Carbon Footprint as a Single Indicator in Energy Systems: The Case of Biofuels and CO_2 Capture Technologies

Diego Iribarren and Javier Dufour

Abstract The energy sector is one of the main sources of greenhouse gas emissions, in both the transport and electricity subsectors. Taking into account the current context of the energy sector, relevant case studies concerning biofuels and CO_2 capture in power plants are defined and inventoried to evaluate their carbon footprints; the suitability of these carbon footprints as single indicators is then discussed. The methodological framework proposed in the Life Cycle Assessment standards is followed. The fuel systems evaluated involve second-generation biofuels from short-rotation poplar biomass: (i) synthetic fuels (gasoline and diesel) produced via biomass pyrolysis and bio-oil upgrading and (ii) hydrogen produced via biomass gasification and biosyngas processing. Four case studies of coal power plants with CO_2 capture technology are also evaluated, including post-combustion CO_2 recovery through chemical absorption, membrane separation, cryogenic fractionation, and pressure swing adsorption. Inventory data for the analysis are based on process simulation, robust databases, and scientific literature. The carbon footprints calculated show a promising life-cycle global warming performance of the energy products evaluated. However, conflicting results are found when evaluating other impact categories. Therefore, decisions and recommendations based solely on carbon footprints only capture a partial picture of the environmental performance, although different levels of risk are associated with the use of carbon footprints as single indicators, depending on the type of systems and products under evaluation. The use of multi-indicator approaches is recommended because the inclusion of additional impact categories leads to a more comprehensive evaluation of the environmental performance of energy product systems, thus facilitating a more sensible decision-making process oriented towards environmental sustainability.

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S. S. Muthu (ed.), *Assessment of Carbon Footprint in Different Industrial Sectors, Volume 2*, EcoProduction, DOI: 10.1007/978-981-4585-75-0_4,

Keywords Biofuel · Carbon dioxide capture · Carbon footprint · Energy · Life cycle assessment · Power

Abbreviations

ADP	Abiotic depletion potential
AP	Acidification potential
CCS	CO_2 capture and storage
CCU	CO_2 capture and utilization
CED	Cumulative non-renewable energy demand
CF	Carbon footprinting
CFB	Circulating fluidized bed
CO_2 eq	Carbon dioxide equivalent
DEA	Data envelopment analysis
EEA	European Environment Agency
EP	Eutrophication potential
FU	Functional unit
GCC	Gas and char combustor
GHG	Greenhouse gas
GWP	Global warming impact potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MEA	Monoethanolamine
ODP	Ozone layer depletion potential
PAS	Publicly available specification
POFP	Photochemical oxidant formation potential
PSA	Pressure swing adsorption
RED	Renewable energy directive
SMR	Steam methane reforming
TS	Technical specification
WGS	Water-gas shift

1 Introduction

The energy sector is one of the main sources of greenhouse gas (GHG) emissions. Both the transport and electricity subsectors are currently associated with high GHG emission rates. Moreover, the increasing energy demand worldwide could make this situation of environmental unsustainability even worse. These environmental concerns and the growing energy demand (and prices), as well as energy insecurity and social awareness of environmental issues (mainly climate change), have brought about the search for technological solutions that contribute to establishing a sustainable future energy sector (International Energy Agency 2012).

The attempts to provide the energy sector with sustainable energy systems involve not only conventional renewables (e.g., wind and solar power) but also a wide range of technological options that can be based on either novel processes or the modification of conventional process schemes (e.g., the use of the Fischer-Tropsch process to coproduce synthetic biofuels and electricity).

Biofuels are currently seen as the main option for substituting fossil fuels in the oil-dependent road transport subsector (European Commission 2006; Iribarren et al. 2012a). A wide range of biomass resources and technologies can be used to produce biofuels (Huber et al. 2006). Regarding resources, residual biomass could be a good option to yield sustainable biofuels (e.g., biodiesel production via esterification-transesterification of waste vegetable oils (Iribarren and Dufour 2012)), but it suffers from availability concerns when it comes to satisfying large fuel demands. Microalgae also have been studied as a possible feedstock for future bioenergy systems because of their high productivity and potentially high oil or carbohydrate content. However, significant efforts are still needed to overcome important barriers concerning immature cultivation and processing techniques for the use of microalgae to produce biodiesel and/or bioethanol (Mata et al. 2010; Iribarren et al. 2013a; Kohl et al. 2013). First-generation biofuels, based on food crops such as corn and sunflower, could fulfill the future biofuel demand, but at the expense of high land occupation. In fact, concerns regarding land use and competition between fuel and food have led the promotion of second-generation biofuels rather than first-generation ones. Lignocellulosic biomass from short-rotation plantations can be grown with low input requirements (including land needs) and could guarantee the supply of sustainable second-generation biofuels, therefore arising as a suitable feedstock for bioenergy conversion systems.

A variety of systems can be used to convert biomass into transportation fuels. Even though most of them produce biodiesel (e.g., systems based on oil transesterification) or bioethanol (e.g., via simultaneous saccharification and co-fermentation), other bioenergy systems (e.g., those based on the Fischer-Tropsch process using biosyngas or on the hydroprocessing of pyrolysis bio-oil) produce synthetic fuels (Iribarren et al. 2012a; Swain et al. 2011; Iribarren et al. 2013b). Furthermore, other conversion systems, such as those based on indirect biomass gasification, consider the production of hydrogen as an alternative biofuel (Spath et al. 2005; Susmozas et al. 2013).

Regarding the electricity sector, in addition to the use of conventional renewables and power generation from biomass, important efforts have been made to promote the implementation of CO_2 capture schemes in power plants (Mondal et al. 2012). CO_2 capture technologies are usually separated into pre-combustion, oxy-fuel combustion, and post-combustion technologies. Post-combustion methods include chemical absorption, which is the most developed technology.

Strategies based on CO_2 capture and storage (CCS; with or without enhanced resource recovery) or CO_2 capture and utilization (CCU) are especially interesting in power plants, as these facilities account for high CO_2 emissions (Iribarren et al. 2013c).

Environmental concerns regarding the energy sector are mainly focused on climate change. The promotion of CCS and the existing energy policies (e.g., the Renewable Energy Directive [RED] 2009/28/EC (European Union 2009)) clearly show the leading role of global warming when dealing with the environmental performance of the energy sector. Hence, a thorough and robust methodology for the quantification of greenhouse gas (GHG) emissions is needed. In this sense, the standardized Life Cycle Assessment (LCA) methodology (International Organization for Standardization 2006a, b) provides the basis for the calculation of carbon footprints (i.e., life-cycle GHG emissions). RED guidelines (European Union 2009) and current carbon footprinting (CF) specifications, such as PAS 2050:2011 (British Standards Institution 2011) and ISO/TS 14067:2013 (International Organization for Standardization 2013), follow this life-cycle approach, even though relevant differences exist among the different quantification schemes.

