Sustainable Energy & Fuels

PAPER

View Article Online
View Journal | View Issue

Cite this: *Sustainable Energy Fuels*, 2026, **10**, 311

Feasibility study and reflection on agro-industrial CO_2 point sources as feedstock for chemicals and materials

K. P. H. Meesters, * M. P. Lanting, J. A. Voogt and H. L. Bos

Received 25th September 2025
Accepted 4th November 2025

DOI: 10.1039/d5se01283j

rsc.li/sustainable-energy

This paper investigates the opportunity to produce chemicals from carbon dioxide rich side streams from the agro-industry by the application of carbon capture and utilisation (CCU) technologies. It takes into consideration economic feasibility and puts the potential from sugar beet factories into perspective by comparison with current plastic use and forest area that would be needed to reach a comparable carbon dioxide uptake. A sugar beet factory with anaerobic digestion of sugar beet pulp and fermentation of molasses to ethanol was reviewed as a potential point source of carbon dioxide. Ethanol and methanol were taken as example chemicals produced *via* CCU. Ethanol is assumed to be produced *via* gas fermentation and methanol *via* reversed water gas shift and subsequent methanol synthesis. Mass balances and economic key figures on relevant technologies were taken from literature. In the default scenario, the production costs are 1738 € per ton for ethanol and 1058 € per ton for methanol. In both cases, the major cost factor is the use of electricity that is largely used for the reduction of carbon dioxide. If a significant penalty for fossil carbon dioxide emission (189 € per ton CO_{2eq}) is in place, the costs of production of methanol from carbon dioxide are comparable with current methanol prices under the energy surplus scenario (energy costs reduced from 100 € per MWh to 50 € per MWh and doubled capital costs). Ethanol can be converted to ethylene to produce biobased polymers. The use of carbon dioxide from sugar beet processing could fulfil half of the future ethylene biobased plastic demand under the assumption that recycling will reduce the demand for virgin plastics by 50%.

1 Introduction

To mitigate climate change, fossil-based resources need to be phased out. In that light, many governments have committed themselves to the Paris Agreement.[1] Heat, electricity and transport fuel demands can be (largely) fulfilled by wind turbines, solar PV, hydro power, nuclear power, and geothermal energy. However, to produce materials and chemicals that are presently fossil based, an alternative source of renewable carbon is needed.[2]

Plant biomass (*e.g.* crops such as sugar cane, sugar beet, wheat, oil rich seeds, wood) is one source of renewable carbon for chemical and material production. Carbohydrates from these crops can be converted into valuable chemicals, such as ethanol, lactic acid, furans, and others. Polyunsaturated vegetable oils can be applied in thermosets. Wood can be a source of aromatic components, or of pure cellulose. However, significant amounts of arable land would be needed to fulfil the current demand for chemicals when only biomass is used. Without additional measures this land use could amount to a similar magnitude as present land use for plant-based food production but is still much smaller than the present magnitude of land use for feed.[3] Environmental damage and loss of biodiversity could result from extra land use for biomass production.[4]

Another option is the production of carbon-based materials and chemicals from carbon dioxide, through Carbon Capture and Utilisation (CCU) technologies. These technologies could produce a wide range of products, such as alcohols, waxes, acids, and subsequent polymers. However, these technologies are under development. Capture of carbon dioxide from the atmosphere is expensive and energy intensive due to the low concentration of carbon dioxide in the atmosphere.[5] Therefore, carbon dioxide rich point sources are preferred as input to produce chemicals from carbon dioxide.

Current carbon dioxide point sources are mainly from fossil industry and electricity production. However, the United Nations have set a goal for a maximum temperature increase of 2 °C in the Paris Agreement.[1] Next to that, the EU has set a renewable energy target of 42.5% renewable energy by the year 2030 (ref. 6) and net zero greenhouse gas emissions by the year 2050.[7] Therefore, the availability of fossil-based carbon dioxide point sources is expected to be strongly reduced soon. Agro-industry, however, is expected to remain operating under similar conditions, and is therefore a future-proof resource of carbon.

Wageningen Food and Biobased Research, Bornse Weilanden 9, Wageningen, 6708 WG, The Netherlands. E-mail: Koen.Meesters@WUR.NL

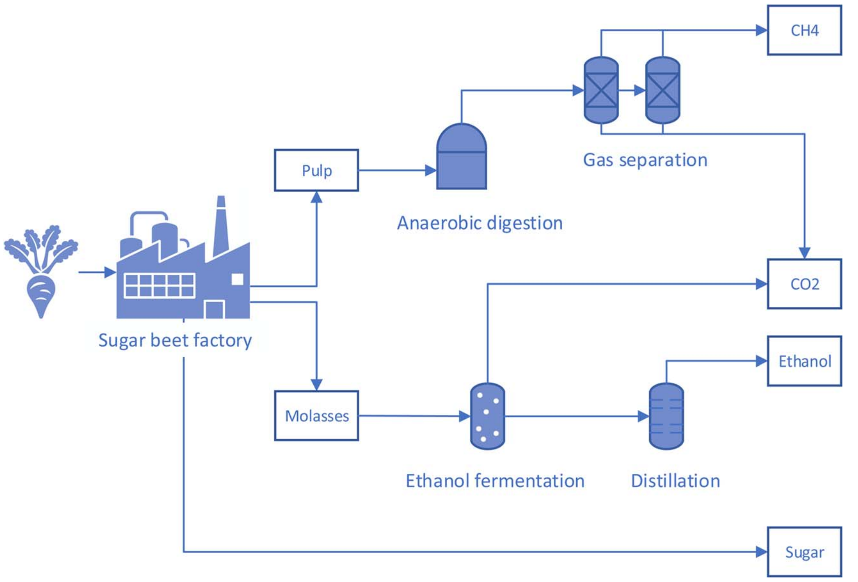

Fig. 1 Sugar beet factory with anaerobic digestion and ethanol fermentation (sugar beet refinery).

In Europe, sugar beet is an important agro-industrial crop, especially in France, Germany, Poland, United Kingdom, Belgium, The Netherlands, and Czech Republic.[8] This study investigates the potential of using carbon dioxide rich side streams from sugar beet factories to produce chemicals and materials through CCU technologies. Sugar beet factories have two important side streams: molasses and sugar beet pulp (Fig. 1). *Via* established and well-known processes, ethanol and methane can be produced from these side streams *via* fermentation and anaerobic digestion, respectively. Both these processes have a carbon dioxide rich side stream.

