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Modelling the future CO_2 abatement potentials of energy efficiency and CCS: The case of the Dutch industry

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ABSTRACT

Reaching the long term goals of climate policies requires the implementation of a portfolio of measures. This paper quantifies the potentials of energy efficiency technologies and CO_2 capture and storage (CCS) for seven Dutch industry sectors between 2008 and 2040. Economically viable energy efficiency technologies offer carbon dioxide (CO_2) emission reduction potentials of 25 ± 8% in 2040 compared to 1990 levels. Economically viable CCS options can raise the industry's total emission reductions to 39–47%. These potentials require abatement costs above 90 € (Euro) per tonne CO_2, but they are still not sufficient to reach European Union's long term emission reduction plans. While economically viable potentials of improving energy efficiency may exist in all sectors (energy efficiency improvements of 2% per annum (p.a.)), attractive CCS potentials exist in the fertilizer, basic metal and refinery sectors with abatement costs estimated at 25–120 €/t CO_2 for 2040. Implementing CCS in these sectors would reduce total industry's primary energy efficiency improvement rates from 2% to 1.6% p.a. and would increase total industrial energy use by at least 10%. Reaching higher emission reductions in the Dutch industry will require the implementation of a portfolio of measures including energy and materials efficiency, renewables and CCS.

1. Introduction

By 2008, economy-wide greenhouse gas (GHG) emissions of the European Union (EU) were approximately 11% below the 1990 level (5 gigatonnes (Gt) carbon dioxide equivalents (CO_2-eq) versus 5.6 Gt CO_2-eq) (UNFCCC, 2011). By 2050, the EU plans to achieve 80% reductions compared to 1990, resulting in total emissions of 1–1.2 Gt CO_2-eq (EC, 2011). According to the same plan (EC, 2011) each sector should reduce its emissions by more than 50% to up to nearly 100% (e.g. 54–67% CO_2 emission reduction in the transportation sector vs. 93–99% for the power sector). Manufacturing industry and refineries (hereafter jointly referred to as 'industry') should aim for 83–87% reductions (EC, 2011)[1]. Among the EU countries, the Netherlands accounted for about 4% of the total GHG emissions (205 megatonnes (Mt) CO_2-eq) in 2008. The share of GHG emissions from the Dutch industry is similar to the EU average (29%; 60 Mt CO_2-eq/yr) (PBL, 2010; CBS, 2011a) and CO_2 emissions represent 94% of the total industrial GHG emissions (57 Mt) (see Fig. 1)[2]. Although no country specific goals are mentioned in the roadmap (EC, 2011), Dutch industry may need to reach similar reductions as for the total EU industry[3]. Reaching these goals will require the deployment of various measures among which improving energy efficiency is considered as economically viable (e.g. Worrell et al., 2009). Although it offers large potentials, alone it may not be sufficient to reach such substantial reductions. CO_2 capture and storage (CCS) technology can play an important role, but it increases energy use and therefore it will have an adverse effect on energy savings. Also if industrial plants invest in CCS, plants' emissions would be reduced. Hence a lower share of emissions would be subject to the CO_2 price which may delay the implementation of energy saving measures. On the other hand, improvements in energy efficiency may reduce the need for CCS.

There are many studies which address the outcome of implementing different technologies together for the global industry as well as for selected regions (e.g. Moya et al., 2011; Banerjee et al., 2012; IEA, 2012; Deetman et al., 2013). While such studies are commonly not performed for the specific case of the Netherlands, the

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[1] The roadmap aims to stabilize the GHG emissions to 450 ppm_v (parts per million volume, CO_2-eq) by 2050 which would limit the mean global average temperature rise to 2 °C compared to the 1990 levels.

[2] 89% of the CO_2 emissions are from fuel combustion (51 Mt) and the remainder 11% of the emissions are non-energy related from industrial processes (e.g. emissions from mineral products and ammonia production) (6 Mt) (see Figure 1) (PBL, 2010).

[3] In this study, the potential differences between the goals of EU member states are excluded and we assume that the same plan for the EU will also apply to the Netherlands.

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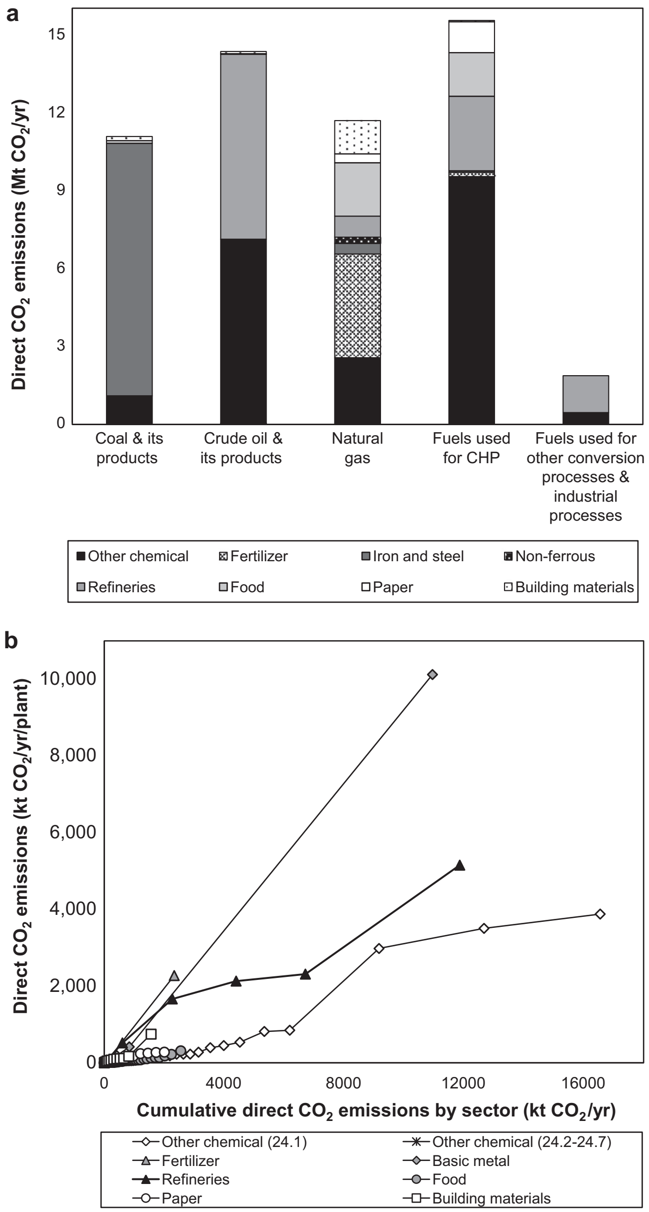

Fig. 1. Total direct CO_2 emissions of the Dutch industry sectors: (a) by fuel type and conversion (data include emissions from joint venture combined heat and power (CHP) plants which were originally excluded from the Dutch energy statistics (CBS, 1990–2008) and the national GHG emission inventories (PBL, 2010)) (own estimates based on CBS, 1990–2008, 2011a), (b) by plant (data includes emissions from CHPs which are covered in the Dutch energy statistics only) (own estimates based on ER (2011) and ECN/PBL (2010)).

analysis of industrial fuel use and the related CO_2 emissions in the Netherlands (e.g. Ramírez et al., 2005, 2006; Neelis et al., 2007) as well as the assessment of its reduction potentials through individual measures were central themes of various studies. These studies assessed the potentials of improving energy efficiency (e.g. Blok and Turkenburg, 1994; de Beer et al., 1996; Phylipsen et al., 2002; Saygin et al., 2013), CCS[4] (e.g. Damen et al., 2009; van Straelen et al., 2010; van den Broek et al., 2010, 2011; Berghout et al., 2013), switching to low carbon energy and raw material supply sources (e.g. biomass) (e.g. PGG, 2006; de Jong et al., 2006; Blaauw et al., 2008; Vesterinen et al., 2010) and improved materials efficiency (e.g. Worrell et al., 1995; Laurijssen et al., 2010; Corsten et al., 2010).

Among these measures, most research for the industrial sector has focused on conservation of fuel use by improving energy efficiency as it is a relatively cheap option (IEA, 2009a, Worrell et al., 2009). On the other hand, potentials and other technical and environmental issues related to CCS have mostly focused on the power sector (e.g. von Hirschhausen et al., 2012). Only few studies assess in detail the CCS potentials for the industry sector and they mostly focus on generic process designs (e.g. IEA, 2009a; UNIDO, 2010; Kuramochi et al., 2012). These studies mainly assess the reduction potentials in a few sectors, in particular those with high emissions and with high CO_2 concentration in the flue gases (e.g. iron, cement production, refinery processes). While this is justified by the current concentration of industrial CO_2 emissions, less energy intensive sectors consist of a large number of scattered plants which also provide capture potentials (e.g. >80 plants in the Dutch food sector, >20 plants in the paper sector) (see Fig. 1).

In view of these knowledge gaps which concern the lack of studies about the combined potentials of energy efficiency and CCS in the Netherlands and the limited sectoral coverage of present analyses, the main goal of this paper is to quantify the extent to which a portfolio consisting of both energy efficiency technologies and CCS technology could offer economically viable CO_2 emission reductions in the total Dutch industry compared to EU's long term plans and how CCS technology could influence the gains from energy efficiency.

This paper is organized as follows: In the next section, we describe the methodology and provide an overview of the input data. In Section 3, we project industrial CO_2 emissions in the Netherlands at sector level between 2008 and 2040 for various energy efficiency scenarios and identify which sectors offer the largest potentials for CCS. We then quantify the emission reduction potentials by improving energy efficiency and by CCS. Next, we discuss the validity of our findings in view of the limitation of our methodology and the uncertainties of our analysis and provide recommendations for future research (Section 4). We end this paper in Section 5 with conclusions which are relevant for policy makers and the industry.

2. Methodology

In the first two sections, we explain our methodology to estimate Dutch industry's CO_2 emissions between 2008 and 2040. Next, we explain the methodology to estimate the emission reduction potentials by improving energy efficiency and CCS.

