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# An LCA-based evaluation of biomass to transportation fuel production and utilization pathways in a large port's context

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**Abstract** This study evaluates whether a transition of large ports facilities to biofuel production for mobility improves the environmental performance and satisfies the renewable energy directive (RED) and it is the first LCA study that considers biofuel production from torrefied wood. The systems studied are wood, torrefied wood, and straw pellets circulating fluidized bed gasification for H<sub>2</sub>, synthetic natural gas, or Fischer–Tropsch (FT) diesel production and use. These systems are evaluated for their global warming, acidification, eutrophication and particulate matter potentials, as well as, for their aggregated environmental performance. The effects of the electricity mix selection and ecoinvent database's economic allocation are also analyzed. All biomass systems result in a better aggregated environmental performance and benefits for the global warming potential. However, regarding the acidification, particulate matter, and eutrophication potentials, most

biomass systems are inferior to the reference systems. Switching to a zero-emission electricity mix offers benefits for all the biomass and fossil-H<sub>2</sub> systems and researchers should use databases cautiously. The bio-H<sub>2</sub> and FT diesel of wood-based systems show the best environmental performance and satisfy the current and future RED targets. On one hand, the bio-H<sub>2</sub> systems result in the largest benefits regarding the global warming potential, and on the other hand, both wood-based FT diesel systems offer overall benefits which concern not only the sustainable target of CO<sub>2</sub> emissions reduction, but also the air quality improvement of the broader area as well.

**Keywords** Life cycle assessment · Torrefaction · Gasification · Transportation fuel · Wood · Straw

## Introduction

The current harbours do not consist only of marine facilities. Especially, the large harbours worldwide consist of industrial infrastructure, such as oil refineries, chemical production clusters, and power plants. The port of Rotterdam (PoR) is the largest European port and the fifth worldwide. The PoR is guided by the Port Vision 2030, which states that the share of sustainable energy in the port's energy mix will increase from 10 to 30% in 2030 and a 60% reduction of the CO<sub>2</sub> emission of the 1990 levels (24 Mton CO<sub>2</sub> eq.) is targeted. In 2030, Rotterdam aims to have a syngas cluster based on biomass, coal, and oil residuals [1]. Thus, the port authorities envisage that, by then, Rotterdam will still be the most important European port and industrial complex, with a strong combination of the Global and Europe's Industrial Cluster [2]. The challenge faced by the port authorities for sustainable development

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requires activities that meet the current and future needs of the enterprise and its stakeholders whilst protecting the human and natural resources well-being. Since the current port's infrastructure consists, for a large part, of industry for automotive fuels and gas production, a potential alternative green business activity would be the production of bio-syngas which will be converted to liquid or gaseous transportation fuels for use in the conventional vehicles and fuel cell (FC) cars. This green alternative must be part of the Port Vision 2030, comply with the Renewable Energy Directive (RED) 2009/28/EC targets and reduce serious threats over human health, as the IEA warned that air pollution will kill millions if environmental policies do not change [3]. The Renewable Energy Directive (RED) 2009/28/EC [4] concerns the greenhouse gas (GHG) emissions during the life cycle of a transportation biofuel and does not address other environmental impacts. With regard to the GHG emissions, the construction of relevant infrastructure and vehicles is yet to be considered in the RED 2009/28/EC. The directive's GHG emission savings target is 35% until 2017 and it rises to 50% by 2017. However, in 2018, the target rises again to 60%, but only for new production plants.

Biomass has been recognized as a sustainable energy source. However, its untreated form is not ideally suited for energy conversion applications. This is due to its generally high moisture content, which corresponds to a low energy content per kg. This makes the conversion of biomass complicated and logistics more expensive. As a result, efforts are being made to develop upgrading processes that convert biomass into a fuel with improved properties with respect to logistics and end-use.

Gasification is a thermochemical technology that converts a (typically) solid fuel into a gas that is rich in CO, H<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O. Gasification, and especially the fluidized bed reactor type, is attractive due to the large variety of feedstock that can be employed and the wide variety of the end-uses of the produced gas. The latter can be converted into liquid fuels, gaseous fuels, and chemicals or it can also be directly combusted in a furnace for heat and/or power generation.

Torrefaction is considered the least severe thermochemical processing of biomass. It is used to upgrade the biomass to a solid biofuel at a typical temperature range between 230 and 300 °C, in an oxygen-deficient atmosphere. Its main product is comparable to low-grade coal, with improved properties compared to the untreated biomass, such as higher carbon and energy density, enhanced grind ability and reduced susceptibility to microbial degradation. Therefore, torrefied biomass has been suggested as suitable feedstock for co-firing with coal, gasification, and thermochemical fuel production [5–7]. Specifically for the gasification of torrefied wood, our

group has shown that the coupling of torrefaction with circulating fluidized bed gasification resulted in benefits regarding syngas quality (H<sub>2</sub> and CO) and tar reduction [33].

Life cycle assessment (LCA) is a tool which since 1992 [8] has been continuously getting more attention as it evaluates the environmental performance of products, services, and systems, and identifies opportunities for improvement. Therefore, LCA is already considered a powerful tool regarding the environmental aspect of sustainable development. There have been a number of LCA and well-to-wheel studies regarding the generation of liquid and gaseous biofuels via wood gasification. However, so far, only two studies [9, 10] used empirical data; and none of them has considered torrefied wood as the gasifier's feedstock. In general, the LCA practitioners construct their life cycle (LC) inventory based on literature data and do not include the construction of the relevant infrastructure (including road infrastructure) in their system boundaries. In addition, they do not consider the effects of biomass storage, even though the supply chain of biomass typically contains a storage period. Sunde et al. [11] conducted a review regarding the environmental impacts of wood-to-liquid fuels production and use, and reported a GHG emissions range between 129 and 200 g CO<sub>2</sub> eq km<sup>-1</sup>. This range of values resulted due to differences in methodology chosen, such as the exclusion of various stages from the life cycle boundaries and allocation methods. They concluded that liquid biofuels derived from woody biomass do offer an environmentally sound and viable solution to the transport sector. The up-to-date relevant literature showed that LCA practitioners use mostly literature sources [12–18] for their foreground data, typically limit their environmental impacts to global warming potential (GWP) and acidification potential (AP), use dedicated plantations or forestry residues as the origin of their selected feedstock, and do not pelletize their considered feedstock. In general, concerning GWP wood is superior to fossil fuels and the studies based on literature foreground data result in greater environmental benefits than studies [9] with empirical data, except from the Joint Research Centre (JRC) [10] study. However, in that study, there is no transparency regarding the setup of the considered biomass system, as the researchers did not present a detailed inventory. On the other hand, wood does not provide environmental benefits regarding AP and eutrophication potential (EP) due to the fertilizer use. Table 1 presents an overview of the relevant studies.

