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Analyzing the Consequences of Sharing Principles on Different Economies: A Case Study of Short Rotation Coppice Poplar Wood Panel Production Value Chain

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Abstract: Quantifying the environmental impacts of value chains on the earth's ecological limits is crucial to designing science-based strategies for environmental sustainability. Combining the Planetary Boundaries (PB) and Life Cycle Assessment (LCA) framework can be used to estimate if a value chain can be considered as Absolute Environmentally Sustainable (AES) in relation to the PB. One of the crucial steps in implementing the PB-LCA framework is using sharing principals to downscale the global PB to smaller scales (e.g., country) and calculate an assigned Safe Operating Space (aSOS). This study assesses the potential AES of a wood panel value chain in Austria and Slovakia to understand the consequences of applying diverse sharing principles on different economies. Two economic and one emission-based sharing principles were compared. The results show that depending on the sharing principle implemented, different conclusions on the AES and potential strategies at a value chain and national level are achieved. Economic-based sharing principles are biased to the value chain's economical contribution. As for the emission-based approach, greater aSOS is given to systems with a higher contribution of emissions. A potential downside of either approach is that it can lead to misleading environmental strategies, such as hindering the development of less wealthy value chains and giving less incentive to improve environmental efficiency. These outcomes highlight the importance of further research into resolving the issues about just assignment of SOS. Moreover, our study contributes to the effort of making the PB-LCA framework relevant for strategic decision-making at a value chain level.

Keywords: wood-based products; environmental sustainability; absolute sustainability; life cycle assessment; planetary boundaries

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1. Introduction

In 2022 it will be fifty years since the pioneering work "limits to growth" by Meadows et al. [1] discussed the unsustainability of pursuing continuous economic growth without including environmental limits and social cost. In line with such concerns, The European Union's Bioeconomy strategy attempts to lead our society toward sustainable development by strengthening the relationship between economy, society, and environment [2]. Such narrative has encouraged the understanding of the operational limits within which our society can develop without irreversibly disturbing the ecological stability that has been present for approximately 11,700 years, known as the Holocene state [3]. An instance of this ongoing effort is the conception of the planetary boundaries (PB) framework [3,4]. This framework describes boundaries for nine key earth system processes that should not be traversed by anthropogenic perturbations, thus indicating a safe operating space (SOS) for humanity to act within. The framework can help to frame the path toward sustainable development [5], such as done by the International Panel on Climate Change with defining the remaining carbon budget to limit global warming to 1.5 °C [6,7]. However, the PB are framed at global level, which challenges their implementation for decision-making at the relevant sub-scales (e.g., region, country, value chain, product) [8,9]. An approach to deal with this issue is to integrate the PB concept into the life cycle assessment (LCA) framework [10]. Following the LCA standard [11], the potential environmental impacts of human-induced activities are quantitatively assessed on the level of products or services with the aim to improve their environmental performance (e.g., eco-efficiency). However, in terms of environmental sustainability, LCA results can be understood as a relative assessment, as it does not provide knowledge on the absolute environmental impact in relation to the biophysical limits of the earth system. To overcome this limitation, researchers have integrated the PB framework into the LCA by using the PB as a reference to indicate whether the product or service (LCA results) is absolutely environmentally sustainable (AES) [12,13]. Accordingly, the PB-LCA method can assist in understanding the potential AES of a value chain and thus help guide science-based strategies for environmental sustainability. For instance, Dao et al. [14] provided an example of how national environmental limits and strategies can be drawn based on PB for Switzerland. In another case study, Ehrenstein et al. [15] implement the PB-LCA method to analyze fuel supply chains in the UK to understand the impact of technological changes and offer strategies to develop sustainable value chains within PB.

A fundamental step within the PB-LCA framework is allocating the PB to a sub-system level (e.g., product). Consequently, a share of the SOS is assigned (aSOS) to the sub-system. If the environmental impacts of the sub-system are below the aSOS, then it can be considered environmentally sustainable in absolute terms [16]. This top-down allocation process is based on the assumption that the PB can be downscaled from global to sub-scale level, such as country (e.g., [17]), industry (e.g., [18]), or product level (e.g., [19,20]). A key challenge in the PB downscaling approach is the normative and ethical nature of the sharing principles used for assigning the SOS [21]. The basis of these principles is not just a matter of natural sciences, since the question of the distribution of our natural resources and environmental burdens also requires an economic, political, and social point of view. Such matter is stressed by the theoretical framework proposed by Häyhä et al. [22], who discuss the importance of integrating biophysical, socio-economic, and ethical dimensions into the sharing principles used for downscaling the PB to national level. One of the main theories that guide the discussion of translating the global-scale PB to subscales is that of distributive justice. For instance, distributive justice is a central frame in sustainable forest management [23]. Similarly, the common but differentiated responsibilities principle mentioned in the 2030 Agenda for Sustainable Development [24] is based on a fair and equitable share of environmental burdens among nations. A demonstration of how distributive justice theories are one of the main foundations used in previous academic case studies was presented in a review study by Ryberg et al. [25]. Four central ethical norms were identified: egalitarian, utilitarian, prioritarian, and acquired rights. The egalitarian perspective emphasizes an equal distribution among people (e.g., based on population per country). As for the utilitarian stand, it advocates for a distribution based on the maximization of total utility (e.g., based on the economic value a product brings to society). Prioritarianism focuses on the given priority to the worse off in the distribution of advantages (e.g., based on the ability to pay). The acquired rights perspective focuses on distribution by the historical or current rights that have been acquired (e.g., based on current or historical environmental impacts of producing a product). Previous PB-LCA studies applied a combination of the sharing principles. However, the study [25] emphasizes the possibility of results discrepancies among PB-LCA studies that are generated by the existing lack of consensus on the most appropriate principle or combination of principles to apply. The importance for a common understanding of ethical norms and application of sharing principles has been highlighted as a research need for further developing the PB-LCA methodology [21]. Analyzing the implementation of diverse sharing principles in case studies can add to the discussion on the selection of default sharing principles by creating a knowledge link between scientists, civic society, industry, and politicians.

