits at the host emitter rather than at the port. Two conditions were attached to that exclusion and neither is tested here. The first is that a host emitter of sufficient scale exists near the port, so a full-replacement methanol hub would require either a very large single emitter or the aggregation of several, and where no such host exists within economic transport distance, DAC is not an alternative choice but the only option. The second is that the CO₂ transport link carries its own footprint inside the system boundary: a pipeline delivering supercritical CO₂ would occupy a corridor of the same character as the fuel pipelines already modelled, and the receiving end would require conditioning and buffer storage at the port that this model does not size, so the saving is smaller than the full DAC footprint. Subject to those conditions the effect is large. Removing the DAC term from Table 4.18 takes the Scenario A production hub to 74.23 ha and Scenario C to 266.45 ha, and brings the Scenario A annual electricity demand to 10.05 TWh/yr, essentially the ammonia figure. The energy penalty does not disappear but moves to the host facility, where regeneration duties are far lower per tonne than atmospheric capture. The carbon source, rather than the synthesis plant or the storage, is what determines whether an on-site methanol production hub is spatially and energetically comparable to an ammonia one. A point-source variant carrying the CO₂ transport corridor and port-side conditioning explicitly inside the boundary would test this rather than bound it.

A further group of inputs affects the magnitude of the totals. Several are adopted at op-

timistic bounds and each moves the totals in the same direction: the stoichiometric yield of unity, which makes every upstream quantity a lower bound; the DAC space factor, an order of magnitude below both directly measured operating plants; the Haber–Bosch space factor at its lower bound, where the midpoint and upper bound both take the Scenario B production hub past the Outer Quayside Parcel; and a buffer duration that assumes no strategic stockholding obligation applies. Running against these, the PEM footprint ratio is taken at the complete-plant reporting basis, the pipeline peak factor at 5 and the Haber–Bosch specific energy at its upper bound. The aggregate is therefore neither a best case nor a worst case, but the optimistic choices are concentrated in the upstream units, so the production-hub figures are the more optimistic of the two configurations. Both synthesis space factors also rest on thin evidence, the methanol figure on a single measured reference facility and the Haber–Bosch figure on two planned projects differing by a factor of four.

Three further sources of error are structural rather than parameter-driven. The synthesis and capture plants scale linearly on the assumption that a facility of the required duty would be built as parallel trains, so the largest production-hub components carry no economy of scale; a redesigned architecture at these throughputs would reduce them by an amount no reference facility can bound. The ammonia maximum fill fraction is transferred from a pressure-vessel code to atmospheric refrigerated tanks as a stated assumption, since no equivalent published limit for that tank type was identified. And the refrigerated tank height-to-diameter regression has an R^2 of 0.032 and behaves as a constant near the population mean, so ammonia tank dimensions carry a scatter of the order of the 36 % coefficient of variation observed in built tanks, which propagates into the Layer 1 and Layer 3 areas.

Four limitations follow from the design of the method itself. The model is deterministic and one-at-a-time, producing a point estimate with a bounded envelope around each input rather than a probability distribution over outcomes, and it does not capture interaction between parameters. The renewable supply is a single year of a regional hourly series, so inter-annual variability and the difference between a regional aggregate and a site-specific resource are not captured, and both propagate into the buffer result. In batch-export mode the import terminal simulation reproduces the working-volume formula by construction, so it corroborates the static sizing rather than testing it independently; only the continuous-offtake mode yields a peak inventory decoupled from the formula. And the capacity factor is referenced to the maximum output observed in the generation series rather than to the installed capacity behind it, which is not published with the dataset; the same reference normalises and rescales the profile, so no storage, bunkering, logistics or energy result depends on the choice, but re-basing on installed capacity would raise the generation capacity, the electrolyser nameplate and its footprint, and would enlarge the buffer for the same reason an increase in r does.

6.5 Generalisability Beyond the Port of Gothenburg

The framework itself is not port-specific: every case-specific quantity enters as an explicit parameter, so applying it elsewhere is a matter of resupplying them rather than rebuilding the model. Many of the values adopted here were chosen because nothing better was available at the required scale, and anyone with a vendor quotation, a measured plant footprint or a site-specific risk assessment should replace them; a developer who knows which electrolyser and capture technology will be installed narrows the production-hub result considerably.

More changes with location than the demand figure alone. The generation profile and the land inventory are site properties, the delivery modes, reference vessel and vehicle capacities are local operating practice, and the setbacks, Seveso thresholds and TEN-T length cap are regulatory, so a port outside the EU would be re-parameterising the safety layer and not only the demand layer.

Two results generalise directly. The first is that both pathways need almost the same amount of hydrogen for the same energy delivered. This follows from the chemistry and the heating values alone, so it holds at any demand level and any port. The second is the reversal of the fuel ordering between the two hub configurations. This comes from containment and setback rules set by codes rather than by the site, and it holds as long as the ammonia distances exceed the methanol ones, which they do under every code surveyed here.

6.6 Directions for Future Work

The five limitations above each name the extension that would resolve them, and the dispersion study is the highest-value single addition. Two further openings are worth stating separately. The oxygen co-product sits outside the boundary at flows large enough to require either a dedicated offtake or a vent system, and whether it is a commercial opportunity or a further siting constraint alongside the hydrogen and ammonia inventories is unresolved here. And the framework sizes a single port in isolation, so it cannot say how bunkering demand would redistribute between ports once some of them are spatially constrained and others are not.

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A

Supplementary Background Material

This appendix collects the reference surveys, engineering detail, derivations, and case studies that stand behind the parameter choices presented in the condensed Background chapter (Chapter 2). The division of material is deliberate: the Background chapter states every parameter carried into the model together with the reason it was adopted, while this appendix holds the underlying survey data, the process chemistry, the alternative values that were considered and not adopted, and the arithmetic behind the derived figures. Values already tabulated in the Background chapter, in particular the fuel properties of Table 2.1, are not repeated here. Section headings mirror the corresponding main-text section and are cross-referenced from the point in the main chapter where the summary appears.

A.1 Hydrogen as a Marine Fuel

Hydrogen possesses a high gravimetric energy density but an inherently low volumetric density, and raising the latter to a level feasible for shipping requires cryogenic liquefaction at -253°C under a standard storage pressure of 1 bar.^{1,11} This liquefaction step is considerably more energy-intensive than the synthesis of e-ammonia, and the resulting well-to-wake power ratio is almost double the energy consumption of current fossil fuels. Adopting e-hydrogen furthermore requires entirely new vessel designs and supply infrastructure, alongside specialized operational standards and crew training.¹

Of the carriers considered in this thesis, liquid hydrogen incurs the largest continuous losses both during land storage and during the ship loading phase, where the vaporization rate is an order of magnitude higher than in storage.¹⁹ Hydrogen is characterized by extreme volatility and flammability, categorized as a cryogenic and explosive safety hazard. Risks include those associated with high-pressure gas handling and cryogenic burns from LH_2 exposure.^{20,21} While hydrogen is the essential chemical building block for all electrofuels, its extremely low boiling point and the high energy demand of liquefaction make hydrogen more effective as a feedstock for e-methanol and e-ammonia, which is the basis for excluding it as a propulsion fuel in Section 2.2.

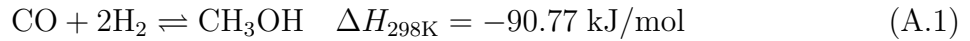
A.2 E-Methanol as a Marine Fuel

While it is theoretically possible to modify a vessel’s diesel engine and fuel system to run on methanol, building new ships might be more economic unless the engines and fuel systems were originally built to be prepared for such a conversion.¹ Bio-methanol can also serve as a practical transition fuel while waiting for e-methanol to become available.¹

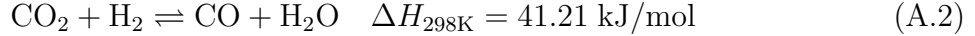
The process of producing e-methanol primarily involves the hydrogenation of captured carbon dioxide (CO₂) using green hydrogen (H₂) derived from water electrolysis. The synthesis requires green hydrogen produced via water electrolysis (Alkaline Electrolysis (AEL), Proton Exchange Membrane (PEM), or Solid Oxide Electrolyser Cell (SOEC)) powered by renewable electricity, and carbon dioxide sourced from industrial point-source capture (CCUS) or Direct Air Capture (DAC).²²

Methanol synthesis occurs through the following exothermic reactions, typically at temperatures of 250–300°C and pressures of 50–100 bar:

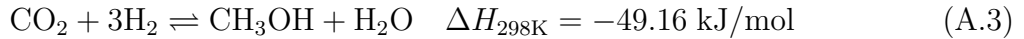
CO Hydrogenation:



Reverse Water-Gas Shift (RWGS):



Direct CO₂ Hydrogenation:



The third of these is the reaction stated in Section 2.2; the first two describe the intermediate route through carbon monoxide.²²

Methanol’s acute toxicity presents severe risks upon skin contact, inhalation, or ingestion, potentially leading to central nervous system damage and blindness. From an infrastructure standpoint, it is hazardous because it burns with a nearly invisible flame that requires specialized fire detection and suppression systems, and because it is chemically corrosive, capable of degrading standard metals and elastomers used in traditional fuel networks. Safety protocols must therefore focus on material compatibility, leak prevention, and rigorous ignition control to mitigate both toxic exposure and fire risks.²⁰

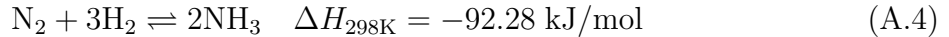
A.3 E-Ammonia as a Marine Fuel

A dual-fuel strategy preparing for both e-ammonia and e-methanol provides the highest flexibility in future fuel choices.¹ On the downside, e-ammonia requires the conversion of

existing infrastructure or completely new vessels, and it also produces higher emissions of nitrous oxide (N₂O), which is a powerful greenhouse gas.¹

Ammonia is listed at three densities in the literature: 602.8 kg/m³ in a pressurized liquid state (10 bar) at ambient temperature¹⁶, 681.97 kg/m³ at its liquid boiling point of −33.33°C under ambient pressure¹⁷, and 0.6943 kg/m³ as a gas at ambient conditions (1 bar, 25°C)¹⁸. The refrigerated density of 681.97 kg/m³ is the value applied throughout the sizing chain, since all bulk storage modelled in this thesis is fully refrigerated. The pressurised density of 602.8 kg/m³ applies only to non-refrigerated containment and is used in the terminal sizing of trucks and train transport.

E-ammonia is synthesized by combining hydrogen with nitrogen extracted from the atmosphere through cryogenic distillation, membrane separation, or Pressure Swing Adsorption (PSA).²² The production process utilizes the Haber-Bosch synthesis to combine green hydrogen and nitrogen. The reaction is highly exothermic and equilibrium-limited, operating at temperatures of 400–500°C and pressures of 150–300 bar:²²



Ammonia presents serious safety challenges due to its high reactivity and acute toxicity. Because of these risks, its use in marine environments is strictly governed by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), and the lack of established ISO and IMO safety codes for ammonia-burning engines remains a significant regulatory hurdle.²⁰

A.4 Global Bunkering Targets

The Port of Rotterdam’s 2030 hydrogen target for Northwest Europe is composed of 4.0 million tonnes of imports and 0.6 million tonnes of local production²⁸. This nearer-term target aligns with Rotterdam’s longer-term ambition to act as the primary hydrogen hub for Northwest Europe, envisioning the handling of 20 million tonnes of hydrogen annually by 2050¹¹².

Singapore has proactively aligned its regulatory framework to enable the scaling of methanol bunkering, and recent initiatives have secured the supply chain for over one million metric tons of low-carbon methanol annually by 2030²⁹.

The Port of Antwerp-Bruges is positioning itself as an essential energy gateway for the European hinterland by establishing infrastructure for the importation of low-carbon hydrogen, ammonia, methanol, and biofuels³⁰.

A.5 Electrolyser Market Review

Table A.1 gives the full survey of ten commercial systems spanning Alkaline, PEM, and SOEC architectures, ranging from compact modular stacks to gigawatt-class reference plants, summarised in Section 2.3.1.^{35,113–121}

Table A.1: Comparison of Industrial Electrolysers by Type, Efficiency, and Footprint per Production Output

Manufacturer & Model	Type	Production (kg/day)	Efficiency (kWh/kg)	Pressure (barg)	Footprint (m ²)	Footprint / Prod. (m ² /(kg/day))
Rely Clear100+. ¹¹³	Alkaline	43 200	51.7	15	22 000	0.509
HydrogenPro ¹¹⁴	Alkaline	~2017 ^c	~55.8 ^c	15	173.2	0.086
Sunfire-HyLink ¹¹⁵	Alkaline	4,800	~48.0 ^d	30	~415 ^e	0.086
Nel A485 ¹¹⁶	Alkaline	1 047	50.0	0.03	60	0.057
Nel PSM Series Module ¹¹⁷	PEM	4 300	53.2	30	32.16	0.0075
Plug GenEco 10MW Array ¹¹⁹	PEM	4 250	49.9	40	117.2	0.028
ITM Power ALPHA 50 ¹¹⁸	PEM	21 600	55.9	30	2590	0.120
Siemens Energy Elyzer ³⁵	PEM	48 000	~55.0 ^a	30	~16,740 ^b	0.349
Bloom Electrolyser ¹²⁰	SOEC	1 536	37.5	0.025	55.65	0.036
FuelCell Energy ¹²¹	SOEC	530 000	43.8	0	41 806	0.079

^a Calculated estimate based on 110 MW total plant power for 2000 kg/hr production.

^b Based on the Thyristor rectifier configuration (186 × 90 m).

^c Estimated based on 1020 Nm³/h capacity and 4.6 kWh/Nm³ consumption.

^d Calculated estimate based on 10 MW total plant power for 200 kg/hr production

^e Calculated estimate based on 10 MW total plant power for 41.5 m²/MW footprint

The spread in the final column is driven by balance-of-plant integration as much as by core stack technology: complete plant solutions including water purification, compression staging, and auxiliary systems (e.g. the Siemens Energy Elyzer, ITM Power ALPHA 50) report substantially larger footprints than isolated modular stacks reported without their balance-of-plant (e.g. the Nel PSM Series module), even within the same technology.

A.6 Maritime Delivery

Ammonia. If an industrial facility or bunkering hub receives ammonia fuel or feedstock via maritime delivery, a single shipment can transport 50,000 m³ of the liquefied chemical. For global supply operations, naval architects utilize Type 2G liquefied ammonia gas carriers engineered for these volumes, with vessels outfitted with independent prismatic cargo tanks designed to maintain the liquid at −35°C. While 50,000 m³ (equating to roughly 35,700 deadweight tonnage) is a standard medium-to-large capacity, similar vessel designs are readily available to scale single marine deliveries up to 80,000 m³ depending on the needs of the downstream supply chain.⁴³

The global ammonia trade frequently relies on Midsize Gas Carriers (MGCs) for typical ocean-going deliveries. A standard MGC delivery transports approximately 37,000 m³ of liquid ammonia, equating to roughly 25,200 tonnes per shipment.⁴⁴ Ammonia vessel sizes vary and can be tailored to specific demand and port constraints. The DNV pre-feasibility study on e-fuels³⁸ utilizes an 87,000 m³ ammonia vessel to model the required tank size for a storage facility. The study confirms a typical capacity of 25,000 tons and estimates an unloading time of three days for a vessel this size.³⁸

Conversely, for regional distribution or terminals with spatial and draft limitations, maritime deliveries can be scaled down significantly. Small-size gas carriers provide flexible logistics for emerging energy hubs. For example, a standard 6,300 m³ mini carrier operates with a deadweight of approximately 5,900 tonnes. Unlike the fully refrigerated prismatic tanks of larger vessels, this smaller ship utilizes independent Type C cylindrical tanks designed to withstand higher pressures (up to 5 bar) and accommodate temperatures down to −48°C. The vessel has two 290 m³/h cargo pumps with a total unloading rate of 580 m³/h.⁴⁵

Methanol. Methanol is primarily transported in purpose-built chemical tankers. Cargo handling on 120,000 m³ vessels typically relies on two steam-driven pumps, each with an operating capacity of 2500 m³/h.⁴⁶ The DNV study³⁸ indicates that vessels ranging from 60,000 to 120,000 m³ are readily available, and that scaling capacities up to 200,000 m³ is technically feasible without major complications.

For regional distribution and short-sea shipping, smaller coastal chemical tankers (typically under 100 meters in overall length) are frequently utilized. These vessels offer cargo capacities generally ranging from 1,200 to 7,000 m³.⁴⁷ Typical discharge configurations include multiple dedicated deep-well pumps with capacities around 250 to 300 m³/h per pump, or specialized gear pumps capable of handling around 300 m³/h.⁴⁷

Table A.2: Coastal Chemical and Product Tankers: Cargo and Pumping Capacities⁴⁷

Vessel Name / Built	Size (Length / DWT)	Capacity	Pump Configuration
W.ARGAN (<i>Chemical Tanker, 2009</i>)	99.80 m / 7,348 t	6,923 m ³	8 pumps total: 8 × 250 m ³ /h (Marflex Deep-well)
CT-3819-02 (M/T TBN) (<i>Oil/Chemical Tanker, 2002</i>)	94.95 m / 3,820 t	4,250 m ³	8 pumps total: 6 × 300 m ³ /h + 2 × 200 m ³ /h (Deep-well)
OKR-392 (<i>Chemical Tanker, 1992</i>)	64.98 m / 1,198 t	1,230 m ³	2 pumps total: 2 × 300 m ³ /h (Gear)

A.7 Rail Transport

Ammonia. The transport of anhydrous ammonia by rail is strictly governed by filling density regulations and route-specific weight limits. Commonly used Rail Tank Cars (RTCs) for ammonia possess holding volumes ranging from 50 to 110 m³.⁵⁰ To prevent catastrophic tank rupture caused by the thermal expansion of liquid ammonia, regulations restrict the maximum fill level to 0.53 kg per litre of effective tank volume.⁵⁰ When operating at scale, logistics require significant infrastructure. For example, the DNV study modeling a throughput of 200,000 tonnes per year of liquid ammonia (at +40 °C and 225 psig (15.51 bar)) calculated a need for 2,857 railcars annually, each carrying 152,700 lbs (69.26 ton). Terminal facilities therefore require unloading systems capable of processing an entire 12-car train within a single 12-hour shift to ensure efficient turnaround.³⁸

Railway lines are categorized by maximum axle pressure and total vehicle weight, ranging from Category A (64 tonnes total weight) to Category D (90 tonnes total weight).⁵⁰ If a railway route's maximum allowable weight is lower than the RTC's theoretical volumetric capacity, the stricter route limit must be enforced.⁵⁰ Considering these volumetric and axle restrictions, a single ammonia RTC typically transports a standard payload of approximately 50 tonnes.⁵⁰ Extrapolating this payload to a standard 100-car unit train⁴⁸, a single discrete railway delivery can supply up to approximately 5,000 tonnes of anhydrous ammonia to a receiving terminal.

According to federal regulations in the United States, bulk rail transport relies on the DOT 105J series insulated tank car. These specialized units are considerably larger than their European counterparts, featuring a holding capacity of 33,500 gallons (approximately 126.8 m³). To safely manage the liquefied gas, these railcars utilize top-mounted valving configurations and are equipped with pressure relief valves calibrated to actuate at an internal pressure of 225 psi (15.5 bar).¹²²

Methanol. For inland distribution, methanol could be transported via specialized chemical tank cars. High-capacity methanol railcars, such as the 15-6880 models manufactured by United Wagon Company (UWC), are designed with an increased payload capacity of 73 tonnes and a usable volume of 88 m³ per car. To safely handle these hazardous goods, these railcars are equipped with top-mounted loading and discharge valves protected by lockable sliding caps, alongside safety valves utilizing foil-clad rupture discs.⁵¹

A.8 Road Transport

Ammonia. For highway distribution, the most common high-pressure cargo tank in the US is the MC 331 trailer. Designed as a mobile logistical link, these road vessels accommodate a standard payload volume of 11,500 gallons (approximately 43.5 m³). They are

engineered for a maximum operating pressure of 300 psi (20.7 bar), with primary valving securely positioned underneath the rear belly of the tank.¹²²

Methanol. In bulk liquid logistics, the ultimate constraint on cargo capacity is not the physical volume of the tank, but rather the maximum legal gross vehicle weight (GVW) permitted on public roads, which in Europe is 40 tonnes⁵³. Because methanol is a relatively dense liquid, a fully loaded trailer will typically trigger regional road weight limits before size limits.

A.9 Pipeline Transport

Ammonia. Operating pipelines, such as the established network traversing the United States Midwest, currently transport up to 1.5 million tonnes of liquid ammonia annually to service agricultural and industrial customers.⁴⁴ Future infrastructure projects demonstrate that the upper limit for pipeline capacity can scale significantly higher to meet decarbonization demands. Recent techno-economic feasibility studies conducted by the Institute for Sustainable Process Technology for a proposed 550-km pipeline connecting the Port of Rotterdam to Germany outline a network designed to accommodate an annual flow capacity of 7.0 million tonnes.⁴⁴

A techno-economic analysis of the UK Humber cluster outlines the engineering required to distribute 6.0 million tonnes of liquid ammonia annually over an 85-km regional network. To keep the ammonia entirely in the liquid phase, the pipeline must operate at an inlet pressure of 50 bar. To handle this throughput while keeping the fluid velocity below the erosional limit of 8.65 m/s, the main trunk requires a 20-inch diameter. Operating under these parameters allows 6.0 million tonnes to be transported without the need for intermediate booster compression stations.⁵⁵

To dimension the ammonia pipeline infrastructure, the DNV methodology establishes an upper flow velocity limit of 1.8 m/s under design operating parameters of 30 barg and a maximum temperature of 50°C with a density of 564 kg/m³. To accommodate intermittent ammonia synthesis driven by fluctuating upstream hydrogen availability, an oversize factor of 5 is applied, resulting in a maximum design volumetric flow of 0.31 m³/s. Applying the 1.8 m/s velocity constraint to this peak flow, the study proposes an initial estimated pipeline diameter of approximately 0.55 m (550 mm), which corresponds to a standard 24-inch steel pipe. While this dimension provides an educated baseline, the study notes that precise sizing must be finalized during the Front-End Engineering Design (FEED) phase by incorporating additional variables such as pipe wall roughness, allowable pressure loss, and the acoustic properties of the liquid ammonia.³⁸

Methanol. Because dedicated, long-distance methanol pipelines are currently scarce, em-

pirical data regarding their maximum operational capacity is highly limited. However, the demonstrated feasibility of transporting methanol through standard oil pipelines establishes that conventional oil infrastructure can serve as a direct engineering reference for methanol transport⁵⁴.

To establish a theoretical upper bound for pipeline transport, the capacities of major global liquid petroleum trunk lines can be examined. Among the most significant pipeline networks is Russia's Druzhba pipeline, with a peak capacity of 1.4 million barrels per day (bpd) (approximately 222,600 m³/day), and the ESPO pipeline, which delivers roughly 1.0 million bpd (159,000 m³/day) to China. In North America, the Keystone system moves up to 590,000 bpd (93,800 m³/day), while Canada's Trans Mountain pipeline was recently expanded to 890,000 bpd (141,500 m³/day)⁵⁶.

These established throughput capabilities demonstrate that pipeline infrastructure is a highly scalable modality. Should a stable, large-scale demand for e-methanol materialize in the future to support maritime decarbonization, the construction of dedicated pipelines, or the repurposing of existing oil networks, is technologically and logistically capable of safely supplying the volumes modelled here.