Based on previous LCA studies, wood appears to be a promising feedstock for gasification-derived transportation fuels. In addition, LCA practitioners so far have constructed their LC inventories mainly by combining different literature sources and databases which reduces the

**Table 1** Overview of relevant environmental studies

References	Transportation biofuel	Feedstock	Impacts	GWP (g CO <sub>2</sub> eq km <sup>-1</sup> )	AP (g SO <sub>2</sub> eq km <sup>-1</sup> )	Foreground data	Assumptions
[9]	SNG <sup>j</sup>	Sawmill residues	GHG	202	–	Empirical	Zero upstream emissions
[10]	FT diesel	Wood	GHG	16	–	n.d.	n.d.
[12]	H <sub>2</sub> , SNG, FT diesel	Poplar wood	GWP, AP	58–132	0.37–0.68	Literature	Exergy allocation
[13]	FT diesel	SRC <sup>k</sup> wood	GWP, AP, EP, POCP <sup>a</sup>	200	0.36	Literature	Exergy allocation
[14]	SNG	Forest residues	GWP	32–40	–	Literature	No by-products considered or used
[15]	H <sub>2</sub>	Poplar wood	GWP, AP, EP, ODP <sup>b</sup> , POFP <sup>c</sup>	385 <sup>h</sup>	0.02 <sup>i</sup>	Aspen Plus <sup>TM</sup>	Fertilizer use
[16]	FT diesel	Willow	GWP, AEP <sup>d</sup>	68 <sup>g</sup>	–	Literature	Different energy scenarios
[17]	H <sub>2</sub>	Wood	ReciPe 2008 <sup>f</sup>	130	1.0	Literature	Various
[18]	FT diesel	SRC <sup>k</sup> wood and straw	Eco-indicator 99 <sup>g</sup>	100–130	–	Literature	Heavy use of fertilizer

<sup>a</sup> Photooxidant creation potential

<sup>b</sup> Ozone depletion potential

<sup>c</sup> Photochemical oxidation

<sup>d</sup> Aquatic eutrophication potential

<sup>e</sup> g CO<sub>2</sub> eq MJ<sup>-1</sup>

<sup>f</sup> Method which includes climate change potential, terrestrial acidification potential, freshwater eutrophication potential, particulate matter formation potential, photochemical oxidant formation potential, human toxicity potential, terrestrial eco-toxicity potential, and freshwater eco-toxicity potential

<sup>g</sup> Includes climate change potential, acidification potential, eutrophication potential, ozone depletion potential, and particulate matter formation potential

<sup>h</sup> In g CO<sub>2</sub> eq kg<sup>-1</sup> H<sub>2</sub>

<sup>i</sup> g SO<sub>2</sub> eq kg<sup>-1</sup> H<sub>2</sub>

<sup>j</sup> SNG stand for substitute natural gas

<sup>k</sup> SRC stands for short rotation coppice

applicability of their results. For example, the use of the ecoinvent database results in incorporating the economic allocation, or LCA practitioners use different types of allocations or just exclude relevant by-products and the biomass storage stage from their LC boundaries. In addition, to the best of our knowledge, there is no LCA study regarding the environmental performance of transportation biofuels derived from torrefied wood which considers the RED emissions targets. Therefore, the goal of this study is to evaluate the overall environmental performance of three transportation biofuels production pathways when a circulating fluidized bed gasifier is considered to generate the syngas which is upgraded and used in a FC car and EURO 5 cars. The hot spots of the related environmental performances will be identified. To improve the applicability of this study, empirical data are used, and the RED target limits and particulate matter potential (PMP) are considered. Therefore, empirical data for the LC stages, such as

torrefaction of wood and its subsequent gasification, are used and system expansion is used instead of allocation when it is possible. Apart from the specific environmental impacts, such as the GWP, AP, PMP, and EP, the aggregated environmental performance is evaluated as well. In addition, the improvement of the carbon footprint of the electricity mix and the type of allocation of the ecoinvent database are evaluated. Finally, the results of this study are expected to be applicable to other ports with relevant infrastructure as the PoR.

## Methodology

The CMLCA software [19] and the CML 2001 and Traci impact models were used to acquire assessment results regarding the GWP, EP, AP, and PMP. All these impacts have been weighted to calculate the aggregated



environmental impact based on the Building for Environmental and Economic Sustainability (BEES) stakeholder panel [20] method. Due to the fact that not all environmental impacts that are included in this method have been considered by this study, the weighting factors were recalculated proportionally. The weighting factors of the impacts that are included in the BEES method and are considered in our study have been increased proportionally based on the impacts that are included in the BEES method, but are not considered in our study; a table with the weighting factors is presented in supplementary material section.

### Goal and scope definition

The goal of this LCA study is to assess the environmental impacts related to the production and utilization of transportation biofuels derived from product gas upgrading when torrefied wood pellets, wood pellets, and straw pellets are used as feedstock. The produced transportation biofuels were compared with their fossil alternatives. The foreground data used in this study are collected from in-house performed gasification experiments, and part of these data is provided by a Dutch torrefaction company or modelled using Aspen Plus<sup>TM</sup>, a commercial flowsheeting package. Furthermore, the background data are collected from the ecoinvent database.

Finally, two sensitivity analyses were performed regarding the influence of the allocation type of the ecoinvent database and the electricity mix. The former concerns the effect of using ecoinvent database in LCA energy studies and the latter concerns the effect of a transition to a more sustainable electricity mix as used in Switzerland. Detailed information concerning the sensitivity analyses can be found in the supplementary material section.

### Functional unit

The main function of all systems is the production of transportation fuels and their utilization in vehicles. Therefore, the selected functional unit is 1 km distance travelled by a vehicle.

### System boundaries

The boundaries of the biomass, petroleum oil, and natural gas systems are all cradle-to-grave (Fig. 1). Materials and energy consumed regarding the construction and demolition of relevant infrastructure were out of the scope of this study, except from the road infrastructure. It has been shown that the contribution of constructing and

demolishing a power plant is insignificant with respect to the fuel conversion and utilization stages [21].