One step toward understanding the implications of using sharing principles is to apply them at a value chain level, as this can provide insights on the applicability of the PB-LCA framework at a corporate level and with this foster the development of strategies beyond eco-efficiency. Some examples are research on the Swedish clothing consumption [26], Swedish apparel sector [27], laundry washing in the EU [18], energy systems in the US [28] and biomass for energy supply chains in Argentina [20]. All these studies have focused on analyzing a single activity within a singular region. However, no study has yet examined the consequences of applying different sharing principles to equivalent value chains in distinct countries. Tackling this question can help detect critical implications of applying current sharing principles in different countries, for instance, analyzing the sensitivity of various economies to an egalitarian-based sharing principle. Moreover, it can open new directions for future research on downscaling methods as well as identify gaps in knowledge in the application of the PB-LCA framework.

This study goes beyond the existing literature by investigating the implications of applying different sharing principles to similar value chains in geographically related but socio-economically distinct countries. For instance, gaining insights on how selected sharing principles generate different PB-LCA-based environmentally sustainable strategies. Thus, the present study is of relevance to the PB-LCA community as it provides further understanding on the consequences of applying downscaling methods in the PB-LCA framework. Moreover, it is of interest for decision-makers who intend applying the framework to develop science-based strategies toward a sustainable bioeconomy.

Considering the previously defined research gap, the cases of Austria and Slovakia are compared by analyzing two similar Short Rotation Coppice (SRC) poplar wood panel value chains. Besides the geographical similarity, SRC has been presented as an attractive agricultural practice to secure woody material for sustaining the bioeconomy, and can be of great importance to the wood industry of both countries [29,30]. In 2016 within the EU, around 5000 ha of SRC had been established [31]. In 2013 Austria had 2236 ha of SRC on agricultural land, whereas Slovakia approximately 150 ha [32]. Regarding the differences between the national legal frameworks for SRC plantations, in Austria it is forbidden to plant SRC on forest land. SCR plantations are considered annual crops if harvested within a 3–5-year time period [33,34] and have to be harvested at least once within 30 years; if not, plantations automatically become forest land [35]. Concerning Slovakia, regulations only allow SRC plantations on “low quality” soil classes 5–9, which are referred to as marginal land [36]; furthermore, the plantations can only be cultivated for a maximum of 20 years [37]. Afterwards the SRC need to be recultivated with annual crops. As for the economic difference, for 2016, Austria presented a population and gross domestic product (GDP) of about 37% respectively 77%, higher in comparison to Slovakia [38]. On the other hand, Slovakia presents more agricultural land (% of the land area) than Austria, approximately 17% of difference for 2016. For each case, three scenarios applied the most commonly used sharing principles identified in previous case studies [21]: egalitarian, utilitarian and acquired rights (using the grandfathering approach). To assess the potential environmental impacts of the value chain against the downscaled PB, the year 2016 was taken as a reference since consistent economic and environmental data were available. This study is structured as follows: the method section summarizes the wood panel production system and introduces the PB-LCA framework and the applied downscaling methods. Following, the results section presents the PB-LCA outcomes and the comparison between the cases and scenarios. Finally, the discussion and conclusion sections deal with the significant findings and implications.

2. Materials and Methods

2.1. Planetary Boundary-Life Cycle Assessment (PB-LCA) Framework

The absolute environmental assessment is carried out by applying the PB-LCA framework by Ryberg et al. [10], who combined the LCA methodology [11], and the PB framework from Steffen et al. [4]. The following sub-chapters present a description of the four methodological phases implemented in the PB-LCA framework. Such as the goal and scope definition, the life cycle inventory (LCI) phase, the life cycle impact assessment (LCIA), and the lifecycle interpretation phase.