With this paper we intend to research the relevancy of production of chemicals from sugar beet refineries to fulfil future plastic demand and reduce greenhouse gas emissions. As example chemicals, ethanol and methanol were chosen. Both are primary alcohols with limited functionality (only one –OH group) that can be used to produce building blocks for the synthesis of larger molecules. Their small size enables easy purification *via* distillation. However, production of these chemicals from carbon dioxide has not been implemented on industrial scale yet.

Pathways for production of ethanol at small scale (*via* syngas fermentation[9–13]) and methanol at large scale (*via* reversed water gas shift[14–17] and methanol synthesis[18–22]) have been identified and described in literature. Below, both options will be described in more detail.

1.1 Production of ethanol *via* fermentation/distillation (local, small scale)

The local processing of carbon dioxide studied in this paper involves a fermentation of carbon dioxide and carbon monoxide into ethanol (Fig. 2). First, 50% of the carbon dioxide is converted to produce carbon monoxide and hydrogen in a co-electrolysis process (eqn (1)). Extra hydrogen, which is needed for further reduction of carbon dioxide and carbon monoxide into ethanol, is produced *via* electrolysis (eqn (2)). Finally, carbon dioxide, carbon monoxide and hydrogen are fermented into ethanol (eqn (3)).[9] Ethanol is recovered from the fermentation broth *via* distillation. All processing is assumed to be done adjacent to the sugar beet factory.

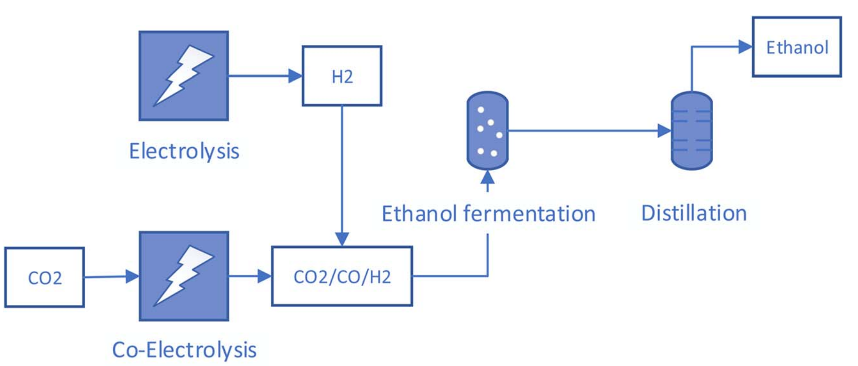

Fig. 2 Production of ethanol from carbon dioxide *via* fermentation/distillation.

Co-electrolysis

$$CO_2 + H_2O \rightarrow CO + H_2 + O_2 \quad (1)$$

Water electrolysis

$$2H_2O \rightarrow 2H_2 + O_2 \quad (2)$$

Gas fermentation

$$CO_2 + CO + 5H_2 \rightarrow C_2H_6O + 2H_2O \quad (3)$$

1.2 Production of methanol *via* reverse water gas shift (RWGS) and synthesis (large-scale)

Fig. 3 presents the flow scheme for the thermochemical processing of carbon dioxide into methanol. The large-scale processing involves electrolysis, reverse water gas shift and methanol synthesis. Hydrogen is produced *via* electrolysis (eqn (2)). Part of the hydrogen is used to convert carbon dioxide into carbon monoxide in a reverse water gas shift reactor (eqn (4)). High temperature heat is added to push the equilibrium into the desired direction. Carbon monoxide and carbon dioxide are converted into methanol in a synthesis reactor (eqn (5) and (6)).

Reverse water gas shift

$$CO_2 + H_2 \rightarrow CO + H_2O \quad (4)$$

Methanol synthesis from carbon dioxide

$$CO_2 + 3H_2 \rightarrow CH_4O + H_2O \quad (5)$$

Methanol synthesis from carbon monoxide

$$CO + 2H_2 \rightarrow CH_4O \quad (6)$$

Thermochemical processes usually have considerable economy of scale (the process is cheaper at larger scale than at smaller scale).[23] Therefore, these processes need a large scale for economical operation. One sugar beet factory cannot produce sufficient carbon dioxide to feed such a large-scale facility. Therefore, transport of compressed carbon dioxide to a central facility will be needed.

2 Method

As the first step, we estimated the quantity of carbon dioxide that could be retrieved from a sugar beet factory with molasses fermentation and pulp anaerobic digestion (paragraph 2.1). From there, two options for producing chemicals were investigated: (1) the small-scale local processing of carbon dioxide into ethanol *via* fermentation (paragraph 2.2) and (2) the large-scale centralized processing of carbon dioxide into methanol *via* thermochemical conversions (paragraph 2.3).

The economic evaluation method is adopted from Lanting *et al.*[24] The process costs are calculated as the sum of annualized capital costs (CAPEX) plus operational costs (OPEX). The annualized capital costs are derived from the total capital investment multiplied by a yearly costs of capital of 0.2 €/(€ per year).[24] The costs of capital include 10% amortization, 5% maintenance and 5% interest. For the operational costs, only energy costs were considered. Other operational costs (such as salaries, laboratory costs, insurance, taxes) were neglected. Energy costs are calculated from the demand for high-quality energy (electricity and high temperature heat) and low-quality energy (heat up to 100 °C). For high quality energy, a price of 100 € per MWh was taken. This is less than the current energy prices in most European countries.[25] For low-quality energy, a price of 40 € per MWh was taken. Low quality heat is assumed to be produced with heat pumps, taking into account a COP of 4 (25 € per MWh) plus 15 € per MWh for the utilities. These energy costs are higher than used in Lanting *et al.*,[24] taking into account the Dutch situation with less sun and no options for cheap energy storage in hydropower reservoirs.

For our analysis we selected three papers that included sufficient details on process scheme, mass balances, energy balances and economic parameters: Huang *et al.*, Rezaei and Dzuryk, and Rajaee *et al.*[9,14,18] Data from Lacerda *et al.*[19] are comparable to the data used in this study (as derived from Rajaee *et al.*[18]). Other literature found was unsuitable for a variety of reasons. Most publications did not provide a full data set.[10–13,16,17,20,21] Data from Bown *et al.*[15] on RWGS used a separate set of starting points that could not be easily recalculated to the starting point of this paper where fossil resources are excluded. Wu *et al.*[22] describe a highly integrated process fuelled with biomass that cannot be easily adopted to a process fuelled with electricity.

