

# Energy demand and emissions of the non-energy sector

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The demand for fossil fuels for non-energy purposes such as production of bulk chemicals is poorly understood. In this study we analyse data on non-energy demand and disaggregate it across key services or products. We construct a simulation model for the main products of non-energy use and project the global demand for primary fuels used as feedstocks and the resulting carbon emissions until 2100. The model is then applied to estimate the potential emission reductions by increased use of biomass, a more ambitious climate policy and advanced post-consumer waste management. We project that the global gross demand for feedstocks more than triples from 30 EJ in 2010 to over 100 EJ in 2100, mainly due to the increased demand for high value chemicals such as ethylene. Carbon emissions increase disproportionately (from 160 MtC per year in 2010 to over 650 MtC per year in 2100) due to greater use of coal, especially in ammonia and methanol production. If biomass is used, it can supply a large portion of the required primary energy and reduce carbon emissions by up to 20% in 2100 compared to the reference development. Climate policy can further reduce emissions by over 30%. Post-consumer waste management options such as recycling or incineration with energy recovery do not necessarily reduce energy demand or carbon emissions.

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## Broader context

Due to the fears associated with the growth in greenhouse gas emissions, there is an increasing interest in understanding how these emissions are related to fossil fuel use and the mitigation possibilities. Most assessments focus on reducing the combustion of these fuels in the energy system. However little attention has been paid to the possibility to reduce emissions from the *non-energetic* use of fossil fuels, *i.e.* use as feedstocks for the production of chemicals. Feedstocks account for 10% of the total primary energy supply, and 7% of global CO<sub>2</sub> emissions and these are set to increase with rising global affluence. Analysis of this sector is complicated by the multiple material flows of these processes as well as the difficulty in assessing the supply and demand of different feedstocks. Yet it is important to understand how the fuel demand of this sector and its emissions may develop and assess different possibilities for reducing energy demand and emissions. Such possibilities include the use of bio-based polymers, climate policy and material efficiency measures such as recycling and waste incineration. We developed a simulation model highlighting key issues and evaluated different possibilities of reducing energy demand and emissions of this sector.

## 1. Introduction

In the analysis of mitigation strategies, much attention is currently paid to the anthropogenic carbon dioxide (CO<sub>2</sub>) emissions associated with the use of fossil fuels for energy purposes. Still, around 10% of the total primary fossil energy supplied worldwide is used for non-energy purposes. Non-energy use of energy carriers is defined as “*fuels that are used as raw materials [...] and are not*

*consumed as a fuel or transformed into another fuel*”.<sup>1</sup> Main uses include (i) feedstock for the production of chemicals such as ethylene, methanol and ammonia in the chemical and petrochemical sector and (ii) coke oven and oil refinery products such as waxes, lubricants, aromatics and bitumen in the energy transformation sector. The share of non-energy use relative to total energy requirements has been increasing<sup>2</sup> and, on a global scale, non-energy usage is responsible for up to 7% of global CO<sub>2</sub> emissions and 15% of industrial emissions.<sup>3,4</sup>

By far, the main energy carrier used for non-energy purposes is oil (75% globally, >90% in the OECD countries). However, also coal and gas are increasingly being used.<sup>2,5</sup> An option to reduce the fossil fuel use for non-energy purposes, and the related CO<sub>2</sub> emissions, is fuel switching (including renewable feedstocks). Recent advances in technology have allowed biomass-based routes to substitute production processes starting from fossil fuels *via* the production of bio-based ethylene, methanol and ammonia next to other widely used compounds as well as novel chemicals that may

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replace fossil-based chemicals.<sup>6–9</sup> The recent Special Report on Renewable Energy Sources of the Intergovernmental Panel on Climate Change (IPCC) highlighted the lack of global studies focusing on the emission reduction potential of biomass for such industrial processes.<sup>10</sup> Further possibilities to reduce the energy demand and emissions are increasing the efficiency of material use<sup>11</sup> or recycling of chemicals and energy cascading where embedded energy in non-energy products can be retrieved.<sup>6,7,12–14</sup>

In order to assess the potential to reduce non-energy emissions, projections of the non-energy demand and feedstock use are needed. Unfortunately, most current projections of global non-energy use are based on aggregate and opaque model descriptions.<sup>15–18</sup> These studies, therefore, provide little insight into the potential to reduce emissions. Complications in assessing this sector arise due to complex material flows, numerous products and different end products being the raw material for other production processes.<sup>11,19,20</sup> Difficulties also arise because of ambiguities in non-energy data sets and uncertainties concerning emission accounting.

This study presents a global model (Non-Energy Demand and Emissions model, NEDE) in which the final demand of the non-energy sector is disaggregated over several key products. Feedstock substitution is determined by the associated costs for the final product. The energy and mass flows of representative non-energy processes are calibrated across a consistent global database. The future projections of the non-energy products are driven by exogenous economic, population and fuel price developments. The model is used in order to investigate the emission reduction possibilities of the non-energy sector *via* substitution (in particular the use of bio-based feedstocks), climate policy and increased material use efficiency (including recycling and incineration with energy recovery from post-consumer waste). The model is designed as a part of the IMAGE/TIMER integrated assessment model which provides a description of global environmental change, including the use and production of bioenergy.<sup>21–24</sup>

The paper is structured as follows. Section 2 gives an overview of the non-energy use and introduces the data set used to construct the model. Furthermore, a comparison between the data set and the IEA energy balances is provided. Section 3 introduces the model outlining the demand functions, processes involved, substitution dynamics as well as the method used to account emissions. Also a description of the scenarios projected with the model is given. Section 4 presents the primary non-energy demand and emission projections for the scenarios. Section 5 offers a discussion on the model's sensitivities and uncertainties. Section 6 summarizes the results and draws conclusions.

## 2. Non-energy use

### 2.1. Overview

*Primary energy* can either be used as a *feedstock* (*i.e.* converted to a product in which it is embodied) or as *process energy* (*i.e.* consumed in the conversion process). *Net energy* use for non-energy purposes is the primary energy used as a feedstock without the required process energy. *Gross energy* for non-energy purposes is the total (feedstock + process) primary energy used to produce *final products* of the non-energy sector. Throughout this paper,

unless otherwise stated, the term *non-energy use* is synonymous with gross energy use. The products of the non-energy sector are used as materials and therefore, the output is mostly quantified in mass terms (tonnes). Since this paper deals with the integration of non-energy use in an energy model (TIMER) we choose to express the production volumes of final products and the raw material inputs in energy terms, *i.e.* gigajoule (GJ) primary, final, feedstock or process. Primary energy is converted to final products at a given conversion efficiency ( $GJ_{\text{Final}}/GJ_{\text{Prim}}$ ). The primary energy carriers included in this study are: coal, oil, natural gas, and biomass. Electricity can be used for process energy.

In the model, the final products of non-energy have been aggregated into four distinct classes (products) whose definitions are broad enough to capture the diversity of non-energy uses while maintaining a simplified representation.‡

- *Steam cracking.* This process produces the building blocks of the organic petrochemical industry, namely ethylene, propylene, butadiene and aromatics (benzene, toluene and xylene). In this paper these products are referred to as *High Value Chemicals (HVC)* according to the definition in Ren *et al.*<sup>25</sup>

- *Ammonia production.* Ammonia is used as the raw material for fertilizer production (90%) or a feedstock for further chemical production (10%).<sup>26</sup> Ammonia is produced by the Haber–Bosch process where hydrogen is reacted with nitrogen at a high pressure over a catalyst. Hydrogen can be derived from natural gas or oil (*via* steam reforming), coal or biomass (gasification). Currently, natural gas is used as the main feedstock in most countries with the exception of China, which uses significant amounts of coal.<sup>14</sup>

- *Methanol production.* Methanol is primarily used for the production of various chemicals (*e.g.* formaldehyde) or it is used directly as a solvent.<sup>27</sup> Syngas produced from natural gas, petroleum products or coal is reacted with hydrogen over a catalyst to produce methanol.<sup>28</sup>

- *Refinery products.* These are the heavier refinery products obtained from the distillation of crude oil and consumed for non-energy purposes. The main products are lubricants, aromatics (BTX – benzene, toluene, xylene) and bitumen.

### 2.2. Historic non-energy use

We have assessed the historical non-energy use for the above products for each of the 26 regions of the IMAGE/TIMER model.<sup>29</sup> Non-energy use of each product is estimated as the product of production volumes and so-called specific non-energy use.§ Production capacities of steam cracking and refinery products are available from the *Oil Gas J.*, ammonia from the US Geological Survey and methanol from the Methanol Institute.<sup>30–33</sup> Production volumes are subsequently estimated by assuming a capacity

‡ Non-energy products, which are not accounted for are soda ash, anodes for aluminium production, carbon black and carbides. They account for a minor part of non-energy use (<5%).<sup>14</sup>

§ Specific non-energy consumption is defined as the factory gate-to-factory gate final energy use required to produce one unit (*e.g.*, one tonne or GJ) of the chemical. It excludes the energy use of processes outside the chemical production processes such as mining and extraction of fuels. For steam cracking, it excludes backflows to refineries.

utilization rate of 90%.<sup>20</sup> As mentioned above we used the *gross* non-energy which includes the related process energy used for the production of these products. We chose to do so due to limitations in the IEA data. The IEA questionnaires request all countries to report their non-energy use based on the net definition of the non-energy use, but studies have shown that most countries do not report their non-energy use by following these questionnaires.<sup>19,20</sup> Specific non-energy use and process energy use data are from the study by Weiss *et al.*<sup>20</sup> and they refer to the global average situation in 2000.