2.1.1. Goal and Scope

Concerning the first phase, the goal is to calculate and compare the potential absolute environmental sustainability of an SRC wood-based panel value chain in Austria and Slovakia under different sharing principles. A Functional Unit (FU) of "producing 350,000 m^3 of wood-based panels per year" was defined based on an average of previously reported production volumes of wood-based panels [39,40]. The main justification for choosing a time-dependent FU was that the PB-LCA requires annual elementary flows, whereas the large FU quantity facilitates the downscaling of PB [16,18]. Figure 1 displays the system boundaries of the wood panel production under study. It includes the agricultural production of SRC-based poplar wood, the input of pine wood from sustainable managed forest, the production and transportation of raw materials (e.g., glue) and energy sources (gas, diesel and electricity), and the wood panel production which involves the manufacturing processes at the industrial site. The wood plantation for poplar and pine are located at an average distance of 80 km from the industrial site. The entire wood panel production value chain is assumed to be located both in Austria and another in Slovakia.

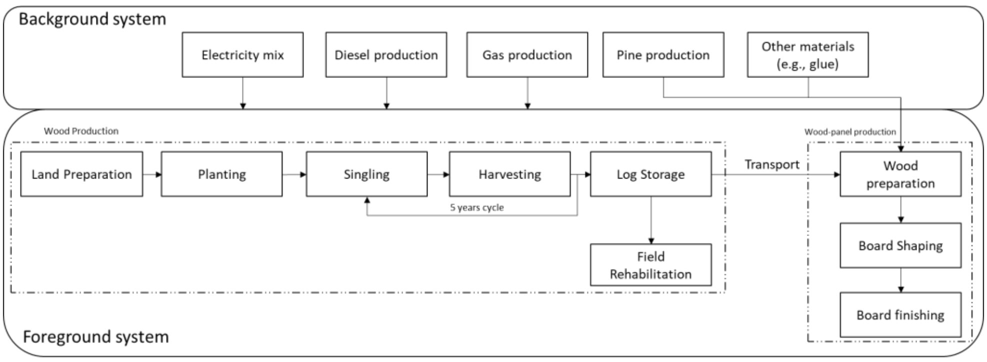


Figure 1. Summary of system boundaries for the case study of wood panel boards.

In order to focus on the assessment of the production system, and to lower uncertainty due to data availability, the wood panel value chain was simplified by the following points: (i) Exclusion of the End of Life (EOL) phase of the wood panels, the production of one single wood panel with a density of 500 kg/m^3; (ii) electricity mixes from Slovakia were used for both cases, the data are provided by the Ecoinvent 3.4 database; (iii) all electricity consumption were allocated to the process-related data; (vi) 50% and 55% of moisture content, wet basis, assumption for pine and poplar wood, respectively [41–43]. As presented by Perdomo E.A [44,45] the processes considered (Figure 1) for modeling wood panel production system represent a cradle to gate system boundary. A division between foreground and background system was based on the availability of primary data. Primary data were collected by survey with related SRC producers and wood-panel manufacturers. Previous case studies and the Ecoinvent database served as the main database source for secondary data [44,45]. To confirm the data quality obtained from the surveys, a cross-check with published secondary data (e.g., [46,47]) was carried out. The results showed that the data are within the range of previous studies (e.g., [48,49]). Following the International Reference Life Cycle Data System (ILCD) handbook, an attributional LCA approach was selected based on the decision context type of this research, which is "accounting for environmental impacts' framework" [50]. Based on previous studies about wood panels (e.g., [49]), a mass-based allocation was used for burden allocation between product and co-products.

2.1.2. Life Cycle Inventory (LCI)

Overall, the foreground system for the LCI includes the SRC-based poplar and the wood panel manufacturing (Figure 1). The SRC-based poplar production starts by the land preparation for planning the rods. Therefore, the land is disked, ploughed, and harrowed. Planting the rods is done both manually and using machinery. Weed control activity is done using a disk harrow during the 1st, 2nd, 3rd, and 4th year. For the 5th year and onwards, normally, no weed control is needed. No chemical herbicides are applied for weed control. Moreover, as the poplar grows, singling and pruning are done manually to select and support the dominant shoot. This last step is done after every harvest event. It is assumed that harvesting operations occur four times with a 5-year rotation period. The harvesting operations consists of felling and bunching the wood, extraction to the required site, crosscutting the logs to their desired length, and chipping the branches and wood tops. The logs and the wood chips are afterwards transported to the manufacturing site to produce wood-based panels. The EOL of the plantation occurs after 20 years, where the land is ploughed, the wood stems and roots are extracted with the goal to reconvert the land to annual cultivation conditions. The wood-based panel manufacturing production system begins with the wood preparation process consisting of debarking, flaking, chip preparation, and drying of the chips. The blending process follows by mixing the necessary additives (e.g., wax). After a size screening step, the flakes are sent to the board shaping process line, consisting of forming line, exhausting, continuous press, and cooling. The final steps consist of sanding, trimming, sawing, and the final panel storage. It is assumed that during the use phase no emissions are produced.