Although a large number of LCA studies on biofuels are available in scientific literature, they usually deal with the evaluation of individual case studies. These studies are often limited to the impact categories of global warming and cumulative energy demand, and they mostly evaluate first-generation biofuels (mainly biodiesel and bioethanol), even though the number of LCA studies on second-generation biofuels is increasing (Hoefnagels et al. 2010; Kendall and Yuan 2013). LCA studies on CO_2 capture in power plants are scarcer. Nevertheless, important efforts have already been made to compare CCS options in power plants, taking into account a life-cycle perspective and a wide range of environmental concerns (Iribarren et al. 2013c; Khoo and Tan 2006; Singh et al. 2011).

Although carbon footprints are valuable indicators of the performance of energy systems, their use as single indicators should be discussed because they could lead to a distorted image of the environmental performance of this type of systems. This chapter addresses this discussion through different case studies of biofuels and CO_2 capture in power plants. Relevant case studies are used to not only quantify the specific carbon footprints of relevant energy products, but also enable the formulation of general recommendations on the use of carbon footprints when it comes to evaluating the environmental performance of energy systems. In this sense, this chapter goes beyond common CF and LCA studies of energy systems because it is not restricted to a particular case study; instead, it attempts to provide (based on the discussion of quantitative results) general guidelines for the appropriate environmental evaluation of any energy system.

Figure 1 shows the roadmap for the chapter. Section 2 addresses the methodological framework of the study by defining its objectives, the life-cycle approach followed, and the specific case studies under evaluation regarding both biofuel systems and power generation systems with CO_2 capture, as well as data acquisition and methodological choices. After defining and inventorying the case studies in Sect. 2, Sect. 3 tackles the quantification of the carbon footprints of the

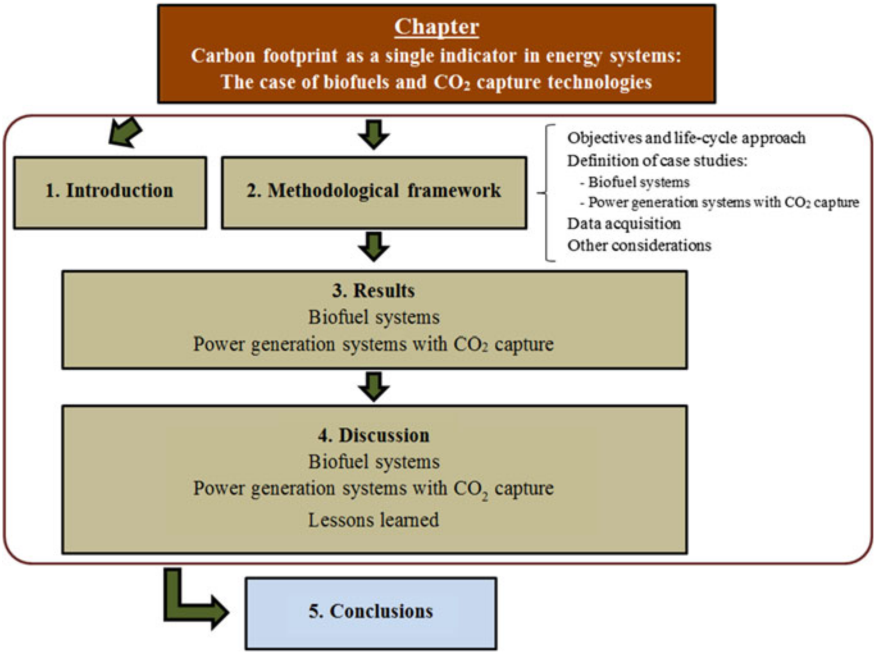

Fig. 1 Structure of the chapter

corresponding energy products, as well as the comparison of these carbon footprints with those of conventional equivalent products. Section 4 focuses on the discussion of the suitability of carbon footprints as single indicators when evaluating the environmental performance of energy systems. With this aim, Sect. 4 broadens the environmental scope of the case studies by evaluating additional impact categories, such as acidification and cumulative energy demand. Sections 4 and 5 use this specific discussion based on relevant case studies to draw more general conclusions and recommendations on the environmental evaluation of energy product systems.

2 Methodological Framework

2.1 *Objectives and Life-Cycle Approach*

The goal of this chapter is to show the potential effects of using carbon footprints as single indicators when evaluating energy systems. Specific case studies developed by the authors are used to illustrate these effects and identify the strong and weak points of CF.

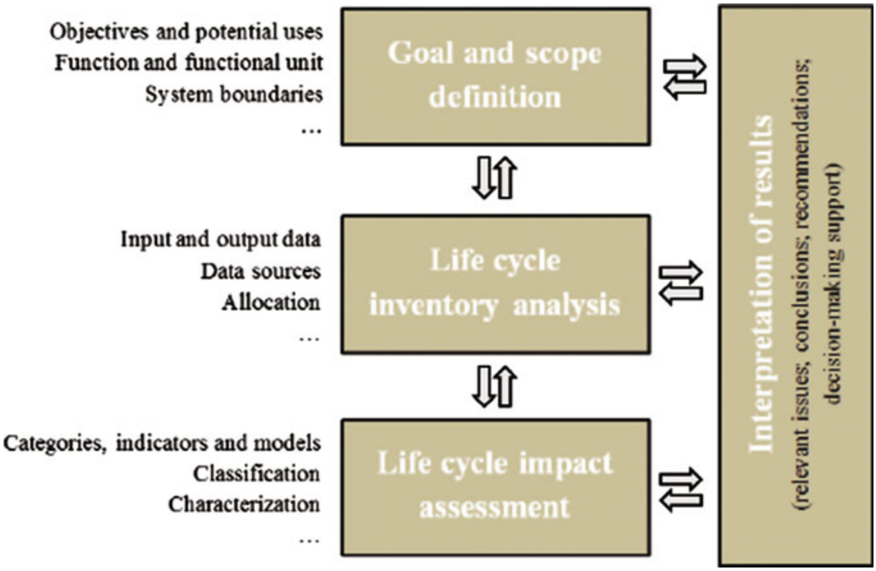

Fig. 2 LCA framework according to ISO14040:2006

The methodological framework proposed in the standardized LCA methodology is followed (International Organization for Standardization 2006a, b). As can be observed in Fig. 2, the study involves four interrelated stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation.

The stage "Goal and scope definition" involves the definition of the objectives and potential uses of the study, as well as other key aspects such as the functional unit (FU), the system boundaries, assumptions, and restrictions. The LCI step requires data collection to carry out an inventory of the input and output data of the system under study. LCIA includes three mandatory steps: (i) selection of impact categories, indicators, and characterization models; (ii) classification (i.e., association of the inventory data with the selected impact categories); and (iii) characterization (i.e., calculation of the results of each category indicator through the conversion of the inventory elements to common units by using characterization factors, and aggregation of the converted results within the same impact category). Finally, in the interpretation stage, the results from the previous steps are summarized according to the goal and scope defined for the LCA study and discussed in order to identify relevant issues and provide conclusions, recommendations, and information for decision-making purposes (International Organization for Standardization 2006a, b).

2.2 Definition of Case Studies

According to the current context of the energy sector, a relevant set of case studies of biofuels and CO_2 capture in power plants is defined to evaluate the corresponding carbon footprints and discuss their suitability as single indicators.