A.10 Ammonia Storage

The integrity of ammonia storage systems is maintained through rigorous inspection regimes. Horton spheres generally follow a statutory requirement for inspection every five years. In contrast, atmospheric tanks often utilize Risk-Based Inspection (RBI) and non-destructive testing (NDT), such as Acoustic Emission Testing (AET), to monitor for Stress Corrosion Cracking (SCC) without necessitating frequent decommissioning.⁶⁶

Large-scale Refrigerated Storage (Flat-Bottom Tanks). The transition from older single-wall tanks to the Double-Wall, Double-Integrity (DWDI) systems adopted in Section 2.3.3 is driven by Quantitative Risk Assessments to achieve an As Low As Reasonably Practicable (ALARP) risk level.^{68,123} DWDI tanks are constructed with a specified annular space between the inner and outer mantles, typically filled with perlite insulation.⁶⁸ In a high-capacity tank storing 45,000 m³ of ammonia, the two steel mantles are positioned 1 m apart, requiring an inner diameter of 43.5 m and an outer diameter of 45.5 m.¹²⁴ Engineering specifications for a 10,000 MT double-wall tank dictate an inner shell diameter of 35 m and an outer shell diameter of 36.53 m.¹²³

The practical ceiling of approximately 40,000 to 50,000 tonnes per conventional flat-bottomed refrigerated tank exists because constructing larger tanks requires steel plates thicker than 38 mm, triggering mandatory post-weld heat treatment (PWHT) that is unfeasible to perform on entire large-volume structures.^{68,69} To overcome this limitation and

scale capacities up to 110,000 tonnes, new prototype designs utilize lean duplex stainless steel (SUS821L1) or prestressed concrete (PC) membrane technologies. PC membrane tanks employ a 2-mm-thick SUS304 steel membrane that transmits pressure to a PC frame, bypassing both the restrictive steel thickness limitations and the susceptibility to SCC associated with high-strength carbon steels.⁶⁹ These prototype capacities are not commercially available, which is why the maximum tank volume applied in the sizing model is set by the conventional limit rather than by the largest volume reported anywhere in the literature.

Intermediate-scale Storage (Horton Spheres). For the design of a terminal’s pressurized ammonia storage, a Horton sphere commissioned by National Fertilizers Limited (NFL) serves as a reference model. The engineering was managed by Projects and Development India Ltd (PDIL). Structurally, the vessel is constructed from Low Temperature Carbon Steel (LTCS) and features an approximate inner diameter of 17 m, providing a total volume of 2,500 m³.⁶⁵ The sphere operates with a design temperature of −30°C and a design pressure of 3.85 kg/cm²g. Additionally, the installation scope includes dedicated refrigeration systems utilizing ammonia compressors, condensers, and inert gas coolers⁶⁵.

Small-scale Pressurized Storage (Bullets). For pressurized ammonia storage at small scale, a 125 m³ horizontal bullet tank manufactured by Hubei Chusheng Vehicle Co., LTD serves as the reference model. Utilizing a larger baseline tank is advantageous, as terminal storage demands are generally high and minimizing the number of smaller tanks is preferred.¹²⁵

Structurally, the selected vessel features an outer diameter of 3.5 m and a total tip-to-tip length of 13.6 m. It is constructed from Q345R steel, includes standard 620°C annealing heat treatment to prevent stress corrosion cracking, and operates at a design pressure of 21.6 bar. Safety regulations restrict the operational filling ratio to 95%; consequently, the tank accommodates a maximum safe working capacity of 61.75 metric tonnes of liquid ammonia.¹²⁵

A.11 DAC and Point-Source Carbon Capture

Point-source carbon capture depends on retrofitting existing CO₂-emitting facilities with a carbon capture and storage (CCS) system. When technically and economically viable, this approach represents a highly efficient pathway for carbon mitigation. Because the spatial footprint of a point-source capture plant is confined to the existing industrial host facility, it does not impose additional space constraints on co-located e-fuel production facilities, and the spatial footprint of point-source capture is not discussed further in the main text.

To evaluate the operational requirements of these systems, the technical report State of the Art: CCS Technologies 2025 by the Global CCS Institute outlines various technologies

alongside their respective performance indicators and energy penalties⁸⁹. Table A.3 compiles the Technology Readiness Level (TRL), target industrial source parameters, capacity ranges, and energy consumption metrics provided by individual technology developers.

Table A.3: Performance and Energy Profiles of Contemporary Point-Source Carbon Capture Technologies.⁸⁹

Technology Name	TRL	Source CO ₂ Purity (mol%)	Capture Rate Range (tpd)	Target Applications / Industries	Energy Consumption / Regeneration Penalty
Air Liquide Chemical Absorption (Amine Wash)	8-9	3-25%	150-5,000	Flue gas (SMR, boilers, fired heaters, waste incineration, refineries, BECCS, power, pulp & paper); Syngas (H ₂ , Oxo-syngas)	1.0 to 2.8 GJ/t CO ₂ (heat)
Air Liquide Physical Absorption (Rectisol/Recticap)	9	20-30%	1,000-10,000	Low-carbon H ₂ or NH ₃ production, biomass/MSW gasification for SAF/MeOH/IGCC	0.2 GJ/t CO ₂ (elec) 0.1 GJ/t CO ₂ (heat)
Axens DMX	8	3-30%	Custom large-scale	Power plants, steel mills, refineries, waste incinerators, chemical, cement, lime, glass, paper, aluminum	1.8 to 2.7 GJ/t CO ₂ (typical reboiler steam)
Baker Hughes Chilled Ammonia Process	7	4-25%	Up to 300	Fossil fuel power, waste to energy, biomass, cement, refineries, petrochemical complexes	2.6 GJ/t CO ₂ (specific thermal)
Capsol Technologies (CapsolEoP / CapsolGo)	7-8	3-30%	100-5,500	Cement, biomass, Energy-from-Waste (EfW), lime, pulp & paper, power generation, process industries	0.7 to 1.5 GJ _e /t CO ₂ (fully electric setup)
Carbon Clean CycloneCC	7-9	3-20%	75-855	Energy, industrial power, gas turbines, maritime, industrial emitters (cement, steel, waste to energy)	1.9 to 2.9 GJ/t CO ₂ (flue gas dependent)
China Energy Amine Capture Plant	7	15%	1,370	Large-scale coal-fired power generation	2.35 GJ/t CO ₂ (heat) 51.5 kWh/t CO ₂ (elec)
CNPC High Efficiency Absorbent	9	7-50%	30-300	Power generation, cement, steel, petrochemical industry	1.34 to 2.36 GJ/t CO ₂ (regeneration energy)

The baseline input profile across these systems highlights that flue gas properties fluctuate significantly between individual source facilities. Carbon dioxide stream fractions typically fall between low-concentration ranges of 3-4% vol for gas-fired architectures or simple cycle gas turbines, moving upward to 15-25% vol for heavy industrial setups like solid fuel boilers, iron/steel processing, or calcination streams. High-pressure syngas synthesis or specialized chemical workflows can provide a source gas containing 15% to 35% CO₂ (or up to 50% in alternative configurations), shifting the processing dynamic towards lower-energy physical separation routes.

The two Direct Air Capture families differ in operating regime as well as in energy demand. Solid DAC (S-DAC) utilizes solid adsorbents and operates at ambient to low pressures (under a vacuum) and medium temperatures, while Liquid DAC (L-DAC) relies on an aqueous basic solution such as potassium hydroxide, with release of the captured CO₂ requiring a series of units operating at high temperature⁹⁰.

The operational energy requirements of Direct Air Capture are large and dictate the technology’s overall environmental impact. For electrical demand, liquid solvent-based (HT-DAC) systems typically require between 345 and 700 kWh per tonne of captured CO₂, whereas solid sorbent-based (LT-DAC) systems typically demand less, between 130 and 700 kWh/tCO₂, with individual configurations reported as high as 1,388 kWh/tCO₂ under specific operating conditions; the spread within each family is driven mainly by air handling requirements, process configuration and system scale⁹¹. Thermally, HT-DAC systems demand 4.0 to 11.9 GJ/tCO₂ to achieve the calcination temperatures required for carbonate decomposition (exceeding 800°C). In contrast, LT-DAC systems benefit from lower regeneration temperatures (60–120°C) and subsequently require less thermal energy, ranging from 2.3 to 7.0 GJ/tCO₂⁹¹.

Expressed on a combined basis, and treating heat and electricity as final energy summed at parity so that no heat pump or waste heat credit is applied, these figures give 769 to 2,644 kWh/tCO₂ for a typical LT-DAC plant, extending to 3,332 kWh/tCO₂ if the reported electrical outlier is included, and 1,456 to 4,006 kWh/tCO₂ for HT-DAC. The resulting 769 to 4,006 kWh/tCO₂ envelope quoted in Chapter 2 and swept in the sensitivity analysis is therefore an outer bound formed from the extremes of both families rather than the operating range of any single reported facility, and its upper end is conservative for any LT-DAC configuration in which regeneration heat is supplied by a heat pump or recovered waste heat rather than by resistive electricity.

Coupled with these large energy demands is a substantial spatial footprint, driven predominantly by the necessary renewable energy generation infrastructure rather than the capture units themselves. To capture 1 Gigatonne (Gt) of CO₂ annually, the core chemical capture units require approximately 85 km² for LT-DAC systems and 400 km² for HT-DAC systems. However, to ensure the process achieves net-negative emissions, the supporting renewable energy infrastructure expands this footprint. Depending on the energy mix, total aggregate land use for a 1 Gt capacity scales from an additional 445 km² for wind-powered systems up to 4,450 km² for solar photovoltaic-driven installations, with some estimates projecting total land requirements exceeding 30,000 km² for fully autonomous, solar-driven HT-DAC configurations⁹¹.

The 85 km²/Gt figure corresponds to 0.085 m²/(t CO₂/yr), close to the baseline space factor adopted in this thesis but an order of magnitude below the measured Orca and Mammoth footprints reported below. The literature is therefore widely spread. The value used in the modelling sits at the optimistic end of that spread and assumes future size optimization, and the full range is swept in the sensitivity analysis.

A DAC plant’s theoretical maximum capture limit (nameplate capacity) is systematically reduced by operational realities to yield the final Net CDR (Carbon Dioxide Removal)⁹³. This sequential “production waterfall” accounts for losses from plant availability (5–15%), performance fluctuations (±20%), gas recovery conditioning (1–10%), and the deduction

of life-cycle “grey emissions” (10–15%).

To quantify these life-cycle losses across the broader industry, a comprehensive review of Life Cycle Assessments (LCAs) for DAC technologies reveals that overall system carbon efficiencies typically range between 56% and 64%⁹¹. When fully accounting for embedded “grey emissions” and the life-cycle of operational energy sources, solid sorbent technologies (S-DAC) achieve an average net greenhouse gas reduction of 640 kg CO₂-eq per tonne of CO₂ captured, while liquid sorbent systems (L-DAC) yield slightly lower net reductions of approximately 560 kg CO₂-eq per tonne⁹¹. Beyond carbon efficiency, these systems impose significant secondary resource demands; depending on the specific configuration and the associated renewable energy generation infrastructure, water consumption can range from 1 to 12 tonnes per tonne of captured CO₂, while aggregated land use requirements can span from 85 to over 4,400 km².⁹¹

Actual net removal is therefore considerably lower than design capacity. Climeworks’ flagship Orca plant yields a maximum Net CDR of 3,000 tonnes/year against a 4,000-tonne nameplate⁹³. The newest commissioned “Mammoth” facility (May 2024) features a 36,000-tonne nameplate capacity, translating to an actual projected Net CDR of 27,000 tonnes/year⁹⁴.

Using geographical estimations through Google Earth, these operational facilities demonstrate the specific footprint requirements in practice (Figures A.1 and A.2). Orca occupies approximately 1,682 m², while Mammoth spans 35,873 m². Based on their actual Net CDR capacities, this results in a specific hardware footprint of approximately 0.56 km²/Mt-CO₂ for Orca and 1.33 km²/Mt-CO₂ for Mammoth. Both figures fall within the broad variance expected for DAC configurations, and both are an order of magnitude above the baseline space factor adopted in this thesis.



Figure A.1: Satellite view of the Climeworks Orca facility.



Figure A.2: Satellite view of the Climeworks Mammoth facility.

A third, independent check on the space factor can be back-solved from the Port of Vancouver concept described in Section A.18.2. Taking 90% of the 31-hectare midpoint gives approximately 27.9 hectares of DAC serving 200,000 tpa of methanol. At the stoichiometric CO_2 requirement this corresponds to a space factor near $1 \text{ m}^2/(\text{t CO}_2/\text{yr})$, which lies between the measured Orca and Mammoth footprints and an order of magnitude above the baseline adopted in this thesis.

For large-scale, long-distance CO₂ delivery, pipeline transport is the optimal method. To ensure stable transport and prevent pipeline erosion from phase transitions, the CO₂ must be maintained in a single-phase supercritical state, keeping the operating pressure above the critical threshold of 7.38 MPa¹²⁶.

System design typically relies on a “booster station + pipeline” configuration, with stations spaced 50 to 150 km apart to support transport capacities of 1,000 to 10,000 t/d. Maintaining an optimal flow velocity is critical: velocities that are too low increase pressure drops (risking sub-critical states), while excessive velocities cause high friction losses and energy consumption. The economic velocity for supercritical CO₂ pipelines is therefore established between 1.1 and 2.35 m/s.¹²⁶

A.12 E-Methanol Synthesis

The EU-funded Circlenergy project successfully developed and scaled a “Emissions-to-Liquids” process to produce renewable e-methanol, transitioning the technology from a TRL of 7 to TRL 8. Unlike conventional fossil-based methanol production, this process utilizes waste CO₂ captured directly from combustion sources alongside green hydrogen generated via water electrolysis. In the synthesis loop, these gases are combined, compressed, and introduced to a catalyst under high temperature and pressure to form a liquid methanol-water mixture, which is subsequently purified through distillation. Operationally, this e-methanol synthesis process is highly energy-intensive, requiring 10 to 11 MWh of electricity per metric ton of methanol produced. This overall energy requirement comprehensively encompasses all integrated sub-systems, including the primary water electrolysis, point-source carbon capture, and process gas compression¹²⁷.

To ensure the fuel remains carbon-neutral and environmentally sustainable, this electrical demand is met entirely using renewable energy sources such as wind and solar power. The commercialization of this technology includes a full-scale plant in Norway designed to capture 150,000 tonnes of CO₂ annually to produce 100,000 tonnes of e-methanol, neutralizing emissions equivalent to 56,000 fossil-fueled vehicles. With further global expansion, the technology aims to achieve an aggregate production capacity of 500,000 tonnes of renewable e-methanol per year from recycled carbon emissions¹²⁷.

The specific energy figure adopted in Section 2.3.5 is derived from recent dynamic modelling of a Power-to-Methanol facility. The modelled plant is driven by a 50 MW electrolyser and designed to produce 25,000 tonnes of e-methanol annually. According to the analysis, the standalone Methanol Synthesis and Distillation (MSD) unit has a relatively low electrical demand compared to the highly energy-intensive electrolysis process. When operating at 100% nominal load, the MSD unit consumes approximately 2.017 MW⁹⁷. Assuming continuous year-round operation (8 760 hours), this translates to a specific energy consumption

of roughly 0.71 MWh per tonne of e-methanol. Since real-world facilities experience maintenance downtime and rarely operate at 100% annual availability, a plant must realistically meet its 25 000-tonne quota in fewer operating hours. This requires a higher true hourly production rate, meaning the 0.71 MWh/tonne calculation serves as a slightly overestimated, conservative baseline for energy consumption. It should also be noted that this figure excludes the energy required for primary feedstock compression.

The Kassø e-methanol facility, developed by European Energy, is recognized as the world’s first large-scale e-methanol production site. Through the “Renewable Energy Liquefied for Tomorrow” video published on their webpage¹⁰⁹, it was possible to cross-reference and identify the various components of the methanol plant using Google Earth imagery. According to the spatial analysis of the Google Earth images, the total plant covers an area of 24,095 m² and different functional components of the methanol plant are identified, as shown in Figure A.3. The facility has the capacity to produce up to 42,000 tonnes of e-methanol per year. To achieve this production volume, the plant uses a combined total of 52 MW of electrolyzers, which stretch across a physical footprint of 6,201 m² (Figure A.5). The methanol synthesis plant itself covers 11,925 m² including the compressor units and 9,073 m² excluding them, according to the boundaries marked in Figure A.6 and Figure A.4. The 42,000 tonnes/year capacity equates to a production rate of approximately 4.79 tonnes per hour (tph). Normalized against the full 11,925 m² synthesis footprint, this yields the specific space demand of roughly 2,487 m²/tph adopted in Section 2.3.5. Operationally, the plant sources approximately 50% of its electricity demands directly from the neighboring 304 MW Kassø Solar Park (Figure A.7). The remaining 50% of the electrical requirement is supplied from the public grid via a balancing and optimization agreement with Danske Commodities¹⁰⁹.

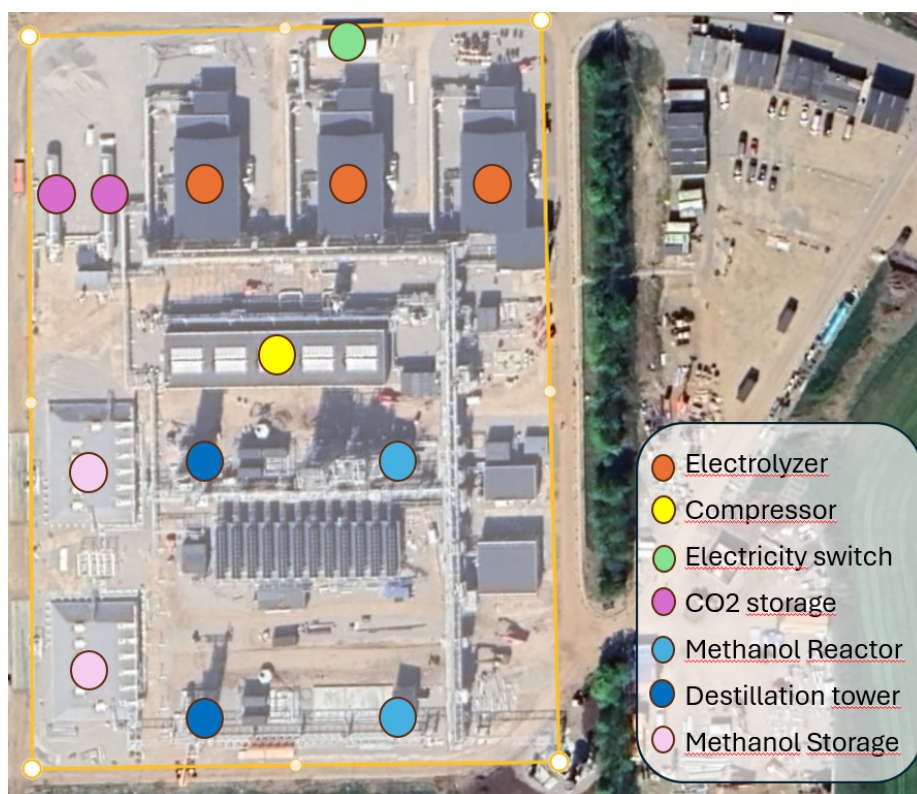


Figure A.3: Overview of the Kassø e-methanol plant footprint. Author's own measurement via Google Earth, 2026



Figure A.4: Spatial footprint of the core methanol synthesis unit. Author's own measurement via Google Earth, 2026

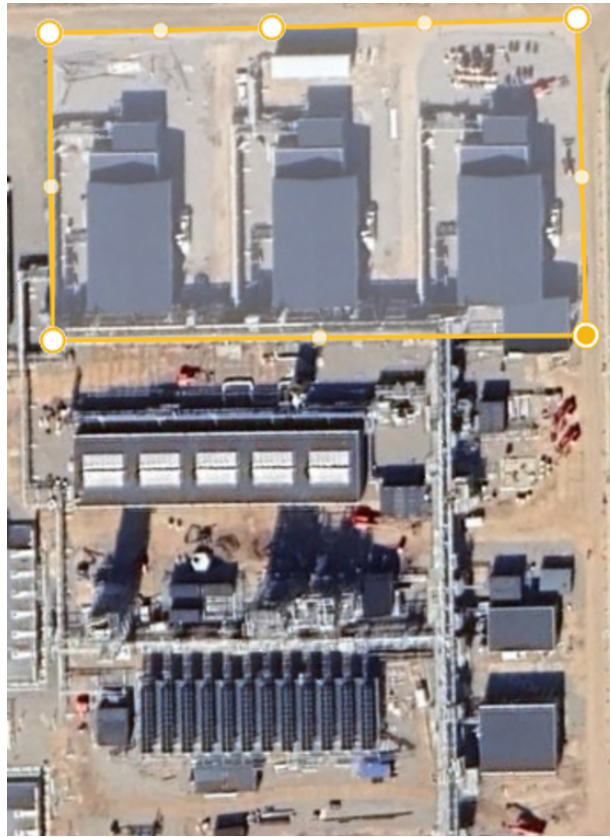


Figure A.5: Footprint of the 52 MW electrolyser facility. Author's own measurement via Google Earth, 2026



Figure A.6: Combined footprint of the methanol synthesis and compressor units. Author's own measurement via Google Earth, 2026



Figure A.7: The neighboring 304 MW Kassø Solar Park. Author's own measurement via Google Earth, 2026

A.13 E-Ammonia Synthesis

Based on steady-state continuous operation data for a 1 GW ammonia plant³⁴, the nitrogen generation process operates with an annual energy demand of 180,459 MWh. Normalized against the baseline production volume of 579.59 kt, this results in the isolated specific energy consumption of 0.311 MWh per tonne of produced ammonia quoted in Section 2.3.5. Because the ASU requires a 36- to 48-hour startup time, this energy demand represents a highly inflexible continuous load³⁴.

The remainder of the synthesis process for the 1 GW plant, comprising the syngas compressors and overall plant utilities, requires a combined 541,377 MWh annually (451,148 MWh for compression and 90,229 MWh for utilities). According to the baseline operational parameters, the direct electrical consumption of the Haber-Bosch synthesis reactor itself is negligible³⁴. Therefore, the combined energy consumption for the ammonia synthesis plant (excluding air separation) is 0.934 MWh per tonne of ammonia. According to Jabarivelisdeh et al.⁸⁸, in a water electrolysis-based plant, the ammonia synthesis process requires an electricity input of 1.35 GJ/t-NH₃ and compression 2.14 GJ/t-NH₃, equal to a total of 0.97 MWh/t-NH₃. A 200 TPD ammonia plant whitepaper¹²⁸ states that total plant energy requires 10 to 12 MWh/t-NH₃ and that the electrolyser alone could account for over 90% of this energy, leaving an energy consumption of around 1.0–1.2 MWh/t-NH₃ for the synthesis process including compression and air separation. The synthesis loop has a cold start-up time of 12 hours³⁴.

While precise numerical data (m²) for individual subsystems is absent from the baseline literature in the Bornholm feasibility study³⁴, visual analysis of the plant layout provides key spatial insights.

