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# Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach

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## Abstract

**Purpose** Waste recycling is one of the essential tools for the European Union's transition towards a circular economy. One of the possibilities for recycling wood and plastic waste is to utilise it to produce composite product. This study analyses the environmental impacts of producing composite pallets made of wood and plastic waste from construction and demolition activities in Finland. It also compares these impacts with conventional wooden and plastic pallets made of virgin materials.

**Methods** Two different life cycle assessment methods were used: attributional life cycle assessment and consequential life cycle assessment. In both of the life cycle assessment studies, 1000 trips were considered as the functional unit. Furthermore, end-of-life allocation formula such as 0:100 with a credit system had been used in this study. This study also used sensitivity analysis and normalisation calculation to determine the best performing pallet.

**Result and discussion** In the attributional cradle-to-grave life cycle assessment, wood-polymer composite pallets had the lowest environmental impact in abiotic depletion potential (fossil), acidification potential, eutrophication potential, global warming potential (including biogenic carbon), global warming potential (including biogenic carbon) with indirect land-use change, and ozone depletion potential. In contrast, wooden pallets showed the lowest impact on global warming potential (excluding biogenic carbon). In the consequential life cycle assessment, wood-polymer composite pallets showed the best environmental impact in all impact categories. In both attributional and consequential life cycle assessments, plastic pallet had the maximum impact. The sensitivity analysis and normalisation calculation showed that wood-polymer composite pallets can be a better choice over plastic and wooden pallet.

**Conclusions** The overall results of the pallets depends on the methodological approach of the LCA. However, it can be concluded that the wood-polymer composite pallet can be a better choice over the plastic pallet and, in most cases, over the wooden pallet. This study will be of use to the pallet industry and relevant stakeholders.

**Keywords** Wooden pallet · Plastic pallet · Wood-polymer composite pallet · Attributional life cycle assessment · Consequential life cycle assessment · Normalisation

## 1 Introduction

Pallets are used for storing, protecting, and transporting freight. They are the most common base for handling and moving the unit load, carried by materials handling units,

such as forklifts. The pallet market is growing due to the rising standard of goods transportation, the adoption of modern material handling units in different industries, and market demand for palletised goods (McCrea 2016). It was estimated that the global pallet market reached 6.87 billion units in 2018 (Nichols 2020). More than 600 million European Pallets Association (EPAL) approved pallets are available to the global logistics industry. In 2019, 123 million wooden EPAL pallets and other carriers were produced, which is 1.2 million more compared to 2018 (EPAL 2020).

The global pallet market can be classified based on materials, sizes, and management strategies (Deviatkin et al. 2019). Among various segments of pallets, wooden pallets dominate the market share, followed by plastic pallets

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(Leblanc 2020). Wooden pallets are inexpensive and can easily be manufactured and repaired compared to plastic pallets. One of the most significant downsides of wooden pallets is the cost to forests (Retallack 2019). Furthermore, wooden pallets are heavier than plastic pallets, imposing an environmental burden on freight shipment. Even though plastic pallets are lighter than wooden pallets, plastic pallets' production is an energy-intensive process. In addition, repairing plastic pallets is impossible because the materials have to be melted down and remoulded in the plastic pallet repairing process.

Waste recycling is one of the pathways taken by the European Union to move towards a circular economy, as highlighted in the circular economy action plan (European Commission 2020). The central idea of a circular economy is to minimise the consumption of virgin materials, which means that an item that can be recycled should not be land-filled or incinerated. The EU is planning to recycle 50% plastic and 25% wood waste by 2025, which will increase to 55% for plastic and 30% for wood by 2030 (European Commission, 2018). By following the EU's target, Finland's objective is to fortify its role as a pioneer in the circular economy by implementing the strategic programme for circular economy (Ministry of Employment and the Economy 2021). The transition to a circular economy is essential for Finland to strengthen its export-driven economy with minimum environmental impact.

The environmental benefits of recycled-based plastic products are well known and quantifiable (WRAP 2019). Also, materials made from wood waste can deliver low carbon-based products with less pressure on forests (WWF 2016). One of the possibilities for reducing the environmental burden of plastic and wood waste is to utilise these wastes for wood-polymer composite (WPC) products, such as WPC pallets. However, analysing the environmental performance of WPC pallets requires a complete life cycle analysis. Furthermore, it is important to consider that different materials have different life expectancies, reuse capabilities, and recyclability.

According to International Organization for Standardization (ISO), life cycle assessment (LCA) is one of the environmental management techniques that "addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal" (EN ISO 14040:2006; EN ISO 14044:2006). Several LCA studies have been conducted on pallets focusing on pallet manufacturing, management strategies and supply chains, repair intensity, and pallets manufactured from various materials, such as wood, virgin plastic, cardboard, and waste plastic. Gasol et al. (2008) conducted an LCA study to compare the environmental performance of wooden pallets with high reuse

intensity and low reuse intensity in the European context, and with the findings showing that due to transportation, high reuse intensity pallets have more adverse impacts on climate change than low reuse intensity pallets. Bengtsson and Logie (2015) performed an LCA comparing one-way wooden pallets, disposable compressed cardboard pallets, pooled softwood pallets, and plastic pallets in Australia and China. The study results pointed out that pooled softwood pallets have the minimum environmental impact among all types of studied pallets. Tornese et al. (2018) examined pallets' economic and climate change impacts, demonstrating that manufacturing a pallet causes more damage to the environment than repairing a pallet. The study also identified that the cross-docking system has equivalent emissions as the take-back system due to higher transportation distance. Almeida and Bengtsson (2017) compared the LCA of waste plastic-based pallets with wooden pallets and virgin plastic-based pallets and demonstrated that plastic waste-derived pallets outperform all other alternatives. Franklin Associates (2007) compared the environmental impacts of pooled pallets versus non-pooled pallets. The study indicated that pooled pallets have less of an environmental burden than non-pooled pallets. Kočí (2019) studied the environmental impact of wooden pallets, primary plastic pallets, and secondary plastic pallets. The study found that wooden pallets have a better environmental impact than primary and secondary plastic pallets if energy recovery occurs. Furthermore, the study also showed that the weight of the pallet plays a significant role on its total environmental impact.

The authors of previously conducted LCA studies analysed various pallets, making their cross-comparison a difficult task. Previous literature, including the above mentioned studies, have conducted LCA from an attributional point of view and excluded consequential LCA, which is thought to be an important method for identifying the changes in the system as a consequence of using a particular pallet. It is important to investigate the differences in the results, conclusions, and suitability of attributional and consequential LCA for cases where waste recycling is included. Furthermore, all the former studies assumed that various pallets perform equally well during their life cycle. None of the studies considered that pallets made with different materials have different life expectancies, repairing times, and recycling rates. In addition, end-of-life (EoL) is an integral part of the cradle to grave LCA. The methodological difference of the EoL allocation might have a significant impact on the overall result of LCA. It is found that the allocation of the environmental burdens of the EoL of the pallets was absent in the studies as mentioned earlier.

By considering the abovementioned aspects, the following questions were formulated and consequently addressed in this study:

1. What are the environmental impacts of WPC pallets produced from construction and demolition waste (CDW) compared to the wooden pallets and plastic pallets?
2. What is the difference in the results from the life cycles of the pallets between attributional LCA and consequential LCA?