### Allocation

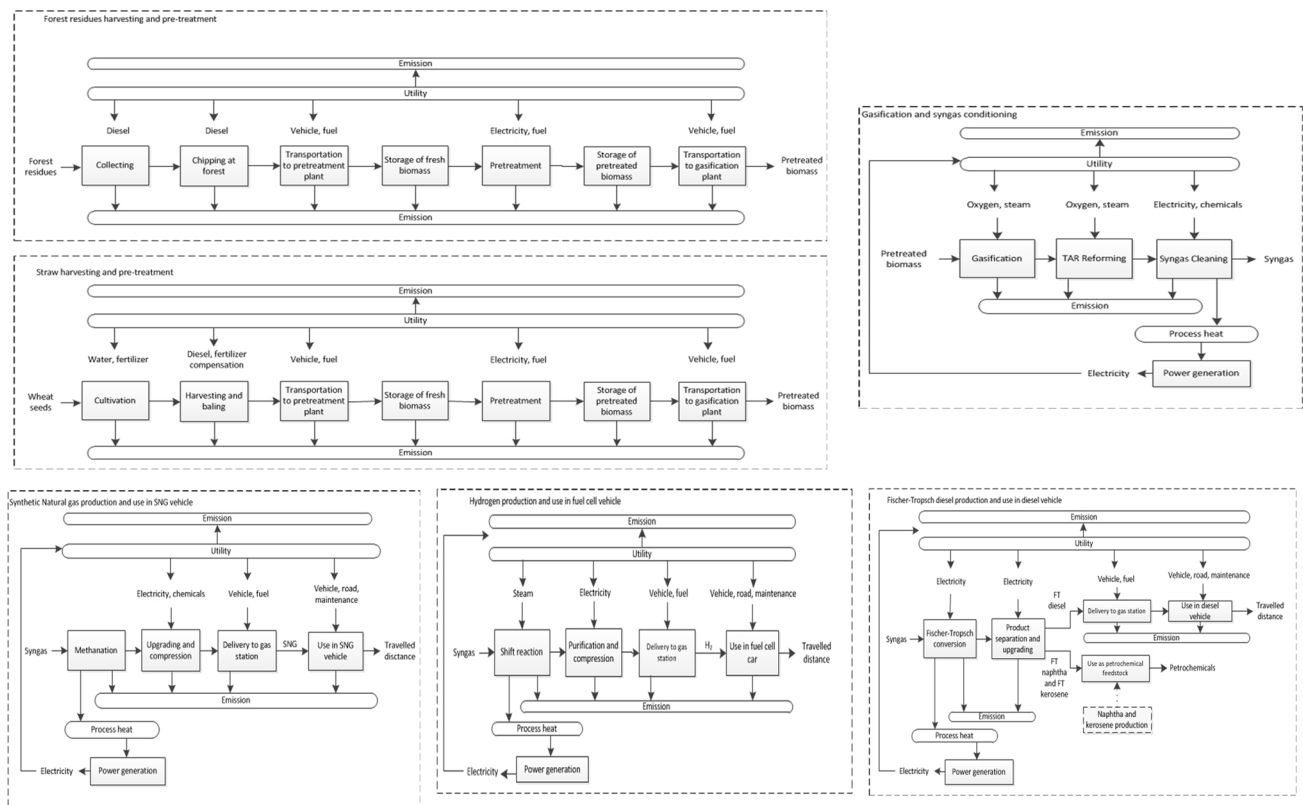
Allocation was avoided whenever possible and system expansion was preferred. However, the ecoinvent database is constructed based on the economic allocation, and therefore, using economic allocation could not be avoided for processes inserted from the database.

### Study assumptions

In this paper, we focused on forestry residues produced in The Netherlands, Belgium, and Germany and wheat straw produced in the western part of The Netherlands. Both biomass kinds were pretreated in The Netherlands, gasified, and converted to transportation biofuels in the South-Holland region. Therefore, the gasification plant was decided to be located in the South-Holland region and a capacity of 20 MW<sub>th</sub>, was chosen, which is of the same order but somewhat smaller than the 84 MW<sub>th</sub> RWE/Essent Amer waste-wood-based circulating fluidized bed gasifier situated in The Netherlands. The gasification data used are derived from the pilot scale gasifier in the Technical University of Delft. These data were not scaled up, only autothermal gasifier operation is assumed, as expected on industrial level. On industrial level, only the carbon conversion efficiency will be higher than measured during the experiments on which the data were based. The wood/straw pellet plant had a production capacity of 70 ktons a<sup>-1</sup> [22] and the torrefied wood pellets plant had a production capacity of 35 ktons a<sup>-1</sup> [23]. Both pretreatment plants were decided to be located at realistic distances (being 100 km) from the production sites of biomass due to associated benefits in logistics, especially for torrefaction. Due to the fact that it was impossible to find relevant industrial data for the biofuel conversion processes, such as the FT process, the Aspen Plus<sup>TM</sup> flowsheeting software was used with input from relevant literature. Finally, even though there are a few refuelling stations for H<sub>2</sub> (one station) and CNG (two stations) in the broader Rotterdam area, it was decided to assume the distance between the gasification plant and the gas station to be the same for all biomass systems (being 15 km).

### Impact categories

All the considered systems were biomass-based energy conversion systems and the PoR focuses on the GHG emissions and the air quality, and the global warming (for 100 years), acidification, and particulate matter impact categories were selected as they contribute to the air



**Fig. 1** LCA system boundaries

pollution. In addition, acidification and eutrophication impacts were also selected as they are affected by transport and energy conversion systems.

**Life cycle inventory**

The life cycle inventory with all the inputs and outputs of the life cycle stages is presented in Table A1 in supplementary material section.

*Harvesting of biomass and chips or bales production*

The first LC stage of each analyzed biomass system was the harvest of the wood or the production and collection of wheat straw. The wood was considered to be derived from an established forest or a natural forest was managed sustainably. For both biomass feedstocks, approximately 1 year was assumed to be required for regrowing the biomass to sequester the initial CO<sub>2</sub> pulse emitted [24].

The wood was harvested, forwarded, and chipped on site. Similarly, the straw was produced, collected, and baled at the farm. The fuel consumption and emissions produced during harvesting, forwarding, and chip/bale production depended on the equipment used. In this paper, consumption data regarding the equipment used for forest residues were retrieved from literature. The forwarder and

chipper equipment had a productivity of approximately 360 ton day<sup>-1</sup> [25]. In addition, the data for the straw equipment were acquired from the ecoinvent database [26].

*Transportation*

The inland transportation was assumed to take place with lorries which follow the Euro 5 emission standards. The wood chips or straw bales were transported over a distance of 100 km, from the production site to the pretreatment plant, then the produced solid biofuel was transported over a distance of 200 km to the gasification plant, and the produced transportation biofuel was transported over a distance of 15 km to the gas station. Data for the transportation stages were collected from the ecoinvent database.