Fig. 1 shows the energy use of the non-energy sector estimated according to the bottom-up methodology described above (aggregating the contribution by product) for some key regions as well as at a global level. Also shown is the total net non-energy use as reported in IEA energy statistics.<sup>34</sup> Globally, the shares of the categories mentioned above were 41%, 25%, 5% and 28% for HVC, ammonia, methanol and refinery products, respectively, in 2007. Western Europe and the USA account for almost half of the global non-energy use (primarily for HVC and refinery products). However, their total volume has not increased during the investigated period. In other regions, where growth rates are significant, ammonia and methanol production take a larger share of the non-energy use. A discrepancy between the bottom-up data and the IEA non-energy estimates for total non-energy use is clearly visible. Though the two approaches show similar trends, the difference in the volume of non-energy use between the two approaches for the 1996–2007 period confirms the earlier findings of Weiss *et al.* regarding the inconsistencies in 2000.<sup>20</sup>

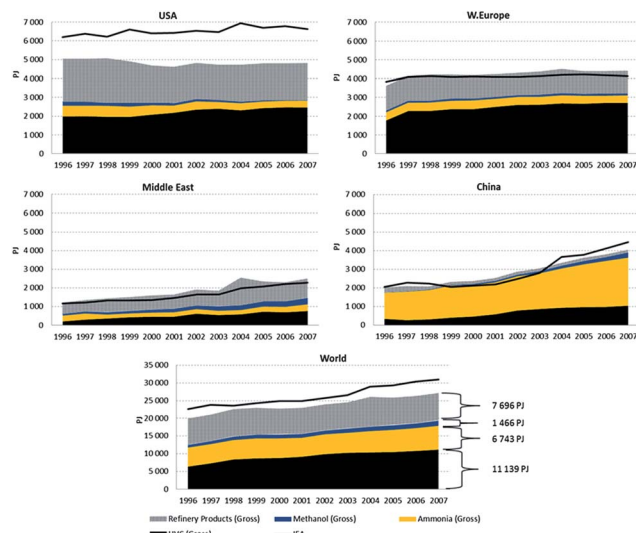


Fig. 1 Gross consumption of non-energy (PJ) for four key regions (accounting for over half of global capacity) and world total, disaggregated over 4 non-energy products. Also included is the total non-energy use as reported by the IEA.

### 3. Non-energy demand and emissions (NEDE) model

The NEDE model is a global long-term simulation model designed to get insight into trends in primary energy use for

non-energy purposes up to the year 2100 and the possible mitigation strategies in this sector. The model describes the non-energy use for the 26 IMAGE/TIMER regions. The long-term focus of the model implies that it needs to aggregate detailed bottom-up data. It does so by linking the non-energy sector's energy demand to the non-energy use products outlined in Section 2.1 and representative production processes in order to maintain both relevance and functionality. An outline of the model's key steps is shown in Fig. 2.

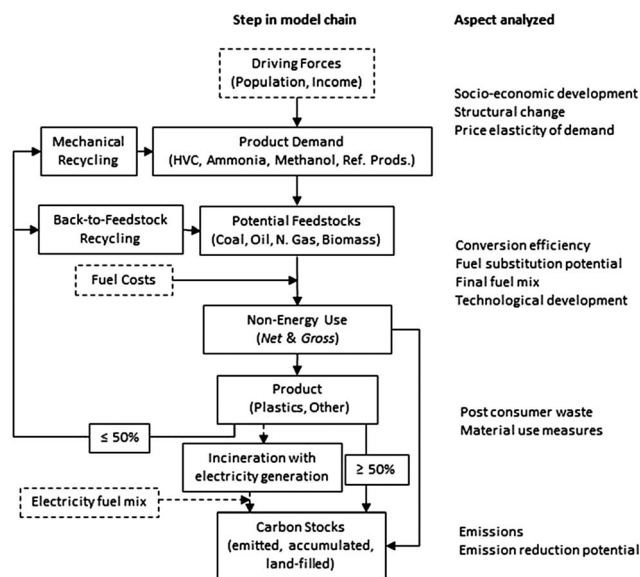


Fig. 2 Overview of the NEDE model. Explicit steps of the model indicated on the left and relevant issues indicated on the right. Dashed boxes show inputs from IMAGE/TIMER and dashed lines show optional calculations (not included as a competing option).

#### 3.1. Demand functions

In the model, demand for primary energy ( $GJ_{Prim}$ ) is driven by the demand for each final product (HVC, ammonia, methanol, refinery products) ( $GJ_{Final}$ ). The regional historic demand outlined in Section 2.2 was analysed in order to determine the relationship between per capita demand for each product ( $GJ_{Final}$  per cap) and economic growth (GDP per cap). Consequently, regional non-energy intensity per product is modelled as a logistic growth relationship between  $GJ_{Final}$  demand per capita and GDP per capita according to eqn (1).<sup>35,36</sup> It is important to note that the model does not include trade of final products between regions. In the NEDE model, regional historic intensity is used which converges to the global per capita demand for non-energy products by 2050. The regional data and 'global' best-fit relationship are shown in Fig. 3.

$$\text{Intensity}_{R,P} = \left( \alpha_P e^{-\frac{\beta_P}{GDP_R}} \right) \times \min \left( \gamma_P^{(GDP_R - 20\,000)} \right) \quad (1)$$

where: intensity =  $GJ_{Final}$  per cap demand of each non-energy product; GDP = exogenous projection of per capita GDP, in real 2005 US dollars ( $\$_{2005}$  per cap);  $\alpha$ ,  $\beta$ ,  $\gamma$  = constants per product.

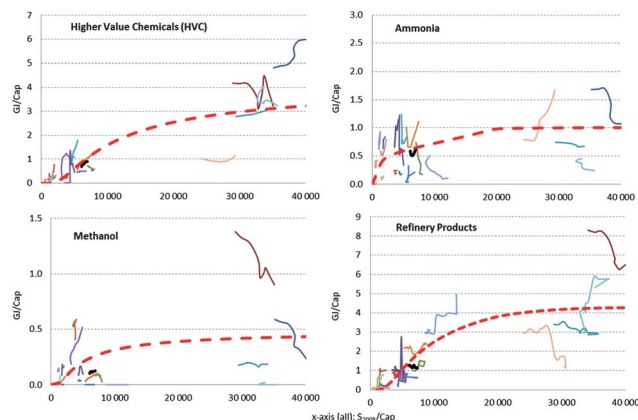


Fig. 3 Intensity of demand for non-energy products,  $\text{GJ}_{\text{Final}}$  per cap vs.  $\text{GDP}_{2005}$  per cap. 1996–2007 IMAGE/TIMER region data (thin lines) and NEDE formulation (dashed red line).

Table 1 Coefficients used in calculating intensity of demand of each non-energy product

	Steam cracking	Ammonia	Methanol	Refinery products
$\alpha$	4.08	1.02	0.48	5.86
$\beta$	9457	679	4330	8525
$\gamma$	1	1.028	1	0.995
$R^2$	0.78	0.39	0.20	0.75

The subscripts R and P refer to regions and non-energy products respectively. All coefficients and respective regression coefficients are listed in Table 1.

We assume that the final demand is also sensitive to increases in energy prices by introducing a price elasticity of demand (PED).<sup>37,38</sup> This simulates decreases in demand (either by behavioural changes or increased efficiency measures) with increasing energy prices. Thus, final demand (in  $\text{GJ}_{\text{Final}}$ ) is driven by the economic growth, population as well as price of energy carriers:

$$\text{final demand}_{R,P} = \text{intensity}_{R,P} \times \text{population}_R \times \text{PED}_R \quad (2)$$

This final demand can be met by a supply (of gross primary energy) of coal, oil, natural gas or biomass. Primary energy demand is calculated from the conversion efficiencies of each feedstock to final products according to representative processes (Section 3.2) as well as the market shares each process achieves (Section 3.3).

### 3.2. Processes

**High value chemicals.** Worldwide, the products of steam cracking (*i.e.* HVC) represent the largest share of the non-energy sector and also offer a substantial potential for emission reduction.<sup>39</sup> The representation of this product group is therefore relatively detailed in NEDE. Primary fuels are converted to *intermediates* (*e.g.* naphtha, ethanol), which are in turn converted to HVC. The routes to HVC from primary fuels included in the NEDE model are shown in Fig. 4. Each step (primary-to-

intermediate and intermediate-to-product) has its own conversion efficiency, cost (capital and operation and maintenance (O&M)) and energy requirement based on an analysis of possible petrochemical production processes.<sup>25,39,40</sup> Fig. 4 also show the potential recycling options for post-consumer wastes of synthetic organic products as described below.