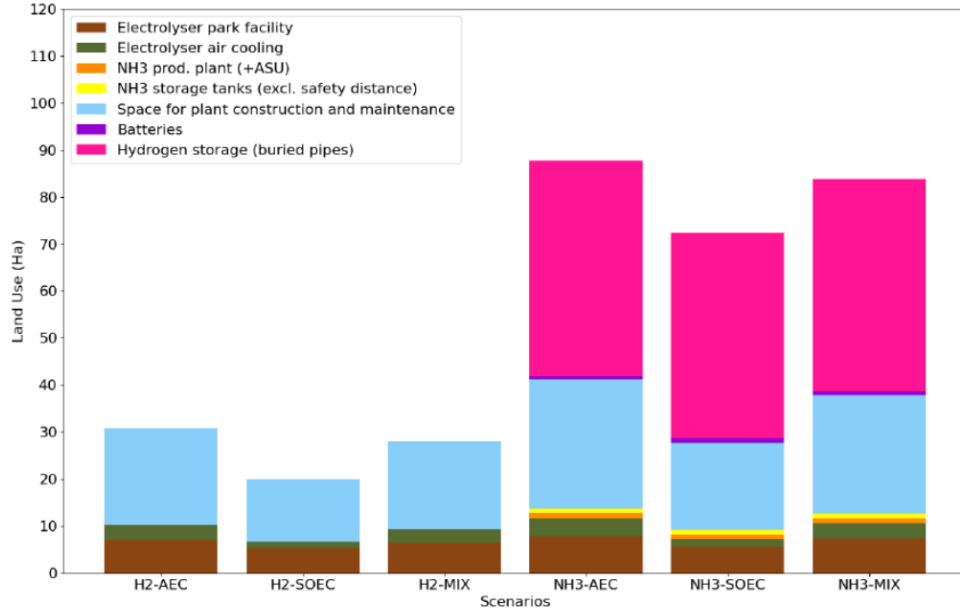


Figure A.8: Estimated spatial footprint breakdown for Bornholm Power-to-X plant configurations³⁴.

The physical footprint for the ASU and Haber-Bosch synthesis loop (categorized together as the *NH3 prod. plant (+ASU)*) constitutes a small fraction of the total facility footprint. Visually, the spatial requirement for this core synthesis infrastructure is roughly equivalent to the area required purely for the final NH3 storage tanks³⁴.

The implementation of an ammonia production facility, as opposed to standalone hydrogen production, necessitates a slightly larger overall footprint. This expansion is driven primarily by the increased space required for plant construction and maintenance, alongside the addition of intermediate hydrogen storage buffers needed to maintain a continuous load for the synthesis operations³⁴.

Based on a planned renewable ammonia project at the Port of Ventspils, Latvia, a facility producing 550,000 tons of green ammonia annually requires a plant area of 10 hectares (100,000 m²). This results in a specific area demand of approximately 0.18 m² per ton of annual ammonia production capacity⁹⁵. Assuming continuous year-round operation (8,760 hours), this translates to the area footprint of roughly 1,593 m²/tph adopted as the baseline in Section 2.3.5.

Based on another planned renewable ammonia facility near Kokkola, Finland, a plant producing 760,000 tonnes of green ammonia annually will occupy 55 hectares (550,000 m²) not including the electrolyser. This equates to a specific area demand of approximately 0.72 m² per tonne of annual ammonia production capacity⁹⁶. This translates to an area footprint of roughly 6,339 m²/tph. The two planned facilities therefore differ by a factor

of four in specific area demand, and the full span is carried into the sensitivity analysis.

A.14 Hydrogen Storage Geology: Salt Caverns and LRCs

The storage of hydrogen in pure, molecular form is the most commercially mature approach. For compressed gaseous hydrogen, underground salt caverns represent a proven, full-scale industrial solution due to their low construction costs, minimal leakage rates, and fast withdrawal capabilities. However, this approach is limited to regions with suitable geological formations. Where caverns are unfeasible, alternative physical architectures include above-ground metallic pipe storage (capable of storing approximately 12 tonnes of H_2 per kilometer of 1.4-meter diameter pipeline at 100 bar) or underground steel-lined rock caverns (which can store upwards of 740 tonnes of H_2 at 200 bar)⁷⁶.

To circumvent the large spatial footprint of gaseous storage, hydrogen can be liquefied. Liquid hydrogen achieves a high density of 70 kg/m^3 at atmospheric pressure. The primary limitation of this technology is the highly energy-intensive liquefaction process, which demands roughly $10 \text{ kWh}_{\text{el}}/\text{kg}$ of electricity in modern plants. While boil-off losses present a secondary challenge, they are effectively minimized in large, spherical, vacuum-insulated tanks; for example, the 230 to 270-tonne vessels operated by NASA exhibit negligible boil-off rates, and facility capacities could theoretically scale beyond 900 tonnes using current technology⁷⁶.

Advanced cryogenic pressure vessels rely on complex double-wall architectures. The commercial baseline adopted in Section 2 is NASA's 1.25-million-gallon ($4,732 \text{ m}^3$) liquid hydrogen sphere at Cape Canaveral, completed in 2022. The sphere operates at 7.24 bar (105 PSIG) and temperatures below -267°C ⁸¹. The physical footprint of the vessel is considerably larger than its liquid capacity dictates: the inner sphere is surrounded by an annular space filled with microsphere insulation under a high vacuum, so while the internal liquid volume corresponds to a theoretical diameter of approximately 20.8 meters (based on volume capacity and the assumption of a perfect sphere), the addition of the insulation gap and the outer structural jacket expands the true exterior footprint to a diameter of 25.3 meters (83 feet)⁸¹. The working capacity of the NASA vessels is reported as 230 to 270 tonnes⁷⁶, which is below the 331 tonnes implied by the internal volume at liquid density and reflects the ullage and operating margin retained in service. The upper end of that reported range is the sphere capacity adopted in the sizing model. This difference highlights that any facility incorporating large-scale liquid hydrogen storage must account for thick thermal insulation gaps when estimating spatial footprints.

Recent techno-economic modelling of salt caverns, specifically evaluating the Larne salt

field in Ireland, provides concrete estimations of their volumetric and mass capacities. A single salt cavern engineered for large-scale hydrogen storage features an estimated void volume of 480,000 cubic meters⁷⁹.

In terms of operational mass, this structure accommodates a total hydrogen inventory divided between cushion gas and working gas. Maintaining the cavern’s structural integrity and a minimum pressure of 90 bar requires approximately 3.5 million kilograms (37 million standard cubic meters) of cushion gas. The active working gas capacity, constrained by a maximum daily injection limit of 10 bar to preserve cavern stability, reaches approximately 7.5 million kilograms (90 million standard cubic meters) of hydrogen per cavern⁷⁹. The operational ratio of cushion gas to working gas is therefore maintained at approximately 30% to 70%⁷⁹. This equates to an active energy storage potential of 255 GWh for just one cavern⁷⁹.

The capacity potential of salt caverns is realized through multi-cavern scaling and operational cycling. By developing a cluster of seven caverns and implementing strategic injection and withdrawal cycles, the total active storage capacity scales considerably. Under cyclic operation, a seven-cavern facility can store up to 300,000 tonnes of working hydrogen, representing an aggregated energy storage capacity of approximately 10 TWh⁷⁹.

Lined Rock Caverns (LRCs) present a highly adaptable geological solution for large-scale hydrogen storage, particularly in regions lacking suitable salt formations. To optimize pressure balancing and ensure the overlying rock mass can withstand the uplift forces, commercial LRCs are typically engineered as vertical cylinders spanning approximately 40 meters in diameter and 100 meters in height, positioned at depths between 100 and 200 meters. The cavern relies on the surrounding rock mass to bear the primary compressive loads, while a multi-layered lining system, featuring a gas-tight steel inner liner and a load-transferring concrete layer, prevents hydrogen leakage. The viability of LRCs specifically for pure hydrogen is currently being demonstrated by the HYBRIT project in Luleå, Sweden. Following the successful inauguration of a 100 m³ pilot facility operating at pressures up to 250 bar, the project envisions scaling to a commercial-scale cavern. Operating at full scale, a single commercial LRC spanning 100,000 to 120,000 m³ could provide a hydrogen energy storage capacity exceeding 65 GWh, acting as a high-deliverability buffer for continuous industrial processes⁸⁰.

Underground geological storage technologies mitigate landscape impact and reduce surface land use by utilizing subterranean formations. The above-surface footprint for LRCs is minimal and mirrors the infrastructure requirements of salt caverns; the surface facilities are limited to housing essential control and process equipment, which includes compressor stations, heating and cooling systems, piping networks, valves, and metering devices⁸⁰.

While the host geological layers are naturally occurring, the gas storage volumes are entirely engineered cavities. Salt caverns are constructed as solution-mined voids, whereas LRCs

are mechanically excavated subterranean chambers within hard rock formations. These structures must be excavated at specific geological depths, typically between 100 and 200 meters, or approximately three times the cavern’s diameter, to ensure the weight of the overlying rock mass provides sufficient counter-pressure against the stored gas. Connecting the subterranean storage to the surface footprint therefore requires extensive infrastructure; for example, the Skallen demonstration project required the excavation of a 1-kilometer access tunnel with a 28 m² cross-sectional area, alongside a 90-meter vertical access shaft with a 1-meter diameter⁸⁰.

A.15 Hydrogen Pipelines: Erosional Velocity and Capacity Benchmarking

When integrating hydrogen transmission networks with underground storage facilities, such as salt caverns, gas pressures can reach up to 200 bar (20 MPa)⁶⁰, with ambient temperatures evaluated up to a maximum of 35°C⁶⁰.

Flow velocity represents a critical constraint in pipeline design. The absolute upper limits are dictated by erosional velocity thresholds to prevent the degradation of the inner pipe wall. According to the API RP 14E guidelines, these maximum safe velocities are determined by an empirical C-factor. Under the more conservative C_{150} standard, the upper velocity limit for hydrogen is calculated at 71 m/s. If the less stringent C_{200} standard is applied, the maximum permissible velocity increases to 95 m/s⁵⁹.

The required inner diameter of the pipeline is highly dependent on the targeted mass flow rate. For smaller-scale distribution networks, recommended inner diameters range from 0.12 to 0.15 m for a mass flow of 1.0 kg/s, scaling up to between 0.18 and 0.25 m to accommodate 2.8 kg/s⁶⁰. In contrast, large-scale transmission infrastructure demands considerably larger dimensions. Major transmission pipelines can feature diameters of up to 48 inches (1.22 m), and in certain high-capacity scenarios, can even exceed 60 inches (1.52 m)⁵⁹.

These large-scale hydrogen transmission pipeline dimensions have a nominal capacity of 13 GW, which corresponds to a mass flow rate of 108.3 kg/s⁵⁹. When evaluating a 48-inch pipeline at its theoretical upper boundaries, the erosional velocity limits reveal substantial transport potential. The C_{150} velocity limit (71 m/s) is exceeded at a mass flow rate of 191.7 kg/s, yielding a theoretical maximum transport capacity of 23.0 GW based on the LHV. Applying the C_{200} limit (95 m/s) pushes this threshold to 198.5 kg/s, equating to a capacity of 23.8 GW⁵⁹.

However, it must be emphasized that these theoretical maximums are derived from fluid

dynamics and erosional constraints. In practical applications, realizing these capacities may be limited by secondary technical and economic factors, including noise emissions and the overall feasibility of the required compression infrastructure⁵⁹.

A.16 Wind and Solar Sizing: Grid-Connected vs. Off-Grid Comparison

1. **Off-Grid vs. Grid-Connected Systems.** If the renewable energy plant is also supplying power to a local electrical grid or regional energy demand, the available surplus energy for the electrolyser drops, requiring a much smaller unit:
 - **Off-Grid (Island Mode):** All generated energy is dedicated to the electrolyser, allowing for the higher sizing percentages quoted in Section 2 (60% for wind, 45% for Solar Photovoltaic (PV))¹²⁹.
 - **Grid-Connected Mode:** If the system is connected to a grid (for example, transmitting 25% of peak power to the grid and using another 25% for local demand), the optimal electrolyser size shrinks considerably. Under these conditions, the optimal size drops to 35%–40% of peak capacity for wind and just 20%–25% for solar PV¹²⁹.
2. **Mixed Renewable Energy (Wind + Solar).** If a region combines both wind and solar power, the combined generation profile becomes more stable with fewer pronounced production peaks. Because the energy supply is more consistent, the optimal electrolyser can be dimensioned considerably smaller than if it were relying on pure PV or pure wind, while still producing a high volume of hydrogen¹²⁹.

The same mechanism applies to the hydrogen buffer rather than only to the electrolyser: a more stable combined profile reduces the duration of the longest generation deficit, and it is that duration which sets the buffer inventory in Chapter 4.

A.17 Re-liquefaction and Boil-Off Management

Re-liquefaction units are essential components of an Ammonia Fuel Supply System (AFSS) designed to maintain ammonia in a liquid state in flat-bottom refrigerated tanks and Horton spheres, ensuring safe storage, preventing pressure buildup, and minimizing fuel loss⁹⁸. Two primary refrigeration cycles are used to achieve this: a Vapor-Compression cycle, which uses a closed-loop ammonia refrigerant to condense boil-off gas (BOG) via a compressor-condenser-evaporator loop, and a Linde-Hampson cycle, which compresses and cools the BOG directly before forcing it through a Joule-Thomson expansion valve to induce condensation³⁶. While these cycles are extensively modelled for ocean-going Very Large Ammonia Carriers, the underlying heat-ingress and boil-off physics are directly transferable to land-based flat-bottom tanks; the principal difference is that terrestrial systems

draw compressor power from the local grid and substitute seawater coolers with cooling towers or air-cooled heat exchangers³⁶.

A detailed thermodynamic sizing model for an 88,000 m^3 ammonia storage capacity, assuming a boil-off rate of 0.024%/day (a continuous BOG mass flow of 592.3 kg/h), found the Linde-Hampson system to be marginally more power-efficient (102.35 kW compressor power, 312 kW cooling duty) than the Vapor-Compression system (112.44 kW compressor power, 322 kW cooling duty)³⁶. Pressurized bullet tanks, by contrast, rely on structural pressure rating rather than active cooling: because these vessels are rated to roughly 21 bar¹²⁵, well above the saturation pressure of ammonia at typical ambient temperatures (approximately 15.5 bar at 40°C¹³⁰), boil-off self-limits at thermodynamic equilibrium without requiring compressors or condensers. Methanol's atmospheric tanks similarly require no active re-liquefaction; its modest boil-off is governed instead by standing and working losses from thermal breathing and liquid displacement^{73,74}.

A.18 Current Practices: Extended Case Studies

A.18.1 Pre-Feasibility Baseline for a 1-Mtpa Ammonia Export Terminal

The DNV pre-feasibility study for an export facility in Chile evaluates a large-scale, 1 million tons per annum (Mtpa) green ammonia facility³⁸. While this study provides valuable quantitative benchmarks for port integration, it inherently relies on idealized assumptions typical of early-stage engineering models.

Within the conceptual 700 m $\times$ 700 m layout, the primary storage infrastructure consists of two 60,000 m^3 refrigerated flat-bottom tanks, supplemented by a smaller 1,500 m^3 pressurized day-tank to buffer peak inbound flows. The 49-hectare figure covers the developed site as a whole, including the jetty and marine works, internal roads and circulation, administration and control buildings, firewater and utility systems, and the separation distances between storage, process, and occupied structures. None of these components are modelled in this thesis, and the comparison in Section 6.3 must be read with that difference in scope in mind.³⁸

To safely accommodate the loading of Very Large Gas Carriers (VLGCs), which transport up to 87,000 m^3 of ammonia, the marine infrastructure demands a jetty extending over 600 meters from the shore. This length ensures it reaches the required 14-meter water depth for VLGC drafts and establishes a critical safety buffer between the highly toxic ammonia loading operations and the shore-based facilities.³⁸

A primary constraint identified in the pre-feasibility model is the physical limitation of

inland delivery methods. To maintain the continuous operations of a large-scale export hub, the port’s intake infrastructure must be sized to handle maximum daily throughputs without causing congestion:

- **Road Transport:** Using standard 23.9-tonne articulated tankers, the facility must physically process up to 18 road tankers per day. Because unloading a single truck requires 60 to 90 minutes, this throughput must be managed within a 12-hour day shift to avoid queuing.
- **Rail Transport:** For bulk delivery, dedicated trains consisting of 12 railcars (each carrying roughly 152,700 lbs (69,264 kg)) are utilized. The port’s unloading gantry must be dimensioned to clear an entire train within a single 12-hour shift to allow for return transit.
- **Pipeline Delivery:** To avoid multi-phase flow and subsequent cavitation damage, ammonia delivered via pipeline must be maintained at a minimum pressure of 20 barg, with liquid velocities restricted to approximately 1.8 m/s.

It is critical to note that the dimensions and logistical limits derived from the DNV model represent a “greenfield” scenario. The model assumes optimal conditions, including a perfectly square, unconstrained plot of land with suitable geotechnical soil conditions to support deep piling for heavy storage tanks. Furthermore, the logistical calculations assume idealized, continuous operational flows devoid of standard supply chain disruptions such as weather delays, port traffic congestion, or mechanical breakdowns.

When adapting these pre-feasibility baselines to real-world, “brownfield” port environments, the required spatial footprint will likely increase or become highly fragmented. Existing infrastructure, irregular port boundaries, and local zoning regulations and toxicity vulnerability zones modeled for potential ammonia leaks will dictate the final feasibility of the terminal layout.

A.18.2 E-Methanol at the Port of Vancouver

A conceptual development plan for a large-scale e-methanol production plant at the Port of Vancouver provides a practical framework for understanding the spatial and physical requirements of integrating e-fuel supply chains into active port environments. The proposed facility is designed to generate 200,000 tonnes per annum (tpa) of e-methanol by 2040, targeted to supply alternative fuel for cruise ships operating on the Pacific Northwest to Alaska Green Corridor and bulk carriers utilizing the North Pacific Green Corridor.¹⁰⁵

To align infrastructure development with emerging market demand, the facility’s construction is divided into four phases, each adding 50,000 tpa of production capacity.¹⁰⁵

Power and Utility Requirements. The 432.4 megawatt (MW) electrical demand quoted in Section 2 is distributed across the facility’s core operations:

- **Hydrogen Production:** 261.6 MW is allocated for the water electrolysis process to create green hydrogen.
- **DAC:** 57.6 MW is dedicated to the DAC modules for extracting CO₂ from the atmosphere.
- **Balance of Plant:** The remaining 113.2 MW supports the rest of the facility’s operations, which include the methanol synthesis reactor, distillation columns, and compression.

Land Requirements. The facility’s footprint expands progressively across the four development phases:¹⁰⁵

- **Phase 1 (50,000 tpa):** 8–12 hectares
- **Phase 2 (100,000 tpa):** 14–20 hectares
- **Phase 3 (150,000 tpa):** 22–28 hectares
- **Phase 4 (200,000 tpa):** 28–34 hectares

Storage and Bunkering. Because e-methanol possesses a lower energy density than conventional Heavy Fuel Oil (HFO), it requires 2.4 times more physical space to store an equivalent amount of energy. To support the 200,000 tpa output, the port requires an estimated 65,000 m³ of dedicated methanol storage, divided into three large 20,000 m³ tanks and one medium-sized 6,000 m³ tank. The preferred distribution method is ship-to-ship bunkering utilizing specialized bunker barges.¹⁰⁵

A.18.3 E-fuels at the Port of Rotterdam

The transition to e-fuels introduces new spatial and capacity challenges for existing port infrastructures. In the Harbour Industrial Cluster Rotterdam, physical space is already extremely scarce, which presents a fundamental bottleneck for scaling local e-fuel production. This physical limitation is further compounded by restricted “environmental space” (such as strict nitrogen emission limits and ecological regulations) that actively hinders large-scale construction projects.¹¹²

To domestically produce all the sustainable fuels required for international transport bunkered in Rotterdam by 2050, the port would need 2,000 petajoules (PJ) of sustainable electricity. Substituting the 960 PJ of conventional bunker fuels currently sold in the Netherlands for international transport with e-methanol by 2050 would necessitate a baseload PEM electrolysis capacity of 68 GW. The Port of Rotterdam’s vision to act as the primary hydrogen hub for Northwest Europe envisions handling 20 million tonnes (2,400 PJ) of hydrogen annually by 2050, requiring over 100 GW of electrolysis capacity and double that amount in renewable electricity generation.¹¹²

To offset the 960 PJ of conventional bunker fuels sold in the Netherlands for international transport, approximately 42,000,000 tonnes of methanol per annum would be required⁹².

A.18.4 E-Ammonia Production in the Greater Bay Area

A techno-economic analysis of a distributed green ammonia plant in the Greater Bay Area offers valuable insights into infrastructure scaling for alternative maritime fuels. The proposed facility is designed to support a 1400-TEU ammonia-fueled container vessel operating on a bi-weekly schedule, requiring approximately 680 tonnes of ammonia per fortnight.¹⁰⁶

The fuel is stored as a liquid in pressurized stainless-steel tanks operating at 16–18 bar at ambient temperature, eliminating the need for complex refrigeration equipment.¹⁰⁶ The facility relies on standardized 200 m³ tanks, each capable of holding roughly 120 tonnes.¹⁰⁶

B

Supplementary Derivations, Parameter Tables and Simulation Detail

This appendix consolidates the literature-sourced parameter tables referenced throughout Chapter 3, together with three derivations that are referenced but not reproduced in full in the main text: the empirical height-to-diameter curve fits used for tank geometry (Section 3.6.1), the local hydrogen buffer packing geometry (Section 3.6.4), and the hour-by-hour logic of the import terminal inventory simulation (Section 3.6.2). Every parameter listed here is referenced by symbol in the governing equations of Chapter 3.

B.1 Parameter Tables

Table B.1 lists the operational boundary conditions and future fuel-mix fractions used in the demand characterisation step (Section 3.4).

Table B.1: Demand Characterisation Parameters: Operational Boundary Conditions and Fuel Mix Fractions

Parameter	Symbol	Unit	Value / Literature range	Source
<i>Operational boundary conditions</i>				
Annual MGO demand	m_{mgo}	ton/yr	$0 - 54.92 \times 10^6$	[23]
Temporal baseline	h_{total}	hr/yr	8 760	–
Safety buffer, e-fuel	t_{buffer}	days	7–90	[38, 62]
Safety buffer, hydrogen	$t_{\text{buffer}, \text{H}_2}$	days	5–10	[78]
Tank heel fraction	f_{heel}	–	0.05	[38]
<i>Future fuel mix fractions</i>				
Ammonia mix fraction	f_{amm}	–	0.25–0.45	[25–27]
Methanol mix fraction	f_{meth}	–	0.134	[25]

Table B.2 lists the fuel physical properties used in the energy-equivalence conversion (Section 3.4).

Table B.2: Demand Characterisation Parameters: Fuel Physical Properties

Parameter	Symbol	Unit	Value / Literature range	Source
MGO density	ρ_{mgo}	kg/m ³	810-890	[13]
MGO lower heating value	LHV_{mgo}	MJ/kg	42.7	[1]
Methanol density	ρ_{meth}	kg/m ³	786.3	[14]
Methanol LHV	LHV_{meth}	MJ/kg	19.9	[1]
Ammonia density (refrigerated, -33°C)	$\rho_{\text{amm,FR}}$	kg/m ³	681.97	[17]
Ammonia LHV	LHV_{amm}	MJ/kg	18.60	[1]
Ammonia density (pressurised, ambient)	$\rho_{\text{amm,NR}}$	kg/m ³	602.8	[16]
Ammonia density (pipeline, 30 barg/ 50°C)	$\rho_{\text{amm,pipe}}$	kg/m ³	564	[38]

The MGO value used is 850 kg/m³, the mean of the reported range; its effect on the results is given in Section 4.2.1. The three ammonia densities correspond to the three states in which ammonia is handled along the chain. Storage and the reference carrier use the refrigerated value; rail and road use the pressurised ambient value; the pipeline value is used for diameter sizing only. The carried-state conversion is defined in Section 3.6.2.

Table B.3 lists the molecular weights and yield factors used in the stoichiometric conversions of Section 3.5.1.