2.1. Dutch industry's CO_2 emissions: 2008

We use a bottom-up model which was developed to analyze the industrial energy use in the Netherlands at product level (Ramírez et al., 2006; Neelis et al., 2007; Saygin et al., 2013). We use a modified version of the model to analyze the CO_2 emissions of seven industrial sectors based on the 62 most energy intensive products (see Appendices A and B). The sectors analyzed are the petroleum refineries and the other chemical, fertilizer, basic metal (total of iron and steel and non-ferrous metals sectors), paper (excluding printing and publishing), building materials and food sectors. For each product, the model includes: (i) The amount of energy consumed per physical unit of product (specific energy consumption

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[4] CCS comprises the separation of CO_2 from industrial and energy-related sources as well as the transport of CO_2 to a storage location where is isolated for long term from the atmosphere (IPCC, 2005).

(SEC), total use of fuels and heat in primary energy terms[5]) for the year 2008 and (ii) the production volumes for 2008.

We estimate the total direct CO_2 emissions ($TE_{j,2008}$ in Mt CO_2/yr) of sector *j* with *x* representing the number of selected processes for 2008 according to Eq. (1):

$$TE_{j,2008} = \sum_{x=1}^{n} \left(SEC_{x,j,2008} \times P_{x,j,2008} \times EEF_{x,j,2008} \right) \quad (1)$$

where $SEC_{x,j,2008}$ is the SEC for process *x* in sector *j* (in gigajoules (GJ) per tonne of product) in 2008, $P_{x,j,2008}$ is the production volume (in Mt/yr) of process *x* of sector *j* in 2008 and $EEF_{x,j,2008}$ is the estimated emission factor (in t CO_2/GJ) of process *x* of sector *j* based on the fuel mix of 2008 for that process (see Appendix A). We estimate the EEF by allocating the fuels consumed for energy purposes (e.g. naphtha in steam cracking process) to individual products in our model (e.g. ethylene) (CBS, 1990–2008; PBL, 2010).

2.2. Projections of CO_2 emissions: 2008–2040

In this study, we project industrial CO_2 emissions for three scenarios and analyze the period 2008–2040 based on earlier work by Saygin et al. (2013). These scenarios are:

(i) Frozen efficiency: no improvements in efficiency, i.e., $SEC_{x,j,2008} = SEC_{x,j,t}$,
(ii) Business as Usual (BaU): autonomous reductions in primary energy use of 1% per annum (p.a.) based on the historical achievements in the Netherlands between 1980 and 2008 (Ramírez et al., 2006; Neelis et al., 2007; Saygin et al., 2013),
(iii) Best practice and new and emerging energy efficient technology (BPT/EME): implementation of BPTs by 2025 and new and emerging technologies by 2040 in all industrial processes based on a literature review of energy efficiency technologies (Saygin et al., 2013).

To project CO_2 emissions, we first estimate the total direct CO_2 emissions of the frozen efficiency scenario ($TES_{j,t,e,2008}$ in Mt CO_2/yr) of sector *j* in year *t* for energy carrier *e* according to Eq. (2):

$$TES_{j,t,e,\text{frozen}} = \sum_{x=1}^{n} \left[\left(C_{j,e,2008} \times EF_e \right) \times \left(1 + r_{j,t} \right)^{t-2008} \right] \quad (2)$$

where $C_{j,e,2008}$ is total primary energy consumption of any of the four components ((i) final consumption energy use, (ii) final consumption non-energy use (accounting for carbon stored in end products of the sector), (iii) conversion balance for other conversion processes, and (iv) conversion balance for CHP) which constitute the *consumption balance* of sector *j* in year 2008 for energy carrier *e* according to Dutch energy statistics (CBS, 1990–2008; see Appendices A and B) (in petajoules (PJ) per year); *r* is the average annual growth rate of sector *j* between 2008 and year *t* (in % p.a.) (for the total industry 0.9 ± 0.3% p.a. for 2008–2040; see Appendices A and B), and EF_e is the emission factor of energy carrier *e* (in t CO_2/GJ)[6]. The sum of $TES_{j,t,e}$ for all energy carriers yields the sector's total CO_2 emissions based on the Dutch energy statistics ($TES_{j,t}$) (CBS, 1990–2008). We use a single scenario for the average annual growth rates based on the reference projections of ECN/PBL (2010) where the authors assume that growth is independent from the climate policy scheme (see Appendices A and B).

For the BaU and the BPT/EME scenarios (*z*), we use the estimated SEC values for each product according to Saygin et al. (2013). We then apply them to Eq. (1) to estimate the $TE_{j,t,z}$ of sector *j* for year *t*. Since our product selection does not cover the total CO_2 emissions of sector *j*, we estimate the uncovered CO_2 emissions (in Mt CO_2/yr) in year *t* for scenario *z* for component *c* of the Dutch energy statistics (CBS, 1990–2008) based on Eq. (3):

$$\textit{Uncovered emissions}_{j,t,z,c} = \frac{TE_{j,t,z}}{TE_{j,t,\text{frozen}}} \times TES_{j,t,\text{frozen},c} - TE_{j,t,z,c} \quad (3)$$

Eq. (3) assumes that the average CO_2 emission reductions (compared to frozen efficiency scenario) achieved at process level will also apply to uncovered processes of the sector. Adding the total of $TE_{j,t,z,c}$ and *Uncovered emissions*$_{j,t,z,c}$ gives the total direct CO_2 emissions for component *c* (in Mt CO_2/yr)[7]. The total of all components (*c*) yield the total direct CO_2 emissions of sector *j* in year *t* ($TE_{j,t,z}$).

Our methodology follows the sectoral emission accounting approach of the International Panel of Climate Change (IPCC, 2006). CO_2 emissions include: (i) direct emissions from fuel combustion (to generate process heat, steam or electricity by stand-alone or CHP units which are registered and fully or partly owned by the industry), and (ii) emissions from industrial processes (e.g. production processes of clinker or glass, limestone use in iron and steel production)[8]. Future CHP capacity is determined by multiplying the current fuel demand for CHP with production growth and by assuming that the demand for CHP products will decrease at the same rate energy efficiency improves (in %). Second, we assume that total fuel utilization efficiency of CHP plants will improve from historic levels of 75–85% (CBS, 1990–2008) to 85–90%, but we keep the load factor identical to the current industrial average of 62% (85% for the sensitivity analysis). Indirect emissions from the power sector (related to electricity use) and emissions from carbon stored in products either during use phase (e.g. urea, solvents) or at the end of product lifetime (e.g. post-consumer plastic waste incineration) are excluded.

2.3. CO_2 emission reduction potentials in the industry by improving energy efficiency and CCS: 2025 and 2040

We estimate the CO_2 emission reduction potentials for the years 2025 and 2040. We first estimate the potentials by improving energy efficiency (*EE*) for sector *j* in year *t* for scenario *z* according to Eq. (4):

$$EE_{j,t,z} = 1 - \frac{TE_{j,t,z}}{TE_{j,t,\text{frozen}}} \quad (4)$$

where *EE* is the *economic* potential of improving energy efficiency at a specific level of CO_2 price. Higher levels of *EE* can be achieved with higher CO_2 price (in EUR_{2008} (Euro) per tonne of CO_2).[9] We give indications of the required CO_2 price by comparing our energy efficiency scenarios to the climate policy scenarios of the International Energy Agency's World Energy Outlook (IEA, 2010). We apply this analogy due to the lack of recent data availability on the related costs. Despite a number of differences in the background assumptions (e.g. production growth, autonomous improvement

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[5] Primary fuel equivalent for steam production is estimated by dividing the specific steam consumption by a factor of 0.9 which refers to the conversion efficiency of industrial stand-alone steam boilers (Neelis et al., 2007).

[6] We use emission factors which are specific to the Netherlands (PBL, 2010). The methodology to estimate the fuel mix of each sector is explained in Appendices A and B.

[7] We repeat this calculation step for each component of the Dutch energy statistics (CBS, 1990–2008).

[8] Energy and industrial process related emissions of the industry are represented by categories 1A2 and 2 respectively, and the petroleum refineries are represented by the category 1AA1B (IPCC, 2006).

[9] Exchange rate in 2008 was 1 US Dollar = 0.68 € (IEA, 2009b).

rates), we expect BaU scenario energy efficiency improvements of 1% p.a. to match with the ambition level of IEA's (2010) *current* policies scenario (CO_2 price level of 23 and 32 €/t CO_2 in 2025 and 2040, respectively). The annual rate of BaU improvements can be doubled from 1% to 2% p.a. by implementing BPTs and new and emerging technologies (Saygin et al., 2013). The additional CO_2 price in the *new* policies scenario of the IEA (2010) (~5 € t/CO_2) could be too conservative to realize this increase. Therefore we regard IEA's most ambitious *450_{ppm} scenario* more realistic to reach higher levels of energy efficiency improvements. This scenario requires 51 and 92 €/t CO_2 by 2025 and 2040, respectively (IEA, 2010)[10] which is an increase by more than 10 times compared to the 2012 CO_2 price in EU-27 (~8 €/t CO_2) (PC, 2012).

For CCS, we estimate the potentials for the years 2025 and 2040 by assuming that a CO_2 capture unit will be implemented for each industrial plant currently in operation (290 plants, see Table 1). We assume that each plant will resume its activity between 2008 and 2040 with the exception of the single clinker plant (see Table 1). For this purpose, we estimate the direct CO_2 emissions at plant level in two steps:

(i) We use the emission source database prepared by the Dutch Pollutant Release & Transfer Register which refers to the activity level in 2008 (PRTR, 'Emissieregistratie' in Dutch; ER (2011)). We estimate the *frozen* efficiency scenario CO_2 emissions of each plant by assuming that emissions will increase in line with production increase of the sector where the plant belongs to,
(ii) We apply the sector level emission reduction potentials by improved energy efficiency according to Eq. (4), assuming that each plant will reduce its emissions at the same rate as the emissions of the sector it belongs to.

In a subsequent step, we categorize the industrial CO_2 emissions of the Dutch industry by size (kilotonnes (kt) CO_2/yr/plant) and CO_2 concentration in flue gas (CO_2 vol%) per sector (see Table 1) for all scenarios. By doing so, we identify which sectors are most suitable for CCS.