The materials and energy used throughout the life cycle of the wood-based panel were quantified in a systematic inventory [44,45]. The data are based on producing a wood-based panel with a density of 500 kg/m^3 composed by poplar (30%) and pine wood (70%). Table 1 presents a summary of the inputs associated to produce the wood-based panels. An overview of all the foreground processes modeled are presented in Supplementary Material 1 (SM1). The electricity and energy mixes of Austria and Slovakia were determined through the Ecoinvent database. The default attributional approach from Ecoinvent "Allocation at the point of substitution" was used to model the LCI of background processes (e.g., electricity production). A summary of the data and calculations is presented in Supplementary Material 2 (SM2).

Table 1. Wood input material for 1 m^3 of wood panel (Source: own calculation).

Wood Input [1] (kg d.m)	
Sum absolute dry wood	646.92
Pine (70%)	345.57
Poplar (30%)	148.10
Bark	153.24
Chemical input [1] (kg)	
Phenol-formaldehyde	15.90
MDI resin	3.06
Wax	7.24
Total Chemical input	26.20
Chemical input with (20%)	20.96

[1] Based on calculations from Kaestner [48]. e.g., 23.68% bark assumption.

2.1.3. Life Cycle Impact Assessment (LCIA) and Interpretation

As for the LCIA phase, the PB-LCIA method and characterization factors described by Ryberg et al. [10] were used to convert the life cycle inventory (LCI) into the PB control variables (see SM2 for calculations). The PB impact categories selected were climate change-energy imbalance (CC-EI), climate change-CO_2 concentration (CC-CO_2), stratospheric ozone depletion (SOD) and ocean acidification (OA), atmospheric aerosol loading (AAL), land system change, temperate (LCt), biogeochemical flows-P, regional (BPr), and biogeochemical flows-N, global (BNg). For the land system change category, the temperate zone was assumed as a simplification of European forest system. The rest of the land system categories were excluded as no activity occurs in tropical, or a boreal area. Freshwater impact category was excluded as no use of freshwater was considered.

The interpretation phase focused on analyzing the results to estimate the potential environmental impacts and the PB transgression levels. Therefore, the environmental sustainability ratio (ESR) was used to estimate whether the studied system is AES or not [17]. The ESR is calculated using Equation (1), representing the ratio between the environmental footprint and corresponding downscaled boundary. If ESR > 1, the footprint surpasses the PB, thus leading to environmental sustainability. Suppose the ESR $\leq$ 1, then the studied system is potentially AES.

$$\mathrm{ESR} = \frac{\mathrm{EI}}{\mathrm{DPB}} \tag{1}$$

where, EI is the environmental impact of the studied system and DPB is the downscaled PB.

2.2. Calculation of Safe Operating Space and Selection of Sharing Principle

The safe operating space (SOS) is defined as the operational budget that an anthropogenic activity should not exceed. This budget delimits the maximum allowable impact that the wood panel manufacturing activities should produce to stay within absolute environmentally sustainable terms. The difference between the PB value and the natural background level without human intervention is the SOS. As the SOSs are defined globally, it is necessary to downscale them and obtain the assigned SOS (aSOS) that corresponds to the specific activity or product assessed. An example can be made with climate change-CO_2 concentration PB. The full safe operating space at a global level is equal to 72 ppm CO_2. A percentage of this global SOS should then be assigned to the anthropogenic activity (i.e., the aSOS). If the impacts of the activity surpass the aSOS then it is considered environmentally unsustainable. Thus, the aSOS serves as an absolute sustainability reference to guide the decision on whether the human activity is environmentally sustainable or not.

A crucial step to calculate the aSOS is selecting a sharing principle to determine the aSOS. This step is controversial due to its normative conceptual bases, which makes it difficult to reach a consensus on the most appropriate method to use. General recommendations to select the sharing principle are given by Bjørn et al. [21], such as selecting the principle based on technical applicability. Additionally, it is suggested to select multiple sharing principles and reflect on their impact on the results. Such recommendations, as well as knowledge gained from previous case studies, and characteristics of a wood panel value chain (e.g., agricultural processes) were considered.

Distributive justice theories have served to understand the normative character of sharing principles. The most common ethical norms applied in previous studies are egalitarian, utilitarian, and prioritarian [21]. An egalitarian stand discusses that environmental budgets should be allocated equally among people. The most common variable used to downscale the SOS is on an equal per capita base (e.g., world population). From a utilitarian stand, the goal is to maximize the well-being of society. Well-being is a multiple-aspect concept that can vary at an individual, cultural, and societal level [51]. Economic value, for example, has been considered as an aspect that contributes to human well-being. Previous PB-LCA studies have used gross value added (GVA) as an indicator to represent well-being generated from economic value added (e.g., [28]). Another commonly used utilitarian-based principle is using final consumption expenditure (FCE), as an indication of consumer preference for an activity or product (e.g., [18]). For instance, the preference of a consumer to buy wood products in Slovakia gives an indication of the relative contribution of this commodity to well-being. For the present study, GVA represents the added value from veneer sheets and wood panels industry in each studied country. Since no disaggregated data for GVA of wood panels were available, veneer sheets were included. For comparability, the FCE and grandfathering (GF) approach also included veneer sheets. FCE refers to the consumers' preference to buying goods and services used to satisfy their individual needs. The FCE in this study is the amount spent by a consumer on wood-based panels. The GF approach is described in the following paragraphs.