Table B.3: Molecular Weights and Stoichiometric Ratios

Parameter	Symbol	Unit	Value / Literature range	Source
Methanol (CH ₃ OH)	M_{meth}	g/mol	32	Standard
Ammonia (NH ₃)	M_{amm}	g/mol	17	Standard
Hydrogen (H ₂)	M_{H_2}	g/mol	2	Standard
Carbon dioxide (CO ₂)	M_{CO_2}	g/mol	44	Standard
Nitrogen (N ₂)	M_{N_2}	g/mol	28	Standard
Water (H ₂ O)	$M_{\text{H}_2\text{O}}$	g/mol	18	Standard
Oxygen (O ₂)	M_{O_2}	g/mol	32	Standard
Methanol yield factor	$\eta_{\text{yield,meth}}$	-	0.85–1.0	Assumed
Ammonia yield factor	$\eta_{\text{yield,amm}}$	-	0.85–1.0	Assumed

Table B.4 lists the tank fill limits, maximum single-tank volumes, and vessel packet sizes used in the storage sizing logic (Section 3.6.1).

Table B.4: Storage Sizing Parameters: Tank Fill Limits, Maximum Tank Volumes, and Vessel Packet Sizes

Parameter	Symbol	Unit	Value / Literature range	Source
<i>Tank fill limits and maximum single-tank volumes</i>				
MGO max fill fraction	$f_{\max,\text{mgo}}$	–	0.95	[131]
Methanol max fill fraction	$f_{\max,\text{meth}}$	–	0.80	[72]
Ammonia max fill fraction	$f_{\max,\text{amm}}$	–	0.82–0.875	[67]
MGO / methanol max tank volume	$V_{\max,\text{meth}}$	m ³	100 000	[71]
Ammonia max tank volume (FR)	$V_{\max,\text{amm}}$	m ³	60 000–181 458	[38, 69]
<i>Logistics, vessel packet sizes</i>				
Ammonia carrier packet	$V_{\text{pkt},\text{amm}}$	m ³	6 300–87 000	[38, 43–45]
Methanol carrier packet	$V_{\text{pkt},\text{meth}}$	m ³	10 000–120 000	[38, 47]
MGO carrier packet	$V_{\text{pkt},\text{mgo}}$	m ³	120 000	[38]

The ammonia tank volume limit corresponds to the 40 000 to 50 000 t commercial ceiling imposed by post-weld heat treatment requirements (Section 2). Prototype designs reaching 110 000 t are not commercially available and are not applied in the baseline; the largest reported unit is carried into the sensitivity sweep only.

Table B.5 presents the industrial reference dataset underlying the tank H/D curve fits derived in Section B.2.

Table B.5: Dimensions for methanol (single-wall) and refrigerated ammonia (double-wall) storage tanks based on industry reference data.

Tank Type	Volume (m ³)	Inner Ht. (m)	Inner Dia. (m)	Outer Dia. (m)	Wall Thick. ^I (m)	H/D ^{II} Ratio	Source
<i>Methanol / Oil (Single-Wall Fixed Roof)</i>							
	13,000	—	—	—	—	0.85 ^{IV}	[132]
	24,736	20.70	39.00	—	—	0.53	[133]
	28,903 ^{III}	23.00	40.00	—	—	0.58	[134]
	40,000	18.00	52.00	—	—	0.35	[135]
	80,000	20.60	73.20	—	—	0.28	[136]
	100,000	21.80	80.00	—	—	0.27	[71]
<i>Ammonia (Double-Wall Double-Integrity, Refrigerated)</i>							
(5,000 t)	7,551 ^{III}	20.25	21.79	23.39	0.80	0.93	[137]
(10,000 t)	15,383 ^{III}	25.90	27.50	29.10	0.80	0.94	[138]
(10,000 t)	15,394 ^{III}	16.00	35.00	36.53	0.77	0.46	[123]
(10,000 t)	16,456 ^{III}	14.51	38.00	—	—	0.38	[139]
(20,000 t)	29,370	28.20	38.00	—	—	0.74	[140]
	45,000	32	43.5	45.5	1.00	0.74	[124]
(30,000 t)	46,000 ^{III,V}	40.56	38.00	40.00	1.00	1.07	[141]
	60,000	26.00	55.00	—	—	0.47	[38]
	181,458 ^{III}	40.00	76.00	—	—	0.53	[142]

^I Wall thickness represents the half diametric difference ($D_{\text{outer}} - D_{\text{inner}}$) accommodating the annular insulation space on each side.

^{II} Height-to-diameter ratio.

^{III} Volume calculated from height and diameter ($\pi r^2 h$).

^{IV} Reported as a ratio only; no dimensions given in the source.

^V This entry gives a tank taller than it is wide, which is not a configuration used for flat-bottom refrigerated ammonia storage. It is retained here as reported but is identified in Section B.2 as the point most responsible for the poor fit quality of the refrigerated regression.

Table B.6 consolidates the tank spacing, containment, and safety setback parameters used throughout the three-layer spatial model (Section 3.6.1).

Table B.6: Storage Spatial Footprint Parameters: Tank Spacing, Containment, and Loss-Prevention Setbacks

Parameter	Symbol	Unit	Value / Literature range	Source
Bund wall height	h_{bund}	m	0.5–1.8	[63]
MGO/methanol shell-to-shell gap	δ_{shell}	m	$\max(30, 0.5 D_{\text{out}})$	[61]
Ammonia shell-to-shell gap	$\delta_{\text{shell,amm}}$	m	$\max(30, D_{\text{out}})$	[61]
Between-group spacing	δ_{btw}	m	$\max(30, D_{\text{out}})$	[61]
Max tanks per containment group	$n_{\text{pg,max}}$	–	6	[61]
MGO/methanol loss-prevention setback	s_{bldg}	m	76	[61]
Ammonia (DWDI) loss-prevention setback	$s_{\text{bldg,amm}}$	m	106 (350 ft)	[61]
Packing (gross-to-net) factor	f_{pack}	–	1.0–2.5 swept	Assumed

The setbacks are insurer loss-prevention recommendations for the protection of adjacent structures, not land-use planning distances. The applicable Seveso III land-use planning distances are discussed in Section 3.6.1. The maximum tanks per group rule is stated in the source for pressurised and refrigerated groups; it is extended here to atmospheric methanol groups, for which no equivalent limit was identified. The shell-to-shell gap and the between-group spacing are applied as the stated maxima in the model, so both carry the 30 m floor.

Table B.7 lists the terminal delivery and modal split parameters used in the import terminal simulation (Section 3.6.2, Section B.4).

Table B.7: Distribution Parameters: Terminal Delivery, Modal Split, and Land-Side Reception

Parameter	Symbol	Unit	Value / Literature range	Source
<i>Modal split (swept 0–1 in the sensitivity analysis)</i>				
Pipeline share	f_{pipe}	–	0.70	Assumed
Rail share	f_{rail}	–	0.20	Assumed
Truck share	f_{truck}	–	0.10	Assumed
<i>Road reception</i>				
Operating days per year	d_{op}	d/yr	240 (48 weeks $\times$ 5)	[38]
Truck capacity	m_{truck}	t/truck	23.9	[38]
Truck operating window	t_{ops}	min	720 (06:00–18:00)	Assumed
Truck turnaround time	τ_{truck}	min	75 (60–90)	[38]
Loading positions per bay	–	–	2 (double-sided)	Assumed
Truck bay dimensions	$L_{\text{truck}} / W_{\text{truck}}$	m	30 / 15 per bay	Assumed
<i>Rail reception</i>				
Baseline train frequency	$n_{\text{trains,base}}$	1/yr	238	[38]
Maximum train length	$L_{\text{train,max}}$	m	740	[49]
Wagon length over couplers	L_{cart}	m	20	Assumed
Wagon usable volume	V_{cart}	m ³	50–110	[50]
Siding length allowance	σ	–	1.2	Assumed
Siding corridor widths	$W_{\text{rail,base}} / W_{\text{rail,wide}}$	m	5 / 15	Assumed
Loading cycles per siding per day	c_{max}	1/d	2	Assumed

A single wagon volume is applied to both fuels. At the carried density this gives an ammonia payload of approximately 51 t, within the 50 to 69 t range reported for European rail tank cars, and a methanol payload of approximately 67 t against the 73 t reported for the high-capacity reference railcar. The baseline train frequency is the DNV value and applies only until the 740 m cap binds, after which frequency is scaled and length held fixed (Equation 3.49). The loading cycle limit of two consignments per siding per day corresponds to a siding turnaround of approximately six hours, covering placement, connection, transfer of a full consignment, purging and release within the 12-hour reception window applied to road deliveries. It binds only where the 740 m train-length cap has already bound and the throughput is being met by frequency, which occurs in the rail-dominant allocations of Section 4.6.7.

Table B.8 lists the parameters used to size the number of onshore-to-ship transfer positions and their footprint (Section 3.6.2).

Table B.8: Bunkering Interface Parameters

Parameter	Symbol	Unit	Value / Literature range	Source
Sustained transfer rate	Q_{bkr}	m ³ /hr	500–2 000 swept	[38, 45, 47]
Daily transfer window	t_{win}	hr	12	Assumed
Connection/disconnection fraction	f_{conn}	–	0.25	Assumed
Bunker arrival peak factor	$k_{\text{peak,bkr}}$	–	1.5	Assumed
Max bunkering vessel length	$L_{\text{vessel,max}}$	m	200	Assumed
Manifold hardware length	L_{bunker}	m	15	[42]
Manifold hardware width	W_{bunker}	m	10	[42]
Methanol hazard radius	$R_{\text{haz,meth}}$	m	25	[84]
Ammonia hazard radius	$R_{\text{haz,amm}}$	m	50	[86]

The transfer rate envelope is bounded by cargo-pump capacities reported for the reference vessels of Section 2.3.2: 250 to 300 m³/hr per pump for coastal chemical tankers, 580 m³/hr combined for a mini ammonia carrier, and approximately 510 m³/hr implied by the DNV three-day unloading time for a 25 000 t tanker. Bunkering transfers are smaller and more frequently interrupted than cargo discharge, so the lower end governs. No published data specific to large-scale onshore-to-ship e-fuel bunkering was identified, and the parameter is therefore swept rather than fixed.

Table B.9 lists the pipeline design velocities and densities at operating conditions used in the dimensioning equations of Section 3.6.2.

Table B.9: Distribution Parameters: Pipeline Design Velocities and Densities at Operating Conditions

Parameter	Symbol	Unit	Value / Literature range	Source
Ammonia design velocity	v_{amm}	m/s	1.8 (erosional limit 8.65)	[38, 55]
Methanol design velocity	v_{meth}	m/s	2.0 (ceiling 5.0)	[57]
Water design velocity	v_{water}	m/s	0.9–2.4	[38]
Hydrogen design velocity (100 bar)	v_{H_2}	m/s	20 (erosional limit 71–95)	[38, 59]
Water density	ρ_{water}	kg/m ³	1 000	–
Hydrogen density (100 bar/20 °C)	$\rho_{\text{H}_2,\text{pipe}}$	kg/m ³	7.8	[76]
Intermittent peak factor	k_{peak}	–	1–5	[38]

Design velocities and erosional limits are different criteria. The design velocity is set by pressure loss over a long transmission line; the erosional limit is an upper bound that the resulting design is checked against. The two are reported together to make the distinction explicit.

Table B.10 lists the synthesis plant sizing parameters used in the DAC, methanol, and ammonia/ASU footprint and power equations of Section 3.6.3.

Table B.10: Synthesis Plant Sizing Parameters

Parameter	Symbol	Unit	Value range	Source
DAC space requirement	s_{dac}	$\text{m}^2/(\text{t CO}_2/\text{yr})$	0.002–2	[92]
DAC specific energy	E_{dac}	kWh/t CO_2	769–4 006	[91]
Methanol plant space demand	$s_{\text{meth,plant}}$	m^2/tph	2 487	[109] [†]
Methanol plant specific energy	$E_{\text{meth,plant}}$	MWh/t	0.71	[97]
Haber–Bosch plant space demand	$s_{\text{amm,plant}}$	m^2/tph	1 593–6 339	[95, 96]
Haber–Bosch specific energy (loop only)	$E_{\text{amm,plant}}$	MWh/t	0.934–0.97	[34, 88]
ASU specific energy	E_{ASU}	$\text{MWh/t}_{\text{NH}_3}$	0.114–0.311	[34, 88]

[†]Author’s own spatial measurement via satellite imagery (2026) based on the Kassø e-methanol facility; synthesis plant area including compressor unit.

The full position-in-range record for every parameter carrying a range, together with the direction of the resulting bias on the aggregated footprint, is given in Table C.11.

Table B.11 lists the wind resource and electrolyser technology parameters used throughout Section 3.6.4.

Table B.11: Renewable Production Parameters: Wind Resource and Electrolyser Technology

Parameter	Symbol	Unit	Value / Literature range	Source
SE3 dataset temporal resolution	–	hr	Hourly (8 760 pts)	[108]
Alkaline specific energy	η_{Alk}	$\text{kWh/kg}_{\text{H}_2}$	48.0–55.8	[113, 115]
Alkaline footprint ratio	s_{Alk}	$\text{m}^2/(\text{kg/day})$	0.057–0.509	[113, 116]
PEM specific energy	η_{PEM}	$\text{kWh/kg}_{\text{H}_2}$	49.9–55.9	[35, 119]
PEM footprint ratio	s_{PEM}	$\text{m}^2/(\text{kg/day})$	0.0075–0.349	[35, 117]
SOEC specific energy	η_{SOEC}	$\text{kWh/kg}_{\text{H}_2}$	37.5–43.8	[120, 121]
SOEC footprint ratio	s_{SOEC}	$\text{m}^2/(\text{kg/day})$	0.036–0.079	[120, 121]
Electrolyser-to-wind ratio	r_{base}	–	0.20–1.00	[41, 129]

Table B.12 lists the local hydrogen buffer parameters used in Section B.3.

Table B.12: Local Hydrogen Buffer Parameters

Parameter	Symbol	Unit	Value	Source
LH ₂ sphere working capacity	$M_{\text{sphere,max}}$	t	230–270	[76]
LH ₂ density	ρ_{LH_2}	kg/m ³	70	[76]
Sphere radial wall addition	t_{wall}	m	2.25	[81]
Max spheres per group	–	–	6	[61]
Intra-group spacing	d_{intra}	m	$\max(D_{\text{out}}, 15.24)$	[61]
Inter-group spacing	d_{inter}	m	$\max(D_{\text{out}}, 30.00)$	[61]
LH ₂ / GH ₂ safety setback	$S_{\text{LH}_2} / S_{\text{GH}_2}$	m	30.48 / 15.24	[103]
GH ₂ pipeline linear capacity	λ_{pipe}	t/km	12	[76]
GH ₂ pipeline diameter	D_{pipe}	m	1.4	[76]
Lined rock cavern storage density	–	kg/m ³	16 (200–250 bar)	[76]

B.2 Tank Height-to-Diameter Curve Fit Derivation

This section presents the full derivation of the empirical height-to-diameter relationships used in Section 3.6.1 to convert a per-tank geometric volume into physical dimensions. The industrial reference dataset underlying the regression is given in Table B.5.

Figure B.1 plots the empirical H/D ratios against tank capacity. The following exponential form is adopted:

$$R(V) = a \cdot \exp(b \cdot V) \quad [-] \quad (\text{B.1})$$

Where a and b are fuel-specific empirical coefficients. To determine these parameters the model is linearised by taking the natural logarithm of both sides:

$$\ln(R) = \ln(a) + b \cdot V \quad (\text{B.2})$$

A first-degree polynomial fit is applied to V versus $\ln(R)$, yielding the slope b and intercept $\ln(a)$, and the coefficient a is recovered by exponentiation. Because fixed-roof atmospheric tanks and flat-bottom refrigerated tanks are governed by different structural design codes, regressions are performed separately for each category.

Fit quality. For fixed-roof tanks the fit is acceptable. The exponential form gives $R^2 = 0.764$ over six points, and a power law fitted to the same points gives $R^2 = 0.947$. The trend toward flatter tanks with increasing capacity is real in this dataset. The exponential form is retained for consistency with the refrigerated case and because the difference between the two forms is immaterial over the interpolation range, but the power law describes

the data better and is reported here so that the choice is visible.

For flat-bottom refrigerated tanks the fit is weak. The exponential form gives $R^2 = 0.032$ over nine points, and the power law gives $R^2 = 0.021$. The fitted curve varies only from 0.693 to 0.536 across the full 7 000 to 181 000 m³ range, while the built ratios scatter from 0.38 to 1.07 about a mean of 0.695 with a standard deviation of 0.248, a coefficient of variation of 36 %. Three tanks of nominally identical 10 000 t capacity differ in H/D by a factor of 2.5. The fitted curve is therefore closer to a constant near the population mean than to a decay relationship. The 46 000 m³ entry, which gives a tank taller than it is wide, is the single point most responsible for lifting the fitted intercept.

The regression is nonetheless retained, on the following basis. Built tank proportions reflect the site, the contractor and the vintage of construction rather than capacity alone, so a strong volume dependence is not expected for refrigerated storage, and the scatter in the dataset is consistent with that. Used as a central value drawn from the range of built tanks, the fitted ratio produces dimensions that lie within the experienced envelope at every modelled volume, which is what the spatial model requires. A fixed ratio would not improve the description of the data, and no significance is attached to the volume dependence of the refrigerated curve. The consequence for the spatial model is stated rather than concealed: the 36 % coefficient of variation in built H/D is carried as a band of the same order on tank height and diameter, which propagates through D_{outer} into the shell spacing of Equation 3.25 and hence directly into the Layer 1 and Layer 3 areas. The exponential form also implies $R \rightarrow 0$ as $V \rightarrow \infty$, which has no physical basis; it is used only over the interpolation range spanned by the dataset and is never extrapolated beyond it.

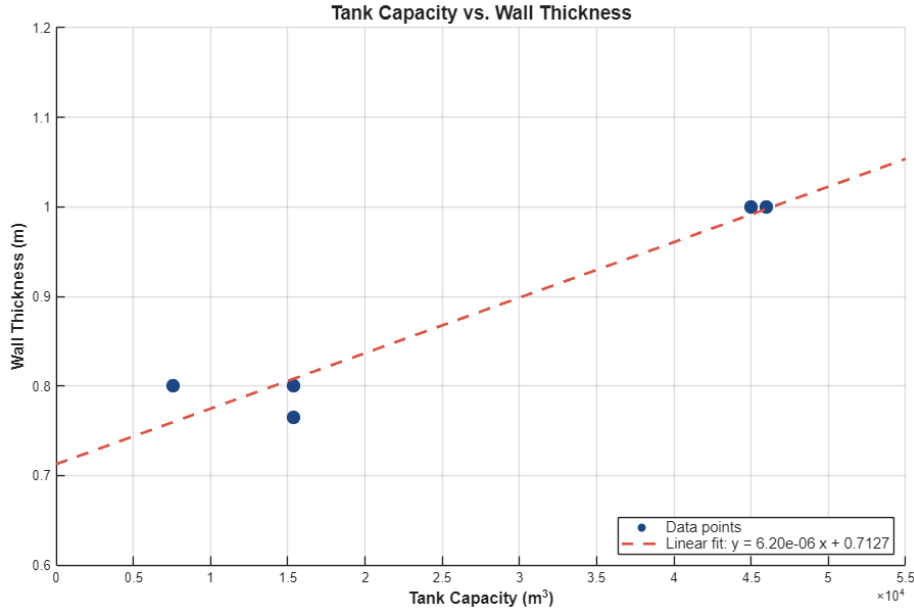


Figure B.2: Linear empirical fit of annular wall thickness versus tank capacity for double-wall refrigerated ammonia tanks ($R^2 = 0.933$ over five points). The increasing insulation thickness with volume governs the outer envelope diameter and therefore the spatial footprint.

The resulting closed-form expressions, Equations 3.17 and 3.18 for the H/D ratio and Equation 3.20 for the annular insulation thickness, are reproduced in Section 3.6.1 and used directly in the tank dimensioning chain (Equations 3.19–3.21).

B.3 Local Hydrogen Buffer Packing Geometry

This section presents the full geometric derivation for the two local on-site hydrogen buffer options introduced in Section 3.6.4. Both apply the same grid-packing and setback logic already established for fuel storage tanks in Section 3.6.1, re-derived here for the hydrogen-specific vessel geometry and OSHA separation distances. Parameter values are listed in Table B.12.

Spherical Storage

The vessel working capacity is taken as the upper end of the range reported for the reference cryogenic vessels⁷⁶, at the liquid hydrogen density. This working capacity is below the mass implied by the geometric internal volume at liquid density, the difference being ullage and operating margin. The number of required vessels is:

$$N_{\text{sphere}} = \left\lceil \frac{M_{\text{onsite}}}{M_{\text{sphere}} \times 1000} \right\rceil \quad [-] \quad (\text{B.3})$$

Assuming perfect spherical geometry, the required inner diameter follows from the volume. To account for the vacuum insulation annulus and the outer structural jacket, a constant radial addition t_{wall} is applied, taken from the difference between the internal and external diameters of the reference sphere:

$$D_{\text{out}} = 2 \left(\frac{3 \cdot V_{\text{sphere}}}{4\pi} \right)^{\frac{1}{3}} + 2 \times t_{\text{wall}} \quad [\text{m}] \quad (\text{B.4})$$

Rather than treating each sphere as an isolated unit with its own safety radius, vessels are clustered into grids to optimise land use while adhering to insurer risk guidelines. Following the same loss-prevention guidance applied to the fuel tanks, the vessels are divided into groups of no more than six. To prevent fire propagation the spacing applied between vessels within a group is the greater of one outer diameter or a 50-foot minimum, and the spacing between adjacent groups applies a 30-metre minimum on the same basis:

$$d_{\text{intra}} = \max(D_{\text{out}}, 15.24), \quad d_{\text{inter}} = \max(D_{\text{out}}, 30.00) \quad [\text{m}] \quad (\text{B.5})$$

The grid dimensions of each group follow the same arrangement rule applied to fuel storage tanks (Equations 3.24 and 3.23):

$$n_{\text{row},i} = \left\lfloor \sqrt{n_{t,i}} \right\rfloor, \quad n_{\text{col},i} = \left\lceil \frac{n_{t,i}}{n_{\text{row},i}} \right\rceil \quad [-] \quad (\text{B.6})$$

The physical width and length of each group are obtained by summing the outer diameters and the intra-group gaps:

$$W_{\text{grp},i} = (n_{\text{col},i} \times D_{\text{out}}) + \max(0, n_{\text{col},i} - 1) \times d_{\text{intra}} \quad [\text{m}] \quad (\text{B.7})$$

$$L_{\text{grp},i} = (n_{\text{row},i} \times D_{\text{out}}) + \max(0, n_{\text{row},i} - 1) \times d_{\text{intra}} \quad [\text{m}] \quad (\text{B.8})$$

The total continuous width of the hardware pad is the sum of all group widths plus the inter-group gaps, while the total length is governed by the deepest individual group:

$$W_{\text{pad}} = \sum_{i=1}^{N_{\text{grp}}} W_{\text{grp},i} + (N_{\text{grp}} - 1) \times d_{\text{inter}}, \quad L_{\text{pad}} = \max_i(L_{\text{grp},i}) \quad [\text{m}] \quad (\text{B.9})$$

$$A_{\text{sphere,hard}} = W_{\text{pad}} \times L_{\text{pad}} \quad [\text{m}^2] \quad (\text{B.10})$$

The land-use requirement is then governed by the OSHA setback for liquefied hydrogen systems above the threshold volume located near other structures, added to all four boundaries of the hardware pad, which reproduces Equation 3.87 of the main text.