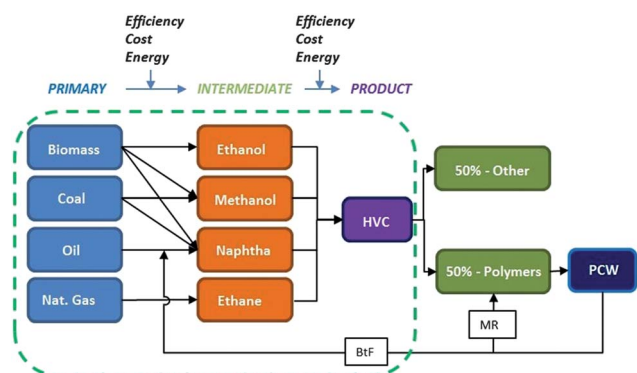


Fig. 4 Material flows for the production of HVCs. Also shown is the downstream production of HVC post-consumer waste and recycling possibilities (described below).

The technical data used for the various potential HVC processes, as well as assumed potential future improvements, are shown in Table 2. Most of the data have been taken from Ren *et al.*<sup>9,25</sup> while for the production of first and second generation biofuels data come from more recent databases.<sup>40,41</sup> The variable costs due to energy requirement (total of feedstock energy and process energy) depend on the cost projection of the relevant energy carriers. In some cases the production of HVC also includes net co-production of electricity which may act as a source of revenue. All energy costs or revenues from co-produced electricity depend on the projections of the price of the relevant energy carrier according to the IMAGE/TIMER model.

**Ammonia.** In ammonia production, natural gas is currently the main feedstock but also other feedstocks (coal, oil, gas and lignocellulosic biomass) can be used. We have introduced these alternative fuels on the basis of an “energy ratio” compared to natural gas, indicating how much of the primary fuel would be required to replace 1 GJ of natural gas for the production of ammonia. The gross energy requirement for ammonia production from fossil fuels is taken from Neelis *et al.*<sup>43</sup> while for lignocellulosic biomass, the relative efficiency of hydrogen production from biomass compared to natural gas is used.<sup>44</sup> The energy ratios of coal, oil and biomass are 1.47, 1.21 and 1.50  $\text{GJ}_{\text{Prim}}/\text{GJ}_{\text{NGas-eq}}$ , respectively.

**Methanol.** The efficiencies of methanol production from fossil fuels are derived from Neelis *et al.*<sup>43</sup> and those for the production from lignocellulosic biomass from Gerssen-Gondelach *et al.*<sup>40</sup> The efficiencies for coal, oil, natural gas and biomass are 0.52, 0.52, 0.63 and 0.60  $\text{GJ}_{\text{Methanol}}/\text{GJ}_{\text{Prim}}$  respectively.

**Refinery products.** Refinery products are a diverse set of chemicals including aromatics, bitumen and lubricants, which



**Table 2** Technical and cost parameters used for each HVC production route. Future (2050) values are shown in brackets. Conversion efficiencies for production of intermediate and final HVC are shown

Feedstock – intermediate	Gross efficiency		For steps 1 & 2			Reference
	Efficiency step 1 <sup>a</sup> (GJ <sub>int</sub> /GJ <sub>prim</sub> )	Efficiency step 2 <sup>b</sup> (GJ <sub>HVC</sub> /GJ <sub>int</sub> )	Fossil energy <sup>c</sup> (GJ <sub>prim</sub> /GJ <sub>HVC</sub> )	Electricity <sup>d</sup> (GJ <sub>elec</sub> /GJ <sub>HVC</sub> )	Fixed costs <sup>e</sup> (\$ <sub>2005</sub> per GJ <sub>HVC</sub> )	
(1) Coal – methanol	0.57	0.97	0.99	−0.01	6.8	25 and 39
(2) Coal – naphtha <sup>f</sup>	0.59	0.55	1.71	0.00	7.4	
(3) Oil – naphtha	1.00	0.60 (0.70)	0.44 (0.23)	0.00	1.9	25 and 40–42
(4) Plastic waste – naphtha <sup>g</sup>	0.45	0.70	0.39	0.00	10.4	
(5) Natural gas – ethane	1.00	0.79 (0.80)	0.43 (0.25)	0.00	2.5	
(6) Lignocellulosic – naphtha	0.33	0.75	3.75	−0.36	10.1	
(7) Lignocellulosic – ethanol	0.41 (0.49)	1.10 <sup>h</sup>	0.21	0.00	4.0 (2.6)	
(8) Maize – ethanol	0.53 (0.59)	1.10	0.71	0.02	4.3 (4.1)	
(9) Sugar cane – ethanol	0.37 (0.43)	1.10	0.21	0.00 (−0.01)	3.6	
(10) Lignocellulosic – methanol	0.60 (0.57)	1.01 <sup>i</sup>	0.11	0.06 (0.00)	5.9 (3.3)	

<sup>a</sup> Conversion efficiency of primary fuels to intermediate products for specific route. Routes 1–6 based on lower heating values (LHVs). Routes 7–10 based on higher heating values (HHVs). Other possible products of each route are ignored. Future values based on the current best available technology. Routes 3 and 5 have a 1<sup>st</sup> step efficiency of 1 since the intermediate is a necessary product of oil or gas distillation respectively.

<sup>b</sup> Conversion efficiency of the route intermediate to HVC. All conversions based on LHV. For routes 1–6 LHV<sub>HVC</sub> = 45 GJ t<sup>−1</sup>. For routes 7 to 10 it is assumed that the HVC is ethylene, and thus LHV<sub>HVC</sub> = 47 GJ t<sup>−1</sup>. For routes 7 to 10 see relevant footnotes. <sup>c</sup> Does not include feedstock energy for the HVC. In the case of multiple products, energy use is allocated on the basis of their economic values as in Ren *et al.* (2006) and Ren *et al.* (2009). <sup>d</sup> Electricity requirement for conversion of primary fuels to HVC. In case there is a net production of electricity, the value is negative. <sup>e</sup> Includes annualized capital costs and O&M costs for steps 1 & 2. A capital recovery factor of 13% and a capacity utilization rate of 90% are assumed. Biomass processes have significant cost reductions due to learning-by-doing in the production of the intermediates according to projections of the IMAGE/TIMER model (Bio case, see Section 3.5). <sup>f</sup> This route is the liquefaction of coal to produce naphtha. Fischer-Tropsch naphtha *via* coal gasification is ignored due to extensive energy and gas cleanup needs. <sup>g</sup> BASF process. Naphtha production from polyolefins *via* liquefaction, pyrolysis and separation, also called Back-to-Feedstock (BtF) recycling in this paper. <sup>h</sup> For routes 7–9, mass yield is 0.61 t<sub>HVC</sub> per t<sub>ethanol</sub> and LHV<sub>ethanol</sub> = 26 GJ t<sup>−1</sup>. Energetic efficiency is greater than 1 (routes 7–10) due to endothermicity with energy derived from fossil energy requirement (column 4). <sup>i</sup> Mass yield is 0.43 t<sub>HVC</sub> per t<sub>Methanol</sub> and LHV<sub>Methanol</sub> = 20 GJ t<sup>−1</sup> (Ren, 2009).

remain after atmospheric distillation of oil. Substituting the feedstock (currently oil) with other energy carriers is not easy since the chemical properties of the product may vary. Other feedstocks (especially biomass) may produce products with a higher added value (such as terephthalic acid, derived from *para*-xylene), which may also perform the functions provided by refinery products. Due to the complexities involved in substituting refinery products with their possible replacements and the significant uncertainties which arise, they are treated in a very aggregate manner.

We assume that under all circumstances oil retains 30% of the refinery products market share since it is unlikely that bitumen (asphalt) will be produced from other feedstocks. We make this assumption for a number of reasons. Bitumen is an unavoidable product of the refining industry, and, as petroleum sources increasingly move towards heavy oil, the availability of bitumen will increase. Furthermore, it is most likely that biomass would be used for products with higher added value and so bio-based asphalt is unlikely. Coal, natural gas and biomass compete with oil for the remaining market share (70%). This competition is based on the relative price of refinery products from coal, natural gas and biomass to the price of equivalent products from oil (price ratio). In the initial conditions of the model, the price ratio of coal, natural gas and biomass is set to three. During the simulation period (starting in 2007), the price ratio for coal and natural gas decreases as the relative price of oil increases. For biomass it is assumed that it approaches unity by 2050 since it is already observed

in Europe that bio-based lubricants are dynamically entering the market.<sup>45</sup>

**Post-consumer plastic waste.** In order to assess possibilities of material efficiency improvement throughout the lifecycle of non-energy products (such as recycling and incineration with electricity generation), we also account for possible routes for post-consumer plastic waste (PCW). PCW represents the total amount of plastics which have reached the end of their lifetimes. The availability of PCW is determined by assuming that a certain fraction of the downstream products of HVC, *methanol* and *refinery products* of the previous year are available as PCW, while the rest is considered accumulated in plastics or used for non-plastic products. More specifically, 50% of HVC, 20% of methanol and 30% of refinery products become plastics.<sup>45–47</sup> It is assumed that 50% of the plastic produced can be recycled since not all plastics can be collected as PCW. In this study, PCW can contribute to HVC production after being processed in two different recycling processes, namely mechanical recycling (MR) or Back-to-Feedstock recycling (BtF). The MR route reduces the demand for HVC, while BtF acts as an alternative route for HVC production (as shown in Fig. 4).<sup>6,13,48,49</sup>

It is assumed that the price of PCW is \$4.4 per GJ in 2010 representing the US and Western Europe.<sup>9</sup> The future price of PCW is linked to the price of fossil fuels. The volume of PCW undergoing MR is capped at 30% in order to account for decreased material properties (downcycling).<sup>13,45–47</sup> It is assumed that this process requires 0.7 GJ of fossil-based heat

and 0.7 GJ of electricity for the production of 1 GJ of HVC equivalent.<sup>50</sup> The remaining PCW can undergo the BtF process (see Plastic waste naphtha in Table 2). Both recycling routes compete for a market share of HVC production with other production routes.