## 2 Materials and methods

The LCA of the studied pallets were conducted by following the requirements stated in the ISO 14040 (EN ISO 14040:2006) and ISO 14044 (EN ISO 14044:2006). LCA is a 4-phase method starting with the definition of the goal and scope. The goal is then pursued by compiling the life cycle inventory (LCI) of the product system defined in the scope. The LCI is then used to conduct a life cycle impact assessment (LCIA). Environmental impact is classified and characterised according to the CML 2001–Jan. 2016. Finally, the results are thoroughly analysed, sensitivity analysis and normalisation were conducted, and conclusions were made. The study was conducted using GaBi software (version 8.6.0.20).

### 2.1 Goal and scope definition

#### 2.1.1 Goal of the study

The goal of this LCA study was to calculate and assess the environmental impacts of manufacturing, utilising, and disposal of pallets made of different materials. Both

attributional LCA (ALCA) and consequential LCA (CLCA) methods were used in the study. An ALCA investigates the environmental impact of the physical flows to and from a product’s life cycle and its subsystems (Ekvall et al. 2016). In contrast, consequential LCA investigates the environmental impacts of the product system and the systems linked to it that are expected to change for production, consumption, and disposal of the product (Ekvall et al. 2016). Despite the ISO 14040/44 standards not explicitly distinguishing between the two types of LCAs, there is a clear difference in the definition of the scope for those assessments, as described below. The study results are intended to guide the selection of materials for the production of pallets.

#### 2.1.2 Scope of the ALCA study

The attributional LCA follows the cradle-to-grave approach, meaning that the product system includes the processes starting with the provision of raw materials from the environment in the form of elementary flows, i.e. the flows created by nature, through the use of the pallets and ending with their disposal and with the release of emissions into air and water, and to the generation of waste.

The system boundary of the ALCA comparing the impacts of the pallet’s production, use, and EoL is shown in Fig. 1. The modelling started with producing the raw materials and the energy generation for the pallets, such as wood harvest, timber production, and plastic production. It should be noted that the system boundary for WPC starteds from the collection of waste. Once the materials are produced and

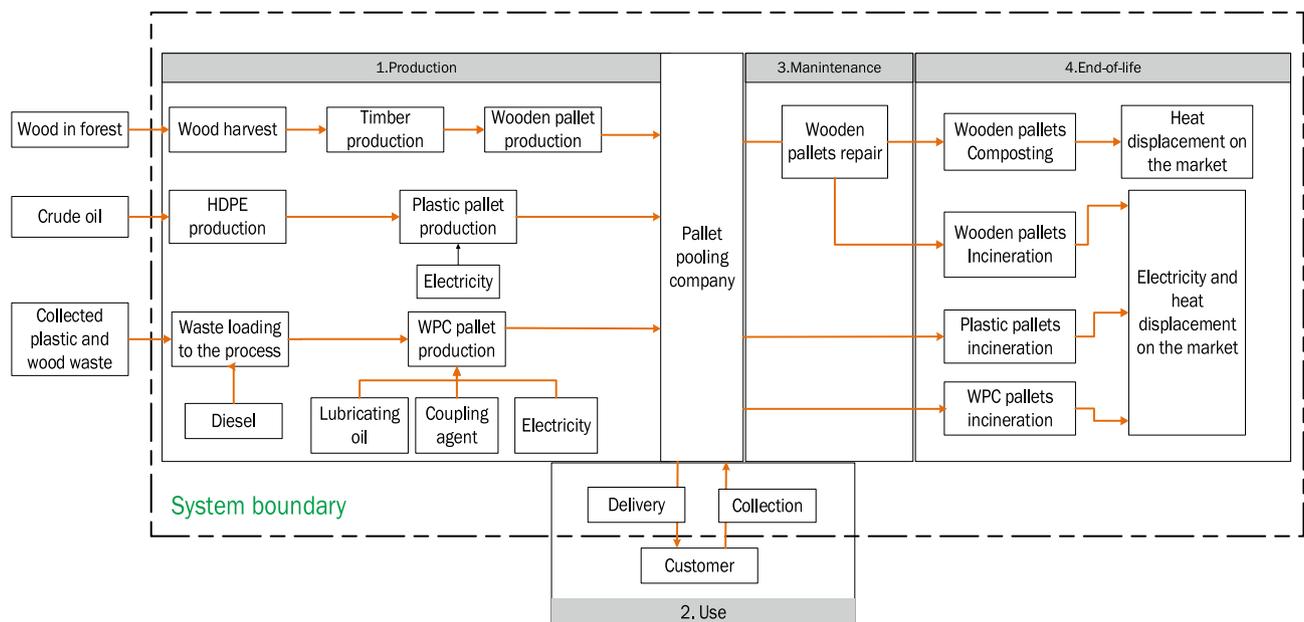


Fig. 1 System boundary of the ALCA study

delivered to the production facilities, the pallets are manufactured. Nails are used to secure the parts of the wooden pallets, whereas plastic and WPC pallets are compressed into the required shape and do not require any fixing elements. The pallets are then delivered to a pallet pooling company, which operates by delivering the produced pallets to customers who can use them for their own purposes. After which, the pooling company collects the pallets and repairs them in the case of wooden pallets, if needed. After being used, the pallets are crushed for incineration. In the case of wooden pallets, ferrous metals are separated before incineration. By incinerating wooden, plastic and WPC pallets' waste, energy is substituted. Nevertheless, materials are also substituted by separated ferrous metals from wooden pallets.

### 2.1.3 Scope of the CLCA study

The system boundary of the CLCA comparing the baseline scenario with the alternative scenario is shown in Fig. 2. The baseline scenario included the life cycle of either wooden pallets or plastic pallets. In addition, the baseline scenario also included the treatment of wood waste and plastic waste that would otherwise be used for WPC production. In this scenario, the wood and plastic waste were considered to be incinerated and subsequently avoided emissions due to the displacement of marginal heat and electricity on the market. The alternative scenario concentrated only on the life

cycle of WPC pallets, which were used to replace the same number of plastic pallets used in the baseline scenario. This scenario excluded the modelling of wooden or plastic pallets by assuming that wood used for wooden pallet production remained in the forest and that crude oil for plastic pallet production stayed under the ground.

### 2.1.4 Functional unit

The functional unit of ALCA and CLCA was 1000 trips. The function in this study was related to the delivery of the products and was arbitrarily set to 1000 trips. A trip-based functional unit has been widely applied in other LCA studies on pallets because it allows for an accounting of the difference in the pallets being compared, such as expected lifetime, repair, and transportation needs (Deviatkin et al. 2019). The reference flow of this study was set to the number of pallets required to provide the customer with enough pallets for 1000 trips. Based on the weight and structure of the pallets, the reference flow was 50 wooden pallets, 15.2 plastic pallets, and 15.2 WPC pallets.