A common approach is to combine the egalitarian and utilitarian approaches. The GVA-based sharing principle can thus be combined with the per-capita approach resulting in Equation (2). The downscaling process then consists of two steps. First, the SOS is downscaled at a national level using the per-capita approach. Second, based on the country GVA and the GVA of the wood panel industry, the SOS is downscaled to the industry level. A similar equation (Equation (3)) is derived for the FCE-based principle.

$$\mathrm{aSoS_{GVA}} = \frac{\mathrm{Pop_{country}}}{\mathrm{Pop_{world}}} * \frac{\mathrm{GVA_{industry}}}{\mathrm{GVA_{country}}} \tag{2}$$

$$\mathrm{aSoS_{FCE}} = \frac{\mathrm{Pop_{country}}}{\mathrm{Pop_{world}}} * \frac{\mathrm{FCE_{industry}}}{\mathrm{FCE_{country}}} \tag{3}$$

For Equation (1), $\mathrm{aSoS_{GVA}}$ is the aSOS for the GVA approach, $\mathrm{Pop_{country}}$ and $\mathrm{Pop_{world}}$ are population of the country and world, respectively. $\mathrm{GVA_{industry}}$ and $\mathrm{GVA_{country}}$ represent the GVA for the industry and country, respectively. For Equation (2), $\mathrm{aSOS_{FCE}}$ is the aSOS for the FCE approach. $\mathrm{FCE_{industry}}$ and $\mathrm{FCE_{country}}$ correspond to the FCE for the industry, and the country, respectively. All values are determined for a certain year.

As for the prioritarian approach, it is believed that distributional justice is reached when "the weighted moral value of people's well-being is maximized" [52]. Thus, as interpreted by Bjørn et al. [21], prioritarianism suggests a need for positive discrimination for the disadvantaged to obtain justice. Previous studies investigating the prioritarian perspective have used historical environmental debt (HD) as a downscaling proxy at the national level. However, this approach was not included in the current study.

Belonging to the acquired rights sharing principle, the GF approach suggests that distribution should be made dependent on the share of environmental pressure generated in a specific year. For instance, at the country level, the country's share in global environmental pressure, and the industry's environmental impact at an industry level. GHG emissions were used as an indicator to represent the environmental impacts of a country or industry. This indicator was selected due to simplification reasons, and since it is presently the most common environmental indicator utilized and registered in the literature. Another approach would be to consider various GF environmental indicators e.g., marine ecotoxicity instead of GHG emissions to compare what are the differences when using one or the other to represent the environmental impacts of a country. However, this approach was out of the focus of the present study. Following these ideas, Equation (4) presents the GF-based sharing principle.

$$\mathrm{aSoS_{GF\_Industry}} = \frac{\mathrm{POP_{Country}}}{\mathrm{POP_{Global}}} * \frac{\mathrm{GHG_{Country,\ WP\ Industry}}}{\mathrm{GHG_{Country}}} \tag{4}$$

where, $\mathrm{GHG_{Country}}$ represent the total GHG emissions at a national level in a certain year. $\mathrm{GHG_{Country,\ WP\ Industry}}$ is the GHG emissions of the wood panel industry within a country in a certain year.

For all the methods described above, a further downscaling step was applied to reach a supply chain level. To calculate the aSOS at a value chain level $(\mathrm{aSOS_{VC}})$, a production volume-based downscaling was applied. The rationale here is that the production volume can be used as an indicator of the contribution of a supply chain to the total national production in a reference year (Equation (5))

$$aSoS_{VC} = \frac{Supply_{\ VC}}{Supply_{Country}} \quad (5)$$

where Supply $_{VC}$ represents the production volume of the value chain, Supply $_{Country}$ is the production volume at a country level, and the aSOS $_{VC}$ is the aSOS at a value chain level.

Required data for the calculation of safe operating space was obtained from Eurostat [53]; corresponding data sources and calculations are presented in SM2.