*Production of pellets*

The wood chips and straw bales arrived at the pretreatment plants and they were stored for one week before and after processing; emissions during the storage period were based on literature sources [27–30]. The feedstocks were processed at the torrefaction plant which was equipped with a pellet mill or at the pelletization plant. In this way, the untreated feedstocks became more uniform and easier to

handle. Therefore, two kinds of wood fuels, torrefied wood pellets, Torrcoal black (TB) and wood pellets, Torrcoal white (TW), and one kind of straw pellets were considered. Only for the TW and TB systems, wood chips and propane were used as fuel for drying purposes, respectively. The composition and lower heating value (LHV) of the feedstocks used are presented in Table 2. Data regarding torrefaction followed by pelletization were collected from a supplier company, Torrcoal [23]. On the other hand, the data concerning pelletization of untreated wood and straw were collected from the literature [31, 32].

#### Gasification and gas cleaning

The pretreated feedstocks arrived at the gasifier site, where they were converted to product gas. The product gas was conditioned to be upgraded to syngas quality and used for further processing. Data for the biomass gasification process were retrieved from experiments performed using a steam-oxygen 100 kW<sub>th</sub> circulating fluidized bed gasifier operating in a steady state, at 850 °C and atmospheric pressure at the Delft University of Technology [34, 33]. The selected process conditions were beneficial due to the increased cold gas efficiency and carbon conversion efficiency. In addition, at such temperature agglomeration issues could be reduced during straw gasification. Due to the process conditions selected, the gasification was considered autothermal. Gas conditioning was essential as impurities, such as particles and tarry compounds, are present in the raw product gas and needed to be removed. The particles were removed with cyclones and a non-catalytic filter operating at 450 °C. In addition, a fixed bed reactor was considered downstream the gasifier, where oxygen and steam are supplied to convert the tarry compounds via catalytic autothermal reforming reactions at 850 °C and atmospheric pressure. The steam feed rate was

varied to adjust the syngas H<sub>2</sub> and CO ratio according to the requirement of the final transportation fuel conversion process. Subsequently, an amine absorber and a stripper were used to remove the CO<sub>2</sub> from the clean syngas. These cleaning and conditioning processes were modelled using the Aspen Plus<sup>TM</sup> software.

#### Biofuel conversion

The syngas was converted into three kinds of transportation biofuels: H<sub>2</sub>, SNG, and FT diesel. Syngas was converted to H<sub>2</sub> by the water–gas shift reaction, purified with PSA, and compressed to a pressure of 350 bar [35]. The by-product of the shift reaction was biogenic CO<sub>2</sub>. The electricity needed in this process was generated from combusting a part of the biomass feedstock of the gasifier. For SNG production, methanation performance was based on the experiments by the Energy research Center of The Netherlands (ECN) [36]. It consisted of a two-step methanation reactor configuration, the first reactor operated at 350 °C and the second reactor operated at 200 °C to shift the exothermal reaction equilibrium towards the product side. In addition, upgrading was performed by drying using a triethylene glycol (TEG) absorber and CO<sub>2</sub> removal with an amine absorber. The FT biodiesel production occurred at 245 °C and 25 bar [37]. The by-products of this process, C<sub>1</sub>- to C<sub>4</sub> hydrocarbons, H<sub>2</sub> and naphtha, were recycled or combusted for power generation. The main product (C<sub>5+</sub> hydrocarbons) is refined to FT biodiesel. During refining, kerosene and naphtha are produced; both by-products are considered via system expansion.

#### Fossil fuels supply chains

Data from the fossil fuels supply chains were collected from theecoinvent database v2.2 [26]. The data used were

**Table 2** Composition and lower heating values of biofuels (on an “as received” mass basis)

	Torrcoal white (TW) <sup>a</sup>	Torrcoal black (TB) <sup>a</sup>	Wheat straw <sup>b</sup>
Moisture	5.9	4.1	6.8
Ash	1.0	2.1	11.7
Carbon	46.6	53.5	40.7
Hydrogen	5.8	5.2	5.5
Nitrogen	0.2	0.5	0.6
Sulphur	0.8	0.7	0.1
Oxygen	39.7	33.9	41
Lower heating value <sup>c</sup>	17.6	20.1	14

<sup>a</sup> From [33]

<sup>b</sup> From [34]

<sup>c</sup> The fuel lower calorific values have been determined by following the method provided by Phyllis database, using the Milne’s empirical formula, in MJ/kg

specifically for petroleum oil and natural gas produced, refined, and used in The Netherlands. Only for the fossil-H<sub>2</sub> system, the steam-reforming process of natural gas did not exist in the ecoinvent database. Therefore, it was modelled using Aspen Plus<sup>TM</sup>.

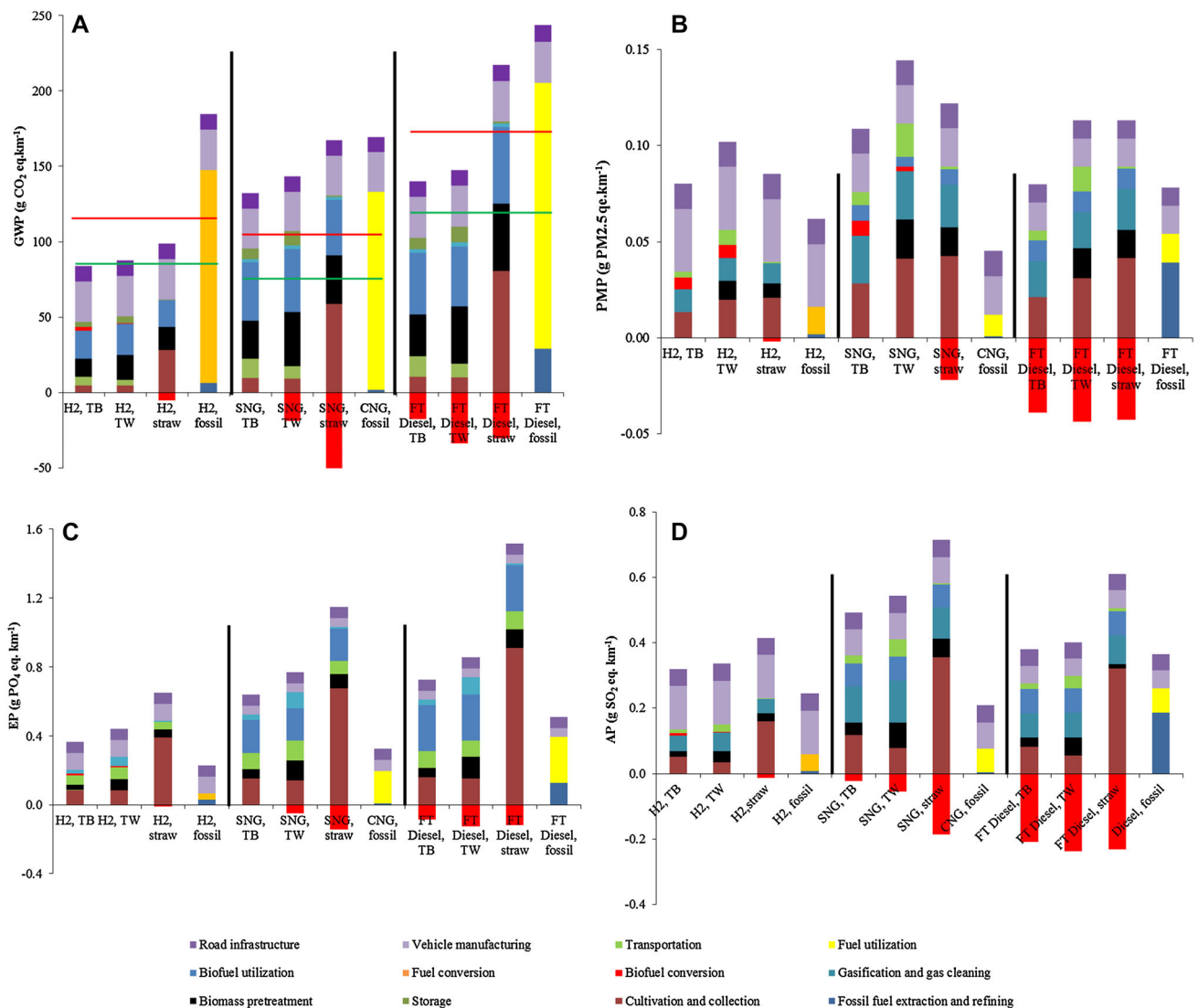
*Use of biofuels and fossil fuels in vehicles*