In addition to recycling processes, PCW incineration with energy recovery can also contribute to emission reduction relative to electricity generation from separate power plants (Section 3.5).<sup>48</sup> This option is also included in our model, but we exclude any competition with the two recycling options. Thermal efficiency of waste-to-electricity is set at 30% with a future projection to 40%. This assumes that power plants are optimised for waste electricity generation.<sup>51,52</sup> Electric efficiency and emission factors of the displaced electricity generation are taken from the baseline of the IMAGE/TIMER model.

### 3.3. Fuel allocation

Allocation of primary energy carriers to each production process depends on the competitiveness of each carrier in producing the final product. Each possible route competes based on their relative costs according to a multinomial logit function shown in eqn (3). This function allows modeling of market heterogeneity by assigning the largest market share to the cheapest route, with the remaining market share being shared amongst the other routes based on their relative costs.

$$MS_{R,P,EC} = \frac{e^{-\lambda c_{R,P,EC}}}{\sum_{EC} e^{-\lambda c_{R,P,EC}}} \quad (3)$$

where MS is the market share each feedstock gets for each product,  $c$  is the cost of each product per primary fuel and  $\lambda$  is the logit parameter which acts as the elasticity between relative prices. The subscripts R, P and EC stand for region, product and energy carrier, respectively. As shown in eqn (4), cost depends on the price of the energy carrier as well as its conversion efficiency, the annualised fixed costs and any potential taxes on the carbon content of fuels (in the scenario where climate policies are accounted for, see Section 3.5). Fixed and variable costs are only included for HVC production since data for all of the other production routes are scarce and fuel prices are the main cost component.<sup>53</sup> The *fuel price* is measured in \$<sub>2005</sub> per GJ<sub>Prim</sub> and the efficiency of conversion (Eff) is GJ<sub>Final</sub>/GJ<sub>Prim</sub>. Thus the *cost* is measured in \$<sub>2005</sub> per GJ<sub>Final</sub>.

$$\text{Cost}_{R,P,EC} = \frac{\text{fuel price}_{R,P,EC} + C \text{ tax}_{EC}}{\text{Eff}_{P,EC}} + \text{fixed costs}_{P,EC} + \text{variable costs}_{P,EC} \quad (4)$$

### 3.4. Emission accounting

The model tracks the carbon flows from the primary energy carrier to the final product, as well as emissions from heat

production required for the conversion process. Only CO<sub>2</sub> emissions are accounted, while potential methane emissions, which may be important in HVC and methanol production, are ignored due to lack of data. The accounting of the emissions is in line with the 'Good Practice' methods outlined by the IPCC guidelines for emission inventories.<sup>54</sup> All emissions are measured in MtC.

- *HVC production.* The model simulates the flow of both process and feedstock energy carriers. Consequently the carbon content of the fuel combusted during the production process is included in the emissions. This includes emissions from any electricity use. The carbon content of the feedstock fuels is assumed indefinitely accumulated (sequestered) unless it is incinerated for energy recovery (see post-consumer waste in Section 3.2). This is in line with the IPCC good practice guidelines for the tier 2 emission accounting method.

- *Ammonia.* As fossil fuels are required for hydrogen used for the production of ammonia, all of the carbon is emitted as CO<sub>2</sub>. Downstream urea production which would reduce these emissions is ignored due to lack of global urea production data and projections and because a substantial share of the global urea production is used as fertilizer which releases CO<sub>2</sub> when decomposing. This is in line with the IPCC good practice guidelines for the tier 1 emission accounting method.

- *Methanol.* Emission factors for methanol production from different feedstocks are taken from Neelis *et al.*<sup>43</sup> These factors assume emissions due to fuel combustion while the carbon embedded in the final product is assumed sequestered and are in line with IPCC tier 1 emission factors.

- *Refinery products.* Most refinery products end up as materials that are used for a long term such as bitumen or aromatics, which are assumed to sequester their embedded carbon. About 10% of refinery products are lubricants of which 20% are oxidised during use (ODU) according to the IPCC tier 1 emissions accounting method.

Carbon not emitted according to the above rules is assumed to be accumulated in the products. Thus, PCW has a certain carbon content, which is conserved in HVC if recycled and emitted if incinerated for electricity production. Further simplifying assumptions are made in order to keep the modelling manageable: many derivatives of the HVCs (particularly ethylene derivatives) may emit CO<sub>2</sub> in the form of ODU.<sup>55</sup> Knowledge of specific flows of chemicals and uses per region would be required in order to properly assess this. Since our analysis is on global and long term scales, it is too uncertain to make such assumptions and therefore most ODU emissions are ignored. An emission factor is attached to biomass production (5–7 kg C per GJ<sub>Prim</sub>, varies across regions) which accounts for the non-renewable energy use during production as well as net emissions due to the displacement of natural vegetation. This is in agreement with the estimates of the International Food Policy Research Institute (IFPRI).<sup>56</sup> The carbon content of biomass itself is zero since it is assumed to come from sustainably grown renewable resources (plantations and residues).

¶ For the refinery products, "Eff" is the inverse of the "price ratio" and for ammonia it is the inverse of the "energy ratio" (described in the respective parts of Section 3.2).

Table 3 Key indicators (global average) of the OECD Environmental Outlook baseline

Year	GDP per cap (\$ <sub>2005</sub> per cap)	Price of oil (\$ <sub>2005</sub> per GJ <sub>Prim</sub> )	Price of coal (\$ <sub>2005</sub> per GJ <sub>Prim</sub> )	Price of gas (\$ <sub>2005</sub> per GJ <sub>Prim</sub> )	Price of biomass (\$ <sub>2005</sub> per GJ <sub>Prim</sub> )
2010	7148	8.3	2.7	3.5	6.0
2020	9155	9.5	2.4	4.0	6.0
2030	11 738	10.5	2.6	5.6	6.1
2040	15 159	12.1	2.6	7.0	7.0
2050	19 360	13.8	2.6	7.5	7.1
2060	24 653	15.7	2.5	8.4	8.2
2070	31 096	18.7	2.5	8.7	8.3
2080	38 912	22.8	2.5	9.5	9.1
2090	47 968	25.7	2.5	11.0	9.6
2100	58 058	26.8	2.5	11.9	9.6

### 3.5. Scenarios

In this study, we apply different scenarios to assess the effects on energy use and emission reduction potential by biomass, climate policy and PCW policies. In all cases, the population, GDP and energy prices are based on the OECD Environmental Outlook.<sup>57</sup> Exogenous global GDP and population growth, as well as energy carrier prices as projected by the IMAGE/TIMER model are shown in Table 3. The prices of energy carriers are governed by resource depletion dynamics (price increases) and learning by doing in technology conversion (price decreases).

A baseline projection is made in order to determine the future demand of non-energy products. This final demand is then met by primary energy carriers whose market shares are based on eqn (3). We simulate two separate cases for the baseline projections: (1) non-energy products are produced from fossil fuel energy carriers only, and (2) in addition to fossil fuels, biomass can also be used as a feedstock, competing with fossil fuels. By doing so, we assess the total emissions, demand for primary energy carriers and the mitigating effect of the use of biomass. These two cases will be referred to as the **NoBio** and **Bio** cases respectively.

**Climate policy scenarios.** Climate policy scenarios are performed for the two base cases. Carbon taxes of \$20, \$50 and \$100 per t C are applied to the price of primary fossil fuels in order to determine how sensitive the energy mix (and associated emissions) of non-energy use is to energy prices and how the availability of biomass affects the fuel substitution possibilities. It is assumed that the tax is applied in 2015 globally and remains constant throughout the simulation period.

Finally, two PCW policy scenarios are developed in order to investigate the effects of (1) increased recycling rates and, (2) incineration with electricity generation. In the first case, the full potential of PCW available for either MR or BtF recycling is used (something which does not happen in the base cases where it competes with other options). In the second scenario, PCW can be used by the power production sector replacing the projected use of fossil-based fuels in the baseline<sup>||</sup>. Regional

demand for electricity and fuel use is based on projections of the IMAGE/TIMER model for the OECD Environmental Outlook scenario. The carbon content of the PCW is assumed emitted, and the total power sector emissions are compared with the baseline emissions. These two scenarios are called the **full recycle** and **incineration** scenarios respectively.