Next, we estimate the CO_2 abatement costs of CCS at sector level as the total costs of avoiding (i.e. CO_2 capture costs by taking into account the additional energy requirements of CO_2 capture and compression), transporting and storing CO_2. We exclude differences in process designs across individual plants and carry out the entire analysis at sector level. We analyze retrofitting CCS for all scenarios, but present and discuss the results for the BPT/EME scenario since Saygin et al. (2013) show that this scenario offers the highest energy efficiency improvements in the long term. Hence we estimate the CO_2 price required to achieve high levels of energy efficiency improvements and implement CCS technology. We also estimate the *economic* potentials of CCS by comparing the abatement cost estimates to the CO_2 price required to realize the BPT/EME scenario according to IEA (2010). We consider all options below the CO_2 price as economically viable.

According to Saygin et al. (2013), each industry sector will replace the current average technology by investing in new plants with BPTs (2025) and new and emerging technologies (2040). We retrofit all plants with amine based post-combustion (iron and steel plant being the only exception with physical absorption capture). We focus on post-combustion technologies only as they are suitable for retrofitting and have the advantage of being commercialized first (Page et al., 2009; Bhown and Freeman, 2011). We assume that a single CO_2 capture unit will treat the CO_2 flows generated in the main processes of each plant. CCS requires additional energy in the form of heat (e.g. for regeneration of the solvent) and electricity (e.g. pumps, blowers, compression). We gather the SEC of CO_2 capture technologies from a literature review. If specific data is not available for a given process, we apply a generic approach to estimate the SEC values based on the relationship between specific heat/electricity (excluding compression) consumption in a post-combustion process (in final energy terms) and the CO_2 concentration in flue gas (TNO, 2012). We assume that CO_2 needs to be compressed to supercritical phase (at 110 bar) for transportation which requires an electricity consumption of 0.4 GJ_e/t CO_2 (Damen et al., 2007; Koornneef et al., 2008). While capture related energy requirement values refer to the current situation, we assume 20–30% energy demand reduction potentials in 2040 compared to 2025 (Feron, 2005; Peeters et al., 2007). For compression, we assume 5% potentials (Peeters et al., 2007). We assume a CO_2 capture ratio of 90% (Kuramochi et al., 2010).

We evaluate two types of plant settings based on how the energy requirements of CCS are supplied[11]:

(i) Each industrial plant will invest in new natural gas-fired CHP capacity to meet the total heat demand of the CCS. CHP plants will also provide electricity to the CCS. Surplus electricity production will be sold to third parties. If more electricity is required, it will be purchased from the grid. Indirect CO_2 emissions due to electricity generation in power plants are assumed to be allocated to the sectors (see Table 2) (unlike the rest of the electricity consumption for industrial processes). We credit the avoided CO_2 emissions from surplus electricity sales which would otherwise be generated from power plants.
(ii) Each industrial plant will invest in new natural gas-fired standalone boiler capacity to meet the heat demand of the CCS. Electricity demand will be supplied from the grid.

In Tables 2–4, we summarize the technical and economic parameters and combine the information to estimate the CO_2 abatement costs of CCS from sector *j* in year *t* for scenario *z* ($CA_{j,t,z}$ in €/t CO_2). We first estimate the CO_2 avoidance costs according to Eq. (5) ($COA_{j,t,z}$):

$$COA_{j,t,z} = \frac{\sum_{p=1}^{n}\left[\alpha \times (IC_{s,p,j,t,z} + IC_{a,p,j,t,z}) + O\&M_{s,p,j,t,z} + O\&M_{a,p,j,t,z} + F_{s,p,j,t,z} + E_{s,p,j,t,z} - ER_{p,j,t,z}\right]}{\sum_{p=1}^{n}\left[\left(TCET_{p,j,t,z} \times CR_a\right) - TCS_s\right]} \quad (5)$$

where α is the annuity factor per year (estimated as $r/(1-(1+r)^{-L}$, *r* is the discount rate (in %) and *L* the economic lifetime (in years)), $IC_{s,p,j,t,z}$ and $IC_{a,p,j,t,z}$ are the installed plant costs of the energy supply system *s* and the CO_2 capture technology *a* for plant *p* of sector *j* in year *t* for scenario *z*, respectively (in million €); $O\&M_{s,p,j,t,z}$ and $O\&M_{a,p,j,t,z}$ are the operation and maintenance (*O&M*) costs of the energy supply system *s* and the CO_2 capture unit *a* for plant *p* of sector *j* in year *t* for scenario *z*, respectively (in million € per year),

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[10] We estimate the CO_2 prices in 2040 by extrapolating the CO_2 price trend between 2030 and 2035 (IEA, 2010).

[11] We exclude CO_2 capture from CHP plants or boilers which are implemented to supply energy to CO_2 capture process.

Table 1
Sectoral breakdown of number of plants, registered emissions and ranges of CO_2 concentration in the flue gas of the industrial plants in the Netherlands. Data refers to the situation in 2008. *Source*: Own estimates based on CBS (1990–2008) and ER (2011).

	Number of installations[a]	Registered emissions (kt CO_2)[b]	Average CO_2 concentration in flue gas (in brackets ranges from various plants)[c] (%)	References
Total chemical	122	16,940	–	–
Other chemical	117	16,900	8 (3–14)	IPCC (2005); Kuramochi et al. (2010, 2012)
Fertilizer	5	40	8 (7–10)	
Basic metal[d]	30	11,415	19 (5–25)	IPCC (2005); Kuramochi et al. (2010, 2012); Meerman et al. (2012)
Petroleum refineries	7	11,860	12 (3–35)	
Food	84	2550	8 (3–14)	IPCC (2005); Kuramochi et al. (2010)
Paper	28	2000	8 (3–14)	
Building materials	15	1600	9 (3–14)	
High purity sources[e]	4	2870	~100	UNIDO (2010)
Total of selected sectors	290	49,235	–	–

[a] In case data was not reported for 2008 (but reported for another year between 2005 and 2009), we corrected the 2005 data with the production growth rates between 2005 and 2008 (ECN/PBL, 2010).

[b] Data exclude the emissions from joint venture CHPs which are reported under the power sector emissions (CBS, 2011b).

[c] Data refers to combustion related CO_2 emissions with the exception of process related emissions from fertilizer (feedstock related) and basic metal (blast furnace gas (BFG)) sectors as well as from ethylene oxide production. We adapt the low and high end of the ranges by ±20% to re-estimate the average of each sector for the sensitivity analysis.

[d] We adapt the system boundaries of the iron and steel plant by including the carbon contained in the BFG which, in the Netherlands, is combusted in a power plant. In this way we account for all the carbon input to the sector (mostly from coke and coal use). In the rest of the study, we follow these adapted system boundaries.

[e] High purity sources include two ethylene oxide and two ammonia plants which emitted in total 55 kt and 2815 kt CO_2/yr, respectively (own estimates based on Neelis et al. (2007) and PBL (2010)). Emissions from ammonia production refer to natural gas use as feedstock, and they account for the CO_2 used in urea production in the Netherlands (based on 0.76 t CO_2/t urea) (Farla et al., 1995).

Table 2
Technical parameters of the energy supply systems. Values in brackets refer to the ranges used for the sensitivity analysis. *Sources*: CBS (1990–2008); van den Broek et al. (2011) own estimates.

	Steam boiler	CHP	Power plant
Fuel utilization efficiency to generate useful output (%)			
2025	90%	85%	N/A
2040	95%	90%	N/A
Power-to-heat ratio (PHR) (-)			
2025/2040	N/A	0.7 (0.4–1)	N/A
Capacity utilization rates (%) (CBS, 1990–2008)			
2025/2040	62 (85)	62 (85)	N/A
CO_2 emissions (t CO_2/GJ total output)			
2025	0.062	0.112	0.089
2040	0.059	0.105	0.01 (0.05)

$F_{p,j,t,z}$ and $E_{p,j,t,z}$ are the total fuel and electricity costs of energy supply system s from plant p of sector j in year t for scenario z, $ER_{p,j,t,z}$ is the total electricity revenues from electricity sales from plant p of sector j in year t for scenario z (in million € per year), $TCET_{p,j,t,z}$ is the total CO_2 emissions of plant p of sector j in year t for scenario z (in Mt CO_2/yr), CR_a is the CO_2 capture ratio of CO_2 capture technology a (in %) and TCS_s is the total CO_2 emissions from heat production and power generation from energy supply system s (in Mt CO_2/yr). All capital costs are multiplied with a factor of 1.43 to estimate the total capital requirements (total of equipment and installation costs, engineering fees, contingencies, owner costs and interests during construction) (Kuramochi et al., 2012). We include the additional costs related to transporting and storing CO_2 by systematically adding 10 €/t CO_2 to all plants based on a range of 2–16 €/t CO_2 estimated for various years between 2020 and 2050 in the Netherlands (Damen et al., 2009; van den Broek et al., 2010).

Specific capital costs of CO_2 capture units found from literature are assumed to refer to year 2025 (see Table 4). Several studies

Table 3
Economic parameters used in the analysis. Values in brackets refer to the ranges used for the sensitivity analysis.

	Units	2025	2040	References
Economic lifetime (L)	Years	25		UNIDO (2010)
Discount rate (r)	(%)	10 (5–15)		
Electricity price[a]	(€/GJ)	28 (21–35)	31 (23–38)	ECN/PBL (2010); IEA (2010); CBS (2011b)
Natural gas price[a]	(€/GJ)	10 (7–14)	11 (7–15)	
Capital costs				
CHP[b]	(€/kW_e)	330–630	300–570	GTW (2007)
Steam boiler	(€/kW_{th})	430 (325–535)		Azar et al. (2003)

[a] Ranges are determined based on variations of quarterly energy prices for the period between 1997 and 2008 in the Netherlands (CBS, 2011b). The electricity price excludes the additional costs from CO_2 price and or power generation from more expensive renewable technologies and CCS implementation. Surplus electricity is assumed to be sold at the market price.

