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TNO report

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Power-2-Fuel Space requirements

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Contents

1 Introduction

The Climate Agreement and the associated CO_2-reduction goals will have a major impact on mobility and associated sectors such as the chemical sector (e.g. refineries) and all connected value chains. All stakeholders involved in these sectors have to achieve a significant CO_2 emission reduction. Part of this required reduction will be absorbed by increasing electrification (e.g. of passenger cars). However, it is expected that heavy transport such as long-distance road transport, shipping and aviation cannot be electrified so easily. Instead they may continue to be powered by combustion engines, which are fuelled by (an increasing share of) renewable fuels. Such (close to) climate neutral fuels will have to be produced, stored and distributed for these transport modes. This report studies the impact of the production and storage of such fuels in the Netherlands as input to a wider assessment on the feasibility of various synthetically produced renewable fuels as a means to reduce CO_2 emissions in the Dutch transport sector.

Today most of the conventional fuels are produced and bunkered in the Rotterdam harbour. With the planned wind capacity and CO_2 storage at the North Sea, the Rotterdam harbour can play an important role in the transition to e-fuels or power-to-fuels in the Netherlands. A preliminary study focussed on the production of e-methanol has shown that this transition has a big impact on the further development of the Rotterdam harbour regarding the required space and future facilities and services for both the production and import of e-fuels.

In order to further determine the impact of the transition to e-fuels on the Rotterdam harbour, additional information is required. SmartPort has asked TNO to provide additional analysis regarding the required wind capacity on the North Sea, the required space and the required fuel storage capacity for the future production of e-fuels to make a first sketch of the Rotterdam harbour in 2050. The output of this analysis will be included in a TNO White Paper on e-fuels to be published later in 2020.

2 Energy demand and impact on North Sea capacity

Production of e-fuels requires a large amount of electricity from renewable sources. For the Netherlands, offshore wind is expected to be the major source. In this chapter the demand for electricity for production of e-fuels for transport in the Netherlands will be compared with the potential of electricity production from offshore wind at the Dutch continental shelf.

2.1 Energy demand for e-fuels

Energy demand for national and international transport together in the Netherlands was about 1200 PJ in 2017 and is forecasted to stay at this level towards 2050 (see Figure 1[1]).

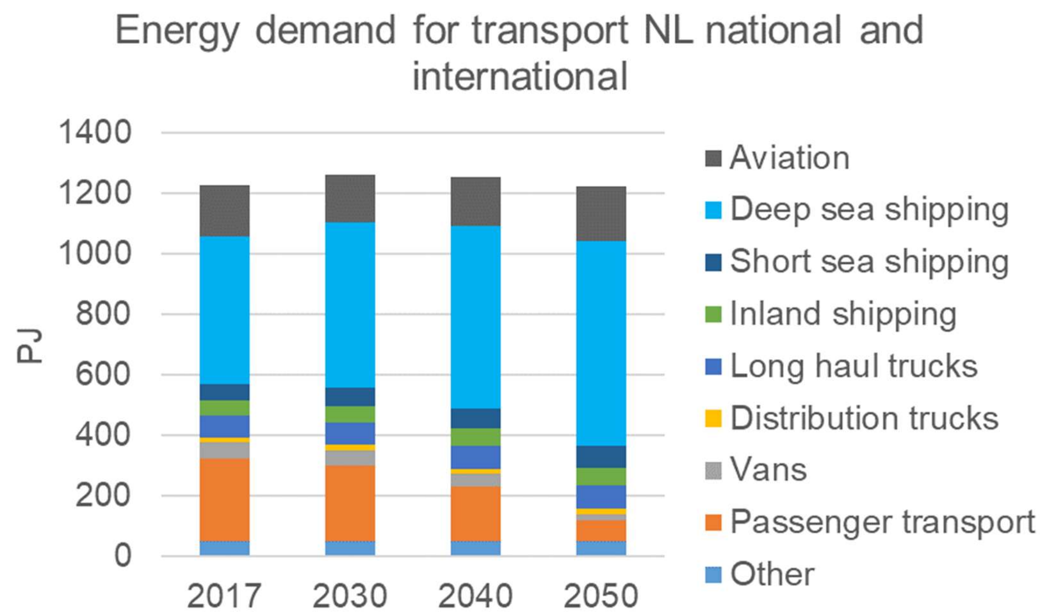

Figure 1 Energy demand forecast[1] for national and international transport (fuelled/bunkered in NL)

Currently almost all energy is supplied in the form of fuels from fossil sources. A transition to battery electric vehicles (BEVs) is already taking place in passenger transport and BEVs will also be the preferred solution for lighter duty vehicles (like vans, small trucks) and shorter distances (regional transport), since the efficiency of electric drivetrains is much better than that of fuel engines. For the long haul transport modalities, like long haul trucks, maritime and aviation, sustainable fuels will be required.

Production of e-fuels will lead to a large demand for electricity from renewable sources. For 2050 a fuel demand for international transport modes of 960 PJ is forecasted. When these fuels are produced as e-methanol for trucks and maritime (with a production efficiency of 49%) and kerosene for aviation (with a production

[1] Based on fuel demand data from Nederlandse Energieverkenning 2017 and the EU reference scenario 2016 from JRC; Energy, transport and GHG emissions: trends to 2050. Joint Research Centre (European Commission).

efficiency of 46%), about 2000 PJ of electricity is required to produce this 960 PJ of fuels.