## 4. Results

The following sections outline the projections of the NEDE model for future demand for non-energy uses and its associated emissions under the different scenarios described in Section 3.5. Detailed numerical results concerning primary energy use and carbon flows under all scenarios are available in the Appendix.

### 4.1. Baseline projections

Fig. 5 shows the projected global non-energy demand until 2100 in EJ<sub>Final</sub> in the baseline with a breakdown by final products (left) or region (right). The respective (global) primary energy demand is shown in Table 6 in the Appendix. The final demand is identical for the NoBio and Bio cases. Total final demand increases from 19 EJ in 2010 to 47 EJ in 2050 and 72 EJ in 2100, as a consequence of volume growth for all products. The increase is asymmetric across products, with the greatest increase in demand coming from HVC and refinery products since these products have the highest intensity of demand at high incomes. Between 2010 and 2100, HVC increases its share from 30% to 38% while the share of ammonia falls from 21% to 12%. The shares of methanol and refinery products are constant at 4% and 46%, respectively. The growth is driven by developing economies, with Europe, North America and the Former Soviet Union (FSU) not contributing to non-energy demand growth. These regions already have high intensity levels which have been declining in the past years, and further economic growth does not increase their non-energy demand (see Fig. 3). On the other hand the Asia-Pacific, South Asia and Africa regions have both growing economies and populations, leading to a large growth in demand.

<sup>||</sup> The European Union (EU) currently incinerates 20% of its PCW.<sup>48</sup> This is ignored in our base cases since the effects of different routes are assessed, not the 'business as usual'.

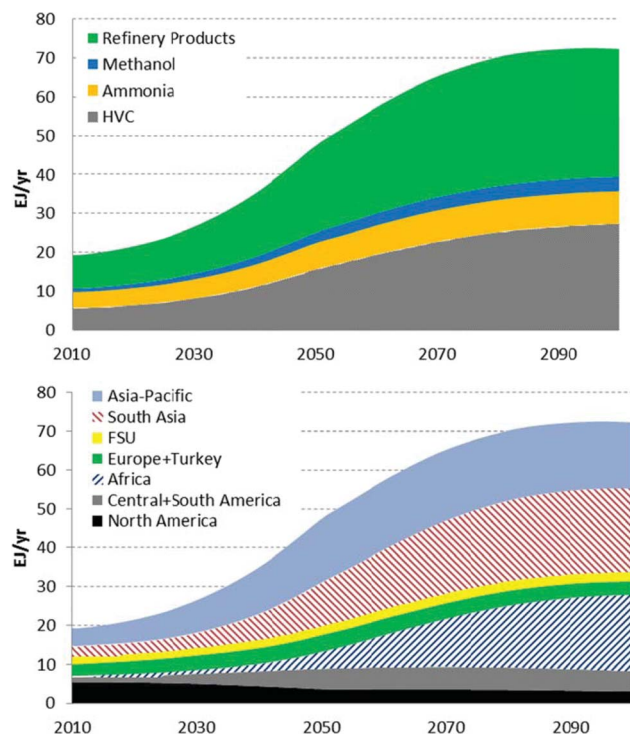


Fig. 5 Total global final non-energy demand. Per product, EJ<sub>Product</sub> (top), per region (bottom).

It is important to consider these changes in product and regional demand when assessing substitutability of different energy carriers and thus primary energy demand and emissions. This is because different products have different fuel switching possibilities (and efficiencies) and energy costs vary across regions. Primary energy demand and emissions will be the focus of the rest of this section.

Fig. 6 shows the primary energy demand per energy carrier (including PCW) for the NoBio and Bio cases. The shares of primary energy carrier use per product are shown in Table 7 in the Appendix. One may note the rapid reduction in oil demand between 2010 and 2020. Pre-2010 the model is forced to reproduce the total fuel use reported in the IEA energy statistics while the shares of each final product are based on the data outlined in Section 2.2. The difference in the total demand between the data and IEA statistics is obvious in Fig. 1 and may come from erroneous reporting in the IEA statistics. Both the total demand and fuel use are re-adjusted to the bottom-up data between 2010 and 2020. The projections show that the global demand for primary energy carriers for non-energy use increases from approximately 30 EJ in 2010 to 100 EJ (and 10 EJ of PCW, most of which is recycled *via* MR) in 2100. This is equivalent to a compound annual growth rate of primary energy of 2% per year from 2010 to 2050 and 1.5% per year for the entire period analysed. Gas becomes increasingly important in the short term, mainly due to fuel switching in HVC production in developed regions, while developing regions continue using oil. Natural gas is also used heavily in ammonia and methanol production. In the longer term, increases in the price of oil lead to further increase in use of natural gas and eventually shift to coal based chemistry. The increase in coal usage

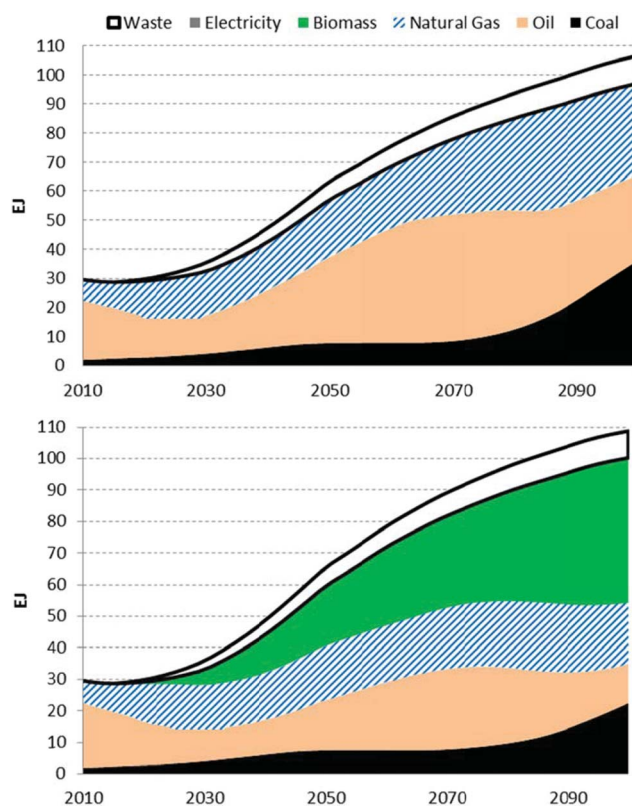


Fig. 6 Total gross primary non-energy demand (EJ) per energy carrier. NoBio (top) and Bio (bottom).

in the long term is largely due to its requirement for process heat generation associated with switching to coal-based HVC. Furthermore, coal is increasingly used for methanol and ammonia production towards the end of the century.

If biomass is also used as a feedstock (Fig. 6, right), it is projected to become a significant non-energy feedstock supplying 19 EJ in 2050 and 45 EJ in 2100. Biomass becomes competitive due to disproportionate price increases in fossil fuels as well as cost reductions in biobased methanol production due to learning. By 2100, most of the biomass (50%) demand replaces oil which is used for the production of refinery products. 43% of the biomass is used to produce HVC, replacing all fossil fuels but primarily coal, which is the marginal fuel in the NoBio case and about 7% is used for ammonia production. Biomass accounts for 65% of refinery product, 46% of HVC and 21% of ammonia production in 2100.

Since feedstocks for HVC account for more than a third of the non-energy use according to the projections (Table 7) and this product is the most interesting concerning renewable feedstocks and PCW recycling, it is worth looking at it in more detail. Fig. 7 shows the primary energy carriers used as feedstocks for HVC production only. The model projects that all the waste available for mechanical recycling is used, while back-to-feedstock recycling is minor. This is due to its high costs and energy requirement. Also the continued importance of oil (especially outside North America) in the medium term is shown. Biomass becomes important after 2030 due to cost reductions in HVC production from bio-based methanol. Primary energy demand, excluding waste, in 2100 increases from 30 EJ in the NoBio case to 34 EJ in



the Bio case due to the lower conversion efficiency of biomass to HVC compared to fossil fuels.

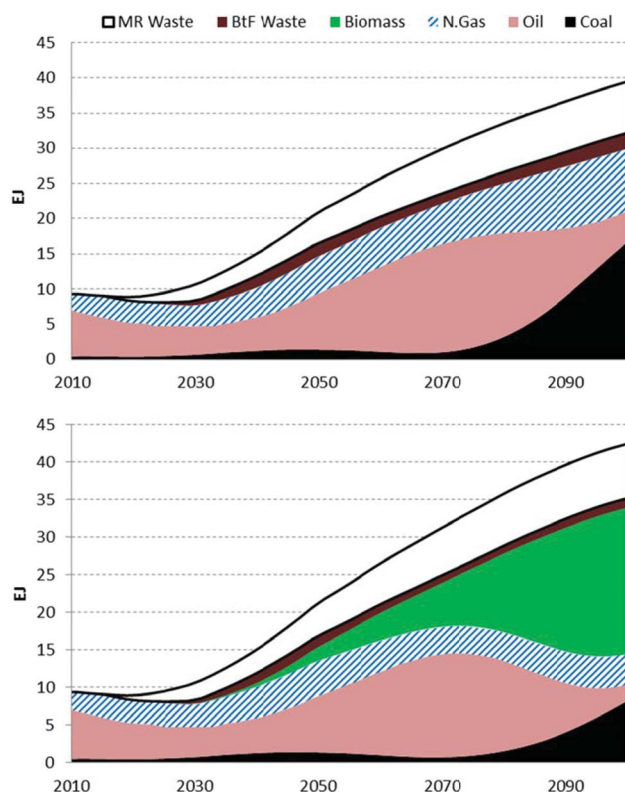


Fig. 7 Net primary energy demand (EJ) for HVC, including recycled fractions. NoBio (top) and Bio (bottom).