2.2.1 Biofuel Systems

Two case studies of biofuel systems are considered. Both systems involve second-generation biofuels from poplar biomass. Poplar is selected as the biomass feedstock due to the current interest in short-rotation plantations with energy purposes. One of the selected systems deals with synthetic fuels (gasoline and diesel) obtained through biomass pyrolysis and bio-oil upgrading, whereas the other produces hydrogen via biomass gasification and biosyngas processing.

Synthetic Fuels from Pyrolysis Bio-Oil

The synthetic biofuel system (Fig. 3) includes cultivation and transportation of poplar biomass, bio-oil production through fast pyrolysis, and bio-oil upgrading to gasoline and diesel blendstocks. Additionally, the transportation of the synthetic fuels and their combustion in conventional engines are included (well-to-wheels approach). The FU for this case study is 1 t of fuel products, which corresponds to 602 kg of gasoline and 398 kg of diesel.

In the pyrolysis plant, poplar biomass (50 % moisture) is first pretreated in order to reduce its moisture content and particle size. The biomass delivered is dried to 7 % moisture in a direct-contact dryer using the hot exhaust gases coming from the gas and char combustor (GCC). Afterwards, it is ground in a crusher and passes through a sieve to guarantee a particle size below 3 mm. The pretreated biomass is converted into gas, char, and liquid fractions via fast pyrolysis in a circulating fluidized bed (CFB) reactor that operates at 520 °C and atmospheric pressure (residence time: 2.5 s) (Iribarren et al. 2012b). The heat required by the reactor is provided by the GCC.

The liquid fraction is usually called bio-oil. A two-stage hydrotreating process converts the bio-oil into a hydrocarbon mix. The bio-oil is stabilized in the first reactor under mild conditions (250 °C, 140 bar) and then deoxygenated to approximately 1.7 % oxygen content at more severe conditions (340 °C, 170 bar) in the second reactor (Iribarren et al. 2012b). The organic stream coming from the hydrotreating section is split up in the desired products using distillation columns and a hydrocracker.

The hydrogen required by the hydrotreating and hydrocracking reactors is produced in a steam reforming process that converts the light hydrocarbons contained in the off-gas streams from the hydrotreating and hydrocracking units into

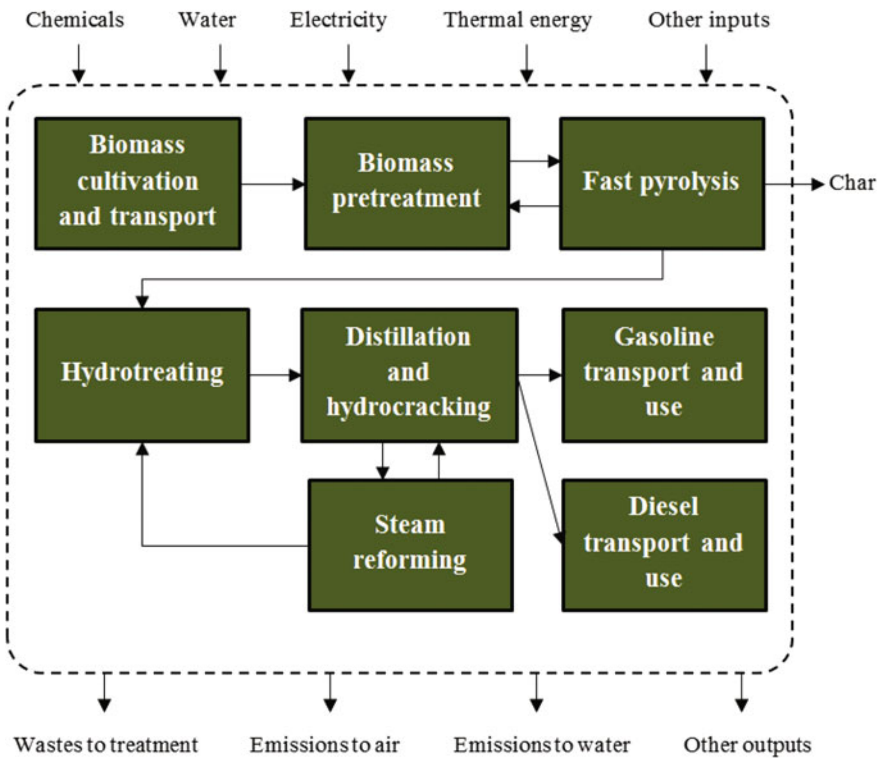

Fig. 3 Simplified diagram of the synthetic biofuel system

H_2 and CO. Additional natural gas is fed to the reactor in order to meet the hydrogen demand. After the steam reformer, a water–gas shift (WGS) reactor and a pressure swing adsorption (PSA) unit are used to finally obtain the desired hydrogen. The PSA off-gas and a fraction of the off-gas stream from the hydrocracker are fed to the off-gas combustor, which provides the heat required by the steam reforming reaction and the distillation columns (Iribarren et al. 2012b).

Hydrogen Via Indirect Biomass Gasification

The biohydrogen system (Fig. 4) includes poplar cultivation and transportation, biosyngas production through indirect gasification, syngas processing to hydrogen, and on-site power generation (cradle-to-gate approach). The FU for this case study is 1 kg of hydrogen produced (at plant; 99.9 vol% purity).

In the gasification plant, the poplar feedstock is milled and dried (from 50 to 12 % moisture content). The gasification process uses a low-pressure indirect gasifier consisting of two fluidized-bed reactors: a gasifier in which biomass reacts with steam at 870 °C and 1.6 bar producing raw syngas and char, and a combustor

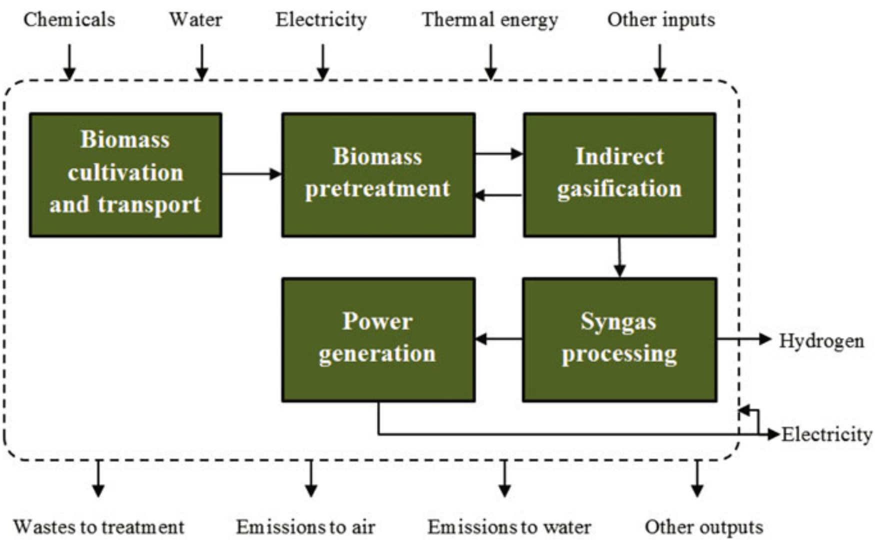

Fig. 4 Simplified diagram of the biohydrogen system

where the char fraction is burnt to provide the heat needed for the gasification process (Susmozas et al. 2013). The flue gas from the combustor is used to dry the poplar feedstock. The raw syngas undergoes a reforming process to convert tars and light hydrocarbons into CO and H_2.