### 2.1.5 EoL allocation

There are no strict or specific requirements for modelling the EoL in LCA, and several allocation methods exist, such as 0:100 approach, 100:0 approach, 100:100 approach, 50:50

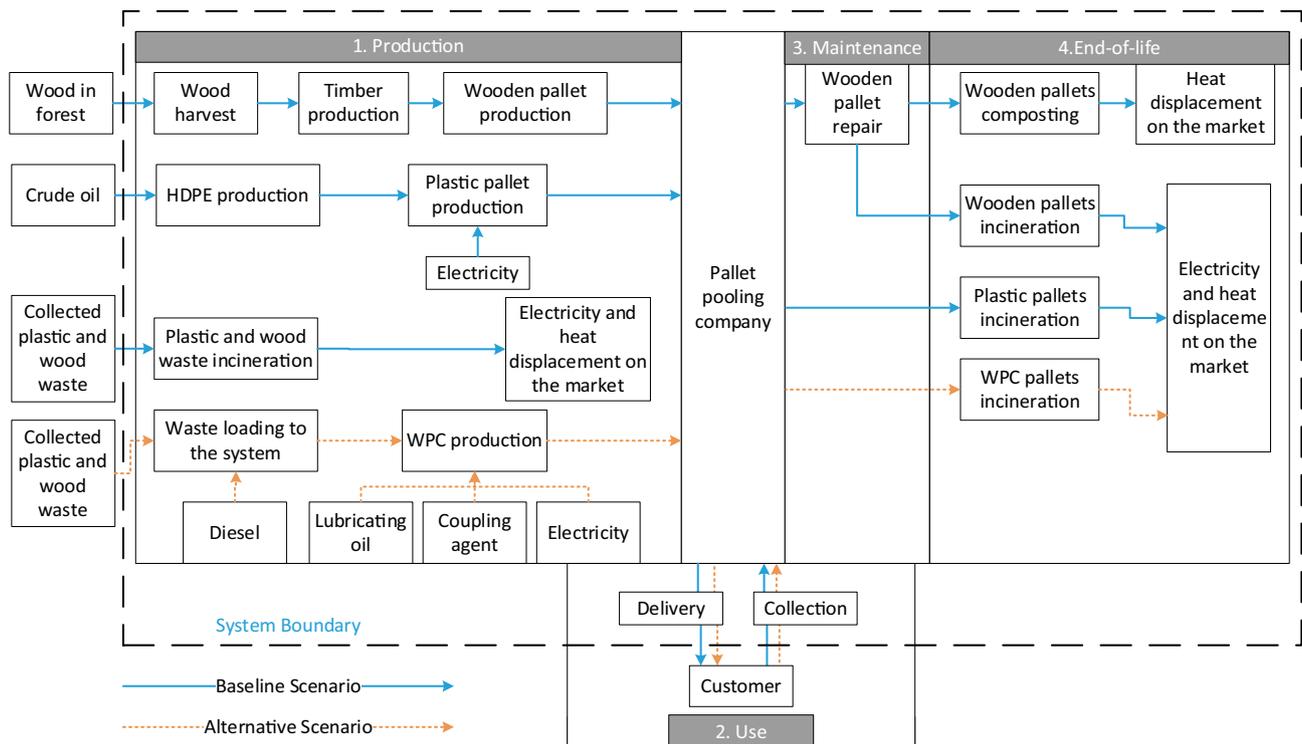


Fig. 2 System boundary of the CLCA study. Solid line represents the baseline scenario, while alternative scenario is indicated by dash line

approach, etc. (Allacker et al. 2017). 0:100 EoL method can be conducted in two different ways, such as 0:100 with no credit for avoiding virgin materials and 0:100 with credit for avoiding virgin materials (Allacker et al. 2017). The system boundary of the study ends at the recovery of energy and material from the EoL phase. Therefore, in this study, the 0:100 EoL method with credit system had been used.

In the CLCA, the correct way of modelling environmental impact is to use marginal production technology data for the substituted product. Marginal production technologies are those technologies that are changed by the small changes in demand (Weidema et al. 1999). It was found from this study that a significant amount of heat and electricity substitution was impacted when wood and plastic waste were not incinerated but used for WPC pallet production. In this case, marginal heat and electricity were used in the modelling of CLCA. Biomass will be the prime heat production source in Finland by 2030 (Ministry of Employment and the Economy 2017), and wind and solar power will provide the maximum share of electricity by 2030 (SKM Market Predictor 2019). Therefore, the biomass-based heat source was selected as the marginal heat source and wind, and solar-power-sourced electricity was selected as the marginal electricity source in CLCA modelling. The more detailed information on the selection of marginal heat and electricity is presented in the supplementary materials.

### 2.1.6 Selection of the pallets

A great variety of pallets exists, as dictated by the specific requirements of customers. However, this study exclusively focused on pooled pallets, with the dimension of 1200 mm × 800 mm, made of either wood, plastic, or WPC. The pallets with the above-specified dimension are widely known as EUR pallets and are the most widely used type of pallets in Europe (EPAL 2019).

Table 1 specifies the key parameters of the studied pallets in their baseline scenario. Wooden pallets are made of virgin wood, which is a mixture of softwood and hardwood

as specific to Finnish conditions. The studied wooden pallets were block-type pallets, which are commonly used in Europe. Based on the review of LCA studies of wooden and plastic pallets by Deviatkin et al. (2019), the expected lifetime of the wooden pallets is 20 cycles, yet the number ranged between 5 and 30 cycles in most of the publications reviewed. The repair need of 7 cycles was estimated based on the mass of produced EUR pallets in Finland ( $3.2 \times 10^3$  kg), alongside with repaired ( $25 \times 10^3$  kg) and reused ( $167 \times 10^3$  kg). The expert views from a Finnish pallet pooling company suggested that the expected lifetime of the wooden pallets is somewhat higher, whereas the repair need for the pallets occurs on average after every 12 cycles. The variations in the expected lifetime of the pallets were examined in the scenario analysis of this study. It was assumed that, at the EoL, 90% of wooden pallets are incinerated, whereas 10% are used as a bulking agent in composting facilities.

The plastic and WPC pallets are identical in structure and production method. Plastic pallets are manufactured using injection moulding, whereas WPC pallets are produced by extrusion followed by a compression moulding process. Both pallets are made to allow their nesting, thus saving the space occupied by the pallets. The exact height occupied by wooden stackable pallets can fit 1.7 times more plastic or WPC pallets. According to the literature on plastic pallets, plastic pallets are more durable than wooden pallets (Deviatkin et al. 2019). The expected lifetime of plastic pallets could be 66 cycles, whereas the lifetime ranges from 50–100 in most of the studies reviewed (Deviatkin et al. 2019). In this study, the lifetime of plastic pallets was considered to be 66 cycles by following the review study conducted by Deviatkin et al. (2019). The WPC pallets were assumed to be of comparable properties as plastic pallets in these terms. Plastic and WPC pallets are suitable for demanding applications, such as those with expected exposure to water, or specific industrial demands, like those of the pharmaceutical industry. Such features of plastic and WPC pallets are, however, not considered in

**Table 1** Specifications of the pallets studied under the baseline conditions used in the study

	Wooden pallets	Plastic pallets	WPC pallets
Material	Virgin wood	Virgin plastic	Waste plastic and waste wood
Type	Block-type	Nestable	Nestable
Dimensions, mm	1200 × 800 × 144	1200 × 800 × 144	1200 × 800 × 144
Pallets at height of 1.44 m	10	17	17
Expected lifetime	20 cycles	66 cycles	66 cycles
Repair need	Every 7 cycles	Not possible	Not possible
Recycling	Partly reused for repair	Closed-loop recycling possible	Closed-loop recycling possible
EoL	90% incineration, 10% material recovery	100% incineration	100% incineration

this study. Once damaged, neither plastic nor WPC pallets can be repaired. In this case, the pallets are either sent to recycling or incinerated with an energy recovery process.

## 2.2 LCI

The data of the unit processes used for modelling the LCI are presented in the supplementary material. The LCI data were collected from the literature, the GaBi thinkstep database, and an operating industrial plant. The data generally represent wooden pallets, plastic pallets, WPC pallets, and wood and plastic waste in Finland. However, the data can be used for other geographical locations by changing unit processes (for example, thermal energy production and electricity grid mix). Maleic acid and lubricant production were not available from the GaBi thinkstep database and collected from the Ecoinvent database. However, these two processes have no significant impact on the life cycle of the WPC pallets.