As the demand for non-energy products increases, emissions of this sector also increase. Fig. 8 shows, for the years 2010, 2050 and 2100, how the global annual carbon flows broken down between emitted, accumulated and recycled are distributed. The use of biomass can overall significantly limit the total amount of carbon flows within the sector in the long run, especially the carbon accumulated in products. It can reduce annual emissions by 2100 from 677 MtC per year to 544 MtC per year (20% reduction) by replacing a large portion of fossil fuels by biomass in ammonia production and reduction in coal-based HVC production.

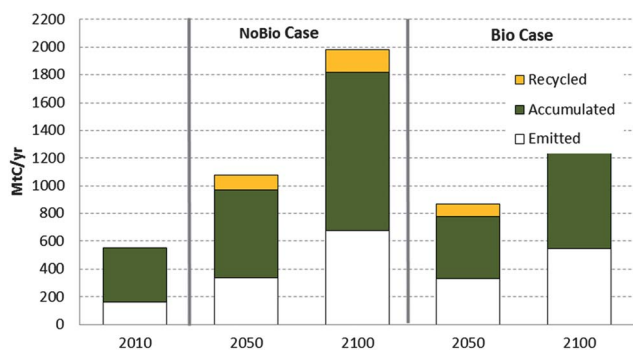


Fig. 8 Non-energy carbon flows in 2010, 2050 and 2100 for the NoBio and Bio cases.

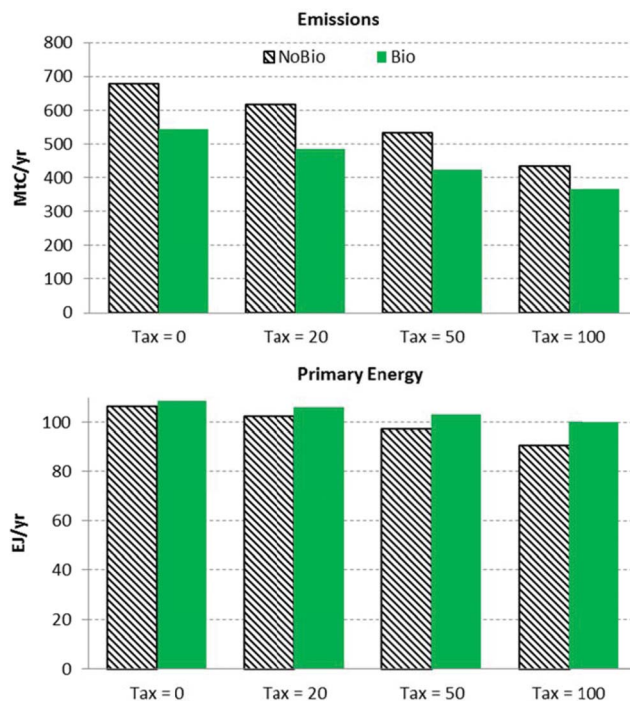


Fig. 9 Top: total emitted carbon (MtC per year), Bottom: Total non-energy demand (EJ per year). For NoBio and Bio cases per tax level for 2100.

#### 4.2. Climate policy

In the climate policy scenarios we tax the carbon content of primary energy carriers at \$20, \$50 and \$100 per t C. The effect of climate policy on total primary energy demand and the sectors' annual emissions for both NoBio and Bio cases in 2100 are shown in Fig. 9 (see Table 8 in the Appendix for the developments in fuel mix). In the NoBio case, climate policy leads to coal being replaced by natural gas and to a lesser extent oil. This reduces the energy use for coal-based HVC and lowers the overall emissions (36% at \$100 per t C). In the Bio case, biomass becomes increasingly important further reducing emissions (33% at \$100 per t C), but as previously mentioned this also reduces the conversion efficiency. Thus, climate policy has a smaller effect on primary energy demand in the Bio case than in the NoBio case. Decreases in total primary energy demand (and consequently emissions) are also driven by reduced final demand due to the price elasticity of demand.

#### 4.3. Post-consumer waste policies

In the base case projections (NoBio and Bio), NEDE indicated that the waste available for mechanical recycling is utilized; back-to-feedstock recycling is not a competitive HVC production option and only used marginally. We discuss now the results of alternative PCW scenarios. The first PCW policy scenario assumes the Bio case with the BtF route forced on 70% of the PCW (the other 30% undergoing MR). The results show that forced BtF does not reduce the demand for primary energy carriers and emissions with respect to the base Bio case (Table 8, Full recycle scenario), a conclusion that other studies have also come to.<sup>48</sup> The reason being BtF's low efficiency and high process energy (Table 2).

The second PCW scenario assumes that the quantity of PCW not used for recycling in the base case can be incinerated with subsequent electricity generation. This is repeated for both NoBio and Bio cases since the carbon content, and thus emitted carbon, of PCW changes. In the power sector, PCW replaces an aggregate mix of the fossil primary energy carriers, whose use in baseline projections according to the IMAGE/TIMER model is shown in Table 9 in the Appendix. Globally coal is projected to become the dominant primary fuel for electricity generation, but the carbon content (CC) of electricity decreases due to improvements in the thermodynamic efficiency of electricity generation.

Table 4 shows the primary fuel demand and carbon content per GJ fuel use of the electricity generation sector in the base case. The carbon content of electricity is 464 g CO<sub>2</sub> per kW h and 453 g CO<sub>2</sub> per kW h for 2050 and 2100 respectively. Also shown are the CC and volume of PCW in the NoBio and Bio cases in 2050 and 2100. It is assumed that waste-to-electricity generation efficiency is 30%, increasing to 40% in 2100.<sup>51,52</sup> Efficiency of fossil based electricity generation, globally increasing from 42% to 62%, is based on the projections of the IMAGE/TIMER model and regional electricity fuel mix. Consequently, each GJ of PCW replaces <1 GJ of primary fossil fuels for electricity generation (fossil replacement rate).

The incineration of PCW with electricity production overall does decrease the demand for primary fuels. However, due to the low fossil replacement rate, PCW can lead to a reduction in electricity emissions only if CC-PCW is much lower than CC-Elec. As shown in Table 4, this is not the case in any of the scenarios with incineration with electricity generation leading to net increases in emissions (up to 466 g C per kW h), with higher emissions in the NoBio case due to the higher carbon content of PCW. PCW cascading can lead to emission reduction if the *fossil replacement rate* can be improved by increasing the efficiency of waste-to-electricity conversion, if baseline electricity generators have lower efficiency or if the carbon content of PCW is further reduced.<sup>48,51</sup>

## 5. Discussion

The main purpose of the model is to project the non-energy use and to study the possibilities for this sector to reduce its CO<sub>2</sub> emissions. An emphasis has been placed on the potential use of biomass as well as various post-consumer plastic waste treatment options. A key outcome is the potentially significant contribution of biomass in this sector, leading to large emission reductions. In order to investigate the robustness of these results and to investigate the effect of important parameters on our findings, we have performed a sensitivity analysis. Furthermore, the results have also been compared with the outcomes of other relevant studies.

In the NEDE model, the non-energy final demand is driven by per-capita economic growth; the model allocates market shares of primary fuels per final product based on relative costs. Fig. 10 shows a sensitivity analysis performed on the use of biomass as well as the carbon emissions by 2100 when varying the projections for GDP per cap and energy prices (see Table 3) by  $\pm 25\%$  for the Bio scenario. As shown in Fig. 3, demand for non-energy products flattens out with increasing affluence, thus the final demand and resultant biomass use and emissions become less sensitive to changes in GDP per cap. Since the model allocates market shares of primary fuels per final product based on relative costs, the results heavily depend on the competitiveness of primary energy carriers. According to the model results, as fossil fuels become more expensive, biomass use increases as it is the marginal fuel. Consequently, the competitiveness of biomass is very sensitive to its price. As the price of individual fossil fuels changes, biomass use is affected to a lesser degree since other fossil fuels can also have marginal gains.