2.2 Potential of offshore wind at the Dutch Continental Shelf

2.2.1 Currently assumed potential

Several studies have been conducted to offshore wind potential of the Dutch North Sea. In most studies a maximum of 60 GW, or sometimes 75 GW is used.
In a recent study from PBL (Planbureau voor de Leefomgeving), “De toekomst van de Noordzee”[2], four scenarios were defined. In the most sustainable scenario, a capacity of 60 GW in 2050 is used. In this scenario, between 17% and 26% of the Dutch continental shelf, including international nature network areas, passive fishery and passage of small vessels is used for wind parks, see **Error! Reference source not found.**. In case an average energy density of windmills of 6 MW per km^2 is used, footprint will be 17% of the continental shelf; a lower energy density of 4 MW per km^2 leads to a footprint of 26%.

[2] Planbureau voor de Leefomgeving, De toekomst van de Noordzee - De Noordzee in 2030 en 2050: een scenariostudie, 2018.

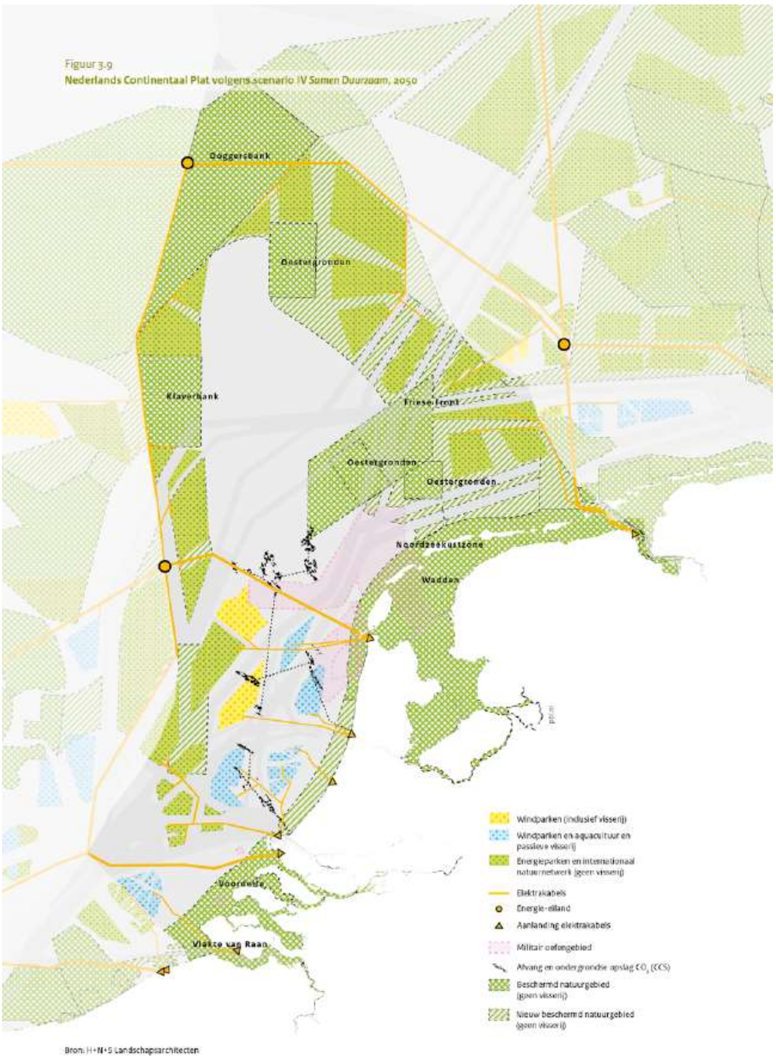

Figure 2 Use of the Dutch Continental Shelf in the PBL scenario “Samen Duurzaam” in 2050. Source: De toekomst van de Noordzee. De Noordzee in 2030 en 2050: een scenariostudie. Planbureau voor de Leefomgeving 2018.

According to PBL an installed capacity of 60 GW delivers 250 Terawatthours, or 900 PJ of electricity. This is based on an efficiency of 48% of maximum capacity of the windmills.

2.2.2 Upward potential scenarios

A number of parameters determine the amount of electricity that can be produced from offshore wind on the Dutch continental shelf:

- the energy density of windmills in MW/km^2
- the capacity factor (the energy production in % of maximum capacity of windmills)
- the percentage of the Dutch continental shelf that is used for offshore wind

There are reasons to believe that the Dutch North Sea has a potential for offshore wind energy that is significantly higher than the 900 PJ in the most optimistic PBL scenario.

The energy density of windmills applied by PBL is 4 to 6 MW per km^2 , combined with a capacity factor of 48%. As PBL states in its report, the Gemini wind parks have an energy density of almost 9 MW per km^2. Technical developments may lead to even higher energy densities. The same holds for the capacity factor: better design of rotor blades and higher towers will result into higher capacity factors. Also wind profiles are smoother when parks are built further from coast. At the same time, a higher energy density is assumed to have a negative impact on the capacity factor, because windmills will impact the wind profile of other windmills in their surrounding negatively (“wake effect”).

The share of the Dutch continental shelf that is used for offshore wind depends on regulation and political choices. Areas are used for military exercise, shipping, fishery and nature. Multipurpose use of areas may lead to a larger area for offshore wind. Because the depth of the Dutch North Sea is below 55 meter, the whole area is technically suitable for offshore wind.

In **Error! Reference source not found.** a number of scenarios (S1 to S4, besides the PBL 60 GW scenarios) are presented with different combinations of installed capacity, energy density, capacity factor and percentage of North Sea area use. Installed capacity and energy density are used to calculate the resulting North Sea are use. Energy delivered is derived from installed capacity and capacity factor.