Finally, the transportation biofuels and fossil fuels were used in passenger vehicles: the bio-H<sub>2</sub> and the fossil-H<sub>2</sub> in a FC car, the FT diesel and the fossil diesel in a Euro 5 diesel car, and the SNG and the natural gas in a Euro 5 car. Data regarding these stages were used from ecoinvent database and from international literature.

**Results and discussion**

**Global warming potential**

The GWP results and the GHG reduction target based on the RED 2009/28/EC criteria are presented in Fig. 2a. In Fig. 3, the average results of this study, with standard deviations values, are compared with other studies' results. Among the biomass systems, the bio-H<sub>2</sub> systems result in the lowest GWP due to the biofuel utilization stage, which is the most significant contributor. This stage improves significantly the system's specific fuel consumption (Table 3), which concerns the amount of energy in the raw biomass that is needed to cover a distance of 1 km. Among the biomass systems, the wood-based systems show the best performance and the GWP benefits can be up to 54 and



**Fig. 2** Environmental impact results. **a** GWP results and targeted emissions reduction based on the RED 2009/28/EC (the red and green horizontal lines concern the savings targets until 2016 and by 2017), **b** PMP results, **c** EP results, and **d** AP results



52% for H<sub>2</sub> and FT diesel, respectively. Regarding the straw-based systems, the SNG system results in the largest benefits, approximately 40%.

The gasification and gas cleaning, biomass pretreatment, and road infrastructure stages contribute significantly to the GWP results for all systems, whereas the cultivation stage is a large contributor for the straw-based systems. In most biomass systems, negative emissions are produced during the biofuel conversion stage as the excess electricity is exported to the grid. Specifically for the FT diesel conversion stage, the production of naphtha and kerosene results in additional benefits. However, these benefits are smaller than the excess electricity benefits. In general, between the TB- and TW-based systems, torrefaction results in benefits in the pretreatment stage, due to decreasing the electricity requirements of the pelletization step, and in the transportation stage due to the feedstock having a higher calorific value. Hence, fewer feedstock (in mass unit) should be transported to produce the same amount of transportation fuel (in energy unit) in the torrefied system. Moreover, torrefaction results in benefits in the gasification and gas cleaning stage by lowering the requirements for the gas cleaning step due to the lower tar content of the product gas. On the other hand, due to the mass and energy losses during torrefaction, more wood chips are required for the TB-based systems, which result in higher storage emissions of the wood chips.

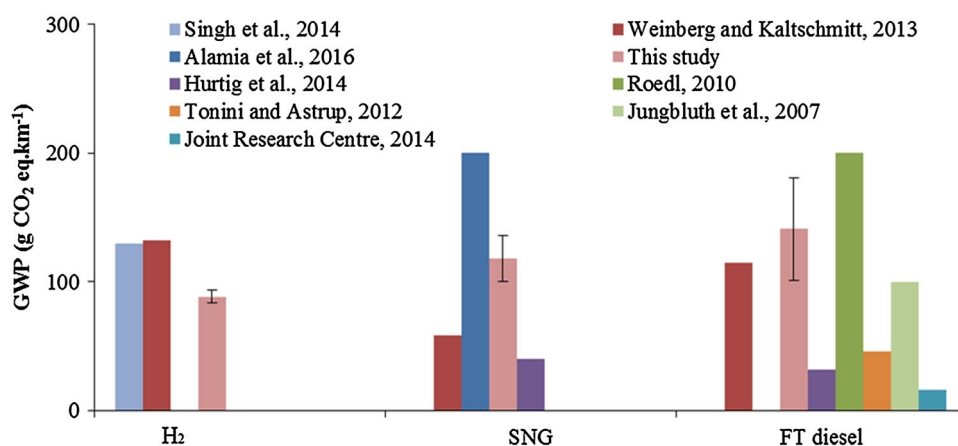
If the road infrastructure and vehicle production stages are excluded from the system boundaries, the CO<sub>2</sub> emission reduction can be recalculated based on the RED 2009/28/EC criteria. In such a case, all biomass systems satisfy the RED target of the 35% reduction. The bio-H<sub>2</sub> systems result in a reduction range between 61 and 68%, the SNG systems result in a reduction range between 28 and 54%, and the FT diesel systems result in a reduction range between 27 and 63%. However, if the target of 2017 is to be achieved, then only the bio-H<sub>2</sub> systems, the straw-based SNG system and both the TW and the TB FT diesel

systems fulfil the target. Finally, if the reduction concerns a new production plant, then the bio-H<sub>2</sub> systems and the TW FT diesel systems satisfy the 60% savings target.