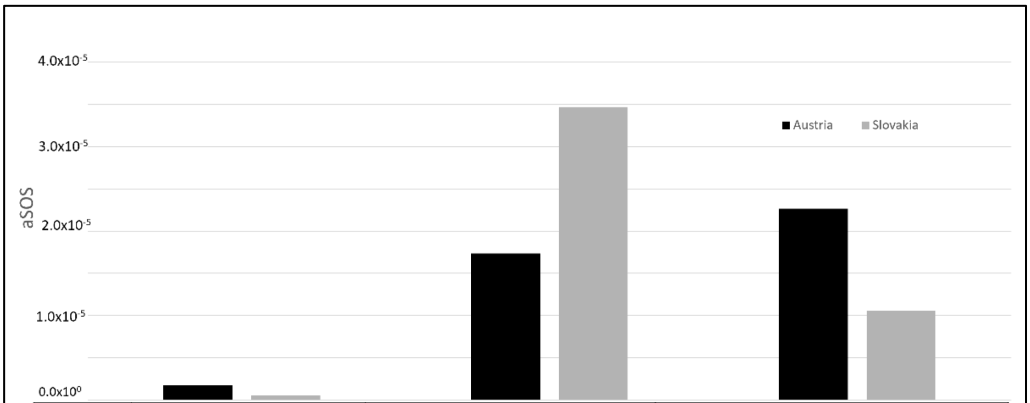
3. Results

The relative environmental impact results for Austria and Slovakia using the PB-LCA framework are presented in Table 2. As mentioned in the previous section, it is assumed that wood-based panels value chains are identical in Austria and Slovakia.

Table 2. Overview of relative environmental impacts for the wood-based panel value chains.

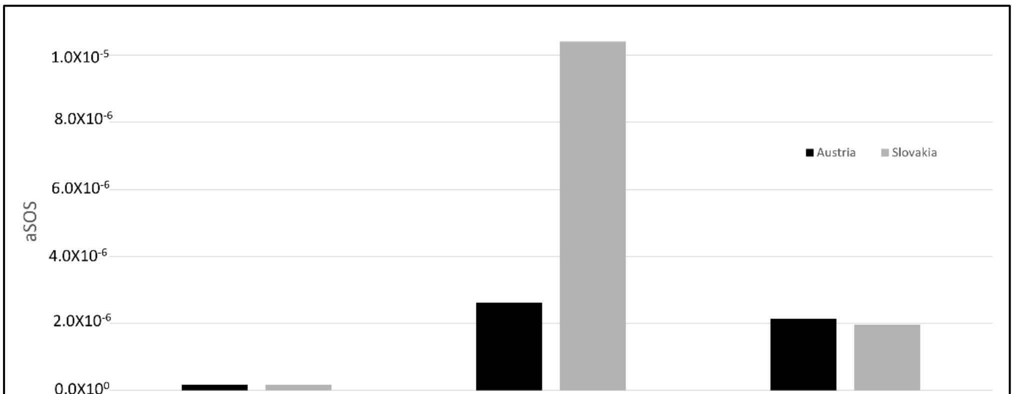
Impact Category	Value	Unit
Climate change-Energy imbalance (CC-EI)	1.55×10^{-5}	Wm^{-2}
Climate change-CO_2 concentration (CC-CO_2)	0.00116	Ppm CO_2
Ocean acidification (OA)	3.51×10^{-6}	Omega Aragonite
Stratospheric ozone depletion (SOD)	5.05×10^{-8}	DU
Atmospheric aerosol loading (AAL)	2.52×10^{-8}	Dimensionless
Biogeochemical flows-Global N (BNg)	3.03×10^{-5}	Tg Nyr^{-1}
Biogeochemical flows-Global P (BPr)	4.06×10^{-10}	Tg Pyr^{-1}
Land-system change: Temperate (LCt)	2.36×10^{-8}	$\%m^{-2}$

The results of using the selected downscaling methods for Austria and Slovakia at industry and value chain levels are shown in Figures 2 and 3. All values are calculated for the reference year 2016 and represent the aSOS as a dimensionless quantity. The first downscaling step was at a national level using the per capita approach. The results show a difference of approximately 47% between both countries, with a bigger proportion given to Austria (8.7 million) as it is the country with the largest population compared to Slovakia (5.4 million). When calculating the aSOS for the wood panel industry using the GVA, FCE, and GF approach, the results vary significantly between countries and methods (Figure 2). The highest of calculated aSOS (3.47×10^{-5}) is assigned by the FCE method to Slovakia. The second highest aSOS result is presented by GF method, for Austria 2.27×10^{-5} and Slovakia 1.6×10^{-5}. The lowest values of aSOS are obtained when using the GVA-based method. These results can be explained by the greater influence of FCE wood panel industry on the total FCE in Slovakia, when compared to Austria. As for the GF approach, the highest aSOS is given to Austria, which evidences higher influence in terms of GHG emissions that the wood panel industry has in Austria compared to Slovakia. Similarly, the GVA method results in a greater aSOS for Austria than for Slovakia.



	GVA	FCE	GF
Austria	1.71 X 10-06	1.73 X 10-05	2.27 X 10-05
Slovakia	5.51 X 10-07	3.47 X 10-05	1.06 X 10-05

Figure 2. aSOS at an industry level using three different downscaling methods.