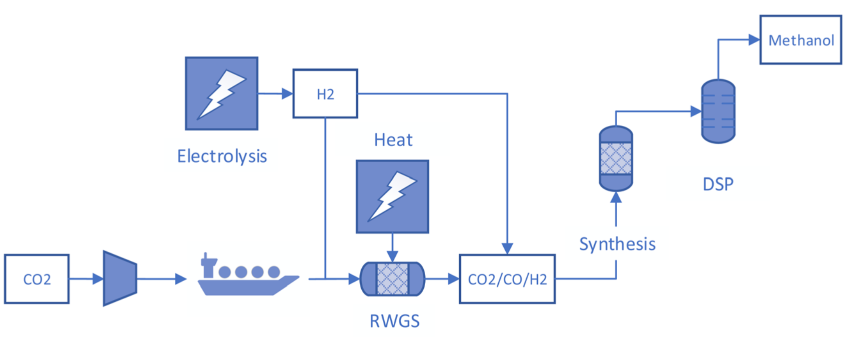

Fig. 3 Production of methanol *via* Reverse Water Gas Shift (RWGS) and synthesis.

Where indicated, adaptations were made to fit the 2050 situation where natural gas will not be used for process heat (see Annex 3 and 4). Cost data on electrolysis and co-electrolysis were taken from Lanting *et al.*[24]

2.1 Sugar beet factories as a resource of carbon dioxide

This study was started from the sugar beet factory example from SuperPro Designer.[26] The input and output of the sugar beet factory example is given in Tables 1 and 2.

The sugar beet factory has two side streams: molasses, and sugar beet pulp. It was assumed in our assessment that molasses is fermented to ethanol and that sugar beet pulp is digested to biogas. Both these processes yield a side stream that is rich in carbon dioxide. To calculate the quantity of ethanol, methane and carbon dioxide produced in these processes, the following was assumed: a yield for ethanol of 0.511 kg kg^{-1} sucrose and for carbon dioxide of 0.489 kg kg^{-1} sucrose was assumed (95% of stoichiometric yield). A yield of methane of 0.297 kg kg^{-1} and carbon dioxide of 0.433 kg kg^{-1} pulp dry matter was used (derived from Hutnan *et al.*[27] and Muzík *et al.*[28]) (see Annex 1). Ethanol fermentation yields a gaseous side stream with almost pure carbon dioxide gas. The biogas from anaerobic digestion is separated in pure methane and pure carbon dioxide. It is assumed that both molasses and pulp are stored, so that ethanol fermentation and anaerobic digestion can run continuously throughout the year.

2.2 Production of ethanol *via* fermentation/distillation (local, small scale)

For production of ethanol from carbon monoxide a stoichiometric conversion according to eqn (3) was assumed. The costs of electrolysis, co-electrolysis and ethanol fermentation were adapted from Lanting *et al.*[24] (Annex 2). The basis for the fermenter costs were taken from Humbird *et al.*[29] for a reactor of 1000 m^3 with a capacity of 20 kton per year.

2.3 Production of methanol *via* reverse water gas shift (RWGS) and synthesis (large-scale)

Before transport, carbon dioxide will need to be compressed to reduce the volume. It is assumed that carbon dioxide will be transported from Roosendaal (the current location of a large sugar beet factory) to Rotterdam harbour area (where other large-scale carbon dioxide streams can easily be collected), 60 km one way. The costs of compression were taken from Chen and Morosuk[30] (19.1 € per ton), the costs of transport per ship were taken from van der Meulen *et al.*[31] (4.7 € per ton) (Annex 7).

The data for electrolysis were taken from Lanting *et al.*[24] The data for the Reverse Water Gas Shift (RWGS) process were adapted from the data given by Rezaei and Dzuryk[14] for a capacity of 1.8 Mton per year syngas (Annex 3). In the study by Rezaei and Dzuryk, all heat is produced from natural gas. In our study, we consider a fossil free future, so natural gas is not an option. Therefore, the reboiler was assumed to be heated with electricity *via* a heat pump with a COP (Coefficient of Performance) of 4, the natural gas fired heater was replaced by an electric heater. The investment costs were corrected for the year 2024 using CEPCI numbers for 2024 and 2017.[32] The data for the methanol synthesis reactor were adapted from Rajaee *et al.*[18] and corrected for the year 2024 using CEPCI numbers for 2019 and 2024 (Annex 4). The data for RWGS and synthesis were collected and recalculated per ton methanol produced (Annex 5).

Table 1 Sugar beet factory main input stream

Input	Component	%	Ton per year	Ton per year
Sugar beet	Sucrose	13.99	130 275	
	Non-sucrose[a]	2.70	25 142	
	Pulp	5.30	49 354	
	Water	78.01	726 429	
	Total			**931 200**

[a] Non-Sucrose refers to dissolved components that are not sucrose (such as glucose, amino acids, betaine).

Table 2 Sugar beet factory main output streams

Output	Component	%	Ton per year	Ton per year
Dry pulp	Sucrose	0.39	195	
	Non-sucrose	1.74	875	
	Pulp	87.87	44 172	
	Water	10.00	5027	
	Total			**50 270**
Molasses	Sucrose	43.96	28 367	
	Non-sucrose	28.18	18 184	
	Water	24.68	15 922	
	Other		2055	
	Total			**64 528**
Sugar	Sucrose	99.97	101 667	
	Other	0.03	21	
	Total			**101 698**

2.4 Overview of process data

Table 3 provides an overview of model data, literature data and derived data. A full overview of all data can be found in Annex 9.

3 Results and discussion

3.1 Production of biobased chemicals from Dutch sugar industry side streams

In the Netherlands, 7.3 Mton per year of sugar beets are grown on 82 000 ha.[34] This harvest is processed in two factories, so the Dutch sugar factories are a factor 4 larger than the SuperPro Designer example[26] we used as starting point. The data from Table 2 were multiplied by this factor to calculate the availability of molasses (sucrose) and pulp (dry matter) from the two Dutch sugar factories as shown in Table 4. The side streams from these factories (molasses and sugar beet pulp) could be used to produce 114 kton ethanol per year and 93 kton methane per year (see Annex 1) *via* ethanol fermentation and anaerobic digestion respectively. Both are well established processes that operate at TRL 9 and could be implemented relatively easily at full scale. Besides ethanol and methane, these processes would produce 279 kton carbon dioxide per year.