[b] The low and high end values refer to electrical capacities of 450 and 10 MW_e, respectively. The maximum CHP efficiency is equal to 90% and the maximum achievable PHR is between 0.7 (for the smallest capacity) and 1.1 (for the largest capacity) (GTW, 2007).

Table 4

Selected CO_2 capture technologies for emission sources of the Dutch industry and the related technical and economic parameters used in the analysis.

		Average size (kt CO_2/yr)	CO_2 conc. in flue gas (%)	Heat requirements (GJ_{th}/t CO_2 captured)	Electricity requirements (incl. compression) (GJ_e/t CO_2 captured)	Specific capital costs[a] (€/t CO_2 captured/yr)	Further information on the technology selected	Application	References
Total chemical	2025	175	11	3.6	0.6	130–370	Chemical absorption (MEA)	All other processes (excl. CHP)	TNO (2003, 2012); Weikl and Schmidt (2010); Sherif (2010)
	2040	175	11	2.7	0.5	95–320		All other processes (excl. CHP)	
Basic metal	2025	430	25	3.0	0.5	40	Chemical absorption (KS-1)	Blast furnace (BF)[b]	Kuramochi et al. (2012)
			13	3.6	0.6	105	Chemical absorption (MEA)	All other processes (excl. CHP)	TNO (2003, 2012); NETL (2010)
	2040	530	95	–	1.0	20	Physical absorption (Selexol)	Advanced smelt reduction (HISarna)	Kuramochi et al. (2012)
			13	2.7	0.5	215	Chemical absorption (MEA)	All other processes (excl. CHP)	TNO (2003, 2012); NETL (2010)
Refineries	2025	1460	15	2.7	0.6	80	Absorption with mixed solvent	Hydrogen	TNO (2003,2012); NETL (2010); Meerman et al. (2012); Berghout et al. (2013)
			9	3.7	0.6	185–340	Chemical absorption (MEA)	All other processes of the refineries (incl. CHP)	
	2040	1290	15	2.0	0.5	60	Absorption with mixed solvent	Hydrogen	
			9	2.8	0.5	125–230	Chemical absorption (MEA)	All other processes of the refineries (incl. CHP)	
Food	2025	23	4–9	3.8	0.7	265–355	Chemical absorption (MEA)	All processes (incl. CHP)	TNO (2003, 2012); NETL (2010); Kuramochi et al. (2011)
	2040	25	4–9	2.9	0.6	230–260			
Paper	2025	66	4–9	3.9	0.7	355–390	Chemical absorption (MEA)	All processes (incl. CHP)	
	2040	30	4–9	2.9	0.6	235–270			
Building materials	2025	40	9–13	3.6	0.6	360	Chemical absorption (MEA)	All processes (excl. clinker production)	
	2040	40	9–13	2.7	0.5	250			
High-purity sources	2025	–	100	–	0.4	20–40	Compression only	Ethylene oxide, ammonia	
	2040	–	100	–	0.4	20–25			
CHP plants[c]	2025	–	3–14	3.8	0.7	300–360	Chemical absorption (MEA)	For all sectors	TNO (2003, 2012); NETL (2010); Kuramochi et al. (2010, 2011)
	2040	–	3–14	2.9	0.6	200–230			

[a] The specific capital costs refer to the equipment and installation costs. Ranges indicate the lowest and highest values used for that sector. The emissions of each plant of the sectors are broken down into the share of emissions from CHP plants, other process heat equipment (e.g. boilers/furnaces), specific processes (e.g. hydrogen production) and, if any, high purity sources and non-energy related emissions. The specific capital costs of CHP plants, specific processes and high purity sources are separately provided in the table. For other process heat equipment where detailed capital cost of CCS technology data was not found, we first scale the size of each CO_2 emission source (without a further breakdown by accounting for number of boilers or furnaces at site) after deducting the total emissions of the sources which were analyzed in detail and subsequently account for the CO_2 concentrations in the flue gas to estimate the capital costs of CO_2 capture units. The size of the reference emission source (scale = 1) used for scaling is 2.5 Mt CO_2 per year with a CO_2 concentration of 7% in the flue gas (TNO, 2003). Data provided in TNO (2003) is assumed to refer to 2003 and to total of equipment and installation costs only. We correct these values to 2008 based on EPPCI (IHS, 2012) indexes. The data for other process heat equipment is provided in the table under "all other processes". We apply a 25% range for the sensitivity analysis on the specific capital costs.

[b] Technology refers to an air-blown blast furnace which does not require modification.

[c] The average size of CHP plants differs per sector from as low as 1–20 MW_e/plant for the food sector to as high as 20–125 MW_e/plant in the chemical sector. While steam and gas turbine plants have the largest capacity (20–125 MW_e/plant), gas motors have the smallest (0.5–1.0 MW_e/plant) (CBS, 2011a). The output of industrial CHP plants are assumed to be consumed by the production processes.

estimate learning rates between 6% and 17% for post-combustion capture technologies for power plants (for flue gas desulphurization (FGD) units; Riahi et al., 2004; Rubin et al., 2007). Based on these learning rates and the ambition level of the climate policy, capital costs of CO_2 capture can be reduced by between 18% (baseline scenario, low learning rates) and 73% (ambitious climate policy scenario, high learning rates) by 2050 compared to today (van den Broek et al., 2009). For 2040, we assumed that the specific capital costs (excluding the compression units where no reductions apply) can be reduced by 45% compared to 2025 by technological learning[12]. We assume an *O&M* cost of 7% over the specific capital costs which could also be reduced by 18% (10–25% range for sensitivity analysis) due to technological learning (van den Broek et al., 2009) (see Table 4). In cases where capital costs refer to mature technologies for 2025 and 2040 (e.g. iron and steel sector), we directly use the data without applying these learning rates.

We present the uncertainties in our results as (±) around the mean value based on Saygin et al. (2013) where authors accounted for the various sources of uncertainties in the energy scenarios. Moreover, our results for the CCS analysis are subject to further uncertainties due to the numerous assumptions made and our data choice. We quantify the effect of the variations in the parameter values by a sensitivity analysis.

We compare the estimated industrial CO_2 emissions in 2025 and 2040 with the 1990 levels in the Netherlands to show whether improving energy efficiency and implementing CCS are sufficient to meet the goals of EU's long term plans[13]. Since no specific goals are provided for these years, we interpolate data available for years 2005 (20%), 2030 (34–40%) and 2050 (83–87%) to estimate the emission reduction goals for 2025 and 2040 as 31–36% and 59–64%, respectively.

3. Results

In the first two sections, we show Dutch industry's CO_2 emission reduction potentials (Section 3.1) and its emission structure at sector level (Section 3.2). We then present the economic potentials of CCS (Section 3.3). In Section 3.4, we compare the potentials of energy efficiency and CCS.

3.1. Dutch industry's CO_2 emissions: Energy efficiency only

By combining sector level production growth estimates (ECN/PBL, 2010) and the energy efficiency improvement potentials (Saygin et al., 2013), we estimate the following CO_2 emissions for the Dutch industry:

(i) Total direct CO_2 emissions will rise from 57 Mt CO_2/yr in 2008 to a total of 67 ± 7 Mt CO_2/yr in 2025 and 75 ± 8 Mt CO_2/yr in 2040 according to the *frozen efficiency scenario* (Fig. 2).
(ii) We estimate total direct CO_2 emissions of 57 ± 6 Mt CO_2/yr in 2025 and 56 ± 6 Mt CO_2/yr in 2040 according to the *BaU scenario* (i.e. stabilizing at the 2008 level). Compared to the frozen efficiency scenario, this is equivalent to 25 ± 11% emission reductions in 2040.
(iii) In the *BPT/EME scenario*, upgrading from the current technology level to BPTs offers reduction potentials of 25 ± 18% by 2025 compared to the frozen efficiency scenario or 13 ± 3% compared to the BaU scenario (Fig. 2). Implementing new and emerging technologies can reduce industrial CO_2 emissions by 36 ± 15% in 2040 compared to the frozen efficiency scenario or by 15 ± 6% compared to the BaU scenario (Fig. 2). This results in total direct emissions of 48 ± 4 Mt CO_2 in 2040.

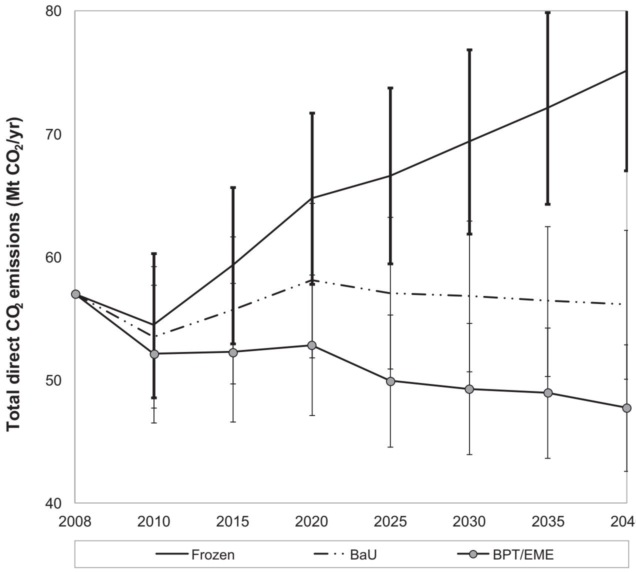

Fig. 2. Total direct CO_2 emissions of the Dutch industry for three scenarios. Error bars show the 95% confidence intervals of each scenario based on Saygin et al. (2013).

Fig. 3 shows the total direct CO_2 emissions and the savings achievable per sector in each scenario. We summarize the key findings according to the BPT/EME scenario below (see Appendix C for detailed results):

(i) In 2025, BPTs offer emission reduction potentials between 32 ± 10% and 39 ± 22% compared to the *frozen efficiency scenario* for various sectors. The iron and steel and the fertilizer sectors are exceptions with potentials of 15 ± 10% and 14 ± 4%, respectively. This is explained by the limited reduction potentials for coke and coal consumption in blast furnaces (for iron and steel sector) and our approach, where we assign all carbon input to the sector as emissions. Similarly, there are no savings in natural gas used as feedstock for ammonia production (~70% of the sector's total final energy use).
(ii) By implementing new and emerging technologies in 2040, the potentials increase by estimated 5% to 30% points compared to the BPTs for the sectors analyzed. We estimate the largest additional potential for the paper sector due to reductions in heat demand in the drying section of paper mills. The iron and steel sector is an exception with negligible additional savings compared to BPT (less than 2% points)[14].