## 2.3 LCIA

As stated in the materials and methods section, this study used CML 2001–Jan. 2016 as an impact assessment method. CML is the most widely used method in LCA (Rigon et al. 2019). This method allows for the assessment of the environmental impacts for several impact categories, out of which the following impact categories were included in the present study: abiotic depletion potential, fossil (ADP<sub>f</sub>), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP, excluding biogenic carbon), and ozone layer depletion potential (ODP). In addition, this study also included GWP (including biogenic carbon) and GWP (including biogenic carbon) with indirect land-use change (iLUC). The GWP, including biogenic carbon, was calculated partially based on the thinkstep database (marginal heat from biomass) and partially based on the carbon content in the wood and available literature. This study used 0.45 kg

CO<sub>2</sub> eq. kg CO<sub>2</sub><sup>-1</sup> as an average value of biogenic CO<sub>2</sub> emission from wood incineration (Cherubini et al. 2016). Finland has significant forest resource to demonstrate the potential iLUC impacts. In this study, 0.32 kg CO<sub>2</sub> eq. kg<sup>-1</sup> wood was considered for calculating the iLUC change from wood harvesting (Faraca et al. 2019).

## 2.4 Normalisation

According to ISO 14040 and 14044 standards, the LCA request characterized results (EN ISO 14040:2006; EN ISO 14044:2006) and thereby used in this study. However, there are difficulties in comparing different impact categories with each other (Abdulkareem et al. 2019). In this case, to understand the relative magnitude of each indicator result, it is essential to conduct normalisation. According to ISO 14044, normalisation is an optional step, defined as “calculating the magnitude of category indicator results relative to reference information” (SFS-EN ISO 14040:2006). The following equation can be used for normalisation calculation:

$$N_i = \frac{S_i}{R_i} \quad (1)$$

where  $i$  is the impact category,  $N_i$  is the normalised impact for a specific impact category,  $S_i$  is the score of the specific impact category, and  $R_i$  is the reference situation's score.  $R_i$ , which was used in this study, was the global equivalents excluding biogenic carbon. The  $R_i$  scores were collected from GaBi software and presented in Table 2.

## 2.5 Sensitivity analysis

The robustness of the result was investigated by performing contribution analysis and sensitivity analysis. According to Bisinella et al. (2016), sensitivity analysis investigates how the system reacts due to the alteration in the model input

**Table 2** Reference score based on CML 2001–Jan. 2016, excluding biogenic carbon (global equivalents)

Impact category	$R_i$	Unit
CML 2001–Jan. 2016, abiotic depletion (ADP elements)	$3.6 \times 10^8$	kg Sb eq
CML 2001–Jan. 2016, abiotic depletion (ADP fossil)	$3.8 \times 10^{14}$	MJ
CML 2001–Jan. 2016, acidification potential (AP)	$2.39 \times 10^{11}$	kg SO <sub>2</sub> eq
CML 2001–Jan. 2016, eutrophication potential (EP)	$1.58 \times 10^{11}$	kg phosphate eq
CML 2001–Jan. 2016, freshwater aquatic ecotoxicity pot. (FAETP inf.)	$2.36 \times 10^{12}$	kg DCB eq
CML 2001–Jan. 2016, global warming potential (GWP 100 years), excl biogenic carbon	$4.22 \times 10^{13}$	kg CO <sub>2</sub> eq
CML 2001–Jan. 2016, human toxicity potential (HTP inf.)	$2.58 \times 10^{12}$	kg DCB eq
CML 2001–Jan. 2016, marine aquatic ecotoxicity pot. (MAETP inf.)	$1.95 \times 10^{14}$	kg DCB eq
CML 2001–Jan. 2016, ozone layer depletion potential (ODP, steady state)	$2.27 \times 10^8$	kg R11 eq
CML 2001–Jan. 2016, photochem. ozone creation potential (POCP)	$3.68 \times 10^{10}$	kg Ethene eq
CML 2001–Jan. 2016, terrestrial ecotoxicity potential (TETP inf.)	$1.09 \times 10^{12}$	kg DCB eq

value. Scenario analysis is one type of sensitivity analysis often used in LCA (Junnila and Horvath 2003). By analysing the used data in the life cycle inventory phase, it was assumed that some of the variables might have had significant impacts on the overall results of the current study. Therefore, four scenario analysis was conducted in this study. A list of the variables with a range of data used in the scenario analysis is presented in Table 3. Both low and high values were collected from the literature, and they represent authentic or realistic practical values for each parameter found from different sources.

### 2.5.1 Scenario analysis I

The substituted heat from different sources and the annual efficiency of the waste incineration plant are important variables that indicate the quantity of avoided emissions that could be achieved by recovered heat from pallet incineration. The recovered energy from pallet waste and wood and plastic waste incineration substitute average heat production in Finland 2017. However, the recovered energy can also substitute heat produced from hard coal, peat, or biomass, which are regionally relevant sources in Finland. Therefore, the scenario analysis investigated the environmental impact of the pallets when the substituted heat sources were hard coal, peat, and biomass in ALCA and average heat production in Finland, hard coal, and peat in CLCA.

### 2.5.2 Scenario analysis II

The efficiency of the waste incineration plant varies depending on the quality of the fuel, boiler types, combustion control, efficient boiler cleaning, etc. In this study, the efficiency was 83% (electricity 23%; heat 60%). Anttila (2011) stated that annual waste incineration plant efficiency in Finland could vary between 45% (37% electricity, 8% heat) and 83% (23% electricity, 60% heat). However, according to CEWEP (2009) data, the efficiencies in combined heat and power (CHP) plants are higher in Nordic countries, being 9.6% for electricity generation and 82.9% for thermal energy. According to the expert views from the Finnish association 'Suomen Kiertovoima', the anticipated efficiencies for electricity and heat generation are close to 10% and 80%, respectively. Since the efficiency data vary substantially, it was important to conduct scenario analysis on these data.

### 2.6 Scenario analysis III

The number of cycles of the pallets is one of the important factors through which, by changing the number of cycles, it might be possible to identify how life expectancy influences the overall impact of the studied pallets. The life cycles of the wooden, plastic, and WPC pallets are not a constant figure. For this reason, in the scenario analysis, the life cycles of the WPC pallets changed by  $\pm 50\%$ .

**Table 3** Parameters and values used for sensitivity analysis

<b>Scenario analysis I</b>			
	<b>Low</b>	<b>High</b>	<b>Reference</b>
<b>Annual efficiency of waste incineration plant</b>	69% (electricity 4%; heat 65%)	92,5% (electricity 9,6%; heat 82.9%)	Anttila (2011)
<b>Scenario analysis II</b>			
<b>Replaced source of heat energy</b>	<b>Lower heating value as received</b>	<b>CO<sub>2</sub> emission factor</b>	
<b>Hard coal</b>	27 MJ/kg	108 g/MJ	Thinkstep (2018)
<b>Peat</b>	8.4 MJ/kg	139 g/MJ	Thinkstep (2018)
<b>Wood biomass</b>	15.5 MJ/kg	1.9 g/MJ <sup>a</sup>	Thinkstep (2018)
<b>Average heat production in Finland 2017</b>	22 MJ/kg	68.6 g/MJ	Thinkstep (2018)
<b>Scenario analysis III</b>			
<b>Life expectancy of the pallet</b>	<b>Low cycle</b>	<b>High cycle</b>	
<b>Wooden pallet</b>	10	30	
<b>Plastic pallet</b>	33	99	
<b>WPC pallet</b>	33	99	
<b>Scenario analysis IV</b>			
	<b>Low electricity consumption</b>	<b>High electricity consumption</b>	
<b>Electricity consumption of the pallet manufacturing</b>	5 MJ/kg	27 MJ/kg	Matarrese et al. (2017); Elduque et al. (2018)
<b>Plastic pallet</b>			

<sup>a</sup>CO<sub>2</sub> emission factor of wooden biomass excluding biogenic carbon

## 2.7 Scenario analysis IV

Plastic pallet production is an energy-intensive process. The electricity consumption in plastic pallet production is also not constant but varies depending on hydraulic machines and electric machines. The electricity consumption rate could vary between  $5 \text{ MJ kg}^{-1}$  and  $27 \text{ MJ kg}^{-1}$  plastic pallet (Matarrese et al. 2017; Elduque et al. 2018) and was therefore used in the scenario analysis.