Pipeline Storage

If local backup is achieved instead by pipeline storage, the required physical length and its structural footprint follow from the linear storage capacity and the pipe diameter:

$$L_{\text{pipe}} = \frac{M_{\text{onsite}}}{\lambda_{\text{pipe}} \times 1000} \quad [\text{km}], \quad A_{\text{pipe,hard}} = (L_{\text{pipe}} \times 1000) \times D_{\text{pipe}} \quad [\text{m}^2] \quad (\text{B.11})$$

Because pipeline storage relies on compressed gaseous hydrogen, the smaller gaseous setback applies, added to both sides of the corridor, which reproduces Equation 3.88 of the main text. The pipeline configuration is retained as a comparator rather than as the baseline. It occupies a long narrow corridor whose safety envelope is dominated by the setback applied along its full length, and at the on-site inventories modelled here it is substantially less land-efficient than the clustered spherical array. The spherical option is therefore carried into the aggregated totals.

B.4 Inventory Simulation Detail

This section presents the complete hour-by-hour inflow, delivery and batch-export logic for the 8760-hour inventory simulation introduced in Section 3.6.2. The two headline outputs carried back into the main text are the required working volume $V_{\text{work,req}}$, the peak of the shifted simulated trajectory, and the implied nominal gross tank volume obtained by grossing $V_{\text{work,req}}$ up with the effective usable fraction. Parameter values are listed in Table B.7.

B.4.1 Inflow and Delivery Equations

All inbound streams are expressed as an annual mass and then converted into the storage volume basis, following the carried-state convention of Section 3.6.2. For mode j with modal share f_j and carried density ρ_j :

$$m_j = f_j \times V_{\text{annual}} \times \rho_{\text{store}}, \quad V_{j,\text{store}} = \frac{m_j}{\rho_{\text{store}}} \quad [\text{kg}, \text{ m}^3] \quad (\text{B.12})$$

The carried density ρ_j enters only through the vehicle or wagon capacity, which is a fixed mass, and through the parcel volume seen by the vehicle itself. Applying a vehicle capacity directly to a refrigerated volume allocation would cause the delivered mass to differ from the mass allocated by the modal split.

The continuous pipeline hourly inflow rate is:

$$\dot{V}_{\text{pipe}} = \frac{f_{\text{pipe}} \times V_{\text{annual}}}{8760} \quad [\text{m}^3/\text{hr}] \quad (\text{B.13})$$

The volume delivered per rail consignment, expressed in the storage basis, is:

$$V_{\text{train}} = \frac{m_{\text{rail}}}{n_{\text{trains}} \times \rho_{\text{store}}} \quad [\text{m}^3] \quad (\text{B.14})$$

Where n_{trains} is the frequency resulting from the length cap of Equation 3.49, not the baseline frequency. Where the cap binds, the frequency exceeds the baseline and the consignment volume is correspondingly smaller.

For road transport, the total annual number of truck trips and the equivalent hourly delivery rate during the daytime shift are:

$$n_{\text{trucks,yr}} = \frac{m_{\text{road}}}{m_{\text{truck}}}, \quad \dot{V}_{\text{truck,hr}} = \frac{m_{\text{road}}}{d_{\text{op}} \times \rho_{\text{store}} \times t_{\text{win}}} \quad [\text{m}^3/\text{hr}] \quad (\text{B.15})$$

Where m_{truck} is the fixed truck payload mass and $t_{\text{win}} = 12$ hr is the daily delivery window, consistent with the 06:00 to 18:00 window applied in Equation B.18 and with the 720-minute operational window used to size the reception bays in Equation 3.44.

B.4.2 Hourly Inventory Balance

The hourly inventory balance is:

$$\text{Inv}(h) = \text{Inv}(h-1) + \dot{V}_{\text{pipe}} + V_{\text{rail}}(h) + V_{\text{truck}}(h) - V_{\text{out}}(h) \quad [\text{m}^3] \quad (\text{B.16})$$

With initial condition $\text{Inv}(0) = 0$. Rail deliveries arrive as instantaneous impulses at noon on each operating weekday. Because the train frequency is generally not an integer number per operating day, arrivals are accumulated as a fractional credit and discharged whenever a whole train is due:

$$V_{\text{rail}}(h) = \begin{cases} \lfloor \kappa(h) \rfloor V_{\text{train}} & \text{if } t_{\text{hr}}(h) = 12 \text{ and } d_{\text{day}}(h) \in \mathcal{D}_{\text{op}} \\ 0 & \text{otherwise} \end{cases} \quad (\text{B.17})$$

Where $\kappa(h)$ is the accumulated fractional train credit, incremented by $n_{\text{trains}}/d_{\text{op}}$ on each operating day and reduced by the integer part whenever a train is dispatched. Truck deliveries are distributed uniformly across the daytime window:

$$V_{\text{truck}}(h) = \begin{cases} \dot{V}_{\text{truck,hr}} & \text{if } 6 \leq t_{\text{hr}}(h) \leq 18 \text{ and } d_{\text{day}}(h) \in \mathcal{D}_{\text{op}} \\ 0 & \text{otherwise} \end{cases} \quad (\text{B.18})$$

The condition $6 \leq t_{\text{hr}} \leq 18$ spans twelve hourly slots, consistent with the divisor in Equation B.15. The operating calendar $\mathcal{D}_{\text{op}}$ is taken as the five weekdays of the first 48 weeks of the year, which places the four non-operating weeks as a single closing block. This is a modelling choice rather than a property of the port, and its consequence for the continuous-offtake-mode peak is quantified in Section 4.6.6.

The outflow term takes one of two forms depending on the terminal operating mode. In the *batch-export* mode the terminal discharges one full vessel packet whenever the accumulated inventory is sufficient to fill it:

$$V_{\text{out}}^{\text{exp}}(h) = \begin{cases} V_{\text{pkt}} & \text{if } \text{Inv}(h-1) + \dot{V}_{\text{pipe}} + V_{\text{rail}}(h) + V_{\text{truck}}(h) \geq V_{\text{pkt}} \\ 0 & \text{otherwise} \end{cases} \quad (\text{B.19})$$

In the *continuous-offtake* mode the terminal instead serves a continuous offtake at the demand rate and there is no packet export:

$$V_{\text{out}}^{\text{bkr}}(h) = \frac{V_{\text{annual}}}{8760} \quad [\text{m}^3/\text{hr}] \quad (\text{B.20})$$

B.4.3 Inventory Shift and Working Volume

The simulation is initialised with a zero inventory and run forward through the year. Rather than pre-specifying the opening inventory, which would require an iterative solution, the trajectory is shifted upward after the simulation so that its global minimum coincides with the mandatory safety buffer:

$$V_{\text{shift}} = V_{\text{buffer}} - \min_h [\text{Inv}(h)], \quad V_{\text{buffer}} = \frac{V_{\text{annual}}}{365} \times t_{\text{buffer}} \quad [\text{m}^3] \quad (\text{B.21})$$

$$\text{Inv}_{\text{shifted}}(h) = \text{Inv}(h) + V_{\text{shift}}, \quad V_{\text{work,req}} = \max_h [\text{Inv}_{\text{shifted}}(h)] \quad [\text{m}^3] \quad (\text{B.22})$$

This shift is mathematically equivalent to starting the year with precisely the minimum pre-fill needed to guarantee buffer compliance on the most critical day, without artificially constraining the shape of the inventory curve.

Relationship to the static formula. In the batch-export mode these definitions produce an identity rather than an independent result. Equation B.19 removes exactly one packet volume the moment the inventory reaches one packet volume, so the raw trajectory oscillates between approximately zero and V_{pkt} , and Equation B.21 then places the minimum of that trajectory at V_{buffer} . The peak of the shifted trajectory is therefore

$$\max_h [\text{Inv}_{\text{shifted}}(h)] \equiv V_{\text{buffer}} + V_{\text{pkt}} \quad (\text{B.23})$$

Which is Equation 3.11 exactly. The agreement reported in Chapter 4 is a consequence of the discrete hourly time step and not a test of the static formula. What the simulation does contribute is the shape of the trajectory: the sawtooth structure produced by discrete rail and road arrivals against continuous pipeline inflow, the depth of the weekend and holiday troughs when land-side deliveries halt, and confirmation that no intermediate state violates the buffer floor under the modelled delivery schedule. The continuous-offtake mode does not share this property, because the outflow is decoupled from the inventory level, and its

peak is therefore an independent result.

Grossing up by the effective usable fraction yields the nominal gross tank volume implied by the simulation:

$$V_{\text{nom,dynamic}} = \frac{V_{\text{work,req}}}{f_{\text{max}} - f_{\text{heel}}} \quad [\text{m}^3] \quad (\text{B.24})$$

C

Supplementary Results Figures and Tables

This appendix carries the case-specific supporting material for Chapter 4: the justification for every case-study parameter value, the record of where each adopted value sits within its literature range, the layouts and trajectories for the scenarios not shown in the main text, the land parcel imagery underlying the feasibility assessment, and the complete numerical sensitivity sweeps.

C.1 Case Study Parameter Justification Tables

Tables C.1 to C.10 record the value adopted for every case-study parameter together with the reason it was selected. The convention governing the selection is stated in Section 3.3.2, and Table C.11 records where each adopted value sits within its documented range. Appendix B, Section B.1 gives the same parameters as literature ranges with their sources; the tables below give the single value carried into the model and why.

Table C.1: Case Study Parameters: Operational Boundary Conditions, Fuel Mix Fractions, and Process Yields

Parameter	Symbol	Unit	Value	Justification
<i>Operational boundary conditions</i>				
Annual MGO demand	m_{mgo}	t/yr	1.7×10^6	Total conventional bunker demand at the Port of Gothenburg ²⁴ .
Safety buffer, e-fuel	t_{buffer}	days	7	DNV pre-feasibility standard for a marine fuel terminal ³⁸ . The 90-day IEA stockholding obligation is assumed not to extend to Power-to-X marine fuels; the assumption is tested in Table C.18.
Safety buffer, H ₂	$t_{\text{buffer,H}_2}$	days	5	Lower bound of the literature range ⁷⁸ ; wind droughts exceeding five consecutive days are rare but not absent.
Tank heel fraction	f_{heel}	–	0.05	Standard practice per the DNV methodology ³⁸ .
Hours per year	h_{total}	hr/yr	8 760	Standard; no leap-year correction applied.
<i>Fuel mix fractions</i>				
Methanol mix fraction	f_{meth}	–	0.25 / 1.00	25 % is adopted rather than the projected 13.4 % ²⁵ to reflect the port's methanol hub ambitions and to enable a symmetric comparison with ammonia at equal demand. 1.00 is the full-replacement upper bound.
Ammonia mix fraction	f_{amm}	–	0.25 / 1.00	Lower end of the projected 25 to 45 % marine ammonia share ^{25–27} . 1.00 is the full-replacement upper bound.
<i>Process yields</i>				
Methanol yield factor	$\eta_{\text{yield,meth}}$	–	1.00	Theoretical stoichiometric basis, so every feedstock flow is a minimum requirement.
Ammonia yield factor	$\eta_{\text{yield,amm}}$	–	1.00	As above.

Table C.2: Case Study Parameters: Fuel Physical Properties

Parameter	Symbol	Unit	Value	Justification
MGO density	ρ_{mgo}	kg/m ³	850	Mean of the Chevron reported density for MGO ¹³ .
MGO lower heating value	LHV_{mgo}	MJ/kg	42.7	Reference value ¹ .
Methanol density	ρ_{meth}	kg/m ³	786.3	Reference value at 20 °C ¹⁴ .
Methanol LHV	LHV_{meth}	MJ/kg	19.9	Reference value ¹ .
Ammonia density, refrigerated	$\rho_{\text{amm,FR}}$	kg/m ³	681.97	Saturated liquid at −33 °C ¹⁷ . Applied to bulk storage and to the reference carrier.
Ammonia LHV	LHV_{amm}	MJ/kg	18.60	Reference value ¹ .
Ammonia density, pressurised ambient	$\rho_{\text{amm,NR}}$	kg/m ³	602.8	Ambient-temperature pressurised liquid ¹⁶ . Applied to rail wagons and road tankers, which do not carry refrigerated ammonia.
Ammonia density, pipeline	$\rho_{\text{amm,pipe}}$	kg/m ³	564	Liquid at 30 barg and 50 °C per DNV ³⁸ ; used for diameter sizing only.

Table C.3: Case Study Parameters: Tank Fill Limits and Maximum Single-Tank Volumes

Parameter	Symbol	Unit	Value	Justification
MGO max fill fraction	$f_{\max,\text{mgo}}$	–	0.95	Standard overfill-protection practice ¹³¹ .
Methanol max fill fraction	$f_{\max,\text{meth}}$	–	0.80	Storage safety guideline reserving 20 % of working volume as vapour space at ambient temperature ⁷² .
Ammonia max fill fraction	$f_{\max,\text{amm}}$	–	0.875	Upper bound of the 82 to 87.5 % OSHA pressure-vessel range ⁶⁷ , giving an effective usable fraction of 0.825 after the heel. The range applies to non-refrigerated containers and its transfer to refrigerated storage is an assumption, not a code requirement; the adopted value is the least conservative end and therefore yields the smallest tank count. The full range is swept in Table C.15.
MGO / methanol max tank volume	$V_{\max}$	m ³	100 000	Largest commercially standard atmospheric fixed-roof tank ⁷¹ .
Ammonia max tank volume, FR	$V_{\max,\text{amm}}$	m ³	60 000	Commercial DWDI reference ³⁸ , consistent with the 40 000 to 50 000 t ceiling imposed by post-weld heat treatment limits. Units up to 181 458 m ³ are reported ⁶⁹ but are not commercially standard; that value is swept in Table C.15.

Table C.4: Case Study Parameters: Tank Spacing, Containment, and Safety Setbacks

Parameter	Symbol	Unit	Value	Justification
Bund wall height	h_{bund}	m	1.5	Upper end of the 0.5 to 1.8 m standard range, capped to preserve personnel egress and firefighting access ⁶³ .
MGO / methanol shell gap	δ_{shell}	m	$\max(30, 0.5 D_{\text{out}})$	AXA XL layout standard, applying the stated 30 m minimum alongside the proportional rule ⁶¹ .
Ammonia shell gap	$\delta_{\text{shell,amm}}$	m	$\max(30, D_{\text{out}})$	AXA XL layout for refrigerated hazardous storage, reflecting the greater consequence of an ammonia release ⁶¹ .
Between-group spacing	δ_{btw}	m	$\max(30, D_{\text{out}})$	AXA XL minimum of 30 m or one tank diameter between containment groups ⁶¹ .
Max tanks per group	$n_{\text{pg,max}}$	—	6	AXA XL containment group limit ⁶¹ . Stated for pressurised and refrigerated groups and extended here to atmospheric methanol, for which no equivalent limit was identified.
MGO / methanol setback	s_{bldg}	m	76	Insurer loss-prevention setback for atmospheric hydrocarbon and methanol storage ⁶¹ . Not a land-use planning distance.
Ammonia setback	$s_{\text{bldg,amm}}$	m	106	Insurer loss-prevention setback for refrigerated DWDI ammonia ⁶¹ . Not a land-use planning distance; see Section 6.4.
Packing factor	f_{pack}	—	1.35	Gross-to-net allowance for internal roads, firewater loop, pipe racks and laydown. Assumed and used for the feasibility study. Swept in Table C.16.

Table C.5: Case Study Parameters: Logistics, Vessel Packet Sizes and Modal Split

Parameter	Symbol	Unit	Value	Justification
Ammonia VLGC packet	$V_{\text{pkt,amm}}$	m^3	87 000	DNV reference vessel, adopted as the upper limit ensuring full coverage of delivery and export transport solutions ³⁸ . Swept down to one fourteenth in Table C.19.
Methanol carrier packet	$V_{\text{pkt,meth}}$	m^3	120 000	Established practical upper limit for ocean methanol transport ³⁸ ; same basis as above.
Pipeline share	f_{pipe}	%	70	Assumed dominant mode for continuous port supply. Swept across five allocations in Table C.21.
Rail share	f_{rail}	%	20	Secondary mode for supplementary batch supply.
Truck share	f_{truck}	%	10	Minor top-up mode consistent with port operational practice. Modal split as per DNV study ³⁸ .
Operating days per year	d_{op}	d/yr	240	48 operating weeks of five weekdays, per the DNV rail model ³⁸ .
Base train frequency	$n_{\text{trains,base}}$	1/yr	238	One train per operating weekday adjusted for holidays ³⁸ . Frequency increases above this wherever the 740 m length cap binds.
Max block-train length	$L_{\text{train,max}}$	m	740	TEN-T freight infrastructure standard ⁴⁹ . Throughput above one capped train per weekday is met by increasing frequency, not train length.
Wagon usable volume	V_{cart}	m^3	85	Single representative wagon volume applied to both fuels ⁵⁰ ; gives approximately 51 t of ammonia and 67 t of methanol at the carried densities, within the reported ranges for each.
Loading cycles per siding per day	c_{max}	1/d	2	Assumed siding turnaround of approximately six hours within the 12-hour reception window. Binds only where the length cap has already bound; see Section 4.6.7.
Truck capacity	m_{truck}	t	23.9	Standard tanker payload per DNV ³⁸ .
Truck operating window	t_{ops}	—	06:00–18:00	Twelve active hours assumed, consistent with the reception window applied in the inventory simulation.
Truck turnaround	τ_{truck}	min	75	Midpoint of the 60 to 90 minute unloading window per vehicle ³⁸ .

Table C.6: Case Study Parameters: Pipeline Design

Parameter	Symbol	Unit	Value	Justification
Ammonia design velocity	v_{amm}	m/s	1.8	Conservative DNV design value at 30 barg and 50 °C, below the cavitation-risk threshold and well below the 8.65 m/s erosional limit ³⁸ .
Methanol design velocity	v_{meth}	m/s	2.0	Long-transmission and pump-suction design velocity governed by pressure loss, below the 5 m/s flashing limit ⁵⁷ .
H ₂ design velocity	v_{H_2}	m/s	20	Conservative lower bound for a 100 bar compressed gas line ³⁸ , against an erosional limit of 71 to 95 m/s.
Water design velocity	v_{water}	m/s	1.5	Midpoint of the 0.9 to 2.4 m/s standard range ³⁸ .
H ₂ pipeline density	$\rho_{\text{H}_2, \text{pipe}}$	kg/m ³	7.8	Real-gas value at 100 bar and 20 °C ⁷⁶ .
Peak flow factor	k_{peak}	–	5	Upper bound of the 1 to 5 range, reflecting a nominal 24-hour transfer compressed into a four to five hour window ³⁸ . Conservative; affects pipeline diameters only.

Table C.7: Case Study Parameters: Bunkering and Land-Side Transfer Infrastructure

Parameter	Symbol	Unit	Value	Justification
Sustained transfer rate	Q_{bkr}	m ³ /hr	500	Lower end of the envelope implied by cargo-pump data for the reference vessels of Section 2.3.2 ^{38,45,47} . Bunkering transfers are smaller and more frequently interrupted than cargo discharge, so the lower end governs. Swept to 2000 in Table C.20.
Bunkering hardware footprint	–	m ²	150 (15 × 10)	Marine loading arm and manifold envelope ⁴² , consistent with Figure 2.2.
Transfer positions	N_{berth}	–	Calculated	Set by peak daily continuous-offtake and per-operation turnaround; scales with demand rather than being fixed.
Methanol hazard radius	$R_{\text{haz, meth}}$	m	25	Port of Gothenburg SIMOPS exclusion zone for methanol bunkering ⁸⁴ .
Ammonia hazard radius	$R_{\text{haz, amm}}$	m	50	QRA-based berth safety zone at operating terminals ⁸⁶ , adopted in the absence of site-specific dispersion simulation. This is a lower bound; see Section 6.4.
Truck bay dimensions	–	m ²	450 (30 × 15)	Assumed per-bay envelope based on a standard double-sided loading platform, consistent with Figure 2.4.
Rail wagon length	L_{cart}	m	20	Assumed length of a chemical rail tank wagon.
Rail corridor widths	$W_{\text{rail, base}} / W_{\text{rail, wide}}$	m	5 / 15	Baseline clearance corridor expanded at the offloading platform to accommodate fluid-handling skids and gangways, assumed based off Figure 2.3.
Siding length allowance	σ	–	1.2	Siding assumed 20 % longer than the consignment to accommodate run-in and run-out.

Table C.8: Case Study Parameters: Synthesis Plant Sizing

Parameter	Symbol	Unit	Value	Justification
DAC space factor	s_{dac}	$\text{m}^2/(\text{t CO}_2/\text{yr})$	0.10	Optimistic baseline within the 0.002 to 2 literature envelope ⁹² , an order of magnitude below the measured Climeworks Orca (0.56) and Mammoth (1.33) plants. Adopted on the expectation that port-scale modular capacity would be laid out more densely than early demonstration units, which has not been demonstrated. Swept across the full range in Table C.13, where it is the dominant source of uncertainty in the methanol result.
DAC specific energy	E_{dac}	kWh/t CO_2	2 639	S-DAC total of 9.5 GJ/tCO ₂ treated as a single electrical load, within the 769 to 4 006 kWh/tCO ₂ literature span ⁹¹ . Assumes regeneration heat is supplied electrically at unit efficiency, which is conservative relative to a heat-pump configuration.
Methanol plant space factor	$s_{\text{meth,plant}}$	m^2/tph	2 487	Measured from the Kassø e-methanol facility via satellite imagery, 11 925 m ² at 4.79 tph including the compressor unit ¹⁰⁹ . Single reference facility with no published range; a plausible 1 500 to 4 000 band is swept in Table C.15.
Methanol plant specific energy	$E_{\text{meth,plant}}$	MWh/t	0.71	Synthesis and distillation loop only, excluding electrolysis, capture and feedstock compression ⁹⁷ .
Haber–Bosch space factor	$s_{\text{amm,plant}}$	m^2/tph	1 593	Ventspils planned facility, the lower and more optimistic end of the available range ⁹⁵ ; the Kokkola comparator implies 6 339 ⁹⁶ . The full span is swept in Table C.15, where it changes the Scenario B verdict.
Haber–Bosch specific energy	$E_{\text{amm,plant}}$	MWh/t	0.97	Upper bound of the loop-only range, a conservative power estimate ^{34,88} .
ASU specific energy	E_{ASU}	$\text{MWh/t}_{\text{NH}_3}$	0.114	Lower bound of the literature range, reflecting an integrated ASU ^{34,88} . Optimistic; reaches the energy balance only, and is swept in Table C.15.

Table C.9: Case Study Parameters: Electrolyser and Wind Resource

Parameter	Symbol	Unit	Value	Justification
Electrolyser technology	–	–	PEM	Selected for fast dynamic response under an intermittent profile, compact footprint relative to the alkaline comparator, and because the reference is a complete industrial plant rather than an isolated stack; see Section 3.6.4. All three technologies are compared in Table 4.22.
PEM specific energy	η_{PEM}	kWh/kg _{H₂}	55.0	Siemens Elyzer reference value ³⁵ .
PEM footprint ratio	s_{PEM}	m ² /(kg/day)	0.349	Siemens Elyzer complete-plant basis ³⁵ . The surveyed PEM span of 0.0075 to 0.349 reflects whether balance-of-plant is included in the reported figure rather than a difference in stack technology, and the complete-plant value is the appropriate basis for a land-use assessment. Conservative.
Capacity ratio	r_{base}	–	0.70	Within the 60 to 89.3 % range reported for off-grid wind-coupled electrolysis. ⁴¹
Wind resource dataset	–	–	SE3 hourly	Published national transmission system operator generation statistics ¹⁰⁸ , representative of the Central Sweden onshore wind resource, where Gothenburg is located. Treated as a profile rather than a swept scalar; the constant-supply comparator is reported in Table C.17.