The syngas stream is cooled and filtered in order to remove fine particles and condensed alkali compounds. Afterwards, the syngas is compressed and goes through a LO-CAT® process to remove sulfur compounds. The clean syngas undergoes a WGS process and, finally, hydrogen is separated from the rest of compounds in a PSA unit with 85 % efficiency (40 °C, 28 bar) (Susmozas et al. 2013).

The PSA off-gas is combusted to produce steam in a heat recovery steam generator. This steam is used on site to produce electricity in a steam cycle (30 MW). Part of the steam from the intermediate- and high-pressure sections of the turbine is used to satisfy the steam requirements of gasification and WGS (Susmozas et al. 2013).

2.2.2 Power Generation Systems with CO_2 Capture

Four alternative case studies of coal-fired power plants provided with post-combustion CO_2 capture technology are considered herein. As can be observed in Fig. 5, the four CO_2 capture systems evaluated involve the same steps, comprising the mining of the coal, through coal conditioning and power generation, to gas treatment and CO_2 capture (cradle-to-gate approach). Nevertheless, each specific

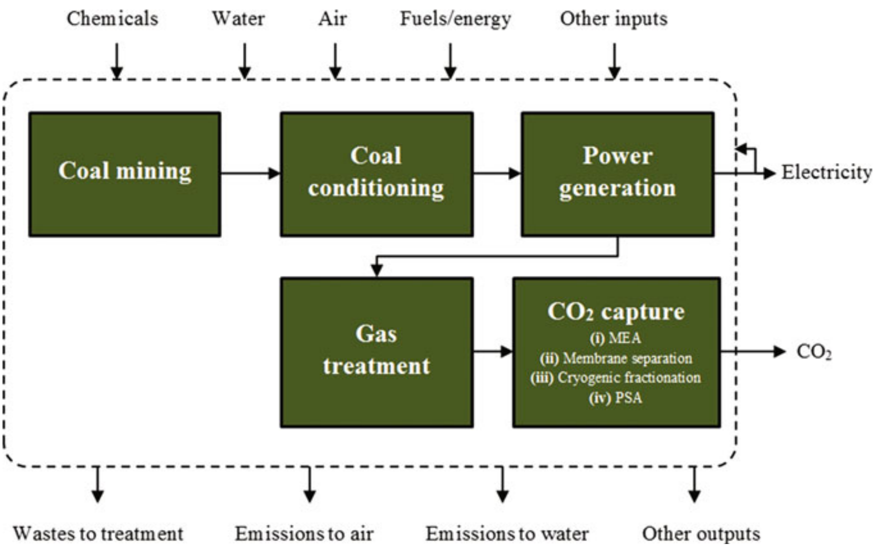

Fig. 5 General diagram of the CO_2 capture systems

post-combustion technology involves different material and energy flows. The FU for the four case studies is 1 kWh of net electricity (at plant).

The four CO_2 capture systems differ from each other in terms of the post-combustion technology selected (Iribarren et al. 2013c):

- Post-combustion CO_2 recovery via chemical absorption with monoethanolamine (MEA).
- Post-combustion CO_2 recovery via membrane separation.
- Post-combustion CO_2 recovery via cryogenic fractionation.
- Post-combustion CO_2 recovery via PSA.

It should be noted that these case studies stop at the generation of liquid CO_2, not including further steps such as CO_2 transport, storage, or beneficial use of carbon dioxide.

2.3 Data Acquisition

Key inventory data for the biofuel systems are derived from process simulation in Aspen Plus® (Aspen Technology 2013). Thus, the fast pyrolysis of poplar biomass and the subsequent bio-oil upgrading to synthetic fuels, as well as the indirect gasification of poplar biomass and the subsequent processing of the biosyngas to produce hydrogen, are simulated in Aspen Plus® in order to obtain LCI data. As an example, Fig. 6 shows the simulation diagram of the gasification plant, where

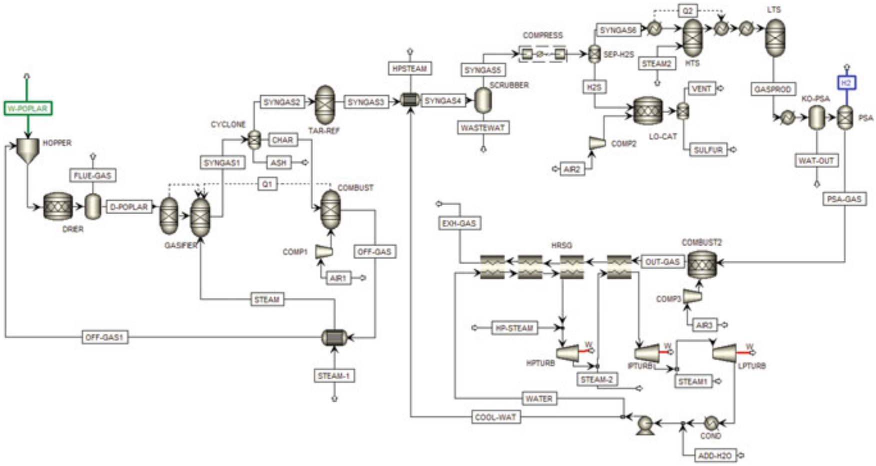

Fig. 6 Simulation diagram of the gasification plant for biohydrogen production

poplar biomass is pretreated and gasified to produce biosyngas, also including biosyngas processing to hydrogen and power generation (Susmozas et al. 2013).

Inventory data for the four CO_2 capture systems are based on scientific literature in the field of CCS (Iribarren et al. 2013c). Data for post-combustion CO_2 recovery through chemical absorption with MEA (Khoo and Tan 2006; Singh et al. 2011; Pehnt and Henkel 2009; Schreiber et al. 2009) are modified according to Khoo and Tan (2006) in order to include the alternative post-combustion technologies (i.e., membrane separation, cryogenic fractionation, and PSA).

Tables 1, 2 and 3 present a selection of key inventory data for each of the biofuel and CO_2 capture case studies. Further information on LCI data can be found elsewhere (Susmozas et al. 2013; Iribarren et al. 2013c; Iribarren et al. 2012b).

Data for poplar biomass are taken from specific literature (Gasol et al. 2009; Fan et al. 2011), whereas combustion emissions for the biosynfuel system are based on European Environment Agency (2009). Finally, data for background processes (e.g., waste management, transport, and production of chemicals and energy carriers) are retrieved from the ecoinvent® database (Frischknecht et al. 2007).