Table 1 Scenarios for the potential of offshore wind at the Dutch Continental Shelf

	PBL	**PBL**	**S1**	**S2**	**S3**	**S4**
Installed capacity (GW)	60	60	120	150	120	200
Energy density (MW/km^2)	4	6	6	7,5	7,5	10
Capacity factor	48%	48%	60%	55%	55%	50%
North Sea area use	26%	17%	34%	34%	28%	34%
Energy delivered (TWh)	250	250	631	723	578	876
Energy delivered (PJ)	900	900	2271	2602	2081	3154

From the table it becomes clear that, when higher energy densities, capacity factors and percentage of North Sea area use are assumed, there is an upside potential to more than 2000 PJ electricity production per year (S1 to S3) and more than 3000 PJ in the most optimistic scenario (S4).

2.3 Conclusions

If the scenarios presented above come within reach, enough electricity can be produced with offshore wind at the Dutch Continental Shelf to meet the forecasted demand for e-fuels of 960 PJ in 2050, that requires 2000 PJ of electricity. Conditions to realise these scenarios are:

- technical developments to realise higher energy densities, combined with higher capacity factors and
- enough North Sea area becoming available for offshore wind.

Besides the transport sector, there are other sectors that also have a need for electricity. In a forecast by TNO, energy demand for Dutch industry, built environment, agriculture and national mobility is estimated at ~ 1900 PJ, of which ~520 PJ is electricity (for direct use and power-2-heat). That leads to a total electricity demand of ~2500 PJ. In case electricity from offshore wind is not sufficient to fulfil this demand, also electricity from other renewable sources, like onshore wind and solar energy, need to be used to fulfil this demand.

3 Space requirements

For 2050 a fuel demand for international transport modes of 960 PJ is forecasted for the Netherlands. Various types of e-fuels could potentially be applied in the future. In the Power-2-Fuel Cost Analysis study[3] several e-fuel types were considered such as green hydrogen, e-methanol, e-diesel, e-ammonia and e-methane. In this study e-methanol was selected for which we will determine the space needed to fulfil the required capacity of e-fuels in the Netherlands in 2050.

E-methanol (CH_3OH) is produced from green hydrogen, CO_2 and electricity. For the production of e-methanol different processes are possible. The process that has been chosen in the Power-2-Fuel Cost Analysis study[3] is CO_2 hydrogenation. It has been chosen to realise circularity, which can be achieved by acquiring CO_2 from biomass or DAC (direct air capture). In this study the CO_2 is acquired from DAC.

In order to correctly estimate the space required for all the facilities that need to be built for the production of e-methanol must be considered. These facilities include**:**
- Electrolysers for the production of green hydrogen;
- Direct air capture plants for CO_2 production;
- Seawater desalination plant (if large amount of water is required);
- Methanol production plants;
- Storage facilities for feed stock and intermediate products such as water, hydrogen and CO_2;
- Storage of e-fuels.

Each facility that that has been considered for the space requiremnet analysis is described in short below.

3.1 E-methanol production facilities

The following facilities for e-methanol production were used as a basis for the space requirements analysis:

<u>Methanol production plants</u>
In a conventional plant methanol is produced from syngas. Natural gas is converted at high temperatures and pressures in a steam reformer to syngas. The syngas, a mixture of hydrogen, CO, and CO_2, is further converted into methanol. The required feedstock and fuel (natural gas) is supplied from the natural gas grid.

Alternative to syngas, methanol can be produced with high selectivity by CO_2 hydrogenation with hydrogen in a gas phase process. To lower methanol processing costs alternative liquid-phase processes are developed, but they require more energy. In this study and in the Power-2-Fuel Cost Analysis study[3] the gas phase conversion was regarded. More details on the gas phase conversion process and related efficiencies can be found in Nieminen et al.[4]

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[3] Ruud Verbeek, Maarten Verbeek, Robert de Kler, Karin van Kranenburg, Richard Smokers, TNO report Power-2-Fuels Cost Analysis, 15 January 2020.
[4] Nieminen et al., CO_2 Hydrogenation to Methanol by a Liquid-Phase: Process with Alcoholic Solvents: A Techno-Economic Analysis, 2019

The required space need for a large scale methanol plant strongly depends on the capacity and the available land. The estimated footprint of a conventional methanol plant (based on the 440 kt/y BioMCM plant in the Netherlands) is 293 m^2/tph of methanol.

Electrolysers for green hydrogen production

Green hydrogen (H_2) is made from green electricity and H_2O (water). The water is split into H_2 (hydrogen) and O_2 (oxygen) by using a PEM electrolyser. An efficiency of the PEM electrolyser of 64% was used.

The footprint of large scale electrolysers strongly depends on their capacity and the technology. On the market are already available large capacities of alkaline electrolysers that have a footprint ~800 m^2 for a capacity in the range of 2400-3900 Nm^3/h (0.25 $m^2/Nm^3/h$). Figure 3 shows that smaller capacity alkaline electrolysers, between 50 and 500 Nm^3/h, will have a footprint between 150 and 225 m^2 (1.5 - 0.89 $m^2/Nm^3/h$). PEM electrolysers have a much smaller footprint ranging from 0.11 $m^2/Nm^3/h$ for 5MW plants to 0.07 $m^2/Nm^3/h$ for 300MW[5]. However electrolysers are not yet build at GW scale and the footprint can also be reduced by stacking of electrolysers in buildings (see Figure 4), so in future both the footprint and required space needed for electrolysers will be much lower.