Table C.10: Case Study Parameters: On-Site Hydrogen Buffer (One-Day Local Terminal)

Parameter	Symbol	Unit	Value	Justification
LH ₂ sphere capacity	$M_{\text{sphere,max}}$	t	270	Upper limit for commercially viable cryogenic spherical storage ⁷⁶ .
LH ₂ density	ρ_{LH_2}	kg/m ³	70	Cryogenic liquid hydrogen at $-253\text{ }^\circ\text{C}$ ⁷⁶ .
Sphere wall addition	t_{wall}	m	2.25	Radial allowance covering the inner vessel, vacuum insulation annulus and structural outer jacket, from the NASA Cape Canaveral reference sphere ⁸¹ .
GH ₂ pipeline linear capacity	λ_{pipe}	t/km	12	Capacity of a 100 bar large-diameter buffer pipeline ⁷⁶ .
GH ₂ pipeline diameter	D_{pipe}	m	1.4	Large-format storage pipeline diameter ⁷⁶ .
Sphere spacing	d_{intra}	m	$\max(D_{\text{out}}, 15.24)$	Same insurer grouping and spacing logic applied to the fuel tanks, at the 50-foot minima ⁶¹ .
Sphere spacing	d_{inter}	m	$\max(D_{\text{out}}, 30)$	Same insurer grouping and spacing logic applied to the fuel tanks, at the 30-metre minima ⁶¹ .
LH ₂ / GH ₂ setbacks	$S_{\text{LH}_2} / S_{\text{GH}_2}$	m	30.48 / 15.24	OSHA separation distances for liquefied and gaseous hydrogen systems above the threshold volumes ¹⁰³ .

C.2 Parameter Selection Convention and Position in Literature Range

Table C.11 records, for every parameter carrying a documented range, the bounds of that range, the value adopted, its position within the range, and the direction of the resulting bias on the aggregated footprint. The convention governing the selection is stated in Section 3.3.2. A position of 0 % is the low end of the range and 100 % the high end; the direction that constitutes an optimistic choice differs by parameter, so the bias column rather than the position column is what should be read.

Table C.11: Adopted Parameter Values and Their Position Within the Literature Range

Parameter	Low	Used	High	Pos. (%)	Bias on the footprint
MGO density (kg/m^3)	810	850	890	100	Volumes are unaffected; the density cancels
DAC space factor ($\text{m}^2/(\text{t}/\text{yr})$)	0.002	0.10	2	5	Optimistic; below Orca at 0.56 and Mammoth at 1.33
DAC specific energy (kWh/tCO_2)	769	2 639	4 006	58	Mid-range; energy only
Methanol synthesis space factor	2487	2487	2487	–	Single measured reference facility (Kassø); no published range. Swept across an assumed 1 500–4 000 band in Table C.15
MeOH synthesis specific energy (MWh/t)	0.71	0.71	0.71	–	Single reference, synthesis and distillation loop only; energy only
Haber–Bosch space (m^2/tph)	1 593	1 593	6 339	0	Optimistic; the Sc-B verdict changes at the top of the range
Haber–Bosch energy (MWh/t)	0.934	0.97	0.97	100	Conservative; energy only
ASU specific energy (MWh/t)	0.114	0.114	0.311	0	Optimistic; energy only
PEM footprint ratio ($\text{m}^2/(\text{kg}/\text{d})$)	0.0075	0.349	0.349	100	Conservative; complete-plant reporting basis
PEM specific energy (kWh/kg)	49.9	55.0	55.9	85	Conservative; energy only
NH_3 fill fraction (–)	0.82	0.875	0.875	100	Optimistic; borrowed from the non-refrigerated rule
Pipeline peak factor (–)	1	5	5	100	Conservative; pipeline diameters only
Yield factor (–)	0.85	1.00	1.00	100	Optimistic; every upstream quantity is a lower bound
Buffer duration (days)	7	7	90	0	Optimistic; assumes no IEA-type stockholding obligation applies
Packing factor (–)	1.00	1.35	2.50	23	Gross-to-net allowance

The deviations are not uniformly directed. Six parameters are adopted at an optimistic bound, four at a conservative bound and the rest at mid-range, so the aggregated totals of Chapter 4 are a mixture rather than a uniformly optimistic or uniformly conservative case. The three optimistic choices that matter most are the DAC space factor, the Haber–Bosch space factor and the buffer duration, and each is bounded explicitly in Section 4.6.

C.3 Storage Footprint Layouts: 100 % Demand Scenarios

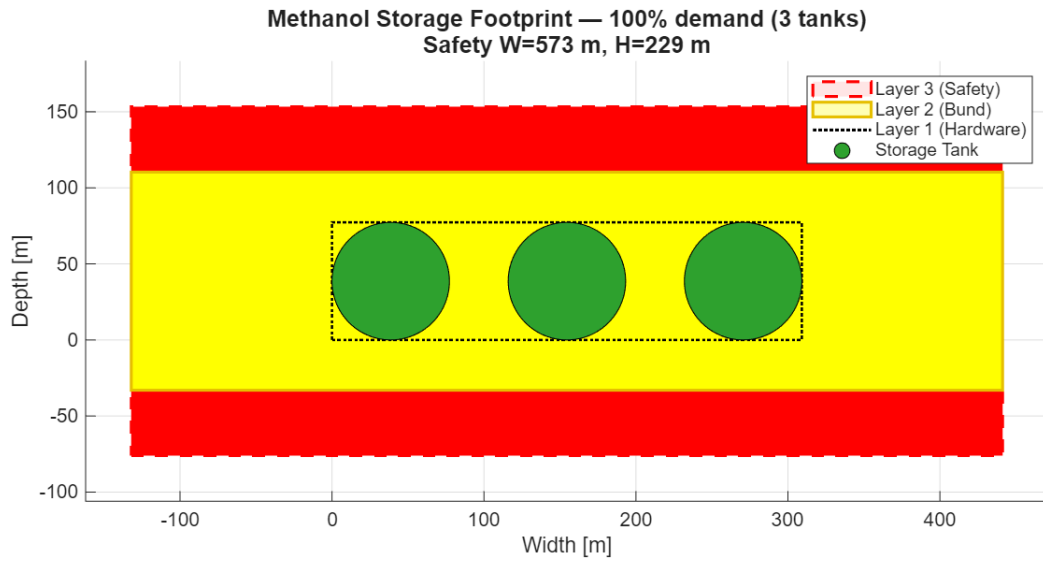


Figure C.1: Three-layer spatial footprint for methanol storage under Scenario C (100 % demand, 3 tanks).

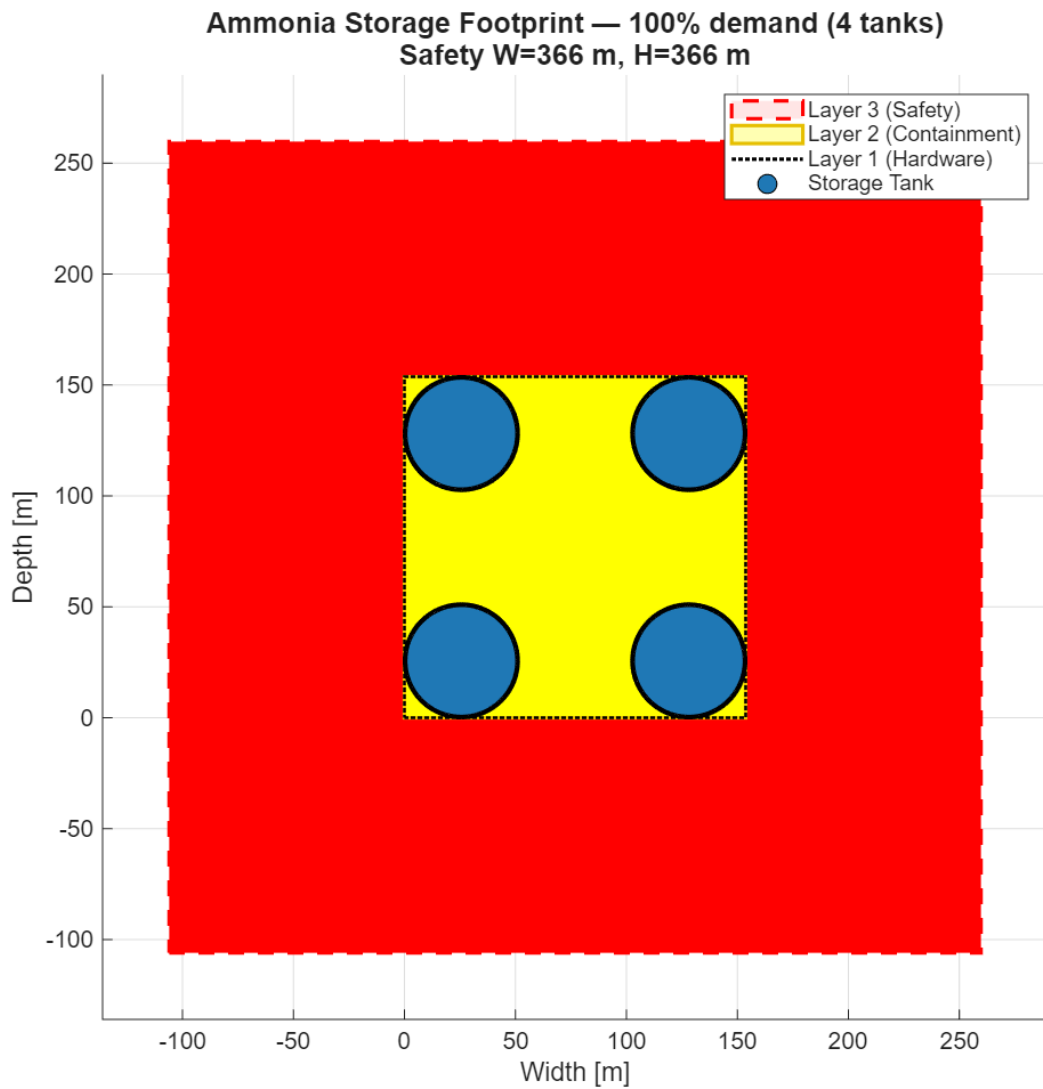


Figure C.2: Three-layer spatial footprint for ammonia DWDI storage under Scenario D (100 % demand, 4 tanks in a two-by-two array).

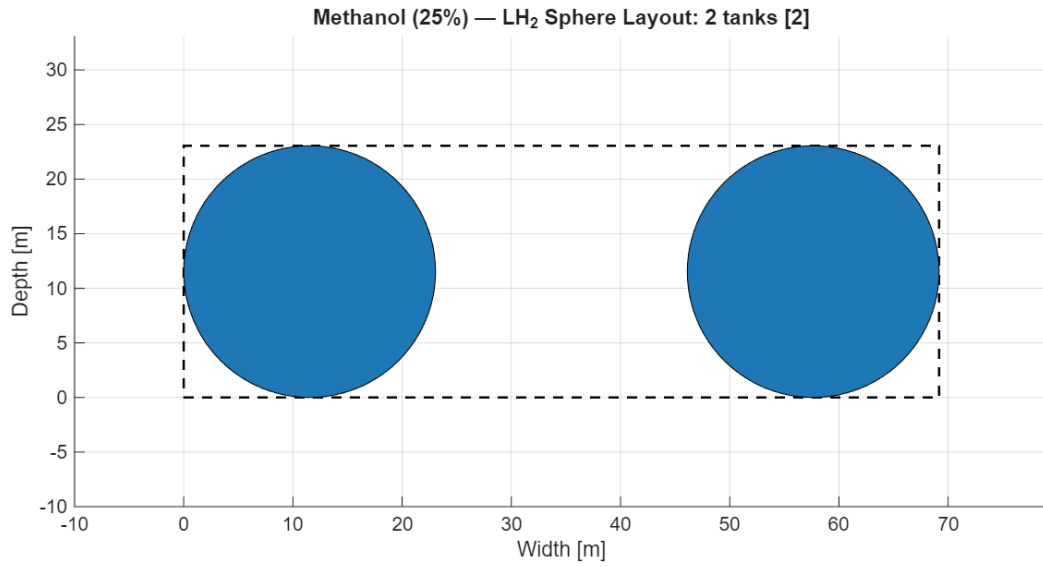


Figure C.3: Hardware pad configuration for the on-site LH₂ buffer supporting the methanol pathway under Scenario A (2 spheres).

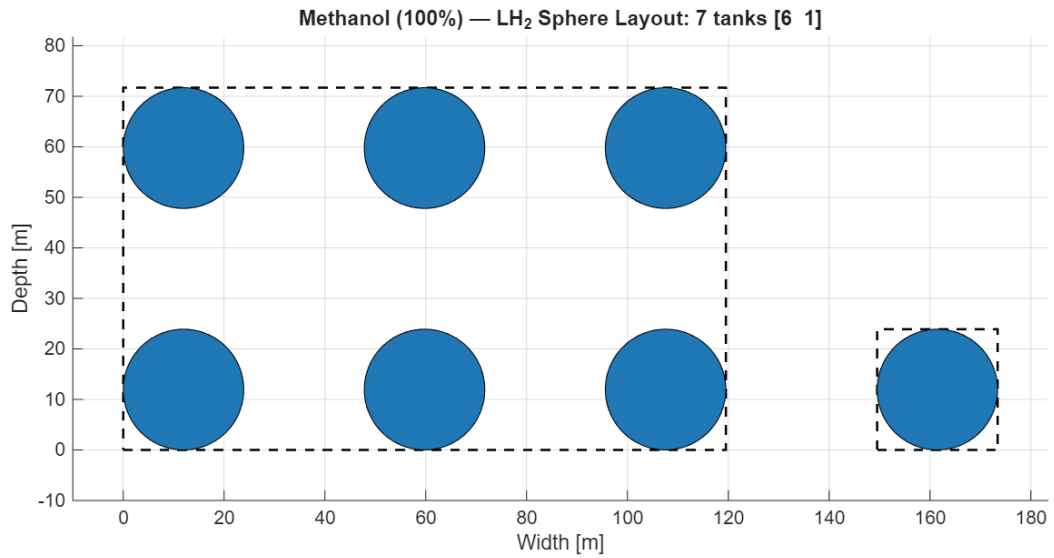


Figure C.4: Hardware pad configuration for the on-site LH₂ buffer supporting the methanol pathway under Scenario C (7 spheres in two groups).

C.4 Inventory Simulation Trajectories

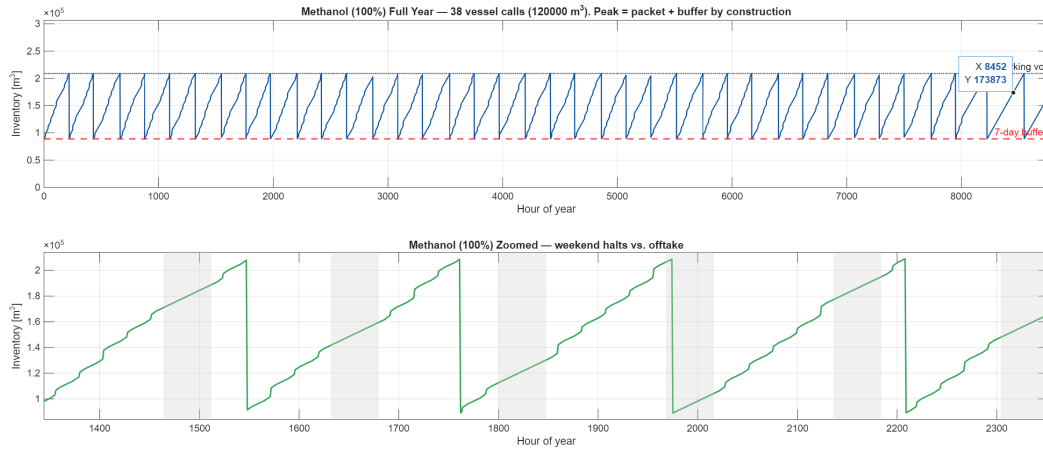


Figure C.5: Simulated 8760-hour inventory trajectory for the Scenario C methanol import terminal in batch-export mode, at approximately 38 vessel calls per year.

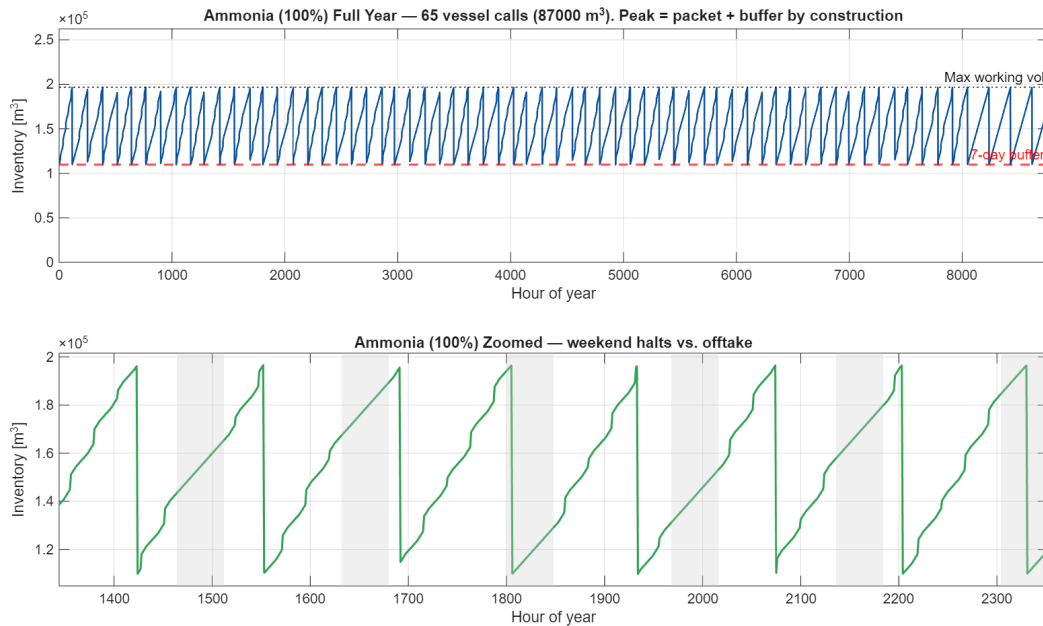


Figure C.6: Simulated 8760-hour inventory trajectory for the Scenario D ammonia import terminal in batch-export mode, at approximately 65 vessel calls per year.

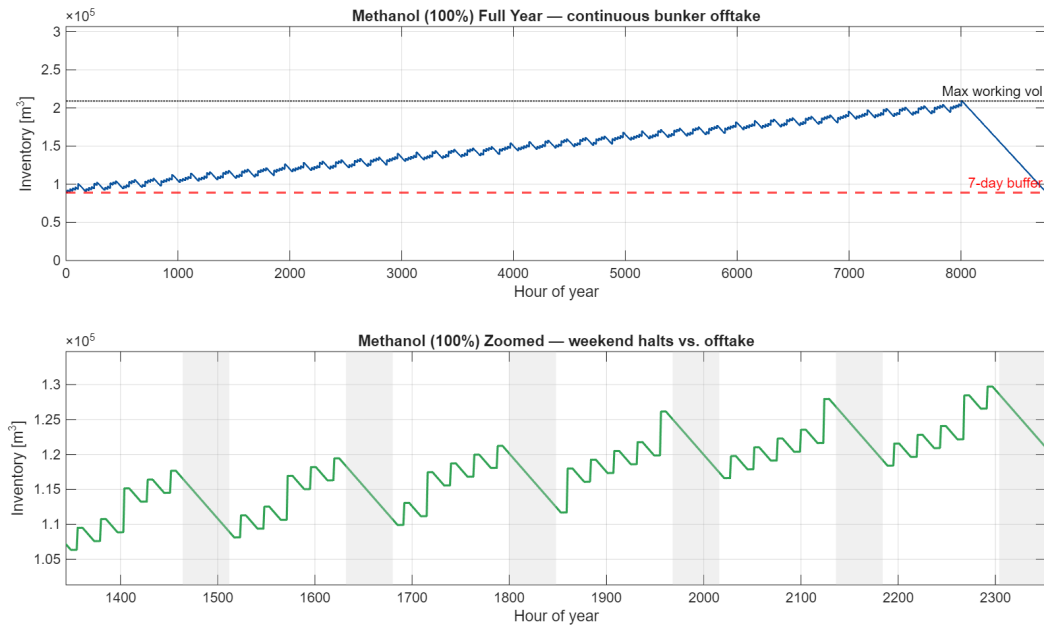
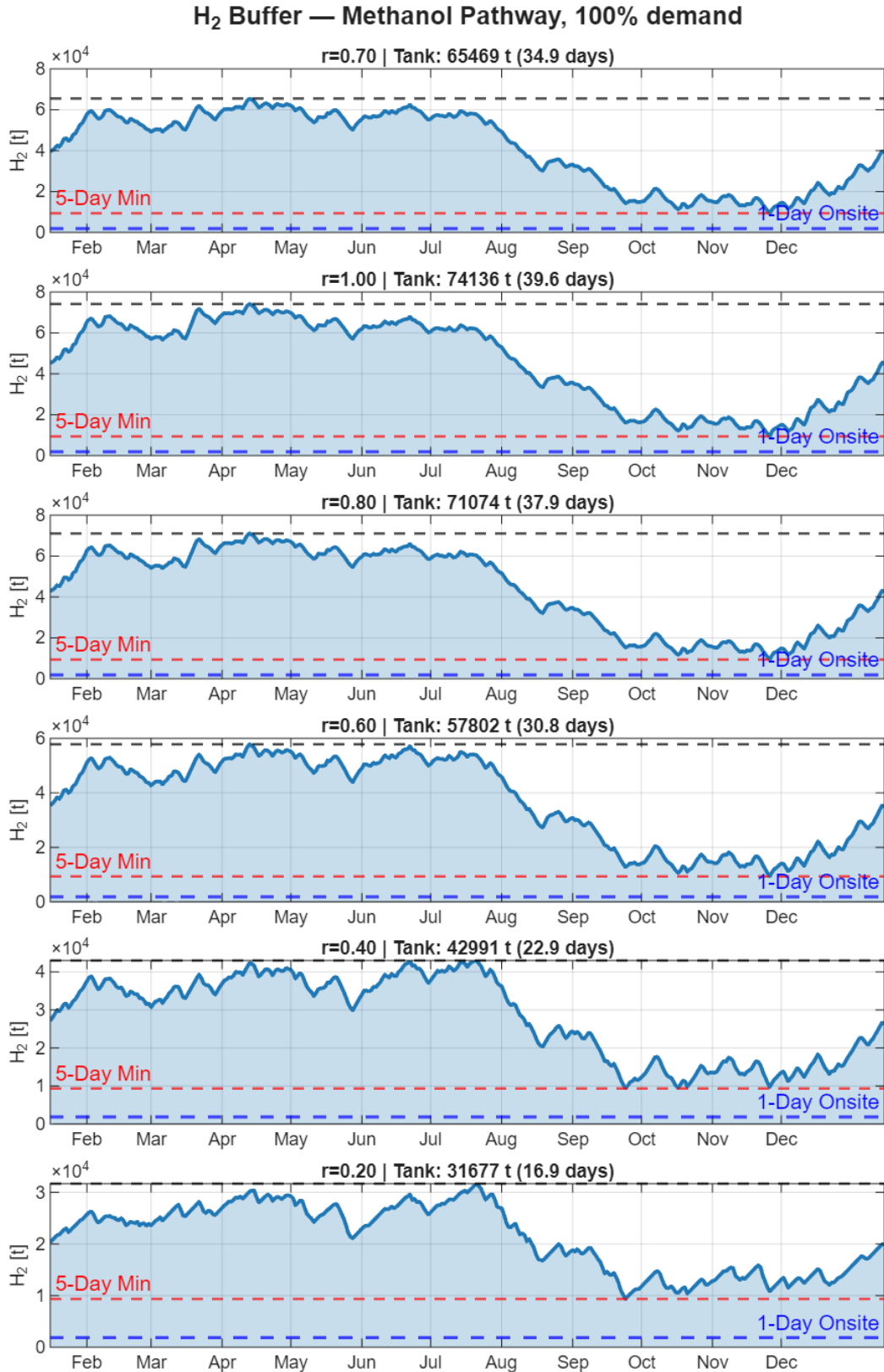


Figure C.7: Simulated 8 760-hour inventory trajectory for Scenario C under the continuous-offtake operating mode.