## 3 Results

### 3.1 ALCA

The ALCA results of this study are comprised of four parts: production, use, maintenance, and EoL. The cradle-to-grave ALCA results show the superiority of the WPC pallets over the wooden and plastic pallets, which can be seen in Fig. 3. WPC pallets had the lowest impact in all impact categories except GWP (excl biogenic carbon), where the wooden pallets had the minimum impact. On the contrary, plastic pallets had the maximum impact in all categories, except EP, where it showed lower impact than the wooden pallets. More detailed results are available in the supplementary material's Table 5.

By analysing the results, four influencing factors have been found which have a significant impact on the ALCA results of the pallets; these are the weight of the pallets, energy consumption during production of the pallet, zero-burden approach for the waste materials, and credit for avoiding environmental burden by substituting material and energy. Wooden pallets had the highest environmental impact in the use phase due to a higher weight than the plastic and WPC pallets. WPC had the lowest impact in most of the impact categories than the wooden and plastic pallets due to the consideration of a zero-burden approach for wood and plastic waste used for WPC production. In the zero-burden approach, the environmental impact of producing a product is imposed on the product itself, while waste from the production line does not take any environmental burden (Khan et al. 2020). In addition, compared to the wooden pallet, WPC did not have any environmental burden from the maintenance phase. As a result of these influencing factors, WPC showed the lowest impact in most impact categories. Plastic pallet showed the highest environmental impact in all categories due to the maximum energy consumption in the production phase.

#### 3.1.1 Impact from the production phase

In the production phase, plastic pallet had the maximum impact in all impact categories because, during high-density

polyethylene (HDPE) production, 21,337 MJ of fossil fuel was consumed, mainly supplied from  $136 \text{ m}^3$  of natural gas and  $244,567 \text{ m}^3$  of crude oil. Wooden pallet consumed 3809 MJ of energy in the production phase for timber production, nail production, transporting nails and timber to the pallet production centre, electricity consumption for pallet production, and thermal energy for heat treatment of the pallet. WPC pallet consumed 293 MJ of energy in the different processes of the production phase.

#### 3.1.2 Impact from the use phase

In the modelling, the weight of the pallet was interconnected with the utilisation factor. The wooden pallet had the maximum environmental impacts from transportation because of its higher weight, which is also evident from Kočí (2019). As a consequence of the higher weight, the wooden pallet had a lower utilisation rate, which resulted in higher fuel consumption. Wooden pallet transportation consumed 6 L of biodiesel and 54 L of diesel in the use phase, while plastic pallet transportation needed 4 L of biodiesel and 36 L of diesel and WPC pallet transportation needed 4 L of biodiesel and 34 L of diesel. Regarding the impact from the different transportation modes, it can be noted that delivery to and collection from the local customers had the lowest impact. This is because the truck trailers operating for local customers were modelled to be using biodiesel, which is the requirement in the capital area. Besides, the transportation distance for local customers was shorter, and the relatively lower weight of pallets (20% of the total delivered weight) being delivered to the local customers.

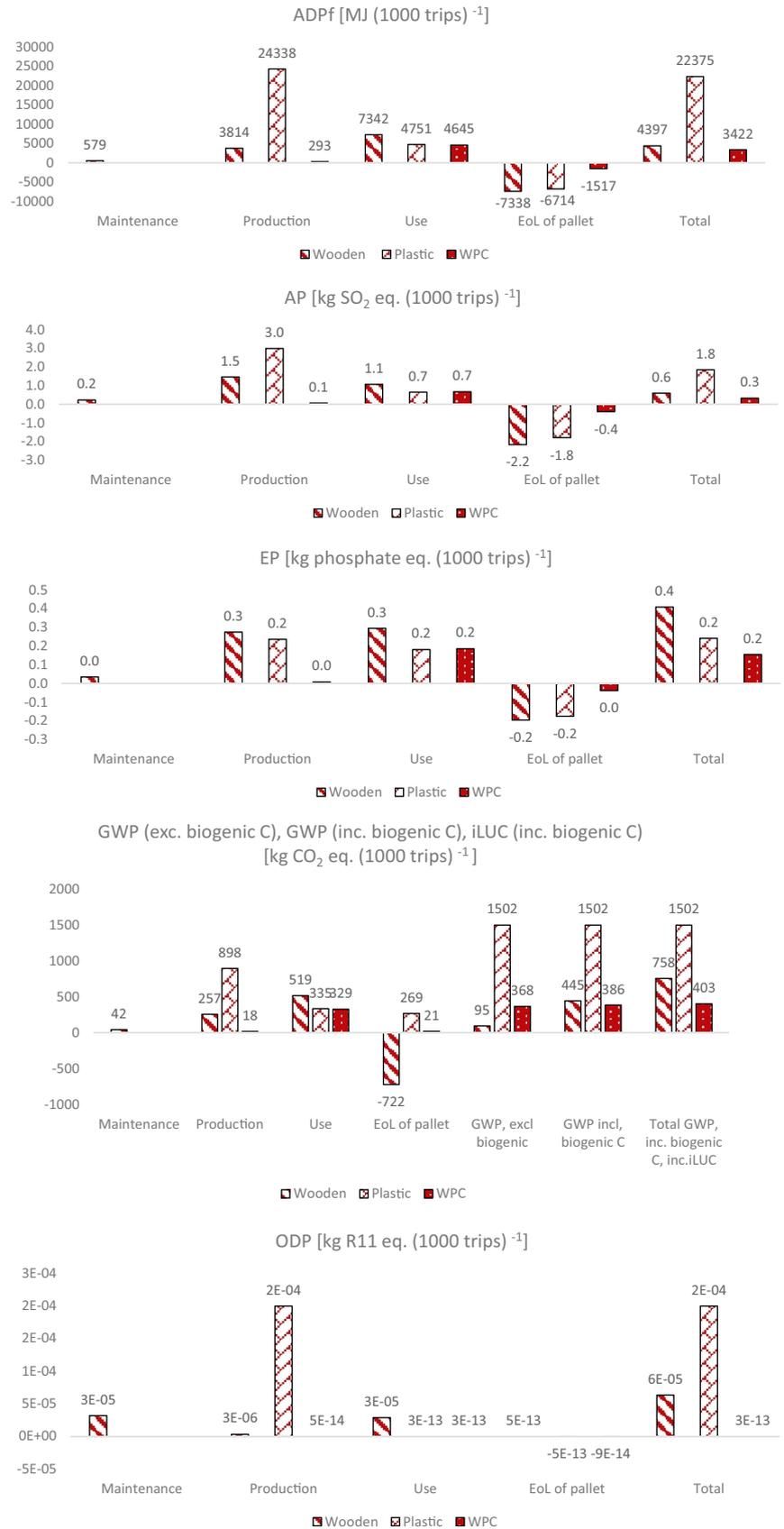
#### 3.1.3 Impact from the maintenance

Maintenance was considered only for the wooden pallet, while for the plastic and WPC pallets, maintenance was excluded since plastic, and WPC pallets cannot be repaired. Total environmental impact of the wooden pallets was increased in all categories due to the maintenance activities such as processes of wood harvesting, timber production and transportation to the repairing centre, production of screws used for repairing wooden pallets, and energy consumption from the repairing process.