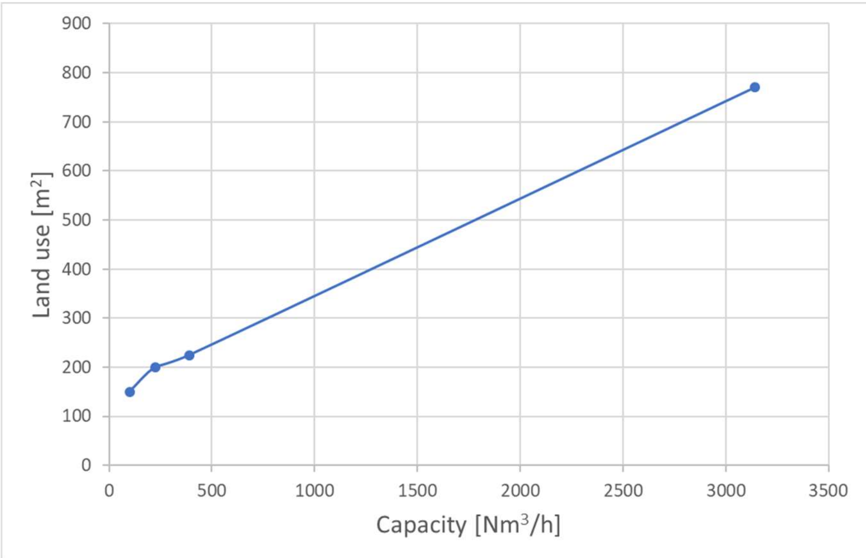

Figure 3 Footprint of Nel Hydrogen alkaline electrolysers as a function of their capacities

[5] https://www.hydrogenics.com/wp-content/uploads/HyLYZER_600_3MW.pdf

Figure 4 Vemork hydroelectric power plant in 1935 with H_2 production plant (front building)

Direct air capture plants for CO_2 production

Mainly for economic reasons, direct air capture (DAC) facilities are far from large scale implementation. The financial target in the upcoming years is to drop the costs from 600 dollars per ton of CO_2 captured to less than 100 dollars per ton of CO_2. It is expected that large scale DAC systems will be commercially available after 2030[6]. The table below summarizes the footprint parameters of various DAC processes.

Table 2 Specific footprint of various DAC processes (source: Viebahn, Energies, 2019). Energy generation plants are not included in these calculations.

Parameters	**Unit**	**DAC: high temp**		**DAC: low temp**			
		APS	**Carbon Engineering**	**Clime-Works**	**Clime-Works**	**Lackner**	**Global Thermostat**
Total	km^2	9	>0,0016	0,00009		3×10^{-5}	
Reference value	Mt CO_2/year	6	0,1	0,0009		$3,65 \times 10^{-4}$	
Specific	km^2/Mt CO_2 year	1,5	>0,016	0,1	2	0,08	0,05 – 0,002

Climeworks (allied with the Dutch company Antecy) developed DAC systems that have a footprint of 0,4 km^2/Mt_{CO2}. Other companies (e.g. Global Thermostat and Carbon Engineering) declare that the footprint of their DAC system is between 0,0016 and 0,08 km^2/Mt_{CO2}, but it is not fully clear what it is considered in the calculation of those numbers.

Energy generation plants are not included in the numbers presented above. DAC plants also require high water consumption (up to 30 m^3/t CO_2).

Seawater desalination plant

If a large amount of water is required, it might not be possible to source it from the water grid. In this case, a seawater desalination plant might be necessary and must be considered in the calculation of the total space requirements.

[6] Viebahn P., The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis, Energies 2019, 12(18), p.3443.

The area required for a seawater desalination plant (including pumps and holding ponds) is about 100,000 m^2 for a plant that produces ~100 million m^3/y[7].

<u>Storage of green hydrogen</u>
For a reliable production of e-methanol a constant supply of feedstock is needed. Green hydrogen can be produced by electrolysers at moments of low electricity prices, to reduce the costs of electricity, that form the main share of the hydrogen production costs. In case of intermittent production, buffering or storage is needed.

Onshore hydrogen storage requirements have to be evaluated for each particular case and might not be needed, e.g. for blue hydrogen use cases[8]. Large scale storage is crucial for the development of the hydrogen market. Storing hydrogen in salt caverns is widely used but it cannot be applied in every region because of geological restrictions. To summarize, onshore H_2 gas storage can be realized in :

- Low pressure vessels (150 MWh);
- High pressure, ~20 bar, vessels (2250 MWh);
- High pressure, ~100 bar, tubes (4300 MWh) that are placed a couple of meters underground;
- Caverns (240,000 MWh).

Vessels can also be placed underground, even if just a couple of meters, to reduce the footprint (also for better insulation and protection from impact). But it will be more difficult to inspect the storage system and control corrosion.
Andersson (2018)[9] collected the several large scale storage options in three different categories: physical storage, adsorption and chemical storage (see figure below).

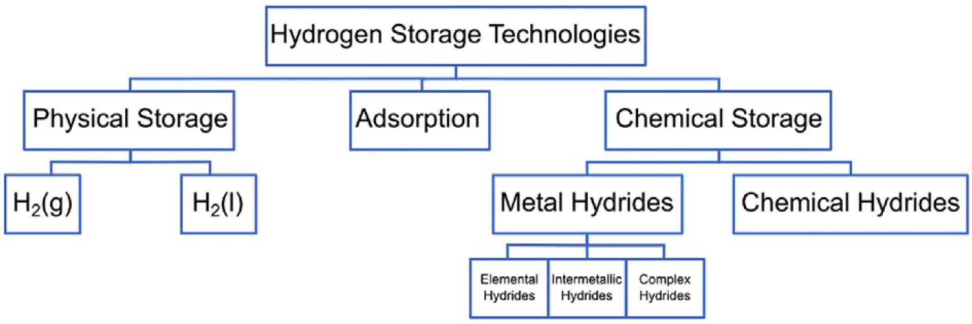

Figure 5 Categorization of hydrogen storage technologies (Source: Andersson, Int. J. Hydr. En., 44, 2019).