C.5 Hydrogen Buffer Trajectories: Methanol Pathway



LXV

Figure C.8: Annual hydrogen buffer tank level trajectories for Scenario C (100% methanol).

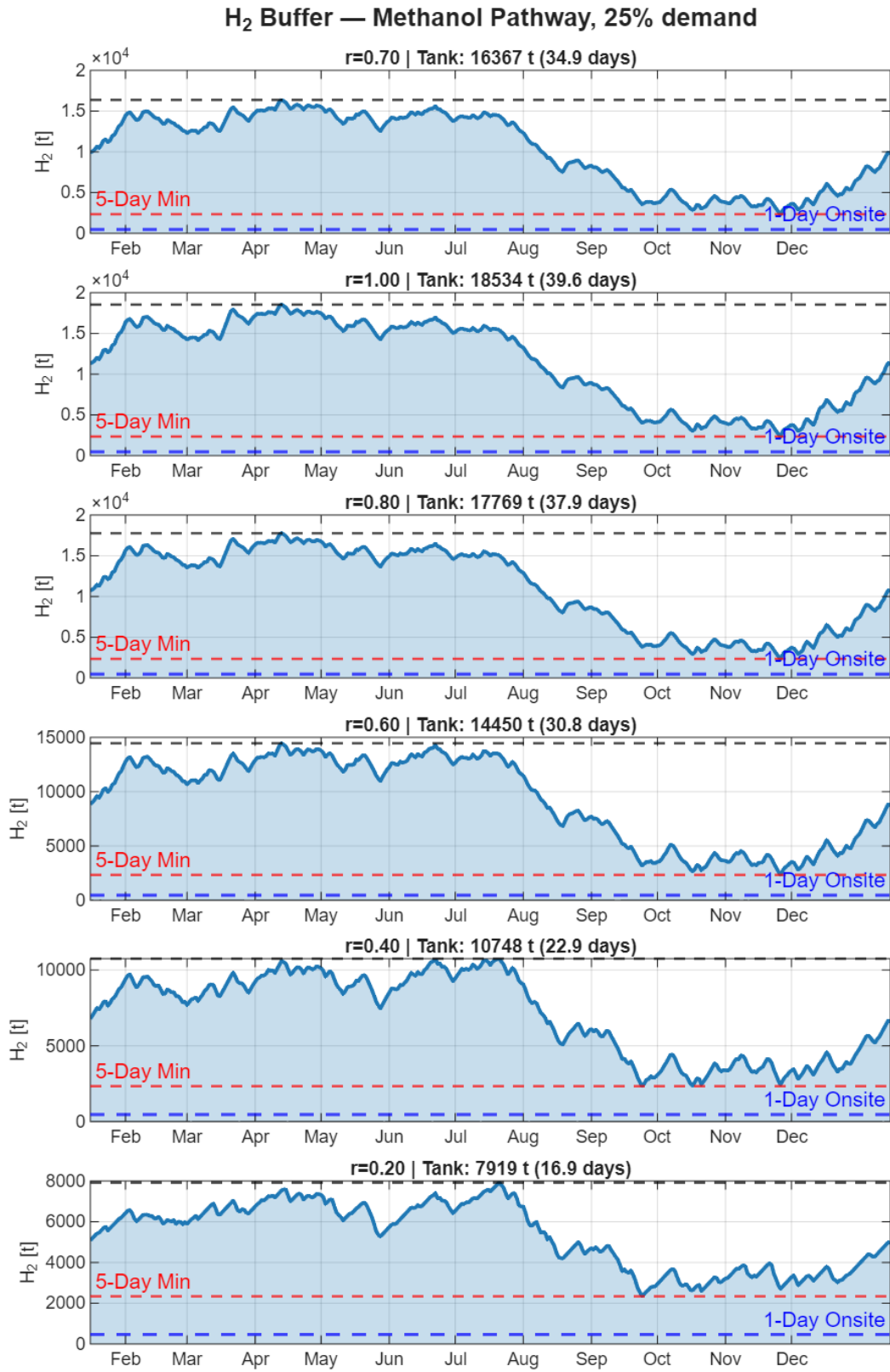


Figure C.9: Annual hydrogen buffer tank level trajectories for Scenario A (25 % methanol).

C.6 Remaining System Trade-off Sweeps

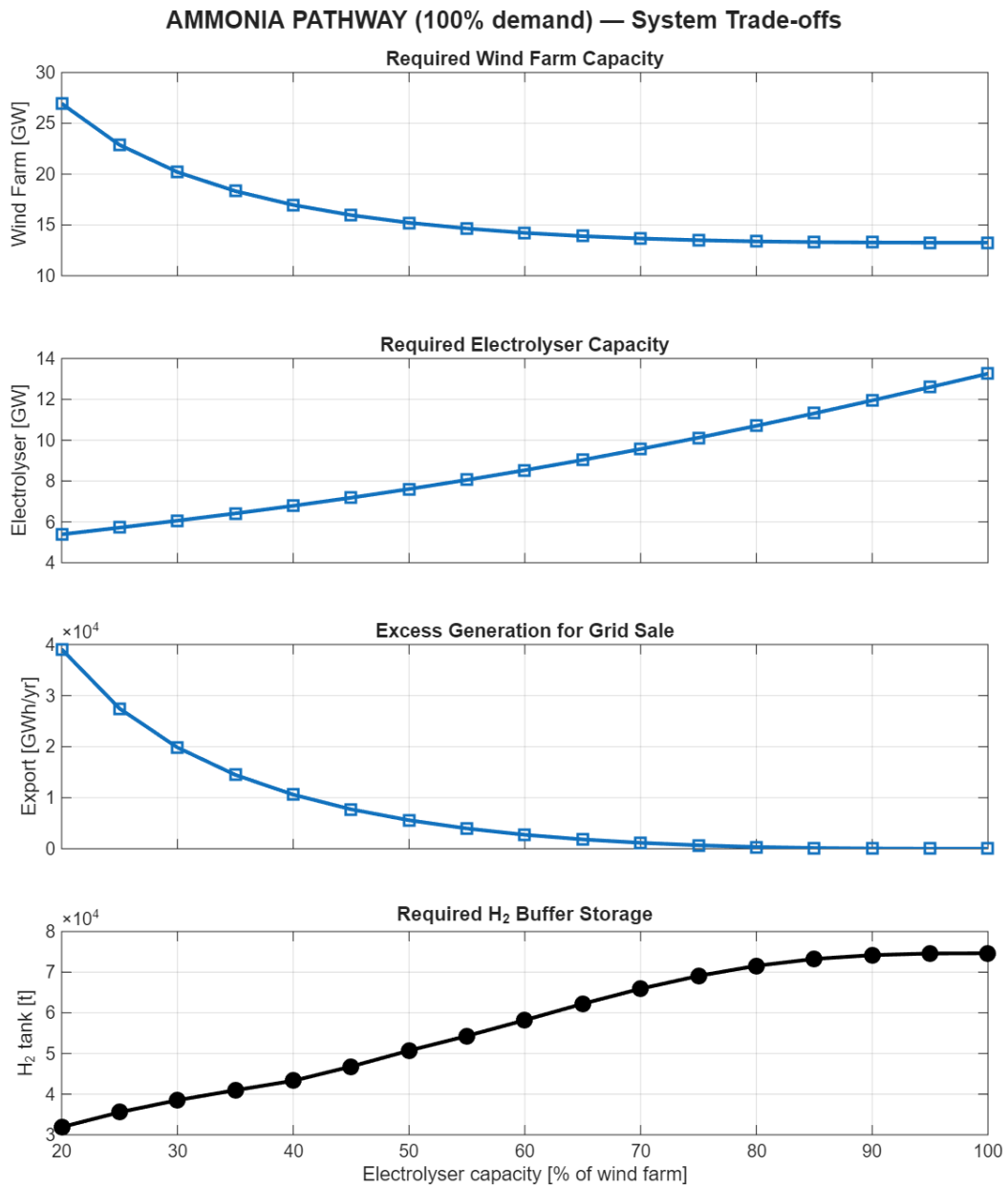


Figure C.10: System trade-off sweep for Scenario D (100 % ammonia).

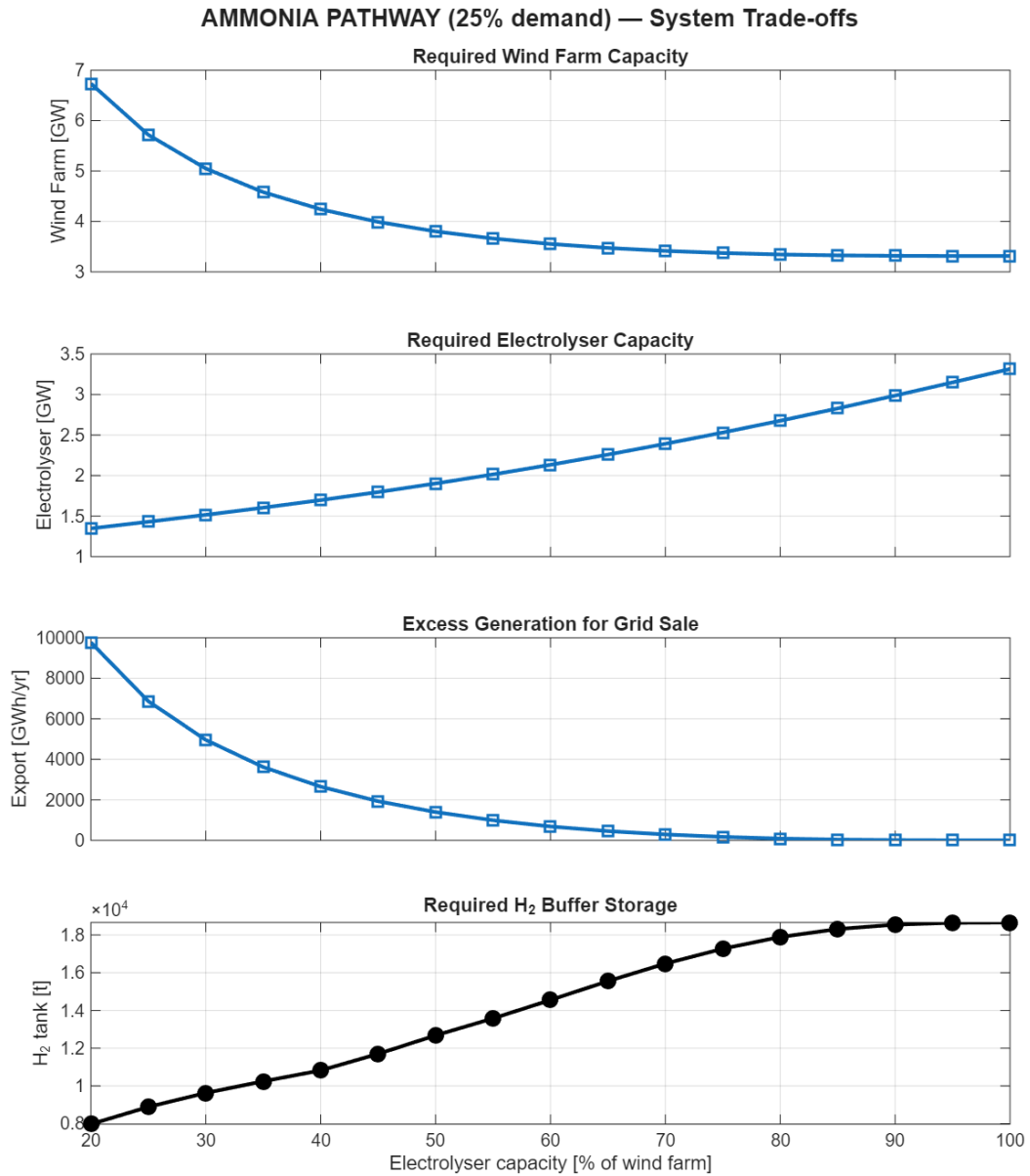


Figure C.11: System trade-off sweep for Scenario B (25 % ammonia).

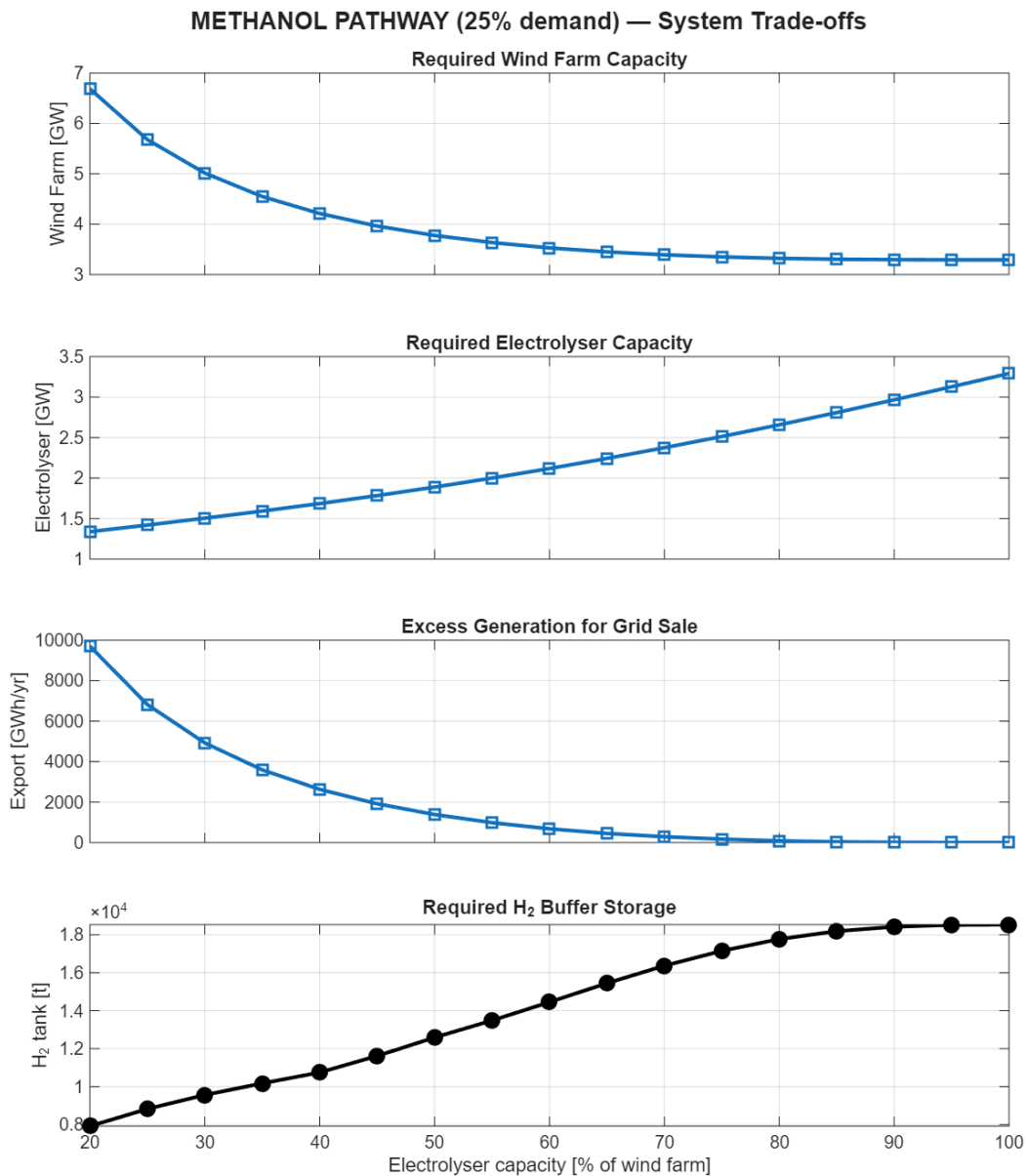


Figure C.12: System trade-off sweep for Scenario A (25 % methanol).

C.7 Land Parcel Reference Photographs

The parcels below are identified from publicly available satellite imagery for the purpose of academic feasibility screening only. They carry no property claim and no planning status, and the assessment deliberately excludes current zoning designations, municipal development plans and ongoing construction, as set out in Section 4.5.1.



Figure C.13: Central Quarry Parcel, approximately 49.52 ha. The largest contiguous undeveloped area identified, located inland with no quayside access.

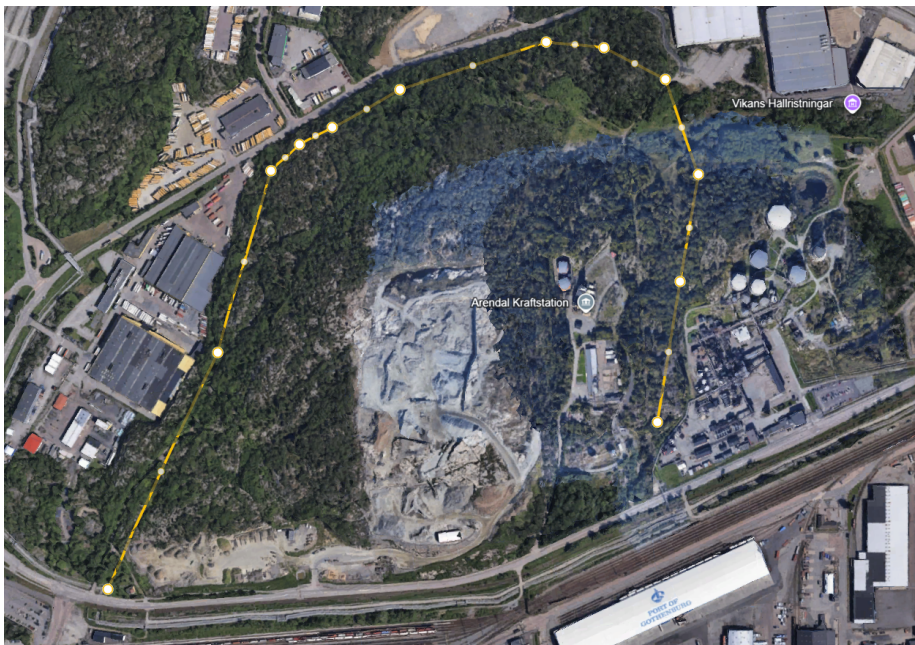


Figure C.14: Test fit of a 2 km dedicated rail spur within the Central Quarry Parcel, confirming that a capped 740 m block-train siding and its run-in and run-out allowance can be accommodated.



Figure C.15: Outer Quayside Parcel, approximately 76.63 ha, with direct quayside access but an irregular shape that restricts usable siding length.





Figure C.18: Aerial imagery of the port area, used to establish the land reclamation trend underlying the opportunistic parcel. Image credit: Lantmäteriet.



Figure C.19: Aerial imagery of the same area in 1960. Comparison with the present-day boundary gives the reclamation rate extrapolated in the opportunistic scenario. Image credit: Lantmäteriet.

C.8 Detailed Spatial Feasibility Reasoning by Scenario

Table C.12 expands the verdicts of Table 4.20 with the governing parcel, the binding component and the decentralisation pathway available in each case.

Table C.12: Spatial Feasibility Reasoning by Scenario and Hub Configuration

Scenario	Hub	Net	Gross	Governing parcel and binding component	Decentralisation pathway
A	Import	13.44	18.14	21 ha acquisition; storage at 10.25 ha is 76 % of the total	None required
A	Production	86.76	117.13	287 ha opportunistic; electrolyser 36.17 and synthesis plus DAC 38.43	Relocating the electrolyser leaves 50.59 net; also moving DAC leaves 38.05
B	Import	20.63	27.85	21 ha acquisition at net, 50 ha quarry at gross; the 50 m setback drives berth and siding	None required
B	Production	69.36	93.64	77 ha outer quayside at net, 287 ha at gross; electrolyser 36.42 and Haber–Bosch 17.74	Relocating the electrolyser leaves 32.94 net, inside the 50 ha quarry parcel
C	Import	21.39	28.87	50 ha quarry; storage 13.15 and capped siding 5.18	None required
C	Production	316.61	427.42	Exceeds all parcels; methanol synthesis 103.56, electrolyser 144.67, DAC 50.16	Relocating the electrolyser leaves 171.94 net, still above the 77 ha parcel; also moving DAC leaves 121.78
D	Import	33.18	44.79	50 ha quarry; six-berth zone 7.59 and rail corridor 9.68	None required
D	Production	240.74	324.99	287 ha opportunistic at net, exceeds all parcels at gross; Haber–Bosch 70.97 and electrolyser 145.68	Relocating the electrolyser leaves 95.06 net, inside the 287 ha parcel and above the 77 ha parcel

All areas in hectares. Every ammonia verdict is conditional on site-specific vapour-dispersion modelling.

C.9 Full Sensitivity Sweeps

This section gives the complete numerical output of the sweeps summarised in Section 4.6, including the quantities that change no feasibility verdict and are therefore not reported individually in the main text. All scalar sweeps are run at the 25 % demand level, so the reference values are 86.76 ha and 13.36 TWh/yr for Scenario A and 69.36 ha and 10.53 TWh/yr for Scenario B.

C.9.1 Direct Air Capture

Table C.13: Direct Air Capture Space Factor Sweep, Scenario A Production Hub

s_{dac} ($\text{m}^2/(\text{t CO}_2/\text{yr})$)	DAC area (ha)	Sc-A net total (ha)
0.002 (most compact reported)	0.25	74.47
0.10 (baseline)	12.54	86.76
0.56 (Climeworks Orca)	70.22	144.44
1.33 (Climeworks Mammoth)	166.77	240.99
2.00 (largest reported)	250.78	325.00

Table C.14: Direct Air Capture Specific Energy Sweep, Methanol Pathway

E_{dac} (kWh/t CO_2)	DAC load (MW)	Sc-A energy total (TWh/yr)
769 (low)	110.10	11.02
2 639 (baseline)	377.75	13.36
4 006 (high)	573.44	15.07
The parameter reaches no footprint term.		