Table 3 Overview of global process data

	Parameter	Reference component	Value	Unit	Ref.
Generic	**Scenario high energy prices**				
	High quality energy price		100	€ per MWh	
	Low quality energy price		40	€ per MWh	
	Scenario low energy prices				
	High quality energy price		50	€ per MWh	
	Low quality energy price		20	€ per MWh	
	Cost of capital		0.2	€/(€·year)	
	CEPCI 2017		567.5		32
	CEPCI 2019		607.5		32
	CEPCI 2024		797.9		32
	USD to euro ratio		0.9	USD per €	33
Electrolysis	CAPEX electrolysis	Hydrogen	1358.4	€/(ton per year)	24
	HQE electrolysis	Hydrogen	45.45	MWh per ton	24
Co-electrolysis	CAPEX co-electrolysis	Syngas	449.3	€/(ton per year)	24
	HQE co-electrolysis	Syngas	550	MWh per ton	24
Ethanol					
	Case CO and CO_2				
	Ethanol yield on syngas	Syngas	1	mol mol^{-1}	9
	Ethanol yield on additional H_2	Hydrogen	0.25	mol mol^{-1}	9
	Case CO				
	Ethanol yield on syngas	Syngas	0.5	mol mol^{-1}	9
	Ethanol yield on additional H_2	Hydrogen	0.5	mol mol^{-1}	9
	CAPEX fermentation	Ethanol	1425.9	€/(ton per year)	24
	HQE fermentation	Ethanol	87.2	MWh per ton	24
	CAPEX distillation	Ethanol	153.8	€/(ton per year)	24
	LQE distillation	Ethanol	74.4	MWh per ton	24
RWGS	CAPEX RWGS	CO	88.6	€/(ton per year)	Annex 3
	HQE RWGS	CO	1.465	MWh per ton	Annex 3
Methanol	Methanol yield on H_2	H_2	1/3	mol mol^{-1}	
	Methanol yield on CO/CO_2	CO	2	mol mol^{-1}	
	CAPEX methanol synthesis	Methanol	384.9	€/(ton per year)	Annex 4
	HQE methanol synthesis	Methanol	0.574	MWh per ton	Annex 4
CO_2 transp	Cost of compression	CO_2	21.3	USD per ton	30
	Cost of transport by ship	CO_2	0.039	€/(ton km)	31
	Travel distance (one way)		60	km	31

Methane produced from anaerobic digestion of pulp can be fed into the natural gas grid or converted into methanol or other chemicals.

The carbon dioxide that results from molasses fermentation and pulp anaerobic digestion can furthermore be used to produce either additional ethanol (Case 1) or methanol (Case 2) (Table 5). Assuming stoichiometric yields, the 279 kton per year carbon dioxide could yield 146 kton ethanol per year or 203 kton methanol per year (see Annex 6). The total potential production of ethanol or methanol from the side streams of the two Dutch sugar factories thus amounts to 260 kton ethanol per year (Case 1) or 114 kton ethanol plus 203 kton methanol per year (Case 2).

3.2 Costs of biobased chemicals from carbon dioxide

Fig. 4 provides an overview of the calculated production costs of ethanol and methanol from carbon dioxide. The total production costs of ethanol are higher (1738 € per ton) than for methanol (1056 € per ton) on a weight basis.

Table 4 Possible biobased chemicals production from the fermentation of molasses and digestion of the pulp of the two Dutch sugar beet refineries

Raw material	Quantity [kton per year]	Process	Ethanol [kton per year]	Methane [kton per year]	Carbon dioxide [kton per year]
Molasses (sucrose)	222	Fermentation	114		109
Pulp (dry matter)	394	Anaerobic digestion		93	171
Total			**114**	**93**	**279**

Table 5 Total ethanol and methanol potential from side streams of Dutch sugar beet factories

Raw material	Quantity [kton per year]	Process	Case 1: ethanol [kton per year]	Case 2: ethanol [kton per year]	Methanol [kton per year]
Molasses (sucrose)	222	Fermentation	114	114	
Carbon dioxide	279	Gas fermentation	146		
Carbon dioxide	279	RWGS + synthesis			203
		Total	**260**	**114**	**203**

It is clear from Fig. 4 that both for ethanol and for methanol production the electrolysis step (production of hydrogen gas from water) is by far the costliest step. In both cases it is the cost of energy (OPEX) that is the culprit. Energy costs are thus a crucial factor for production of chemicals from carbon dioxide. This is mainly because the reactions involved are highly endothermic. In other words: reduction of carbon dioxide to methanol or ethanol takes a lot of electric energy. In traditional ethanol production, the distillation energy costs are a significant contribution to total costs. From Fig. 4 it is clear that here the electricity costs for electrolysis and co-electrolysis are far larger.

Besides high costs for electricity, the production of ethanol *via* gas fermentation also has high capital costs (Fig. 4). Gas fermentation is still in its infancy, but large savings are not expected. A considerable cost factor is associated with the gas to liquid mass transfer of carbon monoxide and hydrogen. Mass transfer of carbon monoxide and hydrogen from the gas phase to the reaction medium might be increased by increasing the pressure (increasing the concentration gradient), but options are limited and come at a cost, so large breakthroughs are not to be expected.

An option to reduce the electricity costs could be the use of cheaper electricity in periods of sunshine or high winds (energy surplus scenario). The costs of offshore wind energy are near 50 € per MWh,[35] but surplus availability is limited to only 4500 hours per year. So instead of a constant supply of high-quality energy at 100 € per MWh and low-quality energy at 40 € per MWh, we may shift to a sun and wind-based supply that delivers energy at half the price during half the time. As low-quality energy is assumed to be produced with heat pumps (that use electricity to pump heat from ambient temperature to the desired temperature level), the costs of low-quality energy are also assumed to drop by 50%. To maintain the same production volume, all equipment would need to be twice as large, doubling the capital costs. Fig. 5 shows that the production costs of methanol could be reduced by 30% in such a scenario.

Electricity costs are expected by some authors to be further reduced in the future due to the implementation of new energy technologies. Jouny *et al.*[36] have suggested an electricity price as low as 18 € per MWh. Such a low electricity price would yield CO_2 based methanol at a price lower than the current market price for fossil based methanol (see 'Very low cost scenario').