The size of H_2 storage tanks depends on the gas pressure. It is possible to find commercially available spherical tanks up to 50,000 liters capacity (~21 m^2 of footprint for a spherical tank of 50,000 liters).
High pressure shallow underground tubes can be long several hundred of meters (and have diameters up to ~1,5 meters) and the total length can reach up to kilometers (1 km of pipeline can store around 12 tons of hydrogen).

[7] Einav R., The footprint of the desalination processes on the environment, Desalination 152 (2002) p.141-154.
[8] Feasibility study into blue hydrogen, Delft, CE Delft, 18.9901.095, July 2018
[9] Andersson J., Large-scale storage of hydrogen, Int. J. Hydr. En., 44, p. 11901-11919, 2019

3.2 CO_2 sources and storage needs for e-methanol production

3.2.1 CO_2 comes from multiple sources

CO_2 is likely to become an important feedstock for industry in the future, with e-fuels production as one of the major uses. Green methanol is one of the most versatile and efficient alternatives for many transport modalities in the future, but its production will require vast amounts of CO_2. In the "max methanol" scenario, about 70Mt of CO_2 would be required, so it is critical to understand where CO_2 could be sourced from in 2050. Three possible sources of CO_2 are considered[10]:

1. Concentrated CO_2 capture from industrial sources, which can be split in two main categories, with different operating parameters and different costs:
   a High pressure capture from process gas streams ("pre-combustion")
   b Low pressure capture from flue gases ("post-combustion") or from fermentation gas
2. Direct air capture (DAC)
3. CO_2 import by pipeline or transport vessels

In the first case, CO_2 will come from power generation and industrial processes. These two will only create about 30Mt of CO_2 (see Table 3 and Table 4), so the rest (40Mt[11]) will need to come from DAC and CO_2 import.

Table 3 CO_2 sources in 2018 vs 2050, Mt/year

Source	**2018 CO_2 emissions**	**2050 CO_2 emissions that can be captured**
Power generation	48	10
Industry	44	22
Build environment	27	0
Transport	35	0
Agriculture	8	0
Total	162	32
	Source: EBN poster 2018	*Source: TNO analysis*

Table 4 Assumptions on sectors decarbonization by 2050

Source	**Comments**
Power generation	Most electricity will be generated from wind, some flexibility can be supplied by blue hydrogen from natural gas (pre-combustion CO_2 capture)
Industry	Assumed that 50% of NL industry will decarbonize
Build environment	fully decarbonized / not practical to capture CO_2
Transport	fully decarbonized / not practical to capture CO_2
Agriculture	fully decarbonized / not practical to capture CO_2

[10] CO_2 from the production of biogas (anaerobic fermentation) is not included in the estimates, because these are typically small-scale plants and capturing CO_2 for industrial use might not be economic.
[11] Based on the "max methanol" scenario: methanol represents 960 PJ of fuels in the Netherlands and requires ~70Mt of CO_2 annually

3.2.2 Not all carbon is the same

The reuse of CO_2 for methanol production does not necessarily lead to full emissions reduction, as that depends on the source. Capturing CO_2 from industrial processes that use fossil energy, like blue hydrogen production from natural gas, or from gas-fired power plants, reduces emissions only to a limited extent. This limit is roughly 50% when the source is fossil carbon, and can be called "non-circular". Mixing in biogas with the natural gas feedstock or fuel improves the overall capture rate.
CO_2 coming from processes that first take it out of the atmosphere, can be considered "circular". Using that for methanol production leads to higher emissions reduction rates. Examples are biomass used as fuel for power generation, biomass as feedstock for gasification for syngas production, and (technical) direct air capture of CO_2. It's important to note this distinction when considering the overall CO_2 emissions reduction targets which correspond to 2050 climate goals.
For imported CO_2, its origin defines how much it will affect total emissions. Future legislation around carbon tax and CO_2 market design will define what import options will be feasible and how they will affect the economics of e-fuels production.

3.2.3 Methanol requires a lot of CO_2

Methanol production is relatively flexible (info from Air Liquide, H-Vision project), in the sense that it CO can be rapidly (within hours) ramped up/down between maximum capacity and a lower limit of 50-60%, and higher flexibility designs are possible. However, shutting down and starting up such a plant can take 1-2 days so it is likely more economical to buffer feedstocks rather than temporarily interrupt production. If we look at the CO_2 sources described above, concentrated CO_2 capture and imports are expected to be stable and predictable. Post-combustion capture from balancing power plants introduces fluctuations in the supply, but DAC is expected to be very flexible and partially compensate for these fluctuations or others caused for example by downtime of industrial plants.
Moreover, given that the North Sea has significant potential for CCS (up to 30 Mtpa CO_2 is considered feasible, according to a 2017 evaluation from EBN and Gasunie[12]) the industry in neighboring countries like Germany could also transport CO_2 via pipelines through the Netherlands towards export points for sequestration. If these CCS pipelines are connected to the supply grid for methanol production, that would also increase supply flexibility.
Taking all these aspects into account, we consider that CO_2 storage facilities for methanol production would only need sufficient buffer capacity for intraday balancing. For the forecasted max annual demand for CO_2 as feedstock for MeOH production of 70 Mtpa, the corresponding storage capacity for buffering half a day to one day of full nation-wide production is ~100-200 kton CO_2. This can be reduced when also the CO_2 of the purge gas from the e-methanol plant is used as feedstock.