In the short term (2025), improved energy efficiency allows reducing Dutch industry's CO_2 emissions by 11 ± 10% (BaU) below the 1990 levels (64 Mt CO_2/yr)[15]. This is about half of EU-27 goals

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[12] Modelling of cumulative installed CCS capacity is excluded from this analysis.

[13] 1990 CO_2 emissions are estimated as the total emissions of energy and industrial process related emissions of the industry, and petroleum refineries and emissions from fuel use in CHP plants which were not reported under the industry sector (PBL, 2010). We also add the carbon contained in the BFG combusted in the power sector (CBS, 1990–2008). We estimate this by multiplying the 1990 pig iron production with the ratio of BFG combusted in the power sector to total pig iron production in 2008. Total CO_2 emissions in 1990 are estimated as 64 Mt CO_2.

[14] Despite higher carbon input per tonne of hot metal (de Beer et al., 1998), smelt reduction is advantageous since flue gas has a higher CO_2 emission concentration which makes CO_2 capture easier (Kuramochi et al., 2012). See Section 3.2 for a more detailed explanation.

[15] This comparison and other comparisons throughout this study include CO_2 emissions from feedstock energy use and other industrial process emissions which cannot be reduced by improved energy efficiency.

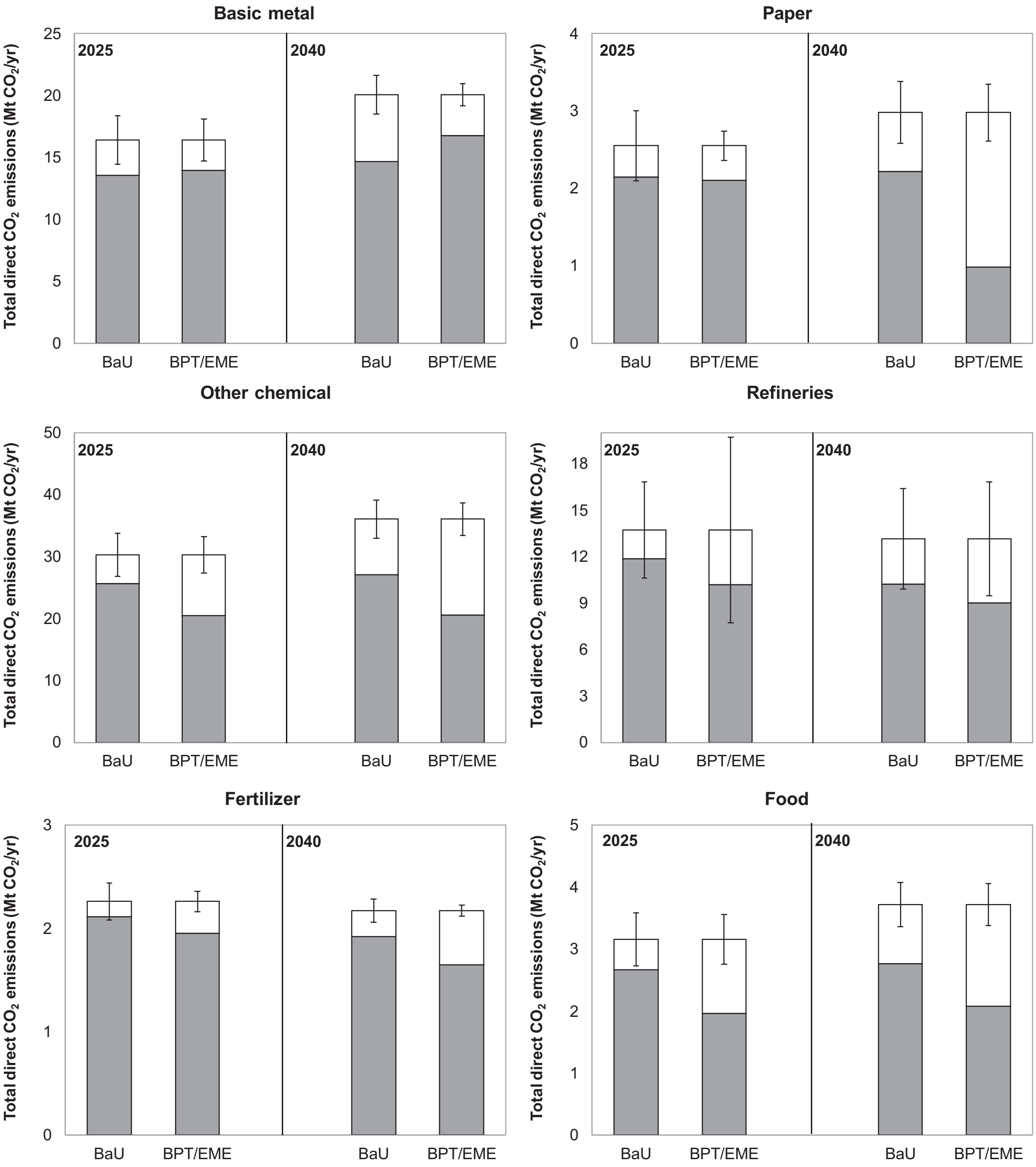

Fig. 3. Total direct CO_2 emissions of the BaU and BPT/EME scenarios (grey shaded bars) and the CO_2 emission savings by improving energy efficiency (white shaded bars) for each scenario compared to frozen efficiency. Building materials sector are excluded (<3% of the total industrial emissions).

to reduce 20% of total emissions. The reductions in the short and long term according to BPT/EME scenarios is higher, 22 ± 8% and 25 ± 8%, respectively which could be realized under the CO_2 price level of 92 €/t CO_2 by 2040 (i.e. IEA's *450ppm scenario*). In the long term, at such high levels of CO_2 price, implementation of BPTs (40–60 €/t CO_2) and other new and emerging energy efficiency technologies (85–100 €/t CO_2) would be economically viable (IEA, 2012), such as advanced catalysis and separation technologies for the chemical sector (e.g. IEA, 2012), process optimization and various technologies for the paper sector (e.g. Fleiter et al., 2012), improved thermal insulation (Neelis et al., 2012) and motor systems (i.e. fans, compressors, pumps) (e.g. McKane and Hasanbeigi, 2011).

The results of our analysis further show that implementing economically viable energy efficiency technologies in the Dutch industry according to the BPT/EME scenario can only meet about 40% of the EU's long term goals of 59–64% CO_2 emission reductions in 2040 compared to 1990 levels (EC, 2011).

3.2. CO_2 emission structure of the Dutch industry and suitability for CCS

Based on production developments and energy efficiency improvements, emissions of individual plants are estimated to grow by up to 25% and 7% according to BaU and BPT/EME scenarios, respectively between 2008 and 2025/2040 (see Table 5). About 70% of the total emissions will remain within the emission category of >1000 kt CO_2/yr/plant as today. In both scenarios, 8–9 plants will operate as large emission sources within this category. The iron and steel plant is projected to emit ~10–13 Mt CO_2/yr in 2025 and ~9–15 Mt CO_2/yr in 2040, with all other plants of the category (from refineries and the other chemical sector) emitting between 1–5 Mt

Table 5
Breakdown of total industrial CO_2 emissions by CO_2 emission size. *Sources*: Own estimates based on ECN/PBL (2010) and ER (2011).

	Average CO_2 emissions within the categories (kt CO_2/yr/plant)				Total CO_2 emissions covered by the categories (kt CO_2/yr)			
	>1000	100–1000	100–10	<10	>1000	100–1000	100–10	<10
2008	3780	265	35	4	34,000	10,075	3700	465
2025								
BaU	4740	320	40	4	41,250	11,785	4260	560
BPT/EME	4200	310	40	4	35,350	8770	4160	630
2040								
BaU	4800	325	40	4	43,325	12,700	4240	590
BPT/EME	4720	345	40	4	37,800	9000	4140	660

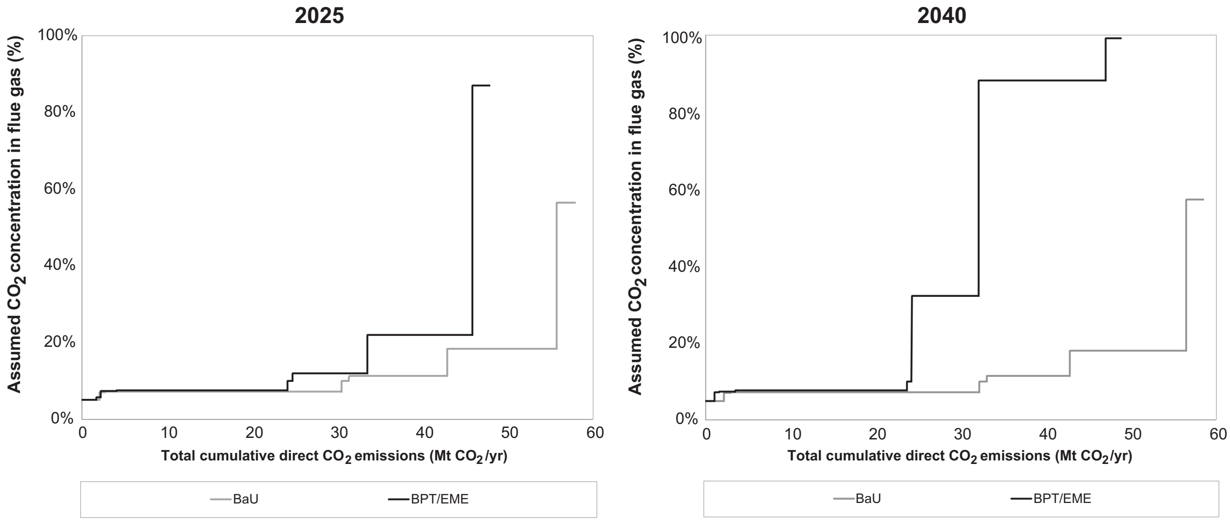

Fig. 4. Distribution of CO_2 concentration in flue gas as a function of the total cumulative direct CO_2 emissions of the Dutch industry at sector level.