It should be noted that discontinuous processing may be troublesome for the ethanol fermentation process as the bacteria cannot be left without 'food' for longer periods. Storage of intermediate products (hydrogen and carbon monoxide) to equalize the supply of hydrogen and carbon monoxide to the

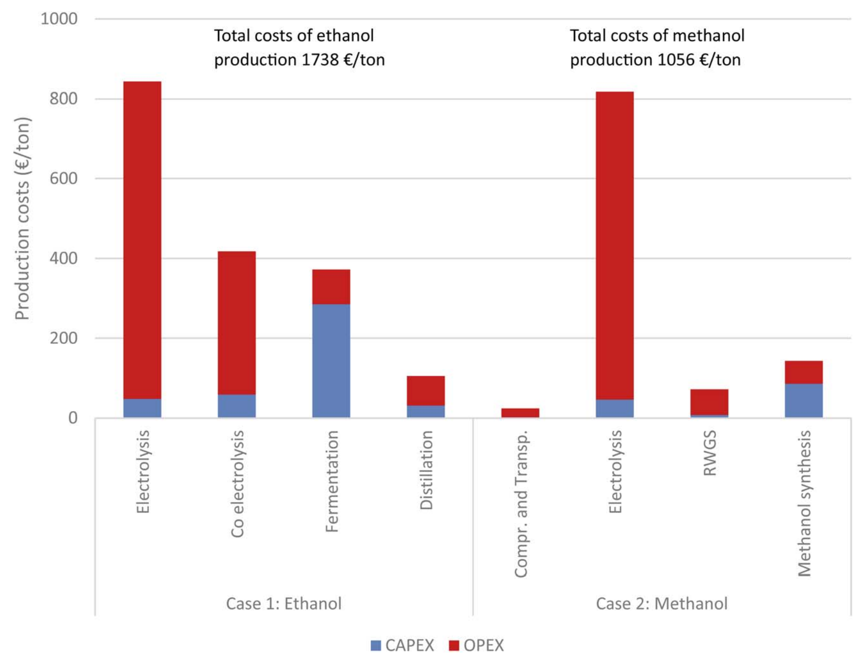

Fig. 4 Production costs (CAPEX and OPEX) in € per ton product for ethanol and methanol production from carbon dioxide.

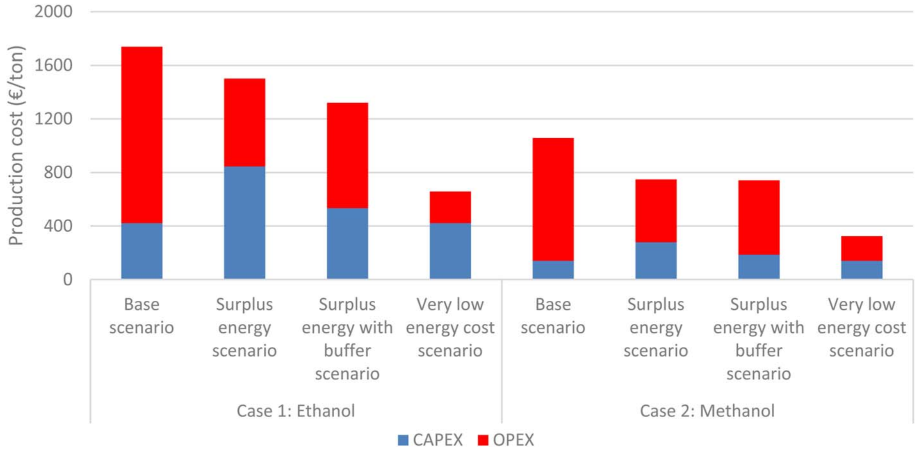

Fig. 5 Sensitivity analysis: base scenario *vs.* surplus energy scenario (with low energy costs and high capital costs) *vs.* surplus energy with buffer scenario *vs.* very low energy cost scenario.

fermenter will bring significant costs due to the low density of gases. Also the risk of explosions and the risks involved with toxicity of carbon monoxide should be taken into account. According to Cocco *et al.*,[37] syngas can be stored on a daily basis with capital costs of 21.1 € per ton and electricity costs of 65 € per ton. According to Abdin *et al.*[38] the costs of hydrogen storage on a daily basis could be as low as at 330 USD per ton (lump sum costs). These data were recalculated per ton ethanol respectively methanol (Annex 8) and added to Fig. 5 as the 'surplus energy with buffer scenario'. Production costs of ethanol are decreased by 24% compared to the base scenario. Production costs of methanol are only slightly reduced compared to the surplus energy scenario.

Another option next to intermittent production might lie in storage of energy for use during periods when renewable energy is not available. Storage costs of electricity in batteries are expected to drop to around 100 € per MWh in 2050,[39] so stored electricity would cost 150 € per MWh (wind derived electricity at 50 € per MWh plus storage at 100 € per MWh). The average of direct wind derived electricity at 50 € per MWh and stored energy at 150 € per MWh would be exactly equal to 100 € per MWh. The same will hold for low quality energy costs. From this it is concluded that no cost reduction is expected from the use of batteries.

The introduction of policies to tax abatement costs for products based on fossil resources is a further option to increase the market potential of carbon dioxide based chemicals. Methanol is currently made from fossil resources. If carbon dioxide abatement costs of 189 € per tonCO_{2eq},[40] (marginal carbon dioxide abatement costs for full abatement in the USA) are added to the price of fossil-based methanol (Table 6), the market price increases to 641 € per ton (taking into account a carbon dioxide emission of 1.37 kgCO_2 per kg methanol). This comes close to the costs of methanol produced from carbon dioxide rich side streams in the surplus energy usage scenario (Fig. 5). From this we can conclude that a serious carbon dioxide tax can help to reach political goals by enhancing the feasibility of production of methanol from carbon dioxide.

Alternatively, a subsidy on renewable plastics could make production viable. A subsidy of at least 2.35 € per kg ethylene would be needed to replace fossil ethylene. The authors do not advocate the use of measure subsidies. Measure subsidies provide more security to industry but may also encourage large scale implementation of less efficient processes and impede implementation of more efficient alternative options. Therefore, target subsidies are preferable.

A capital subsidy cannot make the process profitable as the electricity costs (OPEX) are dominant.

Fig. 4 compares ethanol and methanol on a weight basis (where the cost of ethanol is 64% more than the cost of methanol). But obviously, ethanol and methanol are not identical products. The production costs of these two chemicals might therefore better be compared based on higher heating value (HHV) or alternatively based on carbon content. Both HHV and carbon content have an intrinsic value that is also apparent from the current market price that is 19% higher for ethanol than for methanol. Table 6 shows that ethanol has a 29% higher

Table 6 Alternative options for basis of comparison

	HHV[41] [MJ kg^{-1}]	Carbon content [kg C kg^{-1}]	C–C bonds [mole $mole^{-1}$]	Market price [€ per ton]	Ref.
Ethanol	29.7	0.521	1	452[a]	42
Methanol	23.0	0.375	0	381	43

[a] produced from sugar cane.