2.4 Other Considerations

Capital goods are not included in any case study. Economic allocation is used to distribute inventory data and environmental burdens when dealing with multi-functional systems (Curran 2007). In this respect, economic allocation is applied to

Table 1 Selection of inventory data for the biosynfuel system (functional unit: 1 t of synthetic fuel products)

Input	Units	Amount	Output	Units	Amount
Wet poplar biomass	t	6.77	Gasoline (to combustion)	kg	602.40
Poplar transport	t km	541.20	Diesel (to combustion)	kg	397.60
Natural gas	kg	223.73	Char (product)	kg	546.44
Electricity	MWh	1.20	CO_2 (direct emission at plant)	t	2.38
Biosynfuel transport	t km	200.00			

Table 2 Selection of inventory data for the biohydrogen system (functional unit: 1 kg of hydrogen)

Input	Units	Amount	Output	Units	Amount
Wet poplar biomass	kg	36.28	Hydrogen (product)	kg	1.00
Poplar transport	t km	2.90	Electricity (product)	kWh	2.07
			CO_2 (direct emission at plant)	kg	32.84

Table 3 Selection of inventory data for the CO_2 capture systems (functional unit: 1 kWh of net electricity)

Item	Units	Case MEA	Case membrane	Case cryogenics	Case PSA
Coal (input)	g	672.20	554.00	969.20	609.90
Net electricity (output)	kWh	1.00	1.00	1.00	1.00
Captured CO_2 (output)	kg	1.29	0.91	1.76	1.04
CO_2 (direct emission)	g	67.65	200.71	195.07	184.13

the biosynfuel system for both the pyrolysis section (bio-oil [allocation percentage: 89 %] and char [11 %]) and the bio-oil upgrading section (gasoline [63 %] and diesel [37 %]). Regarding the biohydrogen system, economic allocation is applied between the hydrogen (95 %) and electricity (5 %) products. In the CO_2 capture systems, the whole impact is attributed to the net electricity output (i.e., 0 % to the captured CO_2).

As a general concern in LCA and CF studies, different decisions on methodological choices such as boundary selection and allocation approach would lead to different results within each case study (Reap et al. 2008a). This fact, along with other factors such as data availability and quality, leads to uncertainty in the decision process (Reap et al. 2008b). Nevertheless, this chapter does not aim to report and compare accurate carbon footprints of the energy products evaluated, but rather to discuss the suitability of carbon footprints as single indicators when evaluating energy product systems. In Sect. 4, the discussion is based on broadening the environmental scope of the case studies (i.e., evaluating not only global warming, but also additional impact categories). Because all impact categories are evaluated for each individual case study based on the same system definition and

Table 4 Carbon footprints of the biofuel systems (results per functional unit)

Item	Units	Amount
Combusted synthetic biogasoline	kg CO_2 eq	84.93
Combusted synthetic biodiesel	kg CO_2 eq	164.59
Biohydrogen	kg CO_2 eq	0.39

the same inventory, uncertainty concerns are highly mitigated for the purposes of the study. Hence, no uncertainty analysis has been carried out for the case studies proposed.

3 Results

Specific LCA software (SimaPro 7) is used for the computational implementation of the inventories (Goedkoop et al. 2010). The global warming impact potential (GWP) of each case study is evaluated. Note that the GWP results are the carbon footprints of the energy systems assessed (expressed in terms of CO_2 eq). The calculation of these carbon footprints is carried out according to the characterization factors (100-year period) reported by the Intergovernmental Panel on Climate Change (Forster et al. 2007).

3.1 Biofuel Systems

Table 4 summarizes the carbon footprints of the biofuel products under study. Regarding synthetic biogasoline (combusted in a conventional passenger vehicle engine), the corresponding carbon footprint (84.93 kg CO_2 eq FU^{-1}) is due mainly to direct emissions arising from the fuel use phase, ahead of direct emissions from the energy conversion plant. When compared to conventional (fossil) gasoline (inventoried according to the ecoinvent® database (Dones et al. 2007)) also combusted in a common vehicle engine (European Environment Agency 2009), a GHG saving of 96 % is calculated. This high GHG saving clearly exceeds the 60 % GHG savings criterion stated in the RED for biofuels and bioliquids produced in installations in which production started on or after 1 January 2017 (European Union 2009).

Regarding synthetic biodiesel (combusted in a conventional passenger vehicle engine), a carbon footprint of 164.59 kg CO_2 eq FU^{-1} is calculated. As in the case of synthetic gasoline, direct emissions from the fuel use phase, followed by direct emissions from the energy conversion plant, are the main sources of GWP. In comparison with fossil diesel (inventoried according to the ecoinvent® database (Dones et al. 2007)) combusted in a common vehicle engine (European Environment Agency 2009), an 88 % GHG saving is estimated, also meeting the 60 % criterion of the RED.

The carbon footprint allocated to the hydrogen product within the biohydrogen system is 0.39 kg CO_2 eq FU^{-1}. Direct emissions to the air from the energy conversion plant account for the highest contribution to this carbon footprint. When compared to conventional hydrogen from steam methane reforming (SMR) as defined by Susmozas et al. (2013), a very high GHG saving (96 %) is estimated, which clearly shows that gasification-based biohydrogen is more suitable than conventional hydrogen in terms of global warming.

3.2 Power Generation Systems with CO_2 Capture

Figure 7 shows the carbon footprints of the electricity product from the four power generation systems equipped with CO_2 capture technology. The main sources of GWP identified in the four cases are the coal feedstock (leading contributor in the case study of chemical absorption with MEA) and direct emissions to the air arising from the coal power plant (leading contributor in the remaining case studies).

Furthermore, Fig. 8 compares the carbon footprint of the electricity produced in a conventional coal-fired power plant without CO_2 capture (as defined by Iribarren et al. (2013c)) with that of the electricity generated in the evaluated power plants provided with post-combustion CO_2 capture technology. As can be observed in Fig. 8, significant GHG savings (ranging from 57 to 75 %) are calculated for the different capture alternatives. Hence, from a life-cycle global warming perspective, CO_2 capture is found to be a suitable strategy to be implemented in power plants.

4 Discussion

This chapter does not focus on the quantitative results of the carbon footprints of biofuels and electricity, but it aims to discuss the suitability of these carbon footprints as single indicators of the environmental performance of energy systems.

Taking into account GWP as the sole criterion of environmental suitability, the results for biofuels in Sect. 3.1 show that they are an eco-friendly alternative to conventional fossil fuels. Similarly, Sect. 3.2 considers CO_2 capture as an appropriate option in power plants in order to generate environmentally friendly electricity.