For bio-H<sub>2</sub> production and use, all three biomass systems result in significant benefits. Among them, TB results in the lowest GWP. This difference can mainly be attributed to the lower electricity requirements for the pretreatment stage of the TB-based system compared to the other two systems and due to the quality of the gas produced at the gasification plant which requires less intensive upgrading than TW- or straw-based systems. Nevertheless, in both wood systems, larger emissions during the storage stage exist, which can be reduced, even to zero, if the biomass management is optimized and specialized equipment is used, e.g. limited storage time and indoor storage. Our GWP results are in agreement with Weinberg and Kaltschmitt [12] who reported a value of 132 g CO<sub>2</sub> eq km<sup>-1</sup> and Singh et al. [17] who reported 130 g CO<sub>2</sub> eq km<sup>-1</sup>. Both authors have omitted various stages which are considered in this study, such as storage of biomass, which can contribute up to 7% of the GWP. On the other hand, Susmozas et al. [15] and Wulf and Kaltschmitt [38] reported much lower values of 4.5 and 22 g CO<sub>2</sub> eq km<sup>-1</sup> (when converted with the fuel economy factor of this study; initial value of 30 g CO<sub>2</sub> eq MJ<sup>-1</sup> H<sub>2</sub>), respectively. However, in both cases the system boundaries were limited up to the production of hydrogen.

Regarding the compressed SNG systems, the straw-based system results in the best environmental performance. The three biomass systems are comparable with respect to biomass pretreatment and gasification and gas cleaning stages. However, this difference in the GWP of the straw-based system derives mainly from negative emissions due to the excess electricity produced in the biofuel conversion stage, due to the high steam content of the product gas. The cultivation stage of the straw-based system contributes significantly to its GWP, but not to an extent that offsets the benefits of excess electricity

**Fig. 3** Comparison of the GWP results of this study with relevant literature



**Table 3** Specific fuel consumption (untreated biomass-to-fuel utilization)

	H <sub>2</sub> , TB	H <sub>2</sub> , TW	H <sub>2</sub> , straw	SNG, TB	SNG, TW	SNG, straw	FT diesel, TB	FT diesel, TW	FT diesel, straw
$\eta^a$	3.8	3.7	2.9	8.7	8.1	6.4	9.0	8.7	8.6

<sup>a</sup> In MJ/km, the calculation is based on the LHV of the feedstock

generation. Our GWP results are partially in agreement with Alamia et al. [9] who reported a value of 200 g CO<sub>2</sub> eq km<sup>-1</sup>. These authors modelled the GoBiGas demonstration plant; hence, they assumed larger transportation distances and they considered compressed SNG with a lower LHV (approximately 10%) than this study. On the other hand, Hurtig et al. [14] reported a much lower GWP value of 40 g CO<sub>2</sub> eq km<sup>-1</sup>. However, these authors do not explain what gasifier type they considered which makes any comparison difficult, but they did consider a commuter car; which is different from the car used in this study based on the fuel consumption rates, 0.4 kWh km<sup>-1</sup> instead of 0.6 kWh km<sup>-1</sup> (in ecoinvent database).

Regarding the FT biodiesel systems, the TW-based system results in the lowest GWP; marginally better than the TB-based system and significantly better than the straw-based system. This difference can be attributed to the biofuel conversion stage of the TB-based system and due to the cultivation stage of straw-based system. The former results in less excess electricity, whereas the latter contributes highly. The electricity requirements for stages such as pretreatment (pelletization process) and gasification (O<sub>2</sub> input) and gas cleaning contribute to this lower GWP values of both TW- and TB-based systems compared to the straw-based systems. These results are in agreement with Weinberg and Kaltschmitt [12], Wang et al. [39], Jungbluth et al. [18], and Roedl [13]. However, Roedl [13] reported a higher GWP of 200 g CO<sub>2</sub> eq pkm<sup>-1</sup> when SRC wood was used as feedstock. Due to the nature of the plantation, the author did consider herbicides, site preparation processes, etc. These processes contribute to 80% of his final result, so a larger GWP value is expected, which is the same as for the straw-based system in our study. On the other hand, Hurtig et al. [14] reported a much lower result of 31 g CO<sub>2</sub> eq pkm<sup>-1</sup>. This difference can be explained with the stages that are included in the system boundaries of their study and with the fact that their FT process' selectivity of diesel is approximately 80% of the FT raw products which is much higher than the selectivity data used for our study. Similarly, JRC [10] reported very low GHG emissions when wood-derived FT diesel is produced. JRC reported approximately 16 g CO<sub>2</sub> eq pkm<sup>-1</sup>. The results of JRC are due to their oversimplified wood system, where wood is not pretreated but gasified and upgraded as it is. Therefore, the wood supply system in that report is completely different

from the wood supply systems considered in our study, as biomass is not stored, nor pretreated upstream the gasification stage. In addition, the manufacture of the vehicle or road infrastructure is not considered by the JRC. Finally, only Tonini and Astrup [16] reported very small environmental benefits when FT diesel replaces fossil diesel, due to the cultivation stage of the energy crop that they considered.

### Particulate matter potential

The PMP results are presented in Fig. 2b. The different nature of transportation fuels means that higher PMP values are expected in the fossil diesel system, rather than in fossil H<sub>2</sub> and NG systems. As a result, the PMP result of the fossil diesel is approximately two times the value of the other two reference systems. Benefits are achieved only when FT diesel is produced. The reduction in PM potential is 48, 11, and 8% for TB pellets, TW pellets, and straw pellets, respectively. In general, the conversion stage of the FT systems, i.e., the excess electricity and by-products, has a positive effect. The much better PMP of TB-based FT diesel system is due to the torrefaction pretreatment. Torrefaction strongly enhances energy densification which results in benefits in the transportation stages. Furthermore, due to the decreased electricity requirements in the pelletization step, additional benefits are achieved in the TB-based FT diesel system. Finally, concerning the SNG and bio-H<sub>2</sub> systems, the increase in the PMP is so large due to biomass cultivation and collection, gasification and gas cleaning, as well as biofuel conversion stages. The former two result in requirements on diesel and electricity, whereas the latter does not result in by-products that offer benefits, except for the straw-based SNG system.

### Eutrophication potential

The biomass systems do not offer any EP benefits compared to the fossil systems. Among the fossil systems, the fossil diesel system shows the highest EP (see Fig. 2c). Among the biomass systems, the adverse effects range from 127 to 343%; the lowest potential is achieved with the TB-based FT diesel system, whereas the highest results from the straw-based SNG system. For wood-based systems, the collection and chipping of wood in the forest and

the biofuel utilization are the largest contributors due to the  $\text{NO}_x$  emissions from diesel fuel used for the equipment and the Euro 5 car operation. On the other hand, the use of fertilizers and pesticides contribute more than 50% of the straw-based systems result.