CO_2/yr. Accounting for the plants within the 100–1000 kt CO_2/yr category also (on average 0.2–0.4 Mt CO_2/yr/plant), we cover 90% of Dutch industry's total emissions. Industry's emission structure will remain similar to the current situation and sectors which currently have the largest share of industrial emissions will remain so in 2025 and 2040. The majority of the CCS potential will remain in energy and carbon intensive sectors.

Average CO_2 concentration in the flue gases of the seven industry sectors analyzed will range from 5% to 85% in 2025 and from 6% to 95% in 2040 for both scenarios (Fig. 4). In the other chemical, paper and food sectors, most industrial process heat is provided by CHP plants with low CO_2 concentration in the flue gas (3–10%; IPCC, 2005) and the remainder by stand-alone steam boilers with a slightly higher concentration (7–14%; IPCC, 2005). We estimate that in 2025 and 2040, 50–55% of the total industrial CO_2 emissions will be emitted at a CO_2 concentration below 10%, requiring more expensive capture equipment and higher *O&M* and energy costs compared to high concentration sources. In comparison, high purity sources (>50%) account for about 4–5% of the total emissions in 2025. However, their share could increase to 40% in 2040 if advanced smelt reduction process with high CO_2 concentration in its off-gas replaces the blast furnace for iron making. By combining the information on the size of the emission sources (cut-off criteria, >100 kt CO_2/yr/plant) and the CO_2 concentration (cut-off criteria, >10%), we estimate approximately ~26 Mt CO_2 emissions which would be available for capture in the short and long term according to both scenarios.

3.3. Dutch industry's CO_2 emissions: energy efficiency and CCS

We estimate CO_2 abatement costs of 100–163 €/t CO_2 in 2025 and 71–93 €/t CO_2 in 2040 for the total Dutch industry for CCS technology (see Fig. 5)[16]. In addition to the CO_2 emission savings achievable by improving energy efficiency of 18 ± 11 Mt CO_2/yr (2025) and 28 ± 8 Mt CO_2/yr (2040) according to the BPT/EME scenario, CCS offers further potentials of 33–36 Mt CO_2/yr in 2025 and 38–42 Mt CO_2/yr in 2040 (accounting for the additional CO_2 emissions from the energy requirements of CCS). This is equivalent to about 85% emission reductions compared to the frozen efficiency level. About 40% of the reductions would originate from improving energy efficiency and the remaining 60% from CCS. In 2040, by improving energy efficiency and deploying CCS in all industrial processes Dutch industry can reduce its total emissions by 80% compared to 1990 levels. This is much higher than the 2040 goals of the EU roadmap (59–64%).

While CCS can make important contributions to emission reductions, a total of 10–13 Mt (2025) and 6–9 Mt (2040) CO_2 emissions will be generated due to energy requirements of capturing, transporting and storing CO_2 for the BPT/EME scenario (see Fig. 5). These additional emissions are about 25 ± 4% of the total captured emissions in 2025, but they could decrease to 15 ± 2% by 2040. The additional CO_2 emissions generated are 64% and 27% of the total emission reductions achieved by improving energy efficiency in 2025 and 2040, respectively. This would reduce total industry's annual primary energy efficiency improvements from 2.0 ± 0.5% p.a. (no CCS) to 0.5 ± 0.3% and 1.3 ± 0.2% p.a. in 2025 and 2040, respectively. The magnitude of additional CO_2 emissions mainly depends on the total energy requirements of CCS (and the related

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[16] These values refer to weighted average of all industry sectors in the Netherlands by accounting for each sector's total abated CO_2 emissions and their costs. The low and high ends of this range refer to whether CHPs and steam boilers/power plants provide the energy requirements of the CCS technology, respectively.

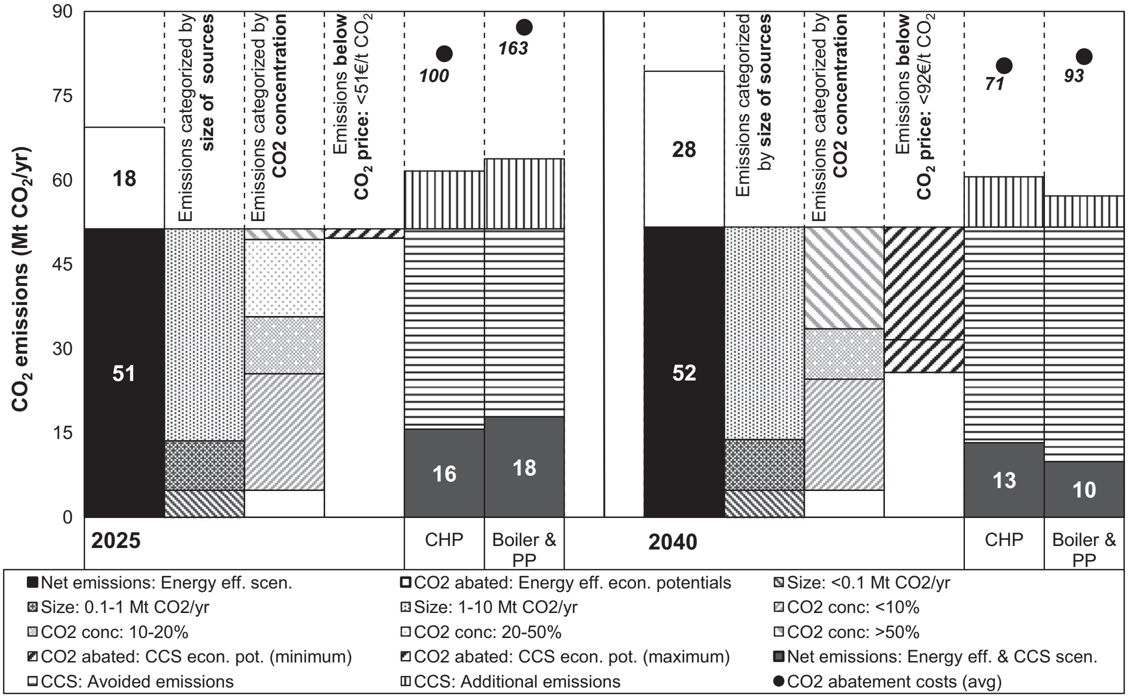

Fig. 5. Total direct CO_2 emissions of the Dutch industry based on the results of the BPT/EME scenario with a breakdown by emission savings from improving energy efficiency and CCS compared to frozen efficiency. PP: Power plant. Notes: We categorize the total industrial emissions (after accounting for the reductions achievable by improving energy efficiency indicated with white bars) by size of the emission sources (see Table 6 for the categories), CO_2 concentration at sector level (see Fig. 4) and economic viability at sector level (i.e. CO_2 abatement costs below the CO_2 price, see Table 6). The bars representing 'Net emissions: energy efficiency and CCS scenario' already account for the additional emissions from CCS which are also displayed separately in the figure.

improvements), but also on the deployment of CCS in the power sector (i.e. decarbonising power sector) (see Table 2) and the developments in technologies to supply the energy requirements of CCS (i.e. CHP or boiler/power plant) (Fig. 5).

In our model, we assume that CCS technology will be first deployed in the power sector (between 2008 and 2040) that leads to CCS capital and *O&M* costs reductions (van den Broek et al., 2009). However, if CCS does not deploy in the power sector, CO_2 abatement costs in 2040 could be 10–17 €/t CO_2 higher (assuming lower capital and *O&M* cost reductions of 25% and 10%, respectively and power generation emission intensity of 0.07 t CO_2/GJ_e)[17]. In contrast, with higher learning rates (i.e. capital and *O&M* cost reductions of 65% and 25%, respectively) abatement costs could be lower by up to 12 €/t CO_2.

We now present the CO_2 abatement costs and the contribution of CCS technology to emission reductions at sector level. In most sectors, CCS accounts for a lower share of the total CO_2 emission reduction potentials in 2040 (25–50%) as compared to 2025 (50–75%) since energy efficiency potentials are higher in 2040. CCS could play an important role in the fertilizer and the basic metal sectors in 2040 by accounting for more than 75% of their emission reduction potentials. Due to large share of emissions which originate from raw material use, energy efficiency improvements do not offer large potentials. We estimate the lowest abatement costs for the fertilizer (~32 €/t CO_2 and ~25 €/t CO_2 in 2025 and 2040, respectively), and the basic metal sectors (55–104 €/t CO_2 and ~42 €/t CO_2 in 2025 and 2040, respectively) (see Table 6). In the fertilizer sector, more than 90% of all CO_2 emissions originate from feedstock used to synthesize ammonia which is of high purity.[18] Early opportunities for CCS exist in the plants of the fertilizer sector as abatement costs are below IEA's CO_2 price of 51 €/t CO_2 (IEA, 2010). This is equivalent to 2 Mt abated emissions in 2025 and 2040.

In 2025, the estimated CO_2 abatement costs of the basic metal sector (55–104 €/t CO_2) are slightly above the CO_2 price in 2025. Capturing these emissions which are dominated by a single iron and steel plant (~95%) would add another 10 Mt CO_2 emissions abated. According to the BPT/EME scenario, we assume that iron would be produced by the smelt reduction process which has a high CO_2 concentration in its off-gas close to pure stream compared to the BFG with on average 25% CO_2 concentration[19]. This change, along with other improvements in CCS, reduces the sector's abatement costs by 7–62 €/t CO_2 between 2025 and 2040. If an improved blast furnace remains in operation, we re-estimate the abatement costs as 50–95 €/t CO_2 based on chemical absorption or the membrane technique (Kuramochi et al., 2012). Although these costs are higher compared to the case of smelt reduction, CCS could still be considered as an economically viable technology in 2040. In total, about 16 Mt CO_2 emissions could be abated below the CO_2 price from the basic metal sector in 2040.