Emissions in 2100 are driven by coal use (especially in ammonia production), and consequently by its competitiveness with gas and biomass which are the marginal fuels. It is important to note that

**Table 4** Details of baseline electricity generation, availability and carbon content (CC) of PCW, and emission effects of PCW incineration with electricity generation. NoBio and Bio cases in 2050 and 2100. Note: table may have rounding errors

	2050		2100	
	NoBio	Bio	NoBio	Bio
<b>Electricity base case</b>				
CC-Elec (kg C per GJ <sub>Prim</sub> )		19.4		21.2
Electricity fuel (EJ <sub>Prim</sub> )		384		628
Electricity emission (MtC)		7429		13 293
Electricity emission factor (g CO <sub>2</sub> per kW h)		465		452
<b>PCW parameters</b>				
CC-PCW (kg C per GJ <sub>PCW</sub> )	20.4	19.5	22.3	16.5
PCW availability (EJ)		2.9		4.9
Fossil replacement rate (GJ <sub>PCW</sub> /GJ <sub>Prim</sub> )		0.55		0.62
<b>PCW incineration results</b>				
Electricity fuel (EJ <sub>Prim</sub> )		381		624
Electricity emissions-fuel (MtC per year)		7398		13 226
Electricity emissions-PCW (MtC per year)	59	57	108	80
Total emissions (MtC per year)	7457	7455	13 335	13 306
Electricity emission factor (g CO <sub>2</sub> per kW h)	466	466	454	453
Emission change (MtC per year)	+29	+26	+42	+13

even in the case where the biomass price is 25% higher, the total emissions are still lower than that in the NoBio case.

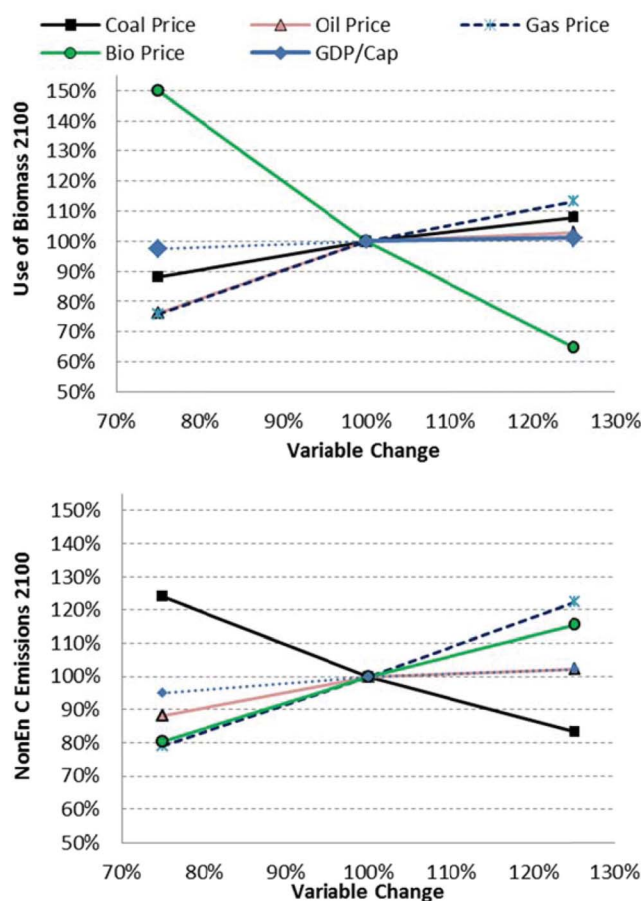


Fig. 10 Results of sensitivity analysis on use of biomass (top) and emissions (bottom) for 2100. Effect of energy carrier prices and per capita GDP (Bio case).

The model projects that all of the PCW available for mechanical recycling is used since it is considered a cheap method to reduce HVC demand. In order to assess how this may affect the conclusions of the model, Table 5 shows how the fossil and biomass energy requirements of the Bio scenario are affected when recycling routes are ignored. As expected the total primary energy demand increases. This increase comes from both biomass and fossil fuel use, which leads to an emission increase when recycling is ignored.

Table 5 Change in the non-energy sector's total biomass and fossil energy demand and its emissions when recycling is excluded (results shown for the Bio case, 2100)

	Bio case	No recycling	%
Total biomass (EJ per year)	45	52	+14%
Total fossil energy (EJ per year)	54	64	+18%
Total primary energy (EJ per year)	100	116	+15%
Emission (MtC per year)	544	593	+9%

An inherent uncertainty of the NEDE model concerns the future projections of non-energy demand and the overall market structure. Demand has been modelled as a function of observed intensities of demand for non-energy products with respect to economic

development. Earlier studies found meaningful relationships to support this hypothesis for bulk materials such as steel, cement, paper and aluminium.<sup>35,36,58</sup> Besides economic growth, the availability of cheap feedstocks and newly installed large refinery capacities (Middle East, more recently shale gas in the USA), or the existence of innovative high value added sectors (Japan, Europe) are also factors determining non-energy demand. This explains why the fits are somewhat worse compared to other sectors. Furthermore, trade of non-energy products is not explicitly modelled. An attempt has been made to incorporate these dynamics in the NEDE model as the regional demand for each product depends both on economic development and energy prices (through a price-induced multiplier). Consequently, at any given GDP, regions with lower energy costs are going to have a relatively higher (production) demand. Institutional aspects of the non-energy sector and its intimate relation to oil and gas extraction capital are ignored, especially concerning the refinery products. Our methodology assumes that there is a given demand for these products, which should be met irrespective of oil and gas extraction and refining trends. Due to the "price ratio" assumptions of bio-based refinery products, the biomass use for this product is projected to be very high. The development of this price ratio is highly uncertain and based on limited current observations. Given the assumed relationship with economic development, a study highlighting how per capita demand before and after 2007 developed would provide valuable insight into the robustness of our method.

The results highlight a very high use of biomass in the non-energy sector. This result is optimistic since it is assumed that no other competitive use of biomass for energy purposes exist. This high use reflects only the projected potential of biomass in the non-energy sector and it is important to investigate how this potential may be limited due to other biomass uses.

Though the model investigates carbon flows per non-energy product, the representation of emissions is simplified in order to maintain relevance and simplicity. Emissions of the non-energy sector are difficult to model due to complex material and energy flows, with huge uncertainties in future projections. Furthermore, it is assumed that whatever carbon not emitted during feedstock conversion or incineration is accumulated indefinitely in non-energy products (and land-fills). Plastic waste degradation has been estimated at 1–5% during a 100 year period.<sup>48</sup> Thus this assumed accumulated carbon may have significant effects if the time period of the analysis were to be expanded, increasing the emissions of the NoBio case and improving the performance of the incineration scenarios.

Despite the uncertainties, the model compares well with other studies. Allwood *et al.*<sup>59</sup> estimate carbon emissions from plastics production in 2006 at 136 MtC, while for the same year NEDE calculates the emissions at 139 MtC. Though the non-energy use estimates between the NEDE model and the IEA statistics differ (see Section 2.2), the annual growth rate for global non-energy demand between 2010 and 2050 according to NEDE is 1.98%, while the IEA-Energy Technology Perspectives baseline is 1.93%.<sup>4</sup> The same IEA study also projects that carbon emissions related to non-energy use will more than double between 2007 and 2050, in agreement with our results under the NoBio scenario. Concerning the ability of biomass to penetrate



into this sector, Gielen *et al.*<sup>60</sup> estimate that biomass can account for 22% of the petrochemical sector in 2050, which is in line with our 28% projection for the Bio scenario (Table 8).

## 6. Conclusions

This paper presented an analysis and possible future trajectories of non-energy demand and the associated emissions. Available data have been assessed and used to construct a simulation model able to project final demand, primary energy demand of different energy carriers under different scenarios and the magnitude of carbon flows.

Analysis of bottom-up data has highlighted inconsistencies in the IEA energy statistics concerning non-energy use; a conclusion which other studies have also drawn.<sup>20</sup> The bottom-up data has been used to develop the NEDE model, a top-down simulation model for global long-term projections of the non-energy sector. The model assumes that the non-energy sector demand can be represented by a limited number of products which can be produced from primary fuels. Each fuel competes for a market share of the final product based on its costs, conversion costs and conversion efficiency.

*The model is a significant step forward concerning the future assessment of the non-energy sector.* The NEDE model can assess the dynamics of the non-energy sector and how its structure changes with time and economic development. Further, it provides projections of overall primary demand for non-energy as well as the potential of fuel switching as representative pathways for each product and fuel are included. In addition to explicit energy flows, carbon flows are also modelled, accounting for both emitted and accumulated carbon. The model can be used to assess how different scenarios such as climate policy and waste incineration with energy recovery affect non-energy demand and its emissions. Finally, the NEDE model is fully integrated in the IMAGE/TIMER integrated assessment model framework. Integrated assessment models usually model non-energy in secondary energy terms (as opposed to final energy in NEDE) thus ignoring effects of energy carrier conversion efficiency and have little detail due to complexities in different flows in the energy system. Important progress has been made with the NEDE model since the level of description is detailed enough to be relevant, and aggregated enough to be included in an integrated assessment model.

*The model projects that global demand for non-energy will increase significantly from 30 EJ today to over 100 EJ by 2100.* HVC is projected to be the most important non-energy product, followed by refinery products and ammonia. Assuming only fossil fuel use, oil and natural gas are the main feedstocks for HVC until 2050. Subsequent oil price increases lead to replacement by coal and natural gas. Coal becomes increasingly important in the production of methanol and ammonia, replacing natural gas.