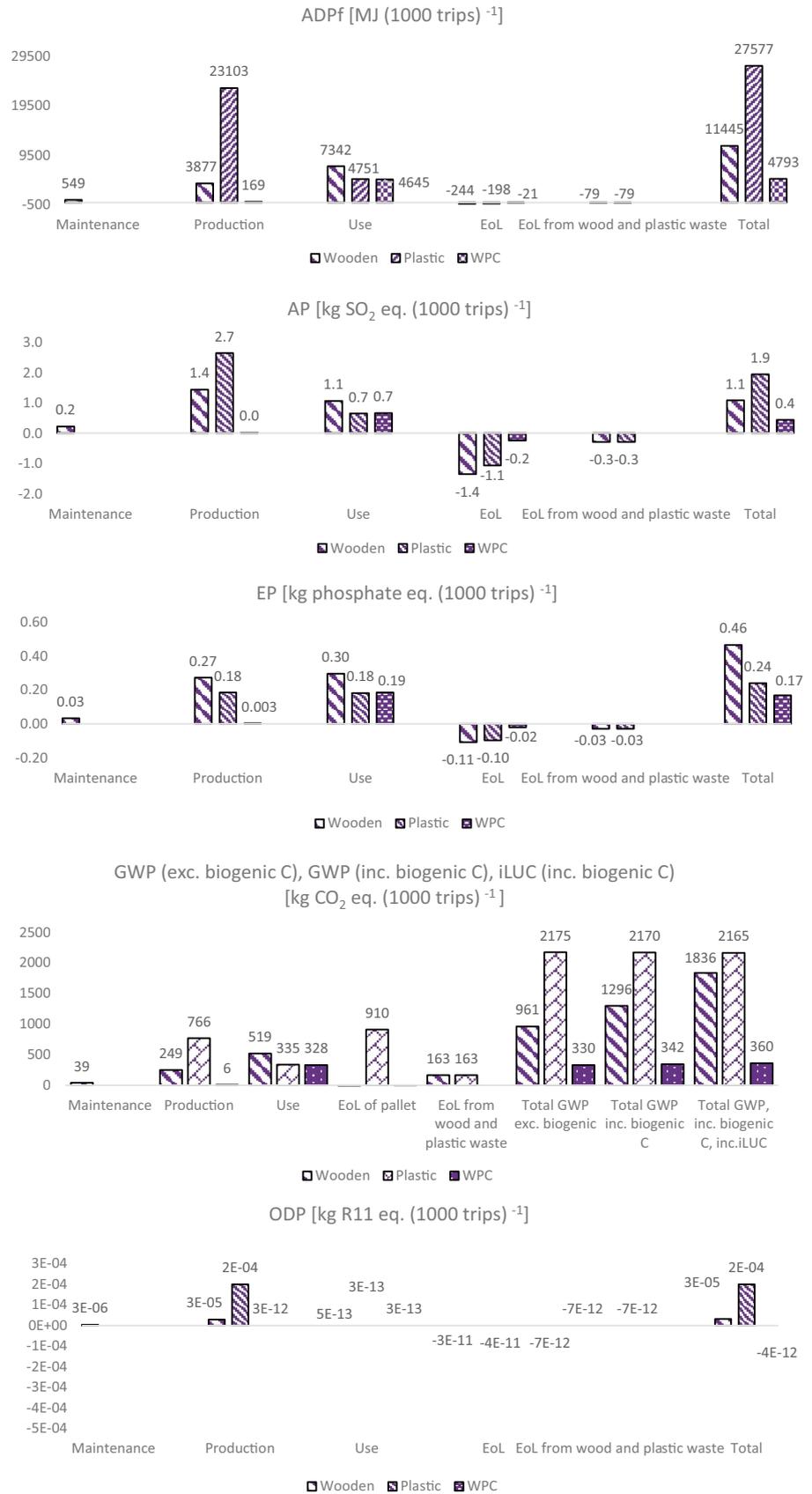
#### 3.1.4 Impact from the EoL

The environmental impact from the EoL phase depends on several factors such as  $\text{CO}_2$  emission factor, heating value, and biogenic carbon content of the material. In addition, higher weight also had an impact on the EoL stage. As shown in Fig. 3, the wooden pallet had the maximum amount of avoided environmental impact in the EoL stage. Because of a higher weight, 1123 kg of wooden pallets were

**Fig. 3** Results of the ALCA of wooden, plastic, and WPC pallets



**Fig. 4** Results of the CLCA of wooden, plastic, and WPC pallets



incinerated, while the weight of incinerated plastic and WPC pallets was 303 kg and 112 kg. As a consequence, wooden pallet incineration avoided 742 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> of greenhouse gases (GHGs) which is 9% higher than the plastic pallets and 80% higher than the WPC pallets.

Due to the higher heating value of the plastic, incineration of plastic pallet waste recovered a higher amount of energy and thus substituted a higher amount of heat (8182 MJ) and electricity (319 MJ) compared to the wooden pallet (1131 MJ heat; 264 MJ electricity) and the WPC pallet (2039 MJ heat; 70 MJ electricity). However, plastic pallet had the highest environmental impact from EoL in all categories because plastic incineration had a higher CO<sub>2</sub> emission factor than wood and WPC. Therefore, the incineration of plastic generated 937 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup>, while the wooden pallet incineration process generated 30 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> (excluding biogenic carbon), 380 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> (including biogenic carbon) and WPC pallet incineration generated 173 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> (excluding biogenic carbon) and 190 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> (including biogenic carbon).

### 3.2 CLCA

The CLCA results of this study are presented in Fig. 4. Resembling the ALCA result, the results of the CLCA were also influenced by the weight of the pallets, energy consumption in the production of the pallets, and the zero-burden approach for plastic and wood waste. Besides, in this part of the study, marginal heat and electricity also played a vital role.

In CLCA, WPC pallets had the lowest environmental impact in all categories. Considering the zero-burden approach for wood and plastic waste, WPC had the lowest impact in the production phase compared to the wooden and plastic pallet. In addition, due to the lighter weight than the wooden pallet, it generated a lower amount of emission in the use phase than the wooden pallet. As a result, WPC showed the lowest environmental impact.