Section 4 broadens the environmental scope of the study by evaluating a higher number of impact categories, thereby verifying the environmental appropriateness of biofuels and CO_2 capture. The CML method is used to evaluate the following impact potentials: abiotic depletion (ADP), ozone layer depletion (ODP), photochemical oxidant formation (POFP), acidification (AP), and eutrophication (EP)

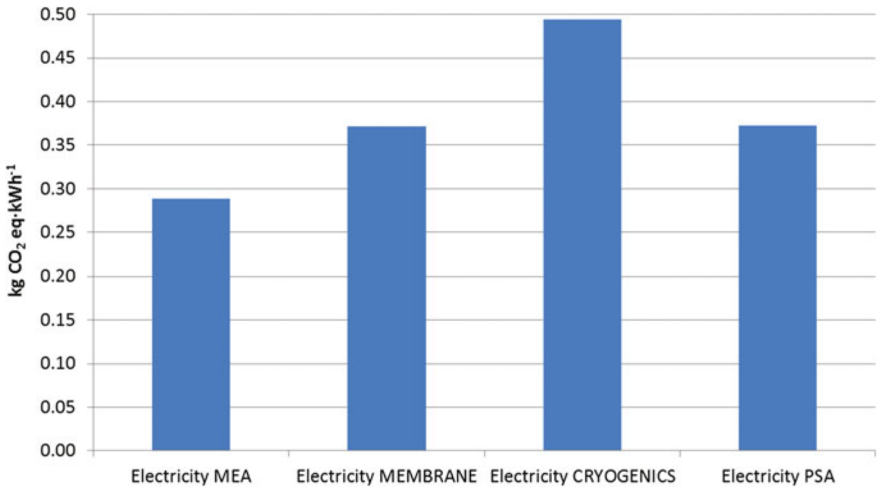

Fig. 7 Carbon footprints of the power generation systems with post-combustion CO_2 capture

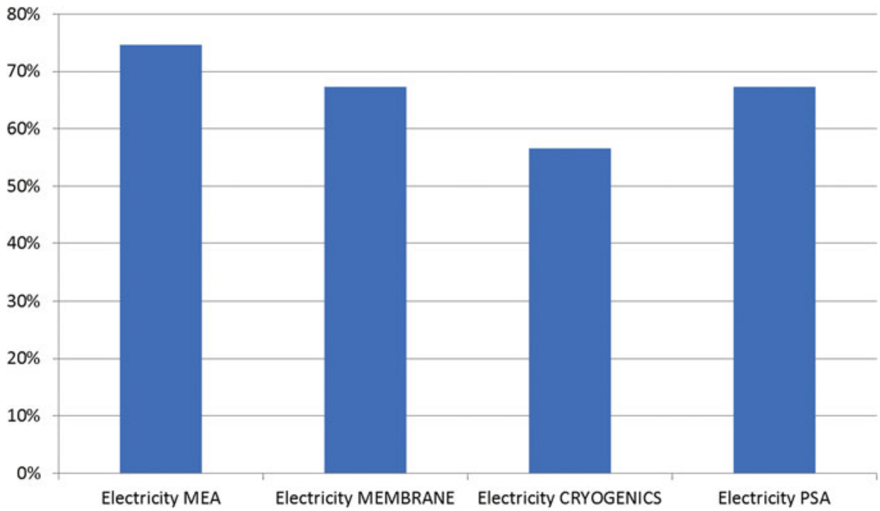

Fig. 8 Greenhouse gas savings linked to coal power plants with CO_2 capture relative to a conventional coal-fired power plant without CO_2 capture

(Guinée et al. 2001). The cumulative non-renewable (i.e., fossil and nuclear) energy demand (CED) is also quantified as an additional impact category (Verein Deutscher Ingenieure 2012). This wider set of common impact categories allows the identification of potential conflicts between GWP and other impacts when giving general recommendations on the substitution of conventional energy systems.

4.1 Biofuel Systems

Biohydrogen and synthetic biofuels result in a promising performance in terms of GWP (Sect. 3.1). However, the inclusion of additional impact categories could lead to a different picture of the life-cycle performance of these biofuels.

Figure 9 shows the comparison between synthetic biofuels and conventional fossil fuels when taking into account the extended set of impact categories. In the case of synthetic biogasoline (Fig. 9a), all categories (except for EP) identify synthetic biogasoline as a suitable alternative to fossil gasoline.

When compared to the use of GWP as a single indicator, the use of additional impact categories does not seem to influence significantly the recommendation in favor of synthetic biogasoline. Nevertheless, if special relevance is given to EP over the rest of categories, then this recommendation could be altered. The unfavorable EP result of synthetic biogasoline is linked to high electricity requirements and biomass cultivation (Iribarren et al. 2012a, b).

With respect to synthetic biodiesel (Fig. 9b), this biofuel is found to perform better than conventional fossil diesel in GWP as well as in four of the six additional impact categories under evaluation (i.e., CED, ADP, ODP, and POFP). Unless special attention has to be paid to AP and EP, the recommendation driven by GWP could be maintained. As seen in the case of synthetic biogasoline, the detrimental EP/AP performance of synthetic biodiesel is mainly due to electricity production and biomass cultivation (Iribarren et al. 2012a, b).

Figure 10 shows the comparison between biohydrogen and conventional SMR hydrogen for the extended set of impact categories. As can be observed in this figure, biohydrogen leads to important impact savings not only in GWP, but also in most of the additional impact categories (i.e., ADP, CED, ODP, and, to a lesser extent, POFP). Under these environmental categories, biohydrogen is recommended as an eco-friendly alternative to conventional hydrogen. However, if AP and EP are prioritized, then this recommendation could be wrong (as also seen in the case of synthetic biodiesel). The unfavorable AP/EP results of biohydrogen are closely linked to the need of fertilizers for biomass cultivation and to direct emissions to the air from the power generation section of the plant (Susmozas et al. 2013).

Overall, when evaluating biofuels, the recommendations driven by GWP seem not to be dramatically affected by the inclusion of additional impact categories. However, despite this generalization, the environmental suitability of biofuels is actually conditioned by the specific impact category in consideration. Although CED, ADP, and ODP usually show a behavior similar to that of GWP, other categories such as AP and EP are likely to lead to opposite recommendations. Furthermore, the consideration of a higher number of additional impact categories would result in a higher number of conflicts between the recommendations driven by GWP and those based on other impact categories.