3.2.4 Underground storage options

There are several alternatives for large volume physical storage of CO_2, both underground and above ground. In this section, we discuss the options for underground storage.

[12] EBN & Gasunie, *Transport en opslag van CO_2 in Nederland*, 2017

Underground storage in salt caverns

Salt caverns are best suited for the purpose of buffering feedstock grade CO_2, since the storage volume available in a single cavern is massive and (much like the case of underground H_2 storage) their use leads to minimal contamination of the gas.
A commonly mentioned downside of using salt caverns is the need to introduce a large starting volume of cushion gas[13], but in the case of CO_2 this would be equivalent to geological sequestration so there's no penalty associated with it.
For the Dutch case, salt caverns present a disadvantage in terms of location – they are concentrated in the Friesland / Groningen / Drenthe area, which means lengthy pipeline connections would be required if they are to service methanol production located in the Rotterdam area for example.

Underground storage in depleted gas fields

Not considered a feasible option for the following reasons: 1) the gas would gradually mix with whatever is still present in the reservoir, negatively impacting the purity of feedstock CO_2 and 2) since CCS on land has become "taboo", offshore depleted gas fields would have to be used.
If such fields are developed for CCS, it's anyway easier to 'intercept' CO_2 on its way towards sequestration rather than design for reverse flow from the field back to shore or, even more costly, have separate wells and a second pipeline for CO_2 extraction from the field.

Underground storage in saline aquifers

Same points as above for depleted gas fields, with the addition that saline aquifers introduce additional unknowns in terms of reservoir behavior and capacity, and will also have significantly higher development costs (depleted gas fields already have much of the required infrastructure in place[14]).

Based on the above overview, salt caverns appear to be the most suitable form of large volume storage. A quick estimate was made to determine how many caverns would be needed to provide the expected flexibility in CO_2 supply. A typical salt cavern (based on data provided by Gasunie in the H-vision project, as well as a recently published overview of underground storage capacity in the NL[15]) is expected to have the following properties and operating constraints:

Min operating pressure	100 bar
CO_2 Density @ 40°C and 100 bar	~620[16] kg/m^3
Max operating pressure	180 bar
CO_2 Density @ 40°C and 180 bar	~820 kg/m^3
Total cavern volume	600,000 m^3
Max daily pressure difference	10 bar

Based on these values, a single cavern could hold roughly 120 kt of CO_2 (working volume) and, corresponding to the maximum allowed pressure difference, sustain a

[13] It is the volume of gas that is intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season.
[14] Zero Emissions Platform - *The Costs of CO_2 Capture, Transport and Storage - Post-demonstration CCS in the EU*, 2011
[15] Joaquim Juez-Larré et al (TNO), *Assessment of underground energy storage potential to support the energy transition in the Netherlands*, 2019
[16] Source: NIST (webbook.nist.gov/)

maximum daily flow rate in the order of 15 kt/d. As such, 7-14 'standard' salt caverns could theoretically provide the previously mentioned buffer capacity of 100-200 kt/d of CO_2. This is a modest number in comparison with the total estimate of 321 salt caverns which could be possibly available in the Netherlands, and as such, competition with natural gas or hydrogen storage is not seen as an issue.

3.2.5 Above ground storage options

Above ground storage in pressurized and refrigerated tanks

The boiling point of CO_2 is -78.5°C, lower than NH_3 but significantly higher than CH_4, two commodity gases stored and transported at large scale as liquids. However, because the triple point is 5.1 atm it can only be stored as a liquid in pressurized tanks.

The proposed conditions for transporting CO_2 by ship are at pressure slightly above the triple point (7-9 bar) and a corresponding temperature of -55°C to -45°C. Existing LPG carriers can be retrofitted for CO_2 transport and it is expected that carrier vessels would have capacities in the range of 10,000-40,000 m^3, with multiple pressure vessels on board.[17] The density of CO_2 at those conditions is roughly 1150 kg/m^3 (NIST, webbook.nist.gov/).

What can be placed on a ship can be built on land as well, so it's feasible that some of the buffer capacity will be covered using such storage systems. As opposed to supercritical phase storage of CO_2, the use of liquid storage tanks would require costly refrigeration units of suitable capacity.

3.2.6 Space needed for above ground storage in Rotterdam area

If most of e-methanol is produced around port of Rotterdam area, above ground storage near Rotterdam is also possible. In order to compare this option to salt caverns in the north, additional detailed techno-economic analysis would be needed, because such factors as existing infrastructure, exact volume of CO_2 transported and future CCS infrastructure in the region would need to be taken into account.

Large volume CO_2 storage is not common practice in industry currently. The required conditions for liquid CO_2 storage (pressure of 7-11 bar and a corresponding temperature of -55°C to -35°C) are similar however to other molecules which are stored in large volumes in refrigerated pressurized vessels, such as LPGs (propane, propylene, butane, butadiene). Horton spheres are typically preferred over cylindrical tanks, since they are more cost-effective for storing large volumes and require a smaller footprint.[18]

Typical capacities range from 1,000m^3 to 7,500m^3. Single pressurized spheres can hold massive amounts of liquid, for example the largest spherical gas holder built in Japan[19] has a capacity of 20,000m^3.