### Acidification potential

Figure 2d presents the AP values of each system. The fossil- $\text{H}_2$  and NG systems result in a much lower AP than the fossil diesel system. In general, apart from the TW- and TB-based FT diesel systems, the other biomass systems result in no benefits. Especially, regarding the straw-based systems, the cultivation and collection stage is the main contributor, as it contributes up to 80% of the total emissions due to the pesticides used. The benefits in the AP for the TW- and TB-based FT diesel systems can mainly be attributed to the by-product yield of the biofuel conversion stage; replacing fossil naphtha and fossil kerosene affects the results, as these fossil fuels are high in sulphur content. Wood-based systems for the production of  $\text{H}_2$  and SNG do not show benefits when compared with the fossil systems due to the power consumption during pretreatment and gasification stages which are supplied from the Dutch grid that is high on fossil resources. The results of this paper are in agreement with Roedel [13] concerning the FT diesel systems. On the other hand, they are partially in contradiction with Susmozas et al. [15] and Weinberg and Kaltschmitt [12]. These authors did conclude that methane utilization is more beneficial than hydrogen and FT diesel. However, the former authors attributed the worse performance to the cultivation stage of poplar, whereas the latter reported deviating results from this study due to the inclusion of the vehicle manufacturing stage, which contributes significantly to their results, but they omitted the road infrastructure stage. Finally, our results are in contradiction with Singh et al. [17]. These authors reported that their high AP emission result emanates from battery and motor requirements during the production stage, as well as the production of platinum which is used as the catalyst in fuel cells. In total, these stages contribute up to 70% of the total impact result.

### Aggregated environmental results based on BEES stakeholder panels method

The aggregated environmental impact results, based on the BEES stakeholder panel method, are presented in Fig. 4. It was found that even though there are no environmental benefits in specific environmental impact categories for certain biomass systems (Fig. 2), each aggregated biomass system performance results in benefits compared to its reference system. This is attributed to the larger weighting

factor that the GWP has than the other potentials. In general, the total environmental performance can be improved from 20% (SNG case of TB and TW) to even 55% ( $\text{H}_2$  of TB and FT diesel of TW) compared to the reference systems.

### Sensitivity analysis

#### *Economic versus mass allocation*

The difference between economic and mass allocations of straw production is presented in Fig. 5 as in our case straw is not used as fodder, but for energy applications. The mass allocation factor is the mass ratio of grain to straw, which is 2:3. The environmental impact values, when mass allocation is used, are normalized with the previously calculated results for the straw-based systems. Based on the larger yield and lower financial value of wheat straw compared to the grain, the allocation factors in theecoinvent database were modified with a factor of three for all straw-based systems. The new straw results are expected to be worse regarding all impacts, especially EP, as it is mostly influenced by fertilizer usage of the cultivation and collection stage. The results show that the new results vary from 140 to 223% compared to the previously calculated results.

#### *Cleaner electricity mix, the Swiss case*

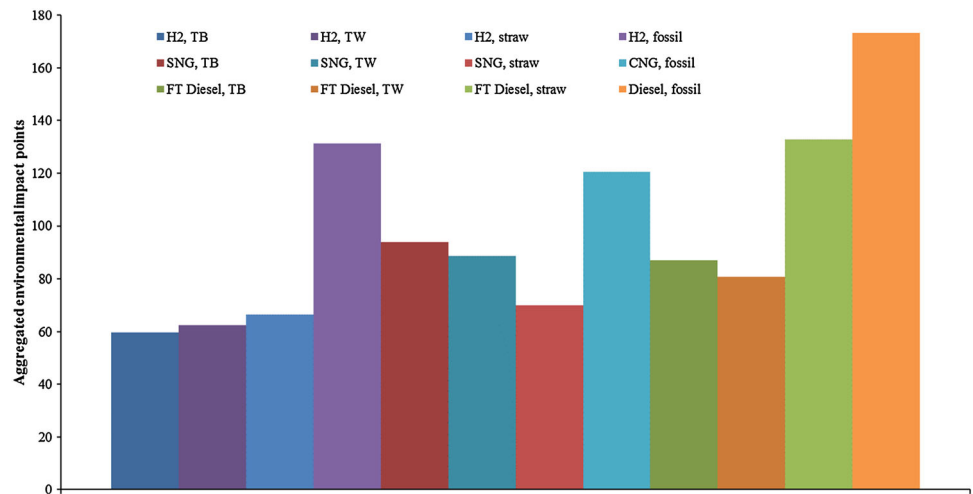
The second sensitivity analysis concerned the effect of the electricity mix on the environmental impacts. An electricity mix consisting of a larger share of zero-emission technologies was selected, that of Switzerland. In Fig. 6, the results of the sensitivity analysis are normalized with the previously calculated results. Changes are expected regarding all stages which consume mainly electricity, such as the pretreatment and the gasification and gas cleaning. Indeed, all systems are affected, showing a reduction of up to 55%, except for the natural gas system and the fossil diesel system. Regarding the natural gas system, energy requirements for the extraction and refining of natural gas stage are achieved with the utilization of natural gas itself. Whereas concerning the fossil diesel system, refinery gas and heavy fuel oil are mainly used in the extraction and refining stage. The largest benefits are achieved in the GWP of FT diesel systems and straw-based SNG system.

### Conclusions and recommendations

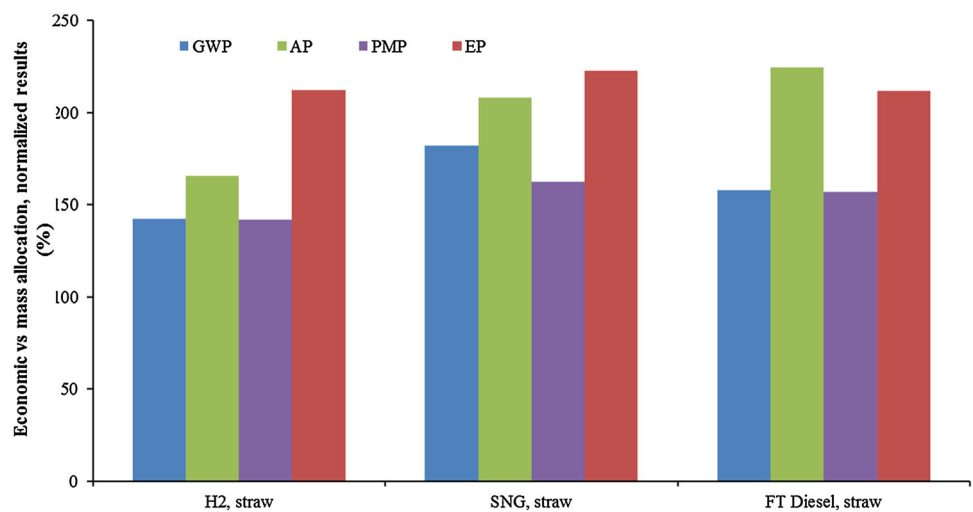
The aim of this study was to use empirical data to investigate whether increasing a port's capacity of biomass for the production of transportation fuels derived from syngas, with torrefied wood pellets, wood pellets, or straw pellets