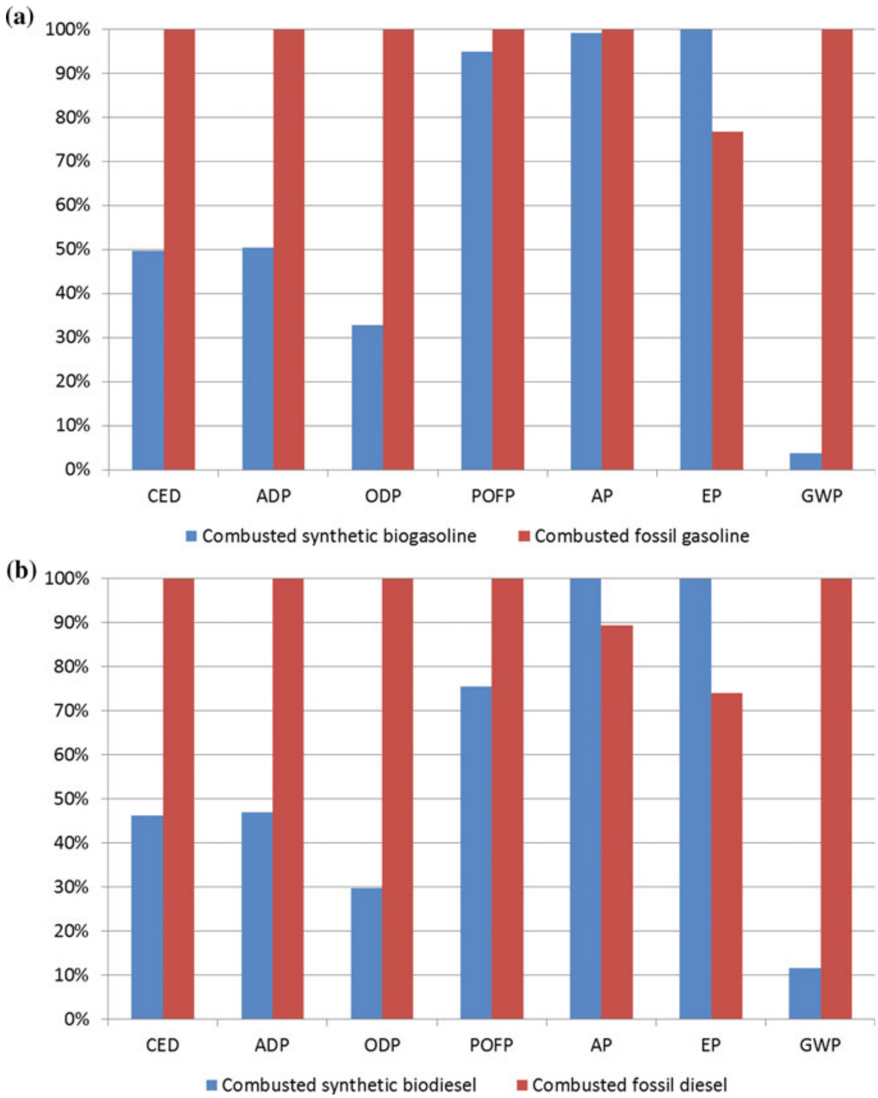

Fig. 9 Comparison of the environmental profile of synthetic biofuels and conventional fossil fuels: **a** gasoline, **b** diesel

4.2 Power Generation Systems with CO_2 Capture

When compared to conventional power plants from a life-cycle global warming perspective, the use of CO_2 capture technologies in power plants is found to be an appropriate strategy (Sect. 3.2). However, this suitability could be affected by the use of carbon footprints as single indicators. Figure 11 presents the comparison

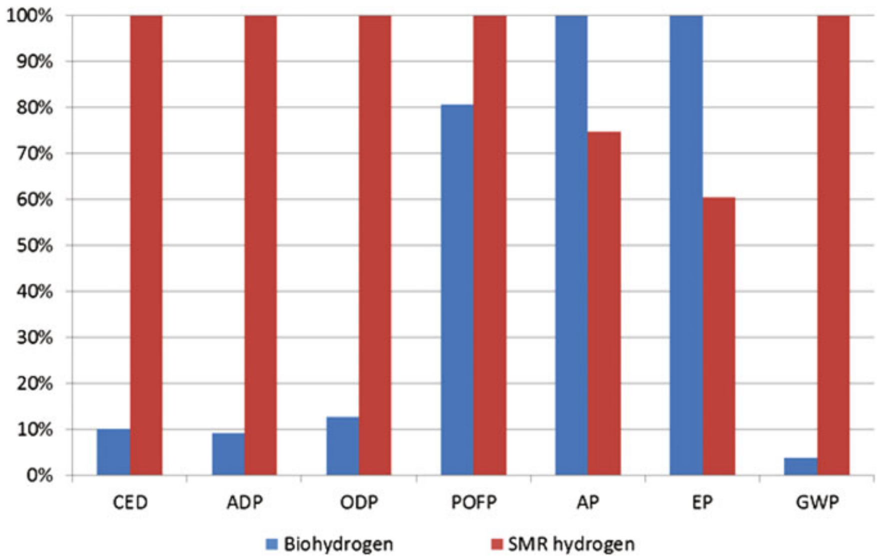

Fig. 10 Comparison of the environmental profile of biohydrogen from indirect biomass gasification and conventional hydrogen from steam methane reforming (SMR)

between conventional electricity (from a conventional coal-fired power plant without CO_2 capture (Iribarren et al. 2013c)) and the electricity generated in each of the four evaluated plants equipped with post-combustion CO_2 capture technology, taking into account the extended set of impact categories.

As can be observed in Fig. 11, most of the evaluated impact categories (namely, ODP, ADP, CED, and EP) show a worse performance of the electricity from coal power plants with CO_2 capture. Therefore, when evaluating power generation systems with CO_2 capture technology, the inclusion of additional impact categories in the assessment dramatically affects the identification of suitable energy systems.

Even though important GWP reductions are attained by implementing CO_2 capture strategies, the increased requirements of coal make the environmental benefits of these systems questionable, also affecting their thermodynamic performance (Iribarren et al. 2013c).

Overall, power generation with CO_2 capture faces concerns regarding its environmental and thermodynamic suitability. The use of carbon footprints as single indicators is very likely to lead to a misleading picture of the environmental performance of this type of systems, whose suitability highly depends on the impact categories considered.

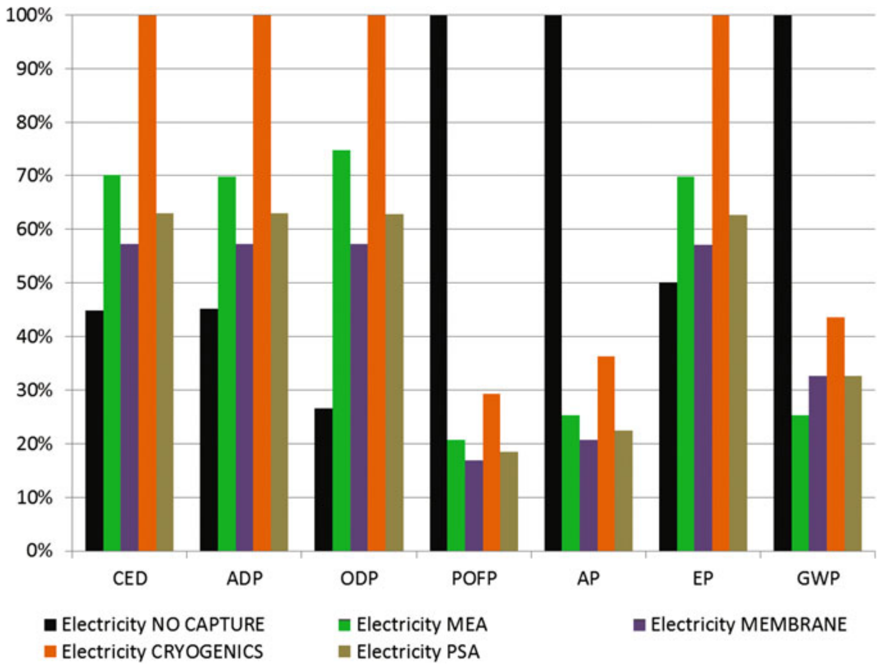

Fig. 11 Comparison of the environmental profile of electricity from coal power plants with CO_2 capture and electricity from a conventional coal-fired power plant

4.3 Lessons Learned

Biofuels and electricity from power plants with CO_2 capture are used in this chapter as relevant case studies of the energy sector. The individual study of their carbon footprints in Sects. 3.1 and 3.2 shows a promising life-cycle global warming performance of both types of energy products. Nevertheless, differences arise when it comes to expanding the scope of the study by including further impact categories (Sects. 4.1 and 4.2).