C.9.2 Production-Hub Scalar Sweeps

Table C.15: Complete Production-Hub Sensitivity Sweep at 25 % Demand

Parameter	Value	Sc-B (ha)	Sc-A (ha)	Sc-B (TWh)	Sc-A (TWh)
Haber–Bosch space (m^2/tph)	1 593	69.36	86.76	10.53	13.36
	3 966	95.76	86.76	10.53	13.36
	6 339	122.22	86.76	10.53	13.36
MeOH synthesis space (m^2/tph)	1 500	69.36	76.49	10.53	13.36
	2 487	69.36	86.76	10.53	13.36
	4 000	69.36	102.51	10.53	13.36
DAC space ($\text{m}^2/(\text{t}/\text{yr})$)	0.002	69.36	74.47	10.53	13.36
	0.10	69.36	86.76	10.53	13.36
	0.56	69.36	144.44	10.53	13.36
	1.33	69.36	240.99	10.53	13.36
	2.00	69.36	325.00	10.53	13.36
Buffer duration (days)	7	69.36	86.76	10.53	13.36
	14	70.02	87.53	10.53	13.36
	30	73.90	89.96	10.53	13.36

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Table C.15 continued from previous page

Parameter	Value	Sc-B (ha)	Sc-A (ha)	Sc-B (TWh)	Sc-A (TWh)
	90	86.11	92.04	10.53	13.36
Yield factor (–)	0.85	76.20	95.76	12.20	15.60
	0.95	71.28	89.32	11.03	14.03
	1.00	69.36	86.76	10.53	13.36
Vessel packet scale (–)	0.072	64.42	80.51	10.53	13.36
	0.50	66.81	83.54	10.53	13.36
	1.00	69.36	86.76	10.53	13.36
NH ₃ fill fraction (–)	0.820	69.56	86.76	10.53	13.36
	0.875	69.36	86.76	10.53	13.36
Max NH ₃ tank (m ³)	60 000	69.36	86.76	10.53	13.36
	100 000	67.75	86.76	10.53	13.36
	181 458	65.82	86.76	10.53	13.36
DAC specific energy (kWh/tCO ₂)	769	69.36	86.76	10.53	11.02
	2 639	69.36	86.76	10.53	13.36
	4 006	69.36	86.76	10.53	15.07
ASU specific energy (MWh/t)	0.114	69.36	86.76	10.53	13.36
	0.311	69.36	86.76	10.72	13.36
MGO density (kg/m ³)	810	69.36	86.76	10.53	13.36
	850	69.36	86.76	10.53	13.36
	890	69.36	86.76	10.53	13.36

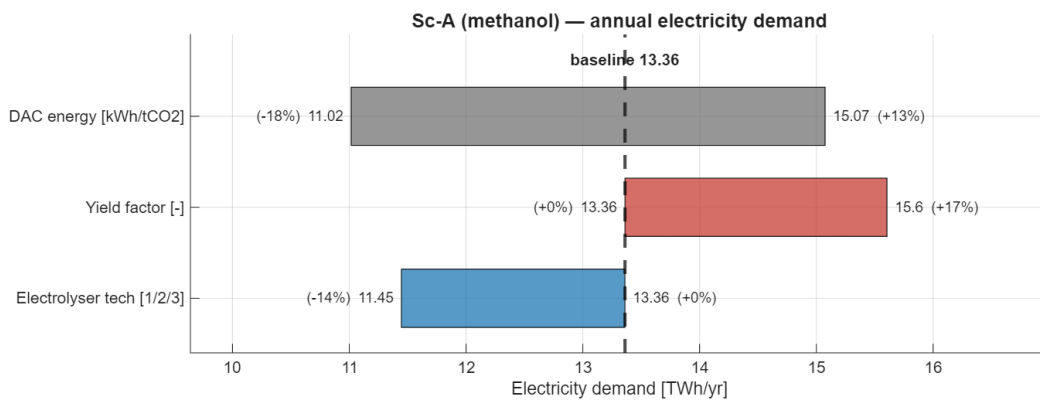


Figure C.20: Tornado plot of the Scenario A annual electricity demand. Three parameters reach the energy balance: the yield factor, the DAC specific energy and the electrolyser technology.

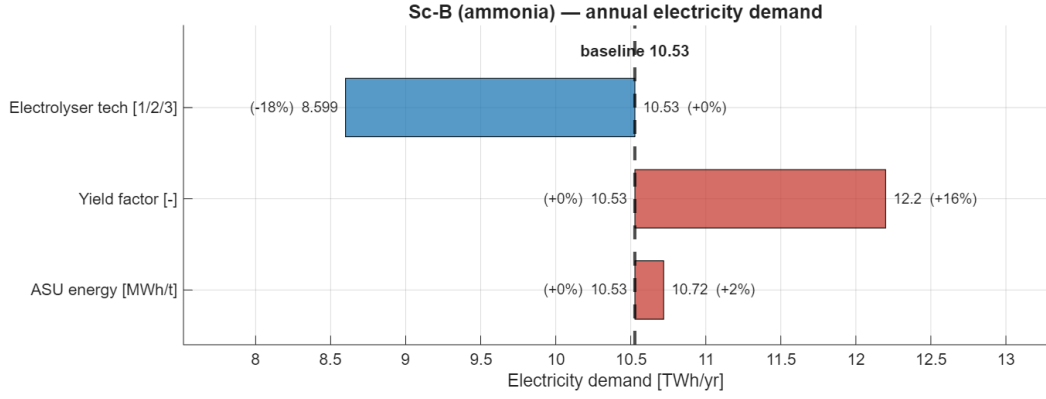


Figure C.21: Tornado plot of the Scenario B annual electricity demand. The ASU specific energy is the only ammonia-specific parameter that reaches it, and it moves the total by less than 2 %.

C.9.3 Gross-to-Net Packing Allowance

The thresholds at which each configuration crosses a parcel boundary are given in Section 4.6.4. The full sweep follows.

Table C.16: Sensitivity of Aggregated Footprints to the Gross-to-Net Packing Factor (ha)

f_{pack}	Sc-A	Sc-B	Sc-C	Sc-D
Option 1, import hub				
1.00	13.44	20.63	21.39	33.18
1.35 (baseline)	18.14	27.85	28.87	44.79
1.50	20.16	30.94	32.08	49.77
2.00	26.88	41.25	42.77	66.36
2.50	33.60	51.57	53.47	82.95
Option 2, production hub				
1.00	86.76	69.36	316.61	240.74
1.35 (baseline)	117.13	93.64	427.42	324.99
1.50	130.14	104.00	474.90	361.10
2.00	173.52	138.73	633.21	481.47
2.50	216.90	173.41	791.52	601.84

C.9.4 Renewable Supply Profile

Under continuous supply the capacity factor is unity, the electrolyser is sized precisely to average daily hydrogen demand, and no buffer beyond the 5-day operational reserve is required.

Table C.17: Intermittent SE3 Wind Against Continuous Supply (25 % demand)

Parameter	Sc-A (MeOH)		Sc-B (NH ₃)	
	Wind ($r = 0.70$)	Continuous	Wind ($r = 0.70$)	Continuous
Effective electrolyser capacity factor	0.452	1.000	0.452	1.000
Electrolyser capacity (GW)	2.37	1.07	2.39	1.08
Electrolyser area (ha)	36.17	16.35	36.42	16.46
Total H ₂ buffer (t)	16 367	2 342	16 481	2 359
Buffer duration (days)	34.9	5.0	34.9	5.0
Off-site LRC cavern volume (Mm ³)	1.02	0.15	1.03	0.15
On-site sphere array (ha)	1.13	1.13	1.13	1.13
Annual electricity demand (TWh/yr)	13.36	13.36	10.53	10.53
Net onshore footprint (ha)	86.76	66.94	69.36	49.41

The buffer result is the quantity most exposed to this assumption. The 34.9-day requirement is a property of a wind-only supply with no firm component, and the 5-day floor is what a fully firm supply would require. Any intermediate portfolio, including the solar contribution excluded in Section 3.6.4, would fall between the two.

C.9.5 Storage, Yield and Secondary Parameters

Four parameters move the totals within their documented ranges without changing a production-hub tier.

Extending the e-fuel safety buffer from 7 to 90 days raises the Scenario A import hub from 13.44 to 18.72 ha and the Scenario D import hub from 33.18 to 85.12 ha. A stockholding obligation of the IEA type, were e-fuels classified as petroleum substitutes, would therefore move the Scenario D import hub past the 77 ha Outer Quayside Parcel while leaving the 25 % scenarios inside the acquisition threshold. The response is not monotonic, because tank count is an integer: the Scenario A total falls from 16.64 ha at 30 days to 14.59 ha at 45 days, where an additional tank reduces the per-tank diameter and squares up the array, and the Scenario C total falls from 21.39 to 20.82 ha between 7 and 14 days for the same reason. This is the stepped behaviour anticipated in Section 3.6.1 and not a numerical artefact.

Reducing the stoichiometric yield from 1.00 to 0.85 inflates every upstream quantity in proportion, raising the Scenario A production hub from 86.76 to 95.76 ha and its energy demand from 13.36 to 15.60 TWh/yr, and the Scenario B hub from 69.36 to 76.06 ha and 10.53 to 12.20 TWh/yr. Because the baseline is the stoichiometric limit, this sweep is one-sided: every reported upstream quantity is a lower bound.

Reducing the vessel packet to roughly one fourteenth of the reference carrier cuts the Scenario A import hub from 13.44 to 7.23 ha and the Scenario B import hub from 20.63 to 15.70 ha. The effect is much weaker at full replacement, where Scenario D falls only from 33.18 to 31.41 ha, because the seven-day buffer rather than the delivery parcel then dominates the working volume.

Raising the maximum ammonia tank volume from 60 000 to 181 458 m³ lowers the Scenario B production hub from 69.36 to 65.82 ha, and relaxing the fill fraction from 0.875 to 0.82 raises it only to 69.56 ha. Varying the reference MGO density across its 810 to 890 kg/m³ range leaves every footprint and every energy total unchanged. Varying the ASU specific energy from 0.114 to 0.311 MWh/t raises the Scenario B energy total from 10.53 to 10.72 TWh/yr and reaches no footprint. The last two are reported as null results rather than omitted.

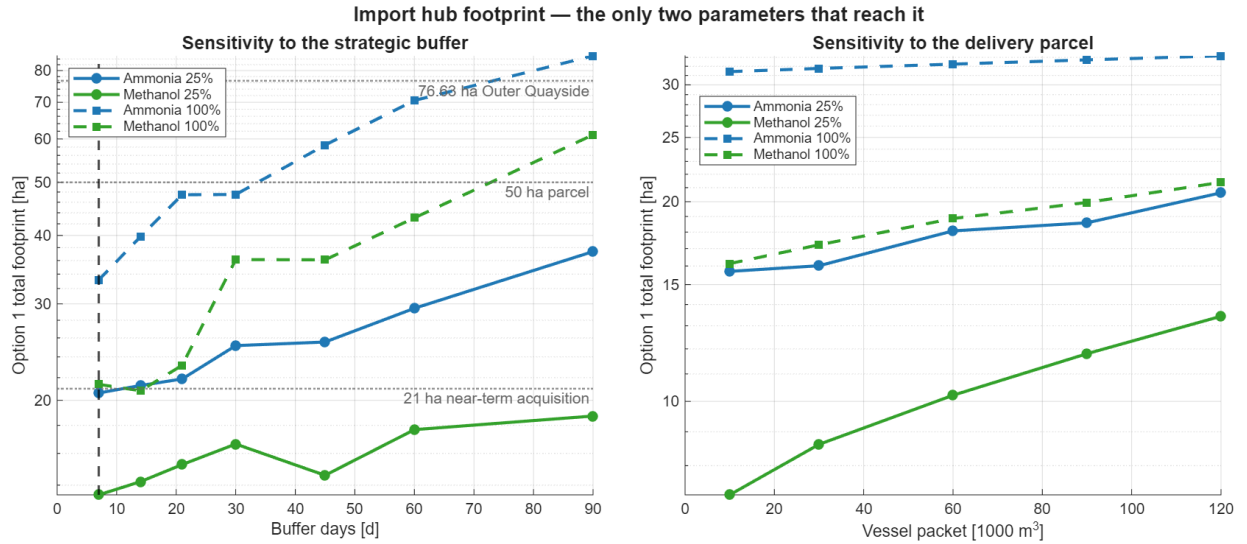


Figure C.22: Import-hub net footprint as a continuous function of the two storage parameters that reach it: the strategic buffer duration (left) and the delivery vessel packet (right), for all four scenarios. The steps and reversals in the buffer panel are tank-count transitions.

Table C.18: Import-Hub Net Footprint Against Strategic Buffer Duration (ha)

Scenario	7 d	14 d	21 d	30 d	45 d	60 d	90 d
A (MeOH, 25 %)	13.44	14.21	15.26	16.64	14.59	17.68	18.72
B (NH ₃ , 25 %)	20.63	21.28	21.88	25.17	25.55	29.44	37.38
C (MeOH, 100 %)	21.39	20.82	23.17	36.14	36.10	43.07	61.06
D (NH ₃ , 100 %)	33.18	39.79	47.46	47.51	58.50	70.55	85.12

The reversals are tank-count transitions; see Section 3.6.1.

Table C.19: Import-Hub Net Footprint Against Delivery Vessel Packet (ha)

Scenario	0.072×	0.25×	0.50×	0.75×	1.00×
A (MeOH, 25 %)	7.23	8.62	10.22	11.80	13.44
B (NH ₃ , 25 %)	15.70	16.01	18.07	18.59	20.63
C (MeOH, 100 %)	16.13	17.22	18.87	19.95	21.39
D (NH ₃ , 100 %)	31.41	31.76	32.24	32.72	33.18

Expressed as a fraction of the reference carrier packet of Table 4.1.

C.9.6 Bunker Transfer Rate

The number of transfer positions is a ceiling function of the sustained transfer rate, so the sweep resolves into a small number of discrete steps.

Table C.20: Sensitivity of the Bunkering Interface to the Sustained Transfer Rate

Q_{bkr} (m ³ /hr)	Sc-A	Sc-B	Sc-C	Sc-D
Transfer positions (–)				
500 (baseline)	2	2	5	6
1 000	1	1	3	3
2 000	1	1	2	2
Option 1 net total (ha)				
500 (baseline)	13.44	20.63	21.39	33.18
1 000	13.05	19.36	20.61	29.39
2 000	13.05	19.36	20.22	28.12

Raising the sustained rate from 500 to 1 000 m³/hr halves the berth count in every scenario and removes 3.79 ha from the Scenario D import hub, the largest single effect of any distribution parameter on that total. No feasibility verdict changes across the range, because the quayside interface is a small share of every aggregate. The constraint the interface imposes is on frontage rather than on area: at the baseline rate Scenario D requires six positions and 1 800 m of quay, and frontage, unlike area, cannot be relieved by moving the asset inland.

C.9.7 Terminal Operating Mode: Trajectory Detail

The peak inventories under the two operating modes are compared in Table 4.23. This section sets out why they diverge in opposite directions at the two demand levels.

At the 25 % level the continuous-offtake peak falls well below the batch-export value, by 62.9 % in Scenario A and 43.1 % in Scenario B. The static formula carries a full vessel

packet, and a terminal drawing its inventory down continuously never receives one as a single event, so the packet term overstates the requirement where bunkering rather than transshipment is the governing operation.

At full replacement the relationship reverses, and the cause is the delivery calendar rather than the offtake. The 240 operating days are taken as five-day weeks falling within the first 48 weeks of the year, so the last land-side delivery falls on day 334 and the closing 31 days run on pipeline inflow alone while the offtake continues. The resulting drawdown reaches $145\,810\text{ m}^3$ in Scenario D against an $87\,000\text{ m}^3$ packet and becomes the governing event. Scenario C stays 1.5 % below its own crossover, with a drawdown of $118\,202\text{ m}^3$ against a $120\,000\text{ m}^3$ packet, which is why its two peaks agree to within 0.1 %.

That interruption is set by how the non-operating weeks are arranged rather than by how much fuel the terminal handles. Spreading them through the year would shorten it to roughly nine days and return the continuous-off-take peak below the batch-export value in every scenario. The single closing block adopted here is the conservative arrangement, and the operating calendar is a modelling choice rather than a property of the port (Appendix B, Section B.4).

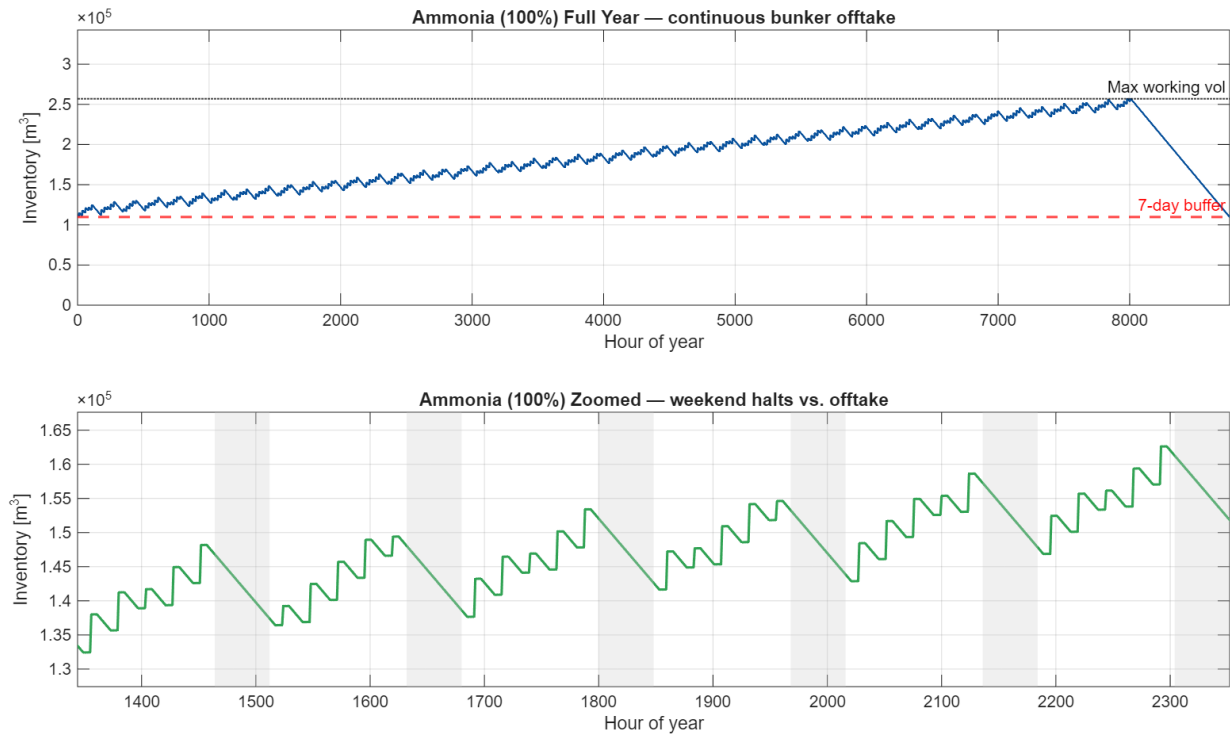


Figure C.23: Simulated 8 760-hour inventory trajectory for Scenario D under the continuous-offtake operating mode. Upper panel: accumulation across the 48 operating weeks and the closing drawdown that sets the peak. Lower panel: six-week zoom showing weekend halts in rail and road reception (grey bands) against continuous pipeline inflow and offtake.

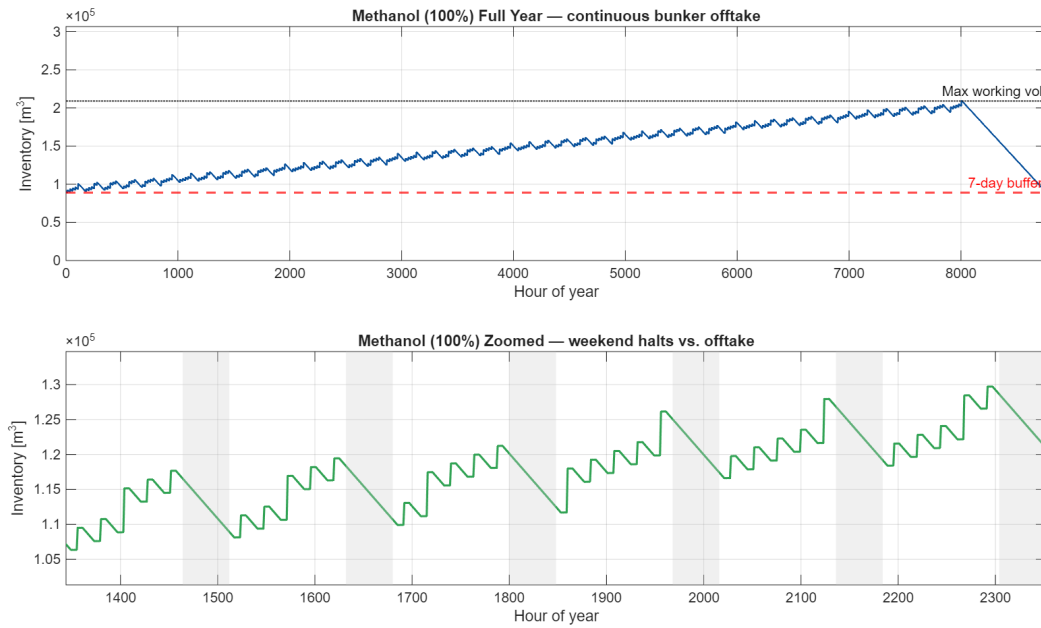


Figure C.24: Simulated 8 760-hour inventory trajectory for Scenario C under the continuous-offtake operating mode. The structure matches Scenario D, but the closing drawdown of 118 202 m³ remains below the 120 000 m³ vessel packet, so the simulated peak of 209 078 m³ agrees with the static working volume to within 0.1 %.

C.9.8 Logistics Modal Split

Table C.21: Import-Hub Footprint by Modal Split, Net and Gross (ha)

Allocation	Sc-A		Sc-B		Sc-C		Sc-D	
	Net	Gross	Net	Gross	Net	Gross	Net	Gross
70 / 20 / 10 (baseline)	13.44	18.14	20.63	27.85	21.39	28.88	33.18	44.79
100 / 0 / 0	11.03	14.89	14.07	19.00	15.10	20.39	20.97	28.31
50 / 25 / 25	14.22	19.20	22.24	30.02	22.36	30.19	44.93	60.66
0 / 100 / 0	16.22	21.90	33.44	45.14	35.83	48.37	69.39	93.68
0 / 0 / 100	13.11	17.70	18.67	25.20	22.44	30.29	35.23	47.56
<i>Invariant components (net, ha)</i>								
Fuel storage	10.25		11.54		13.15		13.38	
Ship berths	0.78		2.53		1.95		7.59	

Table C.22: Land-Side Reception Requirements by Modal Allocation

Sc.	Allocation	Wagons	Trains/yr	Arr./op-day	Platforms	Truck bays	Land-side (ha)
A	70 / 20 / 10	12	238	0.99	1	1	2.41
A	50 / 25 / 25	15	238	0.99	1	3	3.19
A	0 / 100 / 0	37	369	1.54	1	0	5.18
A	0 / 0 / 100	–	–	–	0	9	2.08
B	70 / 20 / 10	17	238	0.99	1	1	6.56
B	50 / 25 / 25	21	238	0.99	1	3	8.17
B	0 / 100 / 0	37	515	2.15	2	0	19.37
B	0 / 0 / 100	–	–	–	0	10	4.60
C	70 / 20 / 10	37	296	1.23	1	4	6.29
C	50 / 25 / 25	37	369	1.54	1	9	7.26
C	0 / 100 / 0	37	1 476	6.15	4	0	20.74
C	0 / 0 / 100	–	–	–	0	36	7.34
D	70 / 20 / 10	37	412	1.72	1	4	12.21
D	50 / 25 / 25	37	515	2.15	2	10	23.97
D	0 / 100 / 0	37	2 059	8.58	5	0	48.42
D	0 / 0 / 100	–	–	–	0	38	14.26

Land-side is the sum of the rail corridor and truck station safety zones; adding the invariant storage and berth components of Table C.21 gives the net totals reported there.

D

Model Implementation

The calculation chain is implemented as a single MATLAB script, `efuel_terminal_sizing.m`, which also contains the curve fits of Appendix B.2. All parameters are declared in one block at the top and every derived quantity follows from them, so the chain below is not edited between runs. The script runs once per demand level and computes both fuels in each pass, so the four scenarios come out of two runs.

The reported results use the PEM electrolyser, the wind profile, batch-export terminal operation and a rail siding fitted to the required train length. Switching any of these, or the demand level of the sensitivity analysis, is done in the configuration block alone. Every sensitivity run re-derives the configuration and re-runs the identical chain rather than scaling a finished result.

The script is available at <https://github.com/ResearcherLXH/Master-thesis-on-e-fuel-infrastructure-in-ports>¹¹⁰.



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