HHV and a 39% higher carbon content compared to methanol. From this, we can conclude that the cost of ethanol from carbon dioxide is higher than the cost of methanol from carbon dioxide, independent of the basis of comparison.

Ethanol produced from carbon dioxide is considerably more expensive than the current main method for ethanol produced from sugar cane (current market price, Table 6), which is a competing renewable production route. Main advantage is that ethanol produced from carbon dioxide does not need additional agricultural area in tropical regions.

It should also be noted that ethanol has a valuable C–C bond and therefore can be converted into bifunctional molecules (such as ethylene and glycol). This makes ethanol a suitable raw material for making more complex chemicals and polymers, which should be from a renewable source if we phase out fossil feedstocks. Methanol is not an alternative in this respect. Therefore, in paragraph 3.3, the discussion will be limited to the production of polymers from ethanol.

As electricity costs are dominant in the total costs, it would be a promising idea to reduce the demand for reduction equivalents. This could be done by production of chemicals that contain more oxygen than methanol and ethanol, such as formic acid, glycol, or lactic acid. Unfortunately, it is not easy to steer biological fermentations that use a C_1 feed to produce C_2 and C_3 fermentation products. Currently all available research is still in an early laboratory phase. Hence this option was not considered.

3.3 Polymers

The production of ethanol from Dutch sugar factories is a potential feedstock for the chemical industry, for instance as feedstock for plastics production. It is interesting to compare the magnitude of this additional production to the present plastics demand of the Dutch society (see Fig. 6). The current use of plastics in the Netherlands, is around 1900 kton per year.[44] A substantial portion of the plastics is (partially) made from ethylene (PE 26.9%, PVC 12.9%, PET 6.2%[45]). The total amount of ethylene used in the production of these products is 638 kton per year (see Annex 6). This ethylene could be produced from ethanol. In total, 1048 kton per year of ethanol would be needed to produce the ethylene based portion of these plastics.

The role of recycling in future scenarios for the plastics industry has been investigated by several authors,[46,47] and the recycling rate (according to the authors) is expected to lie around 43%. The demand for virgin plastic could thus be reduced by 43% due to recycling practices. Furthermore, the EU has implemented regulations to reduce the amount of packaging by 15% in 2040.[48] Since packaging makes up approximately 40% of the market share of plastics, we assume an additional 6% reduction in demand for virgin plastics. For ease of calculation, we assume a total potential reduction of 50% virgin plastics demand in a 2050 scenario. In such a future scenario, 524 kton per year of ethanol may suffice.

It is interesting to see that the potential production of ethanol from the Dutch sugar beet factories side streams might account for 25% of the ethylene derived portion of today's virgin plastic demand of the Dutch society. From this 25%, 11% can come directly from molasses fermentation, a technology that is well established and the additional 14% may come from CCU, which is still at low TRL. If the demand is indeed reduced according to the 2050 scenario, the Dutch sugar beet refineries could contribute 50% of the future demand.

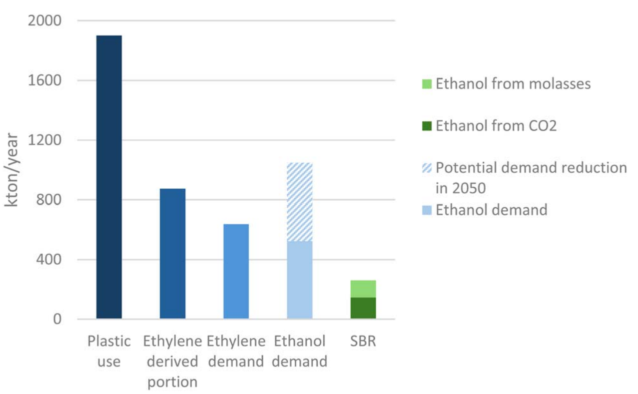

Fig. 6 Dutch plastic use, ethylene derived portion thereof, ethylene demand to produce ethylene derived portion, ethanol demand equivalent to ethylene demand, reduction potential in 2050 compared to the potential supply from Dutch Sugar Beet Refineries (SBR) as calculated in Annex 6.

3.4 Environment

When the side streams from existing sugar beet factories are used to produce chemicals, the carbon dioxide emissions could be reduced. Ethanol from molasses fermentation and methane from pulp anaerobic digestion could replace fossil alternatives. After use, these fossil alternatives would have emitted 473 kton carbon dioxide per year (Fig. 7). The use of carbon dioxide from molasses fermentation and pulp digestion could capture another 280 kton carbon dioxide per year, adding up to a total of 752 kton per year. These numbers are minor compared to the current Dutch carbon dioxide emission of 158 Mton per year,[49] but targets have been set to drastically reduce carbon dioxide emissions in the near future.[6]

In this light, the Dutch agro-industry could help to reduce carbon dioxide emissions and contribute to production of renewable chemicals and or polymers without the need to use extra land, provided renewable energy can be used.

As comparison, the carbon dioxide uptake of Dutch forests is around 4.6 ton CO_2/(ha per year).[50,51] To reach the 752 kton per year reduction, which the Dutch sugar beet production could contribute, a forest of 164 000 ha would be needed. That is more than 40% of the forest area in the Netherlands in the year 2021.[50,52] and twice as much as the area currently used for sugar beet cultivation.[34] This clearly shows that use of side streams from crop production may yield larger carbon dioxide capture than additional forestry.

All these aspects make the potential use of carbon dioxide side streams from the Dutch sugar beet production for CCU a more interesting option than it might seem at first glance.

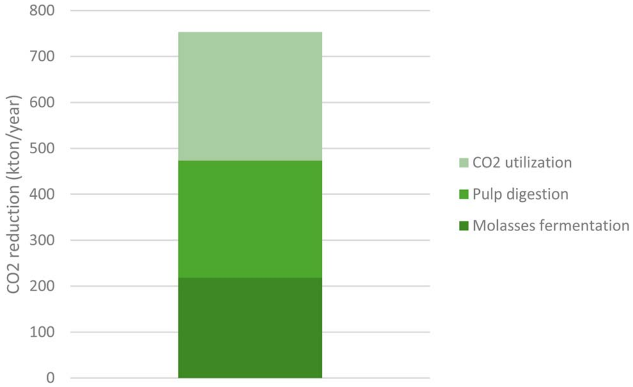

Fig. 7 Carbon dioxide emission reduction from sugar beet refinery residues (see Annex 6).