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[17] Robert de Kler et al (TNO), CATO-2, *Transportation and unloading of CO_2 by ship - a comparative assessment*, 2016

[18] https://www.transtechenergy.com/lpg-ngl-storage-news/lpg-storage-bullet-tanks-vs.-lpg-storage-spheres-/-hortonspheres

[19] https://www.ishii-iiw.co.jp/en/business/steel/?ca=3

Taking 7,500m^3 volume per sphere as a conservative assumption, each storage unit would have a diameter of roughly 25m. Assuming that 80% of this volume can be effectively used for buffer storage, and taking into account the density of CO_2 at storage conditions (1150kg/m^3), each sphere would provide ~6,900t buffer capacity. This means 16 units are required for a buffer capacity of 100kt/d, with one spare for maintenance.

Allowing for 10m spacing between the spheres and a service road, the illustration below provides a rough indication of the minimum plot space required (not taking into account buildings such as a control room, or other plot space needs) for the CO_2 storage facility.

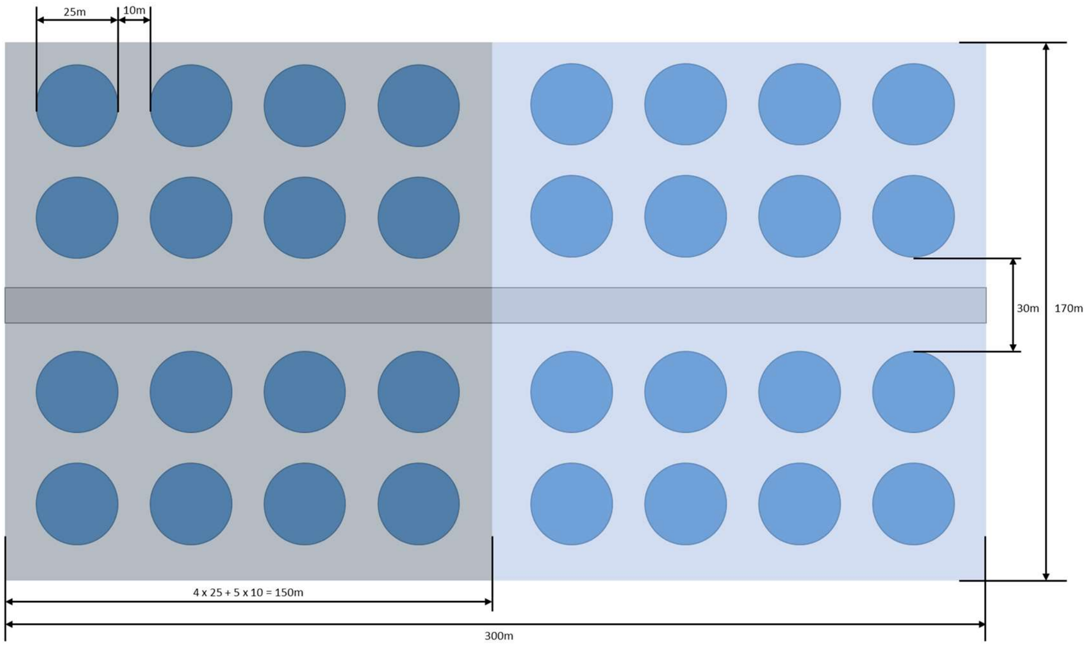

Figure 6 Minimum plot space and arrangement required for placing above ground LPG storage

Therefore a minimum plot space of 150m x 170m (2.55 ha) is estimated for the 100kt/d low case and 300m x 170m (5.1 ha) for the 200kt/d high case.

3.3 Total required space for e-methanol production

An estimation of the space requirements was made, based on the facilities described above. An overview of the specific space requirements for each facility and the total space requirement for the production of 960PJ of fuels in the form of e-methanol is given in the table below.

Table 5 Specific and total space required for all facilities for e-methanol production of 960PJ fuels

Facility	Capacity	Capacity needed	Capacity per m^2	Space requirement [ha]
Alkaline electrolyser	2400 - 3880 Nm^3/h	68 GW 15.6x10^6 Nm^3/h	0.96 m^2 * Nm^3/h	1500
PEM electrolyser	300 MW		16.7 m^2/MW	112
DAC plant	Low temperature	40 Mt_{CO2}/y	0.1 m^2 * t_{CO2}/y	400

Desalination plant		100×10^3 m^3/y	0.001 m^2 * m^3/y	0.1
Methanol plant	440 - 1100 kt/y	42 Mt_{MeOH}/y	293 m^2 * t_{MeOH}/h	145
Above ground H_2 storage	Up to 50,000 liters	147×10^6 liter	0.0017 m^2 * liter	25
Above ground CO_2 storage	7,500 m^3 per sphere	100-200kt/d		4
			Total	686
			Percentage of Maasvlakte 2	68%

When all 960 PJ of fuels is produced in the Netherlands in the form of e-methanol required methanol, it would require a capacity of 68 GW hydrogen electrolysers, 58 methanol plants with a capacity of 2 kton/day and more than 70 Mton of CO_2 yearly, of which 30Mton will come from power generation and industrial processes and the rest requires extensive DAC installations. Table 5 shows that the footprint of an alkaline electrolyser is 20 times larger than for a PEM electrolyser with the same capacity. Taking PEM electrolysers the total space requirement is about 700ha, which is 68% of the Maasvlakte 2, which is dedicated to industrial activities (see Figure 7). However it is possible to stack electrolysers in buildings (see Figure 4), reducing the required space for the electrolysers with a factor 5 to 22ha and resulting in a total space requirement of about 600ha. If the remaining 40Mton CO_2 is produced from air, a large part of the land (~67%) is used for the DAC plant, so reduction of the footprint of such a plant or import of CO_2 is crucial for e-methanol production in the Rotterdam area.