Decisions on the environmental suitability of a product always depend on the impact categories considered. Hence, decisions and recommendations based only on carbon footprints (i.e., only on the GWP results) will unavoidably capture a partial picture of the environmental performance of the evaluated product. Thus, the use of carbon footprints as single indicators is likely to result in a misleading interpretation of the environmental analysis.

However, different levels of risk seem to be associated with the use of carbon footprints as single indicators when assessing energy systems, depending on the type of systems and products under evaluation. In this respect, even though the use of a single indicator does not allow an unequivocal interpretation of the environmental performance of an energy product/system, the only use of carbon footprints to characterize biofuels can succeed in providing a general (simplified) picture of their performance. Nevertheless, analysts should be aware of the singularities of biomass-based systems, which probably affect certain categories such as AP and EP leading to opposite trends as compared to GWP. On the other hand, carbon footprints as single indicators of the environmental performance of electricity from power plants with CO_2 capture often distort the actual performance of the corresponding product systems, which usually involve energy-intensive technologies that seriously affect many categories such as CED and ADP.

Moreover, the correlation between GWP (carbon footprints) and other impact categories does not offer a general pattern for energy products (Laurent et al. 2012). In other words, despite the strong interactions that climate change shows with other global environmental issues, there is a weak correlation between carbon footprints and certain impact categories, such as toxicity-related categories or resource depletion (Laurent et al. 2012). Therefore, the use of a multi-indicator approach is generally safer, as also seen in CF studies of non-energy systems (Merrild 2009; Iribarren et al. 2010a).

When taking biofuels and electricity from power plants with CO_2 capture as representative case studies of the energy sector and trying to reduce ambiguity concerns, it is concluded that carbon footprints should not be the only criterion to assess energy product systems from a life-cycle environmental perspective. The inclusion of additional impact categories leads to a more comprehensive evaluation of the environmental performance of energy systems, thus facilitating a more sensible decision-making process oriented towards environmental sustainability (Iribarren and Dufour 2012; Iribarren et al. 2013c).

The recommendation on the use of multi-indicator approaches connects with the controversial discussion on the rough definition of CF as an LCA restricted to the GWP category. In this respect, taking into consideration ISO standards on LCA and admitting that CF is based on a life-cycle perspective, the terms CF and LCA should not be mixed in the same definition because LCA refers not only to a holistic approach but also to a comprehensive view of impacts (International Organization for Standardization 2006a, b).

Despite the appropriateness of multi-indicator evaluations, CF should not be trivialized. In fact, CF has succeeded in catalyzing life-cycle thinking, reaching policy makers, companies, and society (Iribarren et al. 2010a; Weidema et al. 2008). This success is closely linked to the interest in reporting environmental results (Finkbeiner 2009; Sinden 2009). The development of CF specifications such as PAS 2050:2011 (British Standards Institution 2011) has facilitated the systematic calculation of life-cycle GHG emissions, enhancing the communicability of carbon footprints.

Furthermore, although the carbon footprint of a product is a single indicator, CF involves a procedure that can be easily extended to evaluate impact categories other than GWP. This feature is due to the fact that the inventory data used in the CF study could be further used in LCA studies in order to get a more comprehensive understanding of the environmental performance of the evaluated product.

Finally, in addition to the possibility of performing an LCA using inventory data from the CF study, other methodological improvements could help to mitigate the concerns regarding the limited scope of CF in terms of evaluated impacts. For instance, when evaluating multiple similar entities, the Data Envelopment Analysis (DEA) methodology (Cooper et al. 2007) can be combined with either CF or LCA approaches, offering synergistic effects (Iribarren 2010; Vázquez-Rowe et al. 2010; Iribarren et al. 2010b; Vázquez-Rowe and Iribarren 2014). In particular, the combined use of CF and DEA moderates the reiterated limitation that CF cannot account for a comprehensive assessment of environmental impacts. This benefit of the combined CF and DEA approach is linked to the underlying nature of the method, which seeks GHG-emission benchmarking through the optimization of resource use (Vázquez-Rowe and Iribarren 2014). Because the optimization of resource use generally results in a better environmental performance in all impact categories (Schmidheiny 1992), the concern about the use of carbon footprints as single indicators is reduced.

5 Conclusions

The assessment of the life-cycle GHG emissions (i.e., carbon footprints) of different second-generation biofuels (synthetic fuels via biomass pyrolysis and hydrogen via biomass gasification) and electricity from coal power plants with alternative CO_2 capture technologies (chemical absorption, membrane separation, cryogenic fractionation, and pressure swing adsorption) was used to discuss the suitability of carbon footprints as single indicators when evaluating the environmental performance of energy product systems.

Although the carbon footprints calculated indicate a promising life-cycle performance of the energy products evaluated, opposite findings are seen when taking into account other impact categories. Therefore, carbon footprints as single indicators lead to a partial (and maybe misleading) picture of the environmental performance of energy products.

Although recommendations based solely on carbon footprints correspond with a partial picture of the environmental performance of the evaluated energy products, different levels of risk are associated with the use of carbon footprints as single indicators depending on the type of systems and products under study. For instance, carbon footprints can provide a general, simplified picture of the environmental performance of biofuels, whereas their use as single indicators for electricity from power plants with CO_2 capture usually distorts the actual environmental performance of the assessed product in a dramatic way.

Analysts are responsible for taking into consideration the singularities of each specific energy product system under evaluation because these singularities can seriously affect a wide range of impact categories, leading to trends opposite to GWP. For instance, the singularities of biomass-based systems affect certain categories, such as acidification and eutrophication, whereas energy-intensive technologies (e.g., CO_2 capture) affect categories such as abiotic depletion and cumulative energy demand.

The results for biofuels and electricity with CO_2 capture—as relevant case studies of the energy sector—show that carbon footprints should not be the only criterion for the environmental characterization of energy product systems from a life-cycle perspective. The use of multi-indicator approaches is considered to be more appropriate because it reduces ambiguity concerns.

Finally, even though the inclusion of additional impact categories facilitates more sensible decision- and policy-making processes oriented towards environmental sustainability, CF studies should continue to be undertaken. They not only address the globally relevant impact category of global warming, but also have proven to be an effective vehicle for the penetration of life-cycle thinking in companies, policies, and society. Furthermore, CF studies constitute a valuable source of inventory data that can be easily implemented in LCA studies to provide a more comprehensive environmental evaluation of energy systems.

Acknowledgements This research has been supported by the Regional Government of Madrid (S2009/ENE-1743) and the Spanish Ministry of Economy and Competitiveness (CTQ2011-28216-C02-02 and ENE2011-29643-C02-01). The authors would like to thank Jens F. Peters and Ana Susmozas for valuable scientific exchange.

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