	GVA	FCE	GF
Austria	1.06 X 10-07	2.62 X 10-06	2.13 X 10-06
Slovakia	1.65 X 10-07	1.04 X 10-05	1.97 X 10-06

Figure 3. aSOS at a value chain level using three different downscaling methods.

At a value chain level (Figure 3), a similar trend in terms of aSOS differences is seen between the downscaling methods. However, for the GF method the difference between the countries is significantly reduced. These results show how the value chain production volumes have a higher influence for Slovakia (3.00×10^{-1}) than for Austria (9.41×10^{-2}). For the FCE at value chain level, the largest aSOS is for Slovakia (2.62×10^{-6}). Similarly, for the GVA at value chain level the highest aSOS is given to Slovakia.

Next, the environmental impact outcomes were assessed against the downscaled PB by estimating the ESR (Equation (1)) for each impact category. Figure 4 presents the results of the ESR calculation (SM2) for the Austrian and Slovakian case study at a value chain level. Moreover, three downscaling methods, such as GVA, FCE, and GF are compared for each case. The results that are above a ESR of 1 are those that overpass the aSOS, thus being considered not environmentally sustainable.

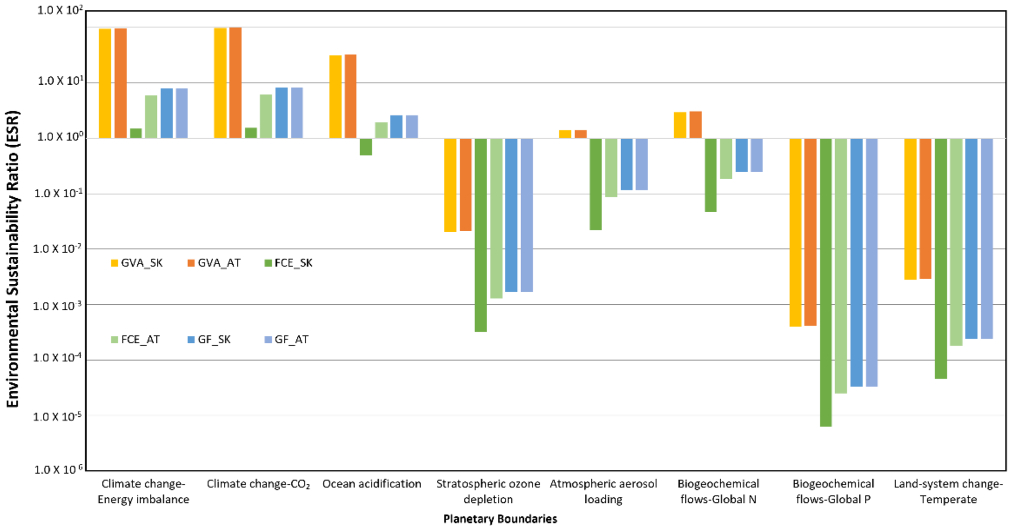


Figure 4. Environmental performance of value chain for Austrian and Slovakian-based value chain in relation the PB.

For the Austrian and Slovakian cases, the impact categories CC-EI and CC-CO_2 resulted in an ESR > 1 for all the sharing principles. As for the OA category, the GVA and GF approach for both countries resulted in ESR > 1. Whereas for the FCE principle, the FCE for Slovakia (FCE_SK) resulted in an ESR < 1, differently than for FCE for Austria (FCE_AT) with an ESR > 1. For SOD category, all the methods produced an ESR < 1. The ESR for BPr and LCt resulted for both countries and all sharing principles in values lower than 1. AAL and BPn for the GVA approach resulted in an ESR for Slovakia (GVA_SK) and Austria (GVA_AT) higher than 1. Contrarily, for both countries the FCE and GVA principles generated an ESR below 1 for AAL.

For both cases the impact categories that severely transgressed the ESR were those of CC-EI and CC-CO_2. To identify the processes that contribute the most to these impact categories, Figure 5 presents a summary of the LCA results for those processes that provide more than 5% to the CC-EI and CC-CO_2 categories. For both indicators the highest impacts are due to the drying process, the resin and MDI production, and the electricity consumed during the board manufacturing. Following are the pine wood transportation and poplar wood from SRC production.

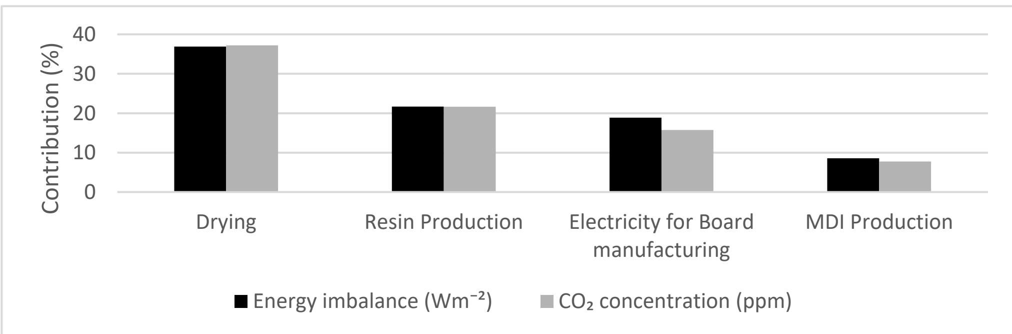


Figure 5. Main environmental hotspots contributing to the CC-EI, and CC-CO_2 impact category.