Figure 7 Total space requirement depicted on the Maasvlakte 2 (Dark grey area)

3.4 Space needed for fuel storage

Bunker oil represents an important activity in the Dutch economy. Annually, more than 20,000 ships bunker fuel oil in the port of Rotterdam, and the product accounts for around one third of the liquid storage and transfer in the port of Rotterdam[20].
Fuel oil is stored in storage tanks at terminals. Storage is done at refineries and at independent tank storage and transfer companies. In the study of CEDelft[9] an overview is given of independent storage and transfer terminals in May 2011. It shows that the storage capacity of 8.6 million m^3 was growing and various companies were expanding.

Since a large part of the transport fuels in the Netherlands are bunker fuels, the transition to e-methanol will also have a big impact on the fuel storage capacity and required space. Calculations based on the specific energy of e-methanol and fuel oil show that for storage of the same total energy content in the form of e-methanol instead of fuel oil, about 19.4 million m^3 of tank storage capacity is needed in the Netherlands. This represents a factor 2.2 increase in storage capacity and required space both for the Netherlands and the harbour of Rotterdam.

3.5 Consequences for Rotterdam

Rotterdam wants to decrease its CO_2 emissions by 50% in 10 years. More than 20% of the Dutch emissions come from Rotterdam of which 90% is emitted in the Rotterdam port area. Therefor the biggest emission reduction has to come from this area. The Port of Rotterdam has developed transition paths that form the basis for achieving CO_2 reduction together with the companies in the port area. Figure 8 shows a map of the port[21] with the projects that have started on energy transition at numerous locations. The projects together add up to about 20 to 25 percent of the national CO_2 reduction ambition in 2030[22].

Figure 8 Port of Rotterdam Roadmap climate targets 2030 – 2050 (Source: Port of Rotterdam)

The roadmap is a three step approach starting with efficiency measures and additional infrastructure such as pipelines and cables (orange). Step 2 is the transition of the industry to electricity and (green) hydrogen (yellow). In the final step all fossil

[20] A. de Buck, M.E. Smit, J. Faber, A. van Grinsven, Blends in beeld: Een analyse van de bunkerolieketen, CE Delft, mei 2011, Publicatienummer: 11.3382.35
[21] https://www.portofrotterdam.com/nl/files/roadmap-klimaatdoelen-2030-2050
[22] https://maritiemnieuws.nl/92910/haven-rotterdam-pakt-leeuwendeel-van-co2-reductie/

resources are replaced by biomass, recycled materials, green hydrogen and CO_2 (white).

The transition to e-fuels in the Dutch transport sector and the production of e-methanol in the harbour of Rotterdam fits very well within the Port of Rotterdam Roadmap climate targets 2030 – 2050. A first sketch of the Rotterdam harbour in 2050 showing the possible locations for the production of e-methanol including feedstock production and storage is shown in Figure 8.

Figure 9 First sketch of the Rotterdam harbour in 2050 with possible e-methanol production locations

4 Conclusions

Today most of the conventional fuels are produced and bunkered in the Rotterdam harbour. With the planned wind capacity and CO_2 storage at the North Sea, the Rotterdam harbour can play an important role in the transition to e-fuels or power-to-fuels in the Netherlands. In this part of the ongoing P2Fuels project, TNO studied the space needed for the transition to e-methanol both offshore to provide the required electricity as onshore for the production facilities.

Production of e-fuels will lead to a large demand for electricity from renewable sources, water and CO_2. For 2050 a fuel demand for international transport modes of 960 PJ is forecasted. When these fuels are produced as e-methanol for trucks and maritime (with a production efficiency of 49%) and kerosene for aviation (with a production efficiency of 46%), about 2000 PJ of electricity is required to produce this 960 PJ of fuels. Currently, the maximum Dutch offshore wind capacity is estimated at 900 PJ (though scenarios are possible in which much more energy can be produced at the Dutch continental shelf). This means that import will become necessary in the form of electricity, hydrogen, CO_2 or e-fuels.

Besides impact on energy demand, also a transition of the Dutch refinery cluster to e-fuels production will have a large impact: when all required methanol would be produced in the Netherlands, it would require a capacity of 68 GW hydrogen electrolysers, 58 methanol plants with a capacity of 2 kton/day and more than 70 Mton of CO_2 yearly, of which 30Mton will come from power generation and industrial processes and the rest requires extensive DAC installations. For comparison: the current Dutch CO_2 emission is around 160 Mton per year.

In total the production of e-methanol requires about 600ha of land, which is 30% of the Maasvlakte 2. About 67% of the total required space is used to obtain CO_2 from air with a direct air capture (DAC) plant, so reduction of the foot print of such a plant or import of CO_2 is crucial for e-methanol production in the Rotterdam area.
Next to that the fuel storage capacity would have to be more than doubled, since e-methanol has a significant lower volumetric energy density than fossil fuels.

The transition to e-fuels in the Dutch transport sector and the production of e-methanol in the harbour of Rotterdam fits very well within the Port of Rotterdam Roadmap climate targets 2030 – 2050. A first sketch of the Rotterdam harbour in 2050 showing the possible locations for the production of e-methanol including feedstock production and storage has been made.