3.5 Global outlook

This paper has focused on the Dutch situation with carbon dioxide rich side streams from sugar beet processing as a resource for production of chemicals. Sugar beets, however, can be grown in many countries with a temperate climate (*i.e.* United Kingdom, Germany, Poland, Denmark). Using sugar production numbers from the European Association of Sugar Manufacturers,[53] the production of chemicals in the EU from sugar beet refinery residues could be a factor 13 larger than the production in the Netherlands (3.4 Mton of ethanol per year). The use of plastics in the EU is a factor 28 larger than in the Netherlands,[44,54] so around 25% of the plastic demand in the 2050 scenario could be fulfilled from sugar beet refinery residues.

Other crops have similar side products (*e.g.* sugar cane has molasses and trash as comparable side products). So, in many countries, carbon dioxide from agricultural side streams could be a relevant source for production of renewable chemicals.

Future electricity prices may be lower in countries near the equator, where the intensity of sunlight is higher or in countries where buffering of electricity supply/demand *via* hydro-electric storage is an option (Sweden, Switzerland, Brazil). Considering the high costs for electricity, CCU may be more profitable in these countries.

4 Conclusions

Side streams of the Dutch sugar beet production can potentially be used to produce 114 kton ethanol per year from molasses, 93 kton methane per year from sugar beet pulp, plus 146 kton per year of ethanol or 203 kton per year of methanol *via* CCU.

Compression, transport, and central large-scale thermochemical conversion of carbon dioxide to methanol is cheaper (1056 € per ton) than smaller scale fermentative conversion to ethanol (1738 € per ton). This is independent of the basis of comparison (weight, Higher Heating Value, carbon content, market price).

Ethanol produced from carbon dioxide is far more expensive (1738 € per ton) than the current market price of ethanol (452 € per ton, produced from sugar cane), even at lower energy prices.

Flexible use of surplus energy from sun and wind could reduce energy costs but would lead to higher capital costs. Assuming halved electricity prices and doubled capital investment costs, the costs of methanol production may be reduced by 29% and the costs of ethanol production may be reduced by 14%. Production costs of both chemicals from carbon dioxide are then still higher than their present market prices. Use of syngas and hydrogen storage reduces costs of ethanol production by 24% compared to the base scenario.

Sugar beet refineries could fulfil 50% of the ethanol needed for the ethylene based portion of the future plastic demand of the Netherlands assuming a reduction of plastic use for packaging and recycling applied to the max (22% from molasses fermentation and 28% from utilization of carbon dioxide rich side streams).

The use of sugar beet refinery side streams could capture 752 kton of carbon dioxide per year. This is equivalent to the carbon dioxide uptake of a forest of 164 000 ha, more than 40% of the current Dutch forest area and twice as much as the area currently used for sugar beet cultivation.

Altogether, extra ethanol from sugar beet refinery side streams (molasses, pulp, and carbon dioxide) comes at a cost, but could contribute to extra renewable chemicals/polymers production and a decrease in carbon dioxide emissions.

Author contributions

Koen P. H. Meesters: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, writing – review & editing, visualization. Marc P. Lanting: methodology, validation, investigation, writing – review & editing. Juliën A. Voogt: methodology, validation, investigation. Harriëtte L. Bos: conceptualization, methodology, writing – original draft, writing – review & editing, supervision, project administration.

Conflicts of interest

There are no conflicts to declare.

Abbreviation

CAPEX	CApital EXpenditures
OPEX	OPerational EXpenditures
CEPCI	Chemical Engineering Plant Cost Index
CO_{2eq}	Carbon dioxide equivalent
CoC	Cost of Capital (=0.2 €/(€ per year))
COP	Coefficient of Performance of heat pumps (heat output/electric energy input)
CCU	Carbon Capture and Utilization
HQE	High Quality Energy
LQE	Low Quality Energy
MWh	Unit of energy: 1 MWh is equal to 3.6 GJ
PE	Polyethylene
PET	Polyethylene Terephthalate
PVC	Poly Vinyl Chloride

RWGS Reverse Water Gas Shift
SBF Sugar Beet Factory
SBR Sugar Beet Refinery (a sugar beet factory with molasses fermentation and pulp digestion)
ton Unit of weight: 1 ton is equal to 1000 kg
USD United States Dollar

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: Annex 1 Carbon dioxide rich side streams from sugar beet factories, Annex 2 Carbon dioxide to ethanol via fermentation, Annex 3 Reverse Water Gas Shift, Annex 4 Methanol synthesis, Annex 5 Sum of RWGS and Methanol synthesis, Annex 6 Wider perspective, Annex 7 Transport of carbon dioxide to central facility, Annex 8 Storage costs, Annex 9 Overview of data used in Annex 1–8. See DOI: https://doi.org/10.1039/d5se01283j.

Acknowledgements

This research received no external funding. It was funded by the internal WUR program 'Towards a Circular and Climate Neutral Society', KB-34-003-032.