*The use of biomass for non-energy purposes can significantly reduce fossil energy demand and emissions.* Assuming only the use of fossil fuels, the annual emissions of non-energy increase from 163 MtC per year in 2010 to 677 MtC per year in 2100. However, biomass can supply over 40% of the total required primary energy, reducing emissions to 544 MtC per year. The sensitivity analysis has shown that this result is robust since even if the price of biomass were 25% higher, the emissions would still be significantly lower than the

NoBio case. However, it is important to keep in mind that in this study, biomass does not compete for other energy services (biofuels, residential heating, *etc.*). Thus, this paper does not study the optimal use or the competition of biomass across various options in the energy system, but rather its potential in the non-energy sector alone.

*Emissions can be further reduced by promoting fuel switching via climate policy.* At a carbon tax rate of \$100 per t C, the sector's emissions are projected to reduce to 433 MtC per year and 367 MtC per year by 2100 in the NoBio and Bio cases, respectively. This re-emphasizes the importance of biomass at reducing emission abatement costs since the Bio case at no tax offers similar emission levels with those of the NoBio case at a \$50 per t C tax (534 MtC per year).

*Cascading uses of post-consumer waste do not necessarily reduce the total primary energy demand and emissions of non-energy use.* The model projects that when competing freely, all of the waste available for mechanical recycling is used. Back-to-feedstock recycling is marginal due to its high costs and energy requirements. The full recycle scenario showed that forcing back-to-feedstock recycling does not reduce energy demand and emissions compared to the Bio case. Mechanical recycling reduces total primary energy demand for feedstocks by 15%, but affects emissions to a lesser extent since it has emissions of its own. If 30% of PCW is used as a feedstock for electricity production, though reducing the demand for primary energy carriers, it may increase the emissions of the power sector. This happens despite projections that coal becomes a significant primary fuel for electricity generation. The emission increase is due to the reduced efficiency of electricity generation from PCW with respect to fossil fuels. Emission reductions *via* this measure are possible with efficient waste-to-electricity technologies and avoiding the use of carbon intensive non-energy feedstocks. A summary of the carbon flows of all scenarios can be found in Table 10.

In conclusion, the NEDE model indicates that energy and emissions reduction in the non-energy sector can profit most from fuel switching to biomass and avoiding the use of coal feedstocks. This may reduce the annual emissions by up to 20% in 2100. Post-consumer waste measures may reduce emissions only if recycling and cascading processes become more efficient. A similar analysis of other possible uses of biomass in the energy system is required in order to determine if biomass for non-energy use is the optimal option for reducing emissions.

## Appendix

Table 6 Primary energy demand (including PCW) for non-energy products and HVC-heat as well as total demand for NoBio and Bio cases

	NoBio			Bio		
	2010	2050	2100	2010	2050	2100
HVC-net	32%	33%	37%	32%	32%	39%
HVC-heat	9%	6%	12%	9%	6%	8%
Ammonia	24%	18%	14%	24%	19%	15%
Methanol	5%	7%	6%	5%	7%	6%
Refinery products	30%	35%	31%	30%	36%	32%
Total EJ	29	63	107	29	65	109



**Table 7** Shares of primary energy carriers and total primary energy demand (including waste) per final product and HVC–heat. For NoBio/Bio cases and recycling scenarios in 2050 and 2100

		Coal	Oil	Natural gas	Biomass	Waste	Electricity	Total Eje	
2050	NoBio	HVC-net	7%	38%	25%	0%	30%	0%	21
		HVC-heat	20%	32%	41%	0%	0%	8%	4
		Ammonia	29%	1%	70%	0%	0%	0%	11
		Methanol	47%	0%	53%	0%	0%	0%	5
		Ref. prods	0%	90%	10%	0%	0%	0%	22
	Bio	HVC-net	6%	35%	22%	9%	28%	0%	63
		HVC-heat	18%	31%	42%	0%	0%	8%	21
		Ammonia	27%	1%	62%	10%	0%	0%	4
		Methanol	47%	0%	53%	0%	0%	0%	12
		Ref. prods	0%	30%	5%	65%	0%	0%	5
	Full recycle	HVC-net	4%	23%	15%	6%	52%	0%	24
		HVC-heat	14%	23%	56%	0%	0%	8%	65
		Ammonia	27%	1%	62%	10%	0%	0%	25
		Methanol	47%	0%	53%	0%	0%	0%	4
		Ref. prods	0%	30%	5%	65%	0%	0%	12
2100	NoBio	HVC-net	43%	11%	23%	0%	23%	0%	5
		HVC-heat	71%	5%	20%	0%	0%	4%	24
		Ammonia	40%	0%	60%	0%	0%	0%	70
		Methanol	70%	0%	30%	0%	0%	0%	39
		Ref. prods	0%	73%	27%	0%	0%	0%	13
	Bio	HVC-net	19%	5%	10%	46%	20%	0%	15
		HVC-heat	52%	4%	38%	0%	0%	6%	7
		Ammonia	32%	0%	47%	21%	0%	0%	33
		Methanol	69%	0%	31%	0%	0%	0%	106
		Ref. prods	0%	28%	7%	65%	0%	0%	42
	Full recycle	HVC-net	12%	4%	7%	33%	44%	0%	9
		HVC-heat	39%	3%	52%	0%	0%	6%	16
		Ammonia	32%	0%	47%	20%	0%	0%	7
		Methanol	68%	0%	32%	0%	0%	0%	35
		Ref. prods	0%	28%	7%	65%	0%	0%	109
								48	
								8	
								16	
								7	
								35	
								114	

**Table 8** Shares of each primary fuel in total non-energy use, total primary energy (including waste) and total emissions. With and without availability of biomass, carbon taxes and recycling of HVC

Scenario	Tax	Year	Energy carrier						Total		
			Coal	Oil	N. gas	Bio	Waste	Elec	Primary energy <sup>a</sup> (EJ)	Emissions (MtC)	
NoBio	0	2010	6%	69%	24%	0%	0%	0%	30	163	163
		2050	12%	47%	31%	0%	10%	0%	63	339	339
	50	2100	34%	27%	29%	0%	9%	0%	107	677	677
		2010	6%	69%	24%	0%	0%	0%	30	163	163
	100	2050	9%	47%	33%	0%	10%	0%	61	308	308
		2100	21%	33%	36%	0%	10%	1%	97	534	534
		2010	6%	69%	24%	0%	0%	0%	30	162	162
		2050	7%	46%	36%	0%	10%	0%	59	282	282
		2100	12%	35%	42%	0%	10%	1%	91	433	433
Bio	0	2010	6%	69%	24%	0%	0%	0%	30	163	163
		2050	11%	24%	26%	28%	9%	0%	65	329	329
	50	2100	21%	11%	18%	42%	8%	0%	109	544	544
		2010	6%	69%	24%	0%	0%	0%	30	163	163
		2050	8%	23%	28%	32%	9%	0%	63	296	296
		2100	10%	12%	19%	50%	8%	0%	103	423	423
	100	2010	6%	69%	24%	0%	0%	0%	30	162	162
		2050	6%	20%	29%	35%	9%	0%	62	269	269
		2100	7%	11%	19%	54%	8%	0%	100	367	367
Full recycle <sup>b</sup>	0	2010	6%	69%	24%	0%	0%	0%	30	163	163
		2050	10%	20%	25%	26%	19%	0%	70	331	331
		2100	17%	10%	17%	36%	19%	0%	114	528	528

<sup>a</sup> Including use of waste. <sup>b</sup> This experiment is based on the Bio case at a 0 tax level.

**Table 9** Baseline (OECD Environmental Outlook) projections of shares of primary fuel for electricity generation according to the IMAGE/TIMER model

	2010	2050	2100
Coal	44%	53%	72%
Oil	5%	0%	0%
N. gas	16%	16%	2%
Biomass	3%	0%	0%
Nuclear	13%	8%	7%
Solar/wind	3%	14%	13%
Hydro	16%	9%	7%
Total (EJ <sub>Elec</sub> )	72	211	387

**Table 10** Annual and cumulative carbon flows for NoBio, Bio, full-recycle, incineration and no-recycle scenarios

Flow type	Scenario	Annual flows (MtC per year)		Cumulative flows (MtC)	
		2050	2100	2050	2100
Emitted	NoBio	339	677	8586	32 105
	Bio	329	544	8459	29 662
	Full recycle	331	528	8471	29 704
	Incineration <sup>a</sup>	356	557	8925	31 306
	No recycle	338	593	8637	30 611
Recycled	NoBio	102	162	1984	8812
	Bio	91	101	1817	7087
	Full recycle	202	242	3452	16 192
	Incineration	91	101	1817	7087
	No recycle	0	0	0	0
Accumulated	NoBio	634	1142	14 638	61 340
	Bio	449	728	11 991	43 945
	Full recycle	282	491	9567	30 114
	Incineration	392	648	10 915	39 072
	No recycle	655	1015	16 014	60 911

<sup>a</sup> Assumes bio-based PCW. Emission increases in electricity generation allocated to the non-energy sector.

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