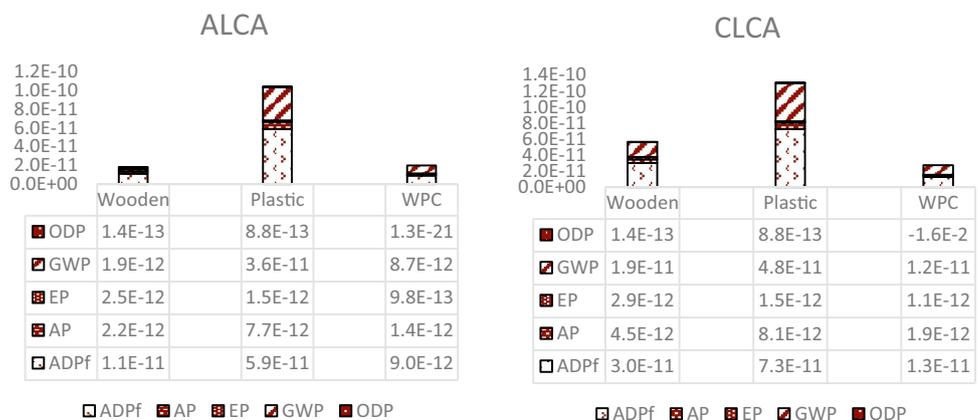
In this study, biomass heat source was considered the marginal heat source and wind, and solar-powered electricity was considered the marginal electricity source. Since biomass incineration produces lower emissions than the average heat production in Finland, a lower quantity of emissions would be avoided by replacing biomass-based heat sources, which is also evident from this study. Wooden pallets avoided 9 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup> of GHGs in CLCA, while in ALCA, the avoided GHGs were 742 kg CO<sub>2</sub> Eq. (1000 trips)<sup>-1</sup>. Since the avoided emission from wooden pallet incineration dropped significantly in CLCA, wooden pallet showed a higher GWP (excluding biogenic carbon) impact than WPC pallet. The environmental impact from the plastic production phase was significant due to the higher amount of fossil fuel consumption compared to the wooden and WPC pallets and thus had the maximum environmental impact in all categories. The details of the result are presented in the supplementary material's Table 6.

### 3.3 Normalisation results

The normalised result of the study is illustrated in Fig. 5. The normalised results include the studied impact categories ADPf, AP, EP, GWP (excluding biogenic), and ODP. By analysing normalised result on ALCA, it can be seen that wooden pallets and WPC pallets had almost similar normalisation score, whereas plastic pallets had the maximum score. In ADPf, AP, EP, and ODP, WPC had the minimum value, wherein GWP, the wooden pallet had the minimum score. In EP, plastic pallet had a lower score in comparison with wooden pallets. In CLCA normalised result, WPC pallets had the lowest score, whereas plastic pallets had the highest scores. In both the ALCA and CLCA normalised results, GWP had the most significant score, followed by ADPf.

It should be noted that the normalisation score should be considered carefully due to the potential biases and reference value choices (Pedersen 2017). The normalisation score

**Fig. 5** Normalised results of the study. The left-hand side of the figure represents normalised ALCA results, and the right-hand side of the figure presents normalised CLCA results



could be biased when  $S_i$  or  $R_i$  or both are incomplete due to the lack of emission data or characterisation factor (Heijungs et al. 2007). As a consequence of the biased score, the conclusion drawn from the LCIA phase could be changed.

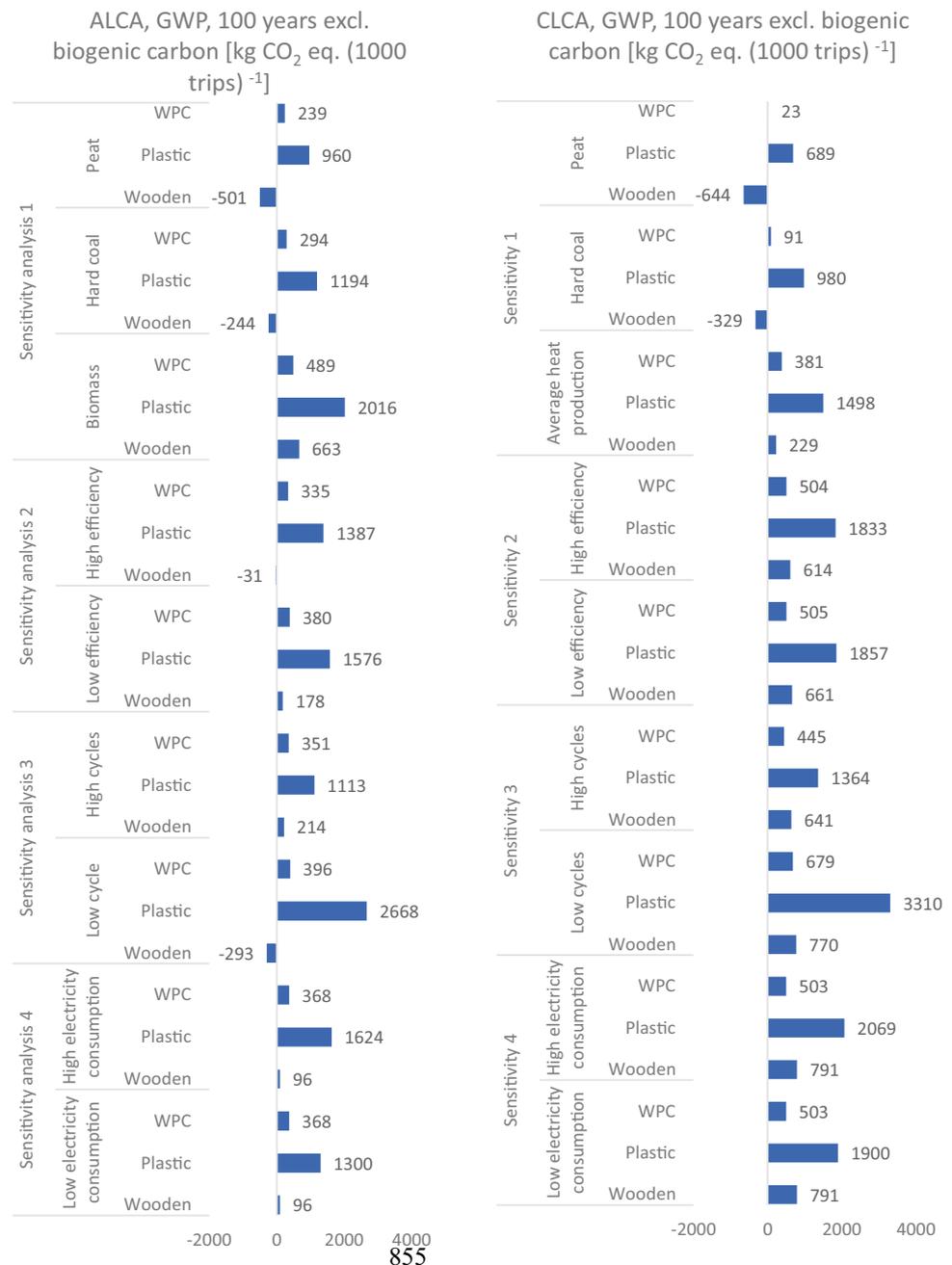
### 3.4 Sensitivity analysis

Figure 6 shows the sensitivity analysis results of this study. In this figure, only the GWP impact is presented, while the details of the sensitivity analysis results are presented in the supplementary material's Table 7 to 24. It was found from

the sensitivity analysis that the ALCA and CLCA results are influenced by the avoided environmental impact, annual power plant efficiency, life expectancy of the pallets, and energy consumption in the plastic pallet production process.

In scenario analysis I of the CLCA, it was observed that, regardless of the substituted heat sources, the plastic pallets had the highest environmental impacts in all categories except for EP, for which the wooden pallets had the highest value. By changing the substituted heat source from biomass to average heat production source, it was found that wooden pallets had the lowest environmental impacts in

**Fig. 6** Results for the GWP impact from the sensitivity analysis in this study. The right-side results are based on the CLCA, and the left-side results represent the ALCA



GWP (excluding biogenic carbon) due to the avoidance of a large quantity of emissions. In contrast, WPC had the lowest impact in ADPf, AP, EP, GWP (including biogenic carbon), iLUC (including biogenic carbon), and ODP. Including GWP, wooden pallets also had the minimum ADPf by substituting hard coal and peat-based heat sources. Because hard coal and peat have a higher LHVar, a higher quantity of energy consumption was avoided by substituting coal and peat-based thermal energy.