References

1 United Nations, *Paris Agreement*, 2015, 1–27.
2 M. Carus, L. Dammer, A. Raschka and P. Skoczinski, *Greenhouse Gases:Sci. Technol.*, 2020, **10**, 488–505.
3 P. Berkhout, H. Bos, J. Nel, A. Schut, T. Vellinga, F. Geerling-Eiff, *Key dilemmas on future land use for agriculture, forestry and nature in the EU*, 2024, DOI: 10.18174/676755.
4 *De Rol Van Biomassa in Een Duurzame Economie*, Natuur & Milieu, 2018.
5 IEA, Is carbon capture too expensive?, https://www.iea.org/commentaries/is-carbon-capture-too-expensive, accessed Oct. 10, 2024.
6 European Union, Directive (Eu) 2023/2413 Of The European Parliament And Of The Council Of 18 October 2023, 2023.
7 European Union, The European Green Deal, 2019.
8 CBS, Sugar beet harvest in Europe down, https://www.cbs.nl/en-gb/news/2019/24/sugar-beet-harvest-in-europe-down, accessed Oct. 21, 2024.
9 Z. Huang, G. Grim, J. Schaidle and L. Tao, *Appl. Energy*, 2020, **280**, 115964.
10 B. D. Heijstra, C. Leang and A. Juminaga, *Microb. Cell Fact.*, 2017, **16**, 60.
11 D. W. Griffin and M. A. Schultz, *Environ. Prog. Sustainable Energy*, 2012, **31**, 219–224.
12 D. Kennes, H. N. Abubackar, M. Diaz, M. C. Veiga and C. Kennes, *J. Chem. Technol. Biotechnol.*, 2015, **91**, 304–317.
13 M. Mohammadi, H. Younesi, G. Najafpour and A. R. Mohamed, *J. Chem. Technol. Biotechnol.*, 2012, **87**, 837–843.
14 E. Rezaei and S. Dzuryk, *Chem. Eng. Res. Des.*, 2019, **144**, 354–369.
15 R. M. Bown, M. Joyce, Q. Zhang, T. R. Reina and M. S. Duyar, *Energy Technol.*, 2021, **9**, 2100554.
16 M. González-Castaño, B. Dorneanu and H. Arellano-García, *React. Chem. Eng.*, 2021, **6**, 954–976.
17 L. Pastor-Pérez, F. Baibars, E. Le Sache, H. Arellano-García, S. Gu and T. R. Reina, *J. CO_2 Util.*, 2017, **21**, 423–428.
18 F. Rajaee, G. Guandalini, M. C. Romano and J. Ritvanen, *Energy Convers. Manage.*, 2024, **301**, 118009.
19 B. Lacerda De Oliveira Campos, K. John, P. Beeskow, K. Herrera Delgado, S. Pitter, N. Dahmen and J. Sauer, *Processes*, 2022, **10**, 1535.
20 H.-W. Lim, M.-J. Park, S.-H. Kang, H.-J. Chae, J. W. Bae and K.-W. Jun, *Ind. Eng. Chem. Res.*, 2009, **48**, 10448–10455.
21 K. M. Vanden Bussche and G. F. Froment, *J. Catal.*, 1996, **161**, 1–10.
22 Z. Wu, Z. Zhang, G. Xu, S. Ge, X. Xue and H. Chen, *Energy*, 2024, 300.
23 J. P. Lange, *CATTECH*, 2001, **5**, 82–95.
24 M. P. Lanting, J. A. Voogt, K. P. H. Meesters, D. S. Van Es, M. Bekker and M. E. Bruins, *Sustainable Energy Fuels*, 2025, **9**, 4660–4673.
25 Eurostat, Electricity price statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics, accessed Jun. 30, 2025.
26 Intelligen, SuperPro Designer, BeetSugar_v13.spf, 2024.
27 M. Hutnan, M. Drtil and L. Mrafkova, *Biodegradation*, 2000, **11**, 203–211.
28 O. Muzík, J. Kára and I. Hanzlíková, *Listy Cukrov. Reparske*, 2012, **128**, 246.
29 D. Humbird, R. Davis and J. D. McMillan, *Biochem. Eng. J.*, 2017, **127**, 161–166.
30 F. Chen and T. Morosuk, *Energies*, 2021, **14**, 7174.
31 S. Van der Meulen, T. Grijspaardt, W. Mars, W. Van der Geest, A. Roest-Crollius and J. Kiel, *Research to Progress*, 2020, pp. 1–85.
32 C. Maxwell, Cost indices, https://toweringskills.com/financial-analysis/cost-indices/, accessed Aug. 5, 2025.
33 European Central Bank, US dollar (USD), https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html, accessed Aug. 4, 2025.
34 P. Berkhout, H. Van der Meulen and P. Ramaekers, *Staat van Landbouw, Natuur en Voedsel: Editie 2023*, Wageningen Economic Research, 2023.
35 S. Lensink and I. Pisca, *Costs of Offshore Wind Energy 2018*, PBL Netherlands Environmental Assessment Agency, 2019.
36 M. Jouny, W. Luc and F. Jiao, *Ind. Eng. Chem. Res.*, 2018, **57**, 2165–2177.
37 D. Cocco, F. Serra and V. Tola, *Energy*, 2013, **58**, 635–643.
38 Z. Abdin, K. Khalilpour and K. Catchpole, *Energy Convers. Manage.*, 2022, **270**, 116241.
39 W. Cole and A. Karmakar, *Cost Projections for Utility-Scale Battery Storage: 2023 Update*, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2023, Report NREL/TP-6A40-85332.

40 J. Farbes, B. Haley, R. Jones, *Marginal abatement cost curves for US Net-zero energy systems*, 2021, https://www.edf.org/sites/default/files/documents/MACC_2.0%20report_Evolved_EDF.pdf.
41 The Engineering Toolbox, Fuels - Higher and Lower Calorific Values, https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html, accessed Dec. 10, 2024.
42 Trading economics, Ethanol, https://tradingeconomics.com/commodity/ethanol, accessed Dec. 6, 2024.
43 Methanex, Pricing, https://www.methanex.com/about-methanol/pricing/, accessed Dec. 6, 2024.
44 L. Snijder and S. Nusselder, *Plastic Use and Plastic Waste Processing in the Netherlands (Dutch)*, Delft, 2019.
45 Plastics Europe, Plastics—The Fast Facts 2023, https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/, accessed Aug. 5, 2025.
46 H. L. Bos, D. S. van Es and P. F. H. Harmsen, *J. Cleaner Prod.*, 2024, **458**, 142413.
47 J. Harrandt, M. Carus, C. vom Berg, *Evaluation of Recent Reports on the Future of a Net-Zero Chemical Industry in 2050*, 2024.
48 European Parliament, New EU rules to reduce, reuse and recycle packaging, 2024.
49 L. van der Net, N. Staats, P. Coenen, J. Rienstra, P. Zijlema, E. Arets, K. Baas, S. van Baren, R. Dröge and K. Geertjes, *Greenhouse gas emissions in the Netherlands 1990-2022, National Inventory Report 2024, RIVM report 2024-0017*, National Institute for Public Health and the Environment, RIVM, Bilthoven, The Netherlands, 2024, DOI: 10.21945/RIVM-2024-0017.
50 M.-J. Schelhaas, S. Clerkx and B. Lerink, *Zevende Nederlandse Bosinventarisatie : 2017-2021*, Wettelijke Onderzoekstaken Natuur & Milieu, 2022.
51 Staatsbosbeheer, Bos en CO2-opslag, https://www.staatsbosbeheer.nl/wat-we-doen/co2-opslaan/bos-en-co2, accessed Oct. 4, 2024.
52 G. van Maaren, J. Velthuis and G. op den Kelder, *Functievervulling en ontwikkelingen van bossen in Nederland*, Probos, 2024.
53 European Association of Sugar Manufacturers, CEFS statistics 2021/2022, https://cefs.org/wp-content/uploads/2023/04/CEFS-European-Sugar-Statistics-Report-for-the-marketing-year-2021-22.pdf.
54 Statista Research Department, Plastic waste in Europe - statistics & facts, https://www.statista.com/topics/5141/plastic-waste-in-europe.