**Fig. 4** Aggregated environmental impact points based on BEES stakeholders panels method



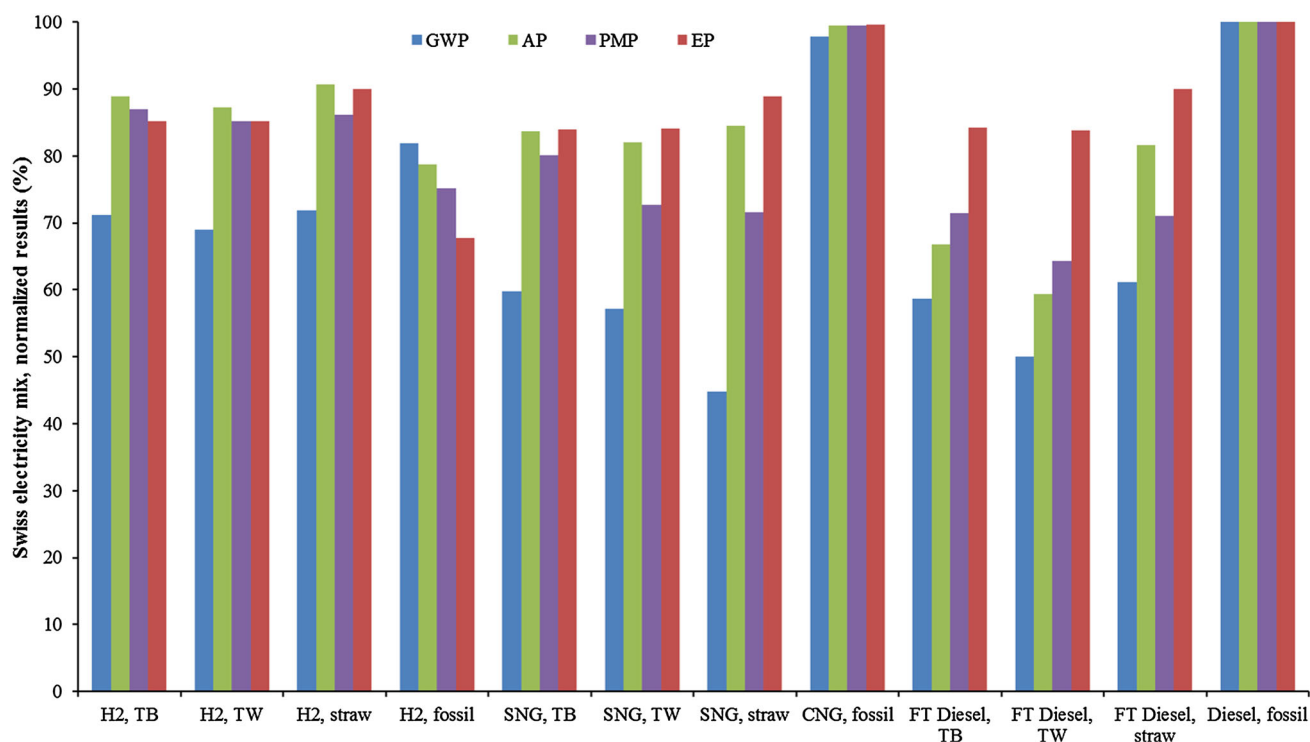
**Fig. 5** Sensitivity analysis when mass allocation is used in the cultivation stage of straw-based systems (in ecoinvent database), normalized results



as feedstock, offers environmental benefits. In addition, our results should be applicable to other ports with similar infrastructure as the port of Rotterdam.

It is concluded that the transportation biofuels did not offer environmental benefits in every single impact category when they replaced fossil fuels. However, all biomass systems resulted in a better aggregated environmental performance than the fossil resource-based systems. Moreover, all biomass systems resulted in a substantial GWP reduction, from 45 to 78%, and they comply with the RED 2009/28/EC. For 2017 only the bio-H<sub>2</sub> systems, the straw-based SNG system and the TW- and TB-based FT diesel systems comply with the RED target. In case European countries have to comply with the even more stringent target of 60% emissions savings for new production plants, then all systems would be benefited if less fossil sources are used. The bio-H<sub>2</sub> systems result in the largest benefits with respect to GWP, ranging between 84 and 93 g CO<sub>2</sub> eq km<sup>-1</sup>, whereas the TB- and TW-based FT diesel systems offer overall benefits which concern not

only the Port Vision 2030 target of CO<sub>2</sub> emissions reduction (122 and 114 g CO<sub>2</sub> eq km<sup>-1</sup>, respectively), but also the air quality improvement of the broader area as well (0.039 and 0.064 g PM 2.5 eq km<sup>-1</sup>, respectively). However, the biomass systems resulted in inferior performance regarding AP, EP, or PMP, except for TB- and TW-based FT diesel systems which showed benefits in the AP and PMP impact categories. In general, wood offers more environmental benefits than straw as feedstock due to the emissions associated with the cultivation and collection stage of straw, and wood torrefaction offers additional benefits in the transportation and in gasification and gas cleaning stages. The storage emissions of wood chips are contributing up to 11% of the GWP; thus, a proper management of the wood supply chain is highly recommended to even eliminate this contribution. Other contributors to environmental impacts are the pretreatment and gasification and gas cleaning stages, up to approximately 34% for both, of the biomass systems. Both stages can be further improved two- or threefold using electricity sources with a



**Fig. 6** Sensitivity analysis of electricity mix used (Swiss compared to Dutch), normalized results

lower carbon footprint. In addition, in this study, propane is consumed in the torrefaction plant for heat production. However, in the future, when the CO<sub>2</sub> targets become more stringent, a torrefaction plant would reduce the fossil fuels utilization and use a renewable energy source for its heat requirements. Finally, the economic allocation (already) integrated in the ecoinvent database affects the final results and LCA practitioners should import data from databases with caution. Therefore, it is recommended that the port authorities investigate the economical aspect of utilizing torrefied wood pellets and wood pellets regarding such biomass to transportation fuel pathways.

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