These two sectors are followed by refineries with CO_2 abatement costs estimated at 119–180 € (2025) and 89–120 € (2040)

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[17] The higher end of this range excludes the iron and steel plant and high purity sources which we do not estimate their costs based on these learning rates because data is separately available for 2025 and 2040 (see Section 2.3). These plants account for about 35% of the total industrial CO_2 emissions in 2040 according to BPT/EME scenario.

[18] Currently, steam export from nitric acid production (high pressure) is typically utilized in steam turbines for power production (EFMA, 2000); however, we assume that some of this steam could also be used as heat source in sector's other production processes. In future, we assume that sector's all heat and electricity demand could be met by steam export from nitric acid production (for ammonia, urea and ammonium nitrate production processes). As a result, natural gas is required only as feedstock for ammonia production.

[19] From an energy point of view, smelt reduction consumes 20% less energy compared to the blast furnace (based on de Beer et al. (1998)). However, the coal input, thereby the CO_2 emissions per tonne of hot metal are about 10% higher compared to the blast furnace in the Netherlands (CBS, 1990–2008; Kuramochi et al., 2012).

Table 6
CO_2 abatement costs (in €/t CO_2) and overview of abated emissions (in Mt CO_2/yr) at sector level for the results of the BPT/EME scenario compared to frozen efficiency.

	CO_2 abatement costs		CO_2 abated: Energy efficiency		CO_2 abated: CCS (=captured – additional)		Net emissions (=frozen – energy efficiency – CCS)	
	2025	2040	2025	2040	2025	2040	2025	2040
Basic metal	55–104	42	2	3	9–10	16	4–5	1
Other chemical	124–199	95–132	10	16	14	14	7–8	7
Fertilizer	32	25	0.3	0.5	2	2	0.3	0.2
Refineries	119–180	89–120	4	4	7	6–7	3	2–3
Paper	156–237	122–152	0.4	2	1	1	1	0.4
Food	143–210	120–150	1	2	1	1–2	1	1
Building materials	146–217	115–143	0.4	0.6	0.4	0.4	0.2	0.2
Total	100–163	71–93	18	28	33–36	38–42	16–18	10–13
Economic potentials	<51	<92	*18*	*28*	2	20–26	49	25–31

Note: Data in italics represent uncertain results due to lack of data availability on costs of energy efficiency technologies.

per tonne of CO_2 (Table 6). Approximately, two-thirds of the sector's emissions are from process heaters/boilers (40–45% of the sector's total emissions) and CHPs (20–25%) which are abated at a cost above 140 €/t CO_2 due to low CO_2 concentration in the flue gas and the small size of the emission sources (CBS, 1990–2008, 2011b). Sector's remainder emissions are abated at 60–100 €/t CO_2 from hydrogen production (~30%) and the catalytic cracking process (~3%) with an average CO_2 concentration of 15% and 19%, respectively. CCS in refineries offers a further economically viable opportunity in the long term (2040) where a total of 6–7 Mt CO_2 emissions could be abated.

For the other chemical sector, we estimate abatement costs of 125–199 € (2025) and 95–132 € (2040) per tonne of CO_2 (Table 6). Although sector's emission sources are large (total of 19 plants cover 90% of the sector's total emissions with an average above 0.1 Mt CO_2/yr/plant), process heat demand of the sector is provided by small size CHP plants (40–45% of total CO_2 emissions) and numerous process heaters/boilers (55–60%) which are both estimated to have high abatement costs[20]. However, for the sector's six steam crackers, CCS offers economically viable opportunities in the long term at an abatement cost of approximately ~80 €/t CO_2 (i.e. 3 Mt CO_2 abated). Both in the short and long term, ~0.1 Mt CO_2 could be abated from the two ethylene oxide plants at an abatement cost of ~25 €/t CO_2.

For building materials, paper and food sectors, abatement costs are 110–150 €/t CO_2 in 2025 and 2040 (Table 6). This is due to the small size of these emission sources and the numerous small size CHP plants which provide process heat (CBS, 2011b).

In total, economically viable CCS can abate up to 2 Mt CO_2/yr in 2025, and as high as 20–26 Mt CO_2/yr by 2040 (Table 6). This also coincides with our earlier finding of 26 Mt CO_2 emissions which are available for capture in the long term (cut-off criteria: emission sources >100 kt CO_2/yr/plant and CO_2 concentration >10%, Section 3.2). Compared to all industrial emissions which could be abated by CCS (33–36 Mt CO_2), economically viable opportunities are equivalent to 5%. In the long term, this share could increase to 50–60% which we regard as the economic potentials of CCS.

We estimate that economic potentials of energy efficiency and CCS can together reduce total industrial emissions by 40–49% below 1990 levels in 2040 under IEA's 450_{ppm} scenario CO_2 price levels. These reductions are below EU's goals of 59–64% (EC, 2011). Industry would emit a total of 49 Mt and 25–31 Mt CO_2 in 2025 and 2040, respectively (see last row in Table 6). Most emission reductions in 2025 will be from improving energy efficiency. The contribution of energy efficiency technologies will be 50–60% in 2040 and the remaining reductions will be from CCS technology. CCS technology would, however, increase the total energy use of the four sectors by 20% to 32% and would consequently reduce the annual energy efficiency improvement rates of the total industry from 2.0 ± 0.5% to 1.6 ± 0.3% p.a. for 2008–2040.

3.4. *Comparison of the potentials of energy efficiency and CCS*

Improving energy efficiency can reduce Dutch industry's total energy costs by approximately 10.0 billion (i.e. 10,000 million) €/yr in 2040 compared to the frozen efficiency (see Table 7). Net reduction in energy costs, after accounting for the additional energy costs of CCS and the electricity revenues, is in the range of 1.8 billion €/yr in 2040. For the total CCS chain, we estimate total costs of 2.8–3.9 billion €/yr in 2040. The benefits from improving energy efficiency would be partly consumed to cover the additional costs of implementing energy efficiency technologies and especially CCS.

4. Discussion

In Section 4.1, we discuss our findings by comparison to other literature and in view of the sensitivity analysis results. We then provide a critical discussion of our methodology in Section 4.2.

4.1. *Discussion of results*

Our CO_2 *avoidance* cost estimates are similar to the findings of studies which analyze specific plant configurations in detail. Our estimates for refineries at 109–170 € and 79–110 €/t CO_2 compare well with the findings of van Straelen et al. (2010) (90–120 €/t CO_2). However, we estimate slightly higher costs than Berghout et al. (2013) for two Dutch refineries (i.e. 76–117 €/t CO_2 in 2025 and 69–98 €/t CO_2 in 2040) since while we assume a single CCS unit for each emission source, Berghout et al. (2013) model large scale CCS configurations to capture CO_2 from various processes simultaneously (e.g. hydrogen unit and CHP). For hydrogen production process, Meerman et al. (2012) estimate CO_2 avoidance costs of 37 €/t CO_2 for the short term (capture from between the water gas shift reactor and the pressure swing adsorption unit which accounts for 60% of the total plant emissions). Based on slightly higher energy prices and by capturing all CO_2 emissions from the process, we estimate avoidance costs of 61 €/t CO_2 for 2025. Our short term estimates for the iron and steel sector (39–94 €/tCO_2) are slightly higher than the findings of Kuramochi et al. (2012) (41–64 €/tCO_2) which is due to higher energy prices of our model as well as the different energy supply configurations for the CO_2 capture units. Kuramochi et al. (2011) estimate avoidance costs of 100–120 €/t CO_2 for small scale (<0.3 Mt CO_2/yr) refinery gas and natural gas industrial furnaces/boilers which matches our findings

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[20] In 2008, other chemical sector owned a total of 53 CHP plants which had a total electricity generation capacity of 1423 MW_e. This is equivalent to 26 MW_e per plant. Based on the annual operation rates of CHP plants in the sector (i.e. 67% in 2008), these plants emitted on average 87 kt CO_2/yr (CBS, 2011b).

Table 7
Comparison of the benefits, costs and potentials of energy efficiency and CCS (total industry). Results are based on the BPT/EME scenario and compared to the frozen efficiency.

		Energy efficiency		CCS		Energy efficiency & CCS	
		2025	2040	2025	2040	2025	2040
Total benefits (all sectors)[a]	(billion €/yr)	5.6	10.0	–	–	5.6	10.0
Total net costs of CCS (all sectors)[b]	(billion €/yr)	*?*	*?*	3.7–5.6	2.8–3.9	*?*	*?*
Total energy costs	(billion €/yr)	*?*	*?*	1.8–3.2	1.1–1.9	*?*	*?*
Total other costs	(billion €/yr)	*?*	*?*	0.8–2.6	1.0–2.1	*?*	*?*
Total electricity revenues	(billion €/yr)	*?*	*?*	−0.8–2.4	−1.0–0.8	*?*	*?*
Total CO_2 abated (all sectors)	(Mt CO_2/yr)	18	28	33–36	38–42	51–54	66–70
CO_2 abatement costs (all sectors)	(€/t CO_2)	*?*	*?*	100–163	71–93	*?*	*?*
Total CO_2 abated (economic potentials)	(Mt CO_2/yr)	*18*	*28*	2	20–26	*20*	*48–54*

Note: Question marks indicate the results which were unavailable and data in italics represent uncertain results due to lack of data availability.

[a] Benefits are estimated by multiplying the total reductions in the total fuel and electricity use of the Dutch industry (Saygin et al., 2013) with the energy prices (Table 3).

[b] Total net costs = energy costs + other (i.e. capital, O&M) costs − electricity revenues (all related to capturing, transporting and injecting CO_2).

for the chemical sector and refineries. Despite similarities of our findings with other studies, our bottom-up estimates, particularly for the long term, are subject to uncertainties due to background data and assumptions.