Similarly, wooden pallets had the lowest ADPf, GWP (including biogenic carbon), and GWP (excluding biogenic carbon) impacts in ALCA when coal and peat-based heat sources were substituted. In the case of biomass-based heat source, WPC showed the lowest impact. By conducting scenario analysis I, it was found that the overall environmental impact of the pallets significantly depends on the substituted heat sources.

In scenario analyses II, III, and IV, the overall results showed similar behaviour as the main result. In ALCA, WPC pallets showed the lowest impact in all categories, while wooden pallets showed the lowest impact in GWP (excluding biogenic carbon). In CLCA, WPC pallets had the best environmental impact in all categories. In ALCA and CLCA, plastic pallets had the highest environmental impact due to the significant quantity of energy consumption in the HDPE production process.

## 4 Discussion

The results on the ALCA, CLCA, sensitivity analysis, and normalisation demonstrate that WPC pallets can be a better choice over wooden and plastic pallets made of virgin materials. In almost all impact categories, the WPC pallet showed better environmental performance. In some of the analysis, wooden pallet showed a better environmental impact than WPC pallet under the consideration of wooden pallet incineration as a carbon-neutral process. However, WPC pallet is a better choice over wooden pallets in places where the consumed heat is supplied by biomass (wood), and electricity is supplied by wind and solar power because biomass, wind, and solar power have a lower environmental impact compared to the fossil sources. By conducting this study, it was found that the substituted heat source consideration can play a significant role in the overall emissions of a product.

It was also found that a carbon-neutral approach from biomass incineration can significantly impact the overall GWP of the product. The EU label wood-based products as carbon-neutral since trees remove CO<sub>2</sub> from the air and, when they are burnt, these products release CO<sub>2</sub> back into the atmosphere. However, several publications (Cherubini et al. 2011; Faraca et al. 2019) have concluded that wood incineration should not be considered carbon neutral, and biogenic carbon emission should be included when the

biomass has a rotation period of several decades. In addition, once an old-growth forest is cut down, it is not guaranteed to regrow within 100 years.

Using wood for pallet production incurs further demand for the wood resulting in more occupation for land (Faraca et al. 2019). Forests reserve tonnes of CO<sub>2</sub> in their wood, and twice as much CO<sub>2</sub> that trees sequester is reserved in the soil (Cassella 2018). Once the trees are cut down, the soil is exposed, resulting in more CO<sub>2</sub> emissions. Even though trees are continuously planted in sustainable foresting, these trees do not store as much CO<sub>2</sub> as natural forests do (Cassella 2018). Therefore, iLUC should be investigated where land transformation happens due to the utilisation of the wooden-based product.

Finland wants to increase its economic competitiveness without relying on the wasteful use of natural resources. The aim is to shift competitiveness from a linear economy to a circular economy and build a low emissions society. Therefore, Finland prepared a road map to a circular economy in 2006. According to SITRA (2019), the EU aims to reduce emissions from heavy industry by 56% through material recirculation, increasing material efficiency and implementing new circular business models. The EU has the target of recirculating 56% of total accumulated plastics. In this case, being a circular product, WPC pallets can help to reach this target by recirculating about 1 million tonnes of plastic waste (considering the production of 123 million pallets under EPAL in 2019) in a year. However, the recirculating amount of plastic waste with WPC pallet depends on the sorting of plastic into different categories, the availability of recycled plastic, and WPC pallet production plants. On the other hand, it is possible to use mixed plastics and some mixtures of plastics and fibres, which are not pure, and in such a way, WPC product can complete the recycling of mono-materials. Additionally, the extent of the circularity of the WPC pallet depends on the scope of material recovery and recyclability at the EoL. Since the material recovery and the quality of recycled WPC pallets were out of the scope of this research work, further assessment is needed to investigate the extent of the circularity of this product.

WPC pallet is made of nearly 50% wood and more than 50% plastic waste. Since this type of pallet is made from waste, the environmental impact from its production is purely based on the production and supply of additives, electricity, and diesel. However, a zero-burden approach in a circular economy has been criticised, as waste is no longer considered waste but rather as raw materials for other purposes (Ilic et al. 2018). Therefore, the impacts from the production of WPC pallets could be increased if plastic and wood were allocated a part of the burden from their preceding life cycles.

Compared to the other EU countries, Finland falls behind in terms of C&D waste recycling. In 2014, the recovery rate of CDW as a material was 58%. However, the recycling target

set by the Waste Framework Directive of the EU and the Finnish Waste Decree is 70% by 2020, which requires new waste legislation and infrastructural development (Salmenperä et al. 2020). In the typical Finnish C&D waste framework, the share of wood waste is 36% (Dahlbo et al. 2015). The recovery rate of wood from C&D waste in Finland is relatively low compared to that in other European countries because timber is relatively cheaper in Finland, and construction industries have little interest in reusing it. Nonetheless, customers are afraid of mould and other dangerous substances from recovered wood. Therefore, wood waste is generally sent to the incineration plant. In this case, utilising wood waste for WPC production could increase the material recovery share of C&D waste in Finland.

In sum, the most important influencing factors responsible for the environmental impacts of the pallets are the weight, energy consumption during production, energy source, and substituted heat sources. In addition, the carbon-neutrality approach for wood incineration and the zero-burden approach for waste also plays a significant role in the pallets' life cycle.

## 5 Conclusions

In this article, a detailed investigation of the environmental impacts of wooden, plastic, and WPC pallets was conducted using ALCA and CLCA. In addition, this article conducted a normalisation calculation and sensitivity analysis utilizing scenario analysis. By investigating the environmental impact of different pallets, it was found that the impact category's result depends on ALCA and CLCA methods, the weight of the pallets, energy consumption during the production of the raw materials, zero-burden approach for waste, and carbon-neutral approach for wood incineration.

CLCA results differ from ALCA because CLCA includes the system affected by the various pallets' production and uses. In addition, the inclusion of marginal heat and electricity in the CLCA significantly impacts the overall emissions of the pallets. In ALCA, WPC pallets had the lowest environmental impacts in all categories except GWP (excluding biogenic carbon). Whereas in the CLCA, WPC pallets showed the best impact in all impact categories. Similar to the ALCA and CLCA, normalisation and sensitivity analysis also showed that WPC had the lowest environmental impact in most cases.

WPC pallet showed the lowest environmental impact because it consumes less fuel in the use phase than the wooden pallet. In addition to that, WPC production did not include the environmental burden from plastic and wood waste generation by following the zero-burden approach for waste. Since the zero-burden approach for waste in the circular economy is a contentious issue, a careful consideration of the zero-burden approach for waste must be taken in future analysis.

After conducting the ALCA and CLCA of the pallets, it can be concluded that plastic pallets made from virgin materials always have the highest environmental impact on the virtue of the high energy consumption in the HDPE production and pallet production. However, plastic pallets made from recycled plastic might show better environmental impact than WPC and wooden pallets but require further analysis. Wooden pallets had the lowest GWP (excluding biogenic carbon and iLUC) impact in ALCA because of the consideration of wood incineration as a carbon-neutral process and the quantity of avoided emissions and substituted average heat production. However, the carbon-neutral approach demands an extensive discussion.

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