We quantify the effects of the variations in the parameter values over the CO_2 avoidance costs for 2040 (61–83 €/t CO_2) (see Fig. 6). CO_2 avoidance costs change by ±15% when the discount rates and energy prices are varied by ±50% and ±35%, respectively. Variations in the capital (±25%) and *O&M* (±70%) costs of CCS have ±10% effect over the avoidance costs. When the power-to-heat ratios of CHP plants are varied by ±45%, the costs change by ±13% due to the changes in the amount of electricity sold to or bought from the grid. Other parameter values have less than ±5% effect over our findings. As a result of variations in parameter values, CCS could also be economically viable for all plants of the chemical sector. In this case, Dutch industry's total CO_2 emission would be 65–70% below 1990 levels which is sufficient to meet EU's 2040 goals (59–64%). This would reduce the primary energy efficiency improvements further down to 1.3 ± 0.2% p.a.

Estimated CO_2 abatement costs for the total industry decrease by about 30–40% between 2025 (100–163 €/t CO_2) and 2040 (71–93 €/t CO_2). The decrease in capital and *O&M* costs due to technological learning and the lower energy requirements contribute to half of this decrease. The other major factor is the CCS technology applied in the iron and steel sector which consumes minor quantities of electricity and no heat while capturing substantial amounts of CO_2 (Kuramochi et al., 2012). Moreover, the sensitivity analysis showed that abatement costs are to a large extent determined by the energy costs. To deploy economically viable post-combustion CCS, less energy-intensive capture processes using advanced solvents will be required. Finally, research and deployment of CCS in both the power and industry sectors are necessary worldwide to accelerate technological learning.

4.2. *Discussion on other uncertainties and limitations of the methodology*

Based on sensitivity analysis results, we regard our model useful to assess the potentials of CCS at sector level and to generate first order estimates of the abatement costs for the total industry. However, our model and analysis could be further improved, in particular since the developments in other sectors of the economy (power, transport) and within the global industry are excluded. Accounting for these would broaden the uncertainty ranges which are currently based on the techno-economic components of our model only. Hence such developments could substantially change our results. We discuss these along with their potential effects in more detail below:

- Having in focus on the Dutch industry sector only, our study considers to a limited extent that the industry sector is globalized and that many factors influence the production volume and where it will be located. In the past decades, industrialized countries have experienced production re-location to developing

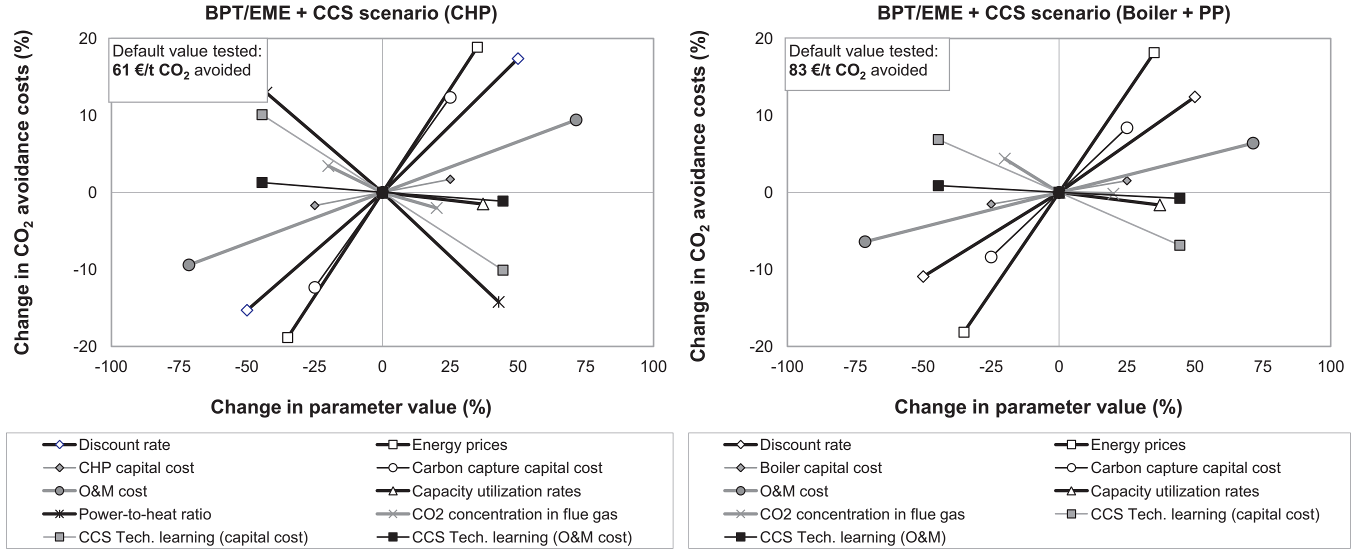

Fig. 6. Sensitivities of the CO_2 avoidance costs to the changes in parameter values (in %) expressed as a percentage deviation from the original model output for year 2040.

countries due to loss of competitiveness (e.g. increasing energy prices, high transportation costs). Similar to the cement sector in our model, other Dutch industry sectors may also experience similar trends (e.g. iron, chemicals) in future due to similar reasons and also from additional cost burdens of climate policies. Such interactions are excluded from our model but they could strongly influence the costs and deployment of energy efficiency and CCS technologies as well as the production volumes. Moreover, in view of EU's long term emission reduction goals, further scenarios on the development of production volumes should be analyzed and the impacts on industry's CO_2 emissions should be assessed.

- Given the fact that energy efficiency and CCS technologies are not sufficient to reach EU's long-term CO_2 emission reduction goals, renewable energy technologies are required to close the gap. To take this into account, our model needs to be extended by assessing the economic viability of process heat generation from biomass-fired boilers and solar thermal and geothermal heat technologies. Under high CO_2 prices and favourable energy prices, renewable energy technologies could be economically viable and contribute to reaching EU's emission reduction goals. Based on their abatement costs and reduction potentials, investing in renewable technologies could gain more priority, thereby leaving less need to energy efficiency and CCS technologies compared to their potentials estimated in this study. Similar developments could also be the case in the power sector. This would impact the cumulative investments of the CCS technology and the capital cost reductions. More combinations including renewable energy technologies at regional and global level should be investigated by developing further scenarios.
- While we assumed 45% reductions in capital costs of the capture units, reductions could be from as low as 18% to as high as 70% based on observed learning rates of FGD units (van den Broek et al., 2009). The size of industrial emission sources is smaller compared to those of the power sector and they vary with respect to their flue gas composition. This may require tailored CO_2 capture units. In view of these uncertainties, capital cost reductions could be different than what we assumed impacting the economic viability of CCS in the long term. Furthermore, a more detailed analysis differentiating between CCS in the power sector only as opposed to the combined implementation of CCS in the power sector and in industry would help to gain better insights into the potential technological learning for CCS.
- Our long term energy efficiency analysis is simplified since we assumed that all plants will implement BPTs by 2025 and new and emerging technologies by 2040 without modelling the incremental technology transition between the two levels. For some industry sectors, information on new and emerging technologies was available; while for others only old information had to be used (see Saygin et al. (2013) for a detailed discussion). With more cost and performance data of new and emerging technologies, the abatement costs of energy efficiency technologies could be estimated in a more reliable manner.
- We quantified the energy efficiency potentials at sector level and approximated our findings to individual plants. For CCS, we collected data from literature referring to specific processes and applied them to the entire sector. The long term abatement cost estimates of the CCS technology need to be improved and our assumptions need to be refined by more plant and process specific analysis, thereby accounting for different process configurations and site specific issues such as space availability or process integration potentials.
- We estimated the economic potentials based on a CO_2 price ceiling according to IEA's 450_{ppm} scenario. While the short term CO_2 price of this scenario is similar to other literature (see Tol, 2012), the long term price may be too low compared to the scenarios of other studies which similarly seek to stabilize global CO_2 emission concentration in the atmosphere at 450 ppm_v (200 €/t CO_2; van den Broek et al., 2011). Differences in the background assumptions explain the variations in price levels across studies, such as GDP and population growth, discount rates, sectoral developments, energy prices, technological learning, potentials of mitigation options and different policy settings. Improved modelling based on the aforementioned suggestions and comparisons of our estimates to the CO_2 price levels determined by other models will improve our findings.
- We exclude the limitations in CCS deployment related to spatial differences in CO_2 storage availability. Given the potential competition for storing CO_2 and the limitations in storage availability (e.g., Damen et al., 2009), this issue requires special attention in future research and can be overcome by geographic information system (GIS) type modelling.

5. Conclusions

In this study, we modelled and analyzed the potentials of improving energy efficiency and CCS for the Dutch industry. Our analysis shows that improving energy efficiency alone (25 ± 8% reductions compared to 1990) will not be sufficient to reach substantial CO_2 emission reductions in the long term. In the short term, economically viable early opportunities for CCS exist in the fertilizer sector. With moderate technological developments, long-term opportunities exist also in the iron and steel sector, refineries and in several plants of the sector "other chemicals". By implementation of economically viable potentials of CCS in these sectors, and by improving energy efficiency in the entire industry, total industrial emissions in the Netherlands could be 39–47% lower in 2040 compared to the 1990 levels with a CO_2 price assuming 92 €/t CO_2 according to IEA's 450_{ppm} scenario. However, these potentials are not sufficient to reach the long term EU goals. Economically viable CCS requires worldwide simultaneous deployment in the power and the industry sectors, thereby making best possible use of the technological opportunities. Industrial CCS can contribute to large reductions in CO_2 emissions as aimed by the EU for the long term; however, industrial energy use would increase and could reduce annual energy efficiency improvement rates in the Netherlands from 2% to 1.3–1.6% p.a. This is equivalent to an increase in industrial energy consumption of 11–22% (or 70–145 PJ) by 2040, compared to the energy efficiency scenario excluding the implementation of CCS. This is an important trade-off to consider in designing future climate and energy policy. Given the concerns about security of energy supply, the energy penalty of CCS may limit its deployment, next to other barriers (e.g. public perception). The successful transition to a low-carbon Dutch industry will hence require a combination of renewable energy technologies alongside energy efficiency and CCS as well as a mix of policies to ensure the deployment of these technologies. Therefore future modelling efforts should investigate and include the potentials of all measures, namely energy efficient breakthrough technologies which are not covered in this analysis, renewable energy technologies and material efficiency.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2013.05.032.

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