4. Discussion

By implementing the PB-LCA methodology, it was possible to express the results of the attributional LCA study against downscaled PB according to different sharing principles, resulting in understanding the potential AES of the assessed wood panel value chain. Hence, dealing with the challenge of translating global-based PB to relevant sub-scales [8,9]. In addition to the conventional LCA approach, aiming to identify where reduction of potential environmental impacts is most efficient, the PB-LCA method allows understanding where reduction of environmental impacts is most necessary. By relating the environmental impacts to a downscaled aSOS, further information on which activities exceed sustainability targets can be generated, thus supporting decision-making on value chain level. For instance, through the case study we revealed that the environmental impacts related to CC-EI and CC-CO_2 are above their aSOS—otherwise unnoticed with the conventional LCA approach. Identifying the activities which contribute the most to the CC-EI and CC-CO_2 categories (Figure 5) aids decision-making in LCA studies by providing knowledge on where it is essential to prioritize the implementation of environmental strategies. For our case study, substituting phenolic resin and MDI to biobased alternatives for resin production (e.g., lignin-based resins) can be a crucial environmental lever to help wood panel value chains reach environmental sustainability targets [54–56]. Rather than only assessing the relative impact compared to another product or system, the PB-LCA helps to contextualize the LCA results of a value chain against national and global terms. An advantage of such interpretation is that value chain decision-makers can realize what activities should be improved to obtain a meaningful contribution to reach, for instance, national-level sustainability targets.

Downscaling of PB is a crucial step to make PB applicable not only on global scale. Building on findings of previous studies as mentioned introductory, the results of our case study showed how the PB-LCA methodology is biased toward the selected downscaling principles. The FCE and GVA methods proposes an economic-based approach, in which a higher aSOS is given to the system that supports the higher economic value to the country. The results show that the GVA method favors the Austrian wood panel industry by assigning a greater SOS. Contrarily, the also economical-based FCE method results in a higher aSOS for Slovakia since the contribution of the wood panel industry to the total Slovakian FCE is greater than that of the Austrian case. These results reflect how using GVA and FCE-based partitioning principle will inherently connect economic benefits with pollution allowance (i.e., aSOS). For instance, considering the GVA approach, the Slovakian wood panel industry would have to increase their national contribution by almost two times to raise their aSOS to equal the Austrian wood panel industry aSOS. The Austrian wood panel industry is favored for the GF method, which rewards the more contributing emitters with higher aSOS. To further downscale the aSOS to a value chain level, the ratio between the value chain production volume and the total countries' production was used. The results present that both the FCE and GVA approaches will favor Slovakia's value chain as the ratio between value chain and national production volumes is higher than that for Austria. Applying such production volume-based downscaling approach to calculate the value chain aSOS implies that pollution allowance is connected to production volumes. Hence, implying that value chains which produce higher quantities would benefit the most. On the other hand, using the GF approach favors Austria for both industry and value chain level. Particularly, higher differences are presented at an industry level (approximately 72%) (Figures 2 and 3).

At a value chain level for both countries, the results of the ESR calculation show a similar trend for almost all sharing principles. When applying the GVA method, all the impact categories lead to a higher ESR compared to the other downscaling methods, which are explained by the lower aSOS for the GVA method. As for the FCE method, a much lower ESR is obtained for both cases. This difference is justified by a higher aSOS given through the FCE method (Figure 4). Thus, for the present case studies, implementing a FCE approach allows the value chains to be further away from transgressing the aSOS (ESR > 1) than when applying the GVA method. The implications of these results are shown by the ESR results for the AAL and BPn categories, which for the GVA method is transgressed, whereas for the FCE and GF is not. Hence, suggesting that the AAL and BPn categories are AES for the FCE and GF approaches only. For the OA impact category results generated by the FCE approach show that Austria transgresses the aSOS, whereas Slovakia does not. This difference can be attributed to a lower aSOS for the

Austrian case. Comparing these results demonstrates how opposite conclusions on the potential AES of an impact category between and within the same sharing principle are obtained. Thus, meaning that different environmental strategies would be implemented depending on the downscaling method used. For instance, the GVA method suggests emphasizing environmental strategies on different impact categories than the FCE and GF method. The economic performance at national, industry, and value chains play a substantial role in the GVA and FCE methods. For the GVA method, it is assumed that as the economic contribution of the value chain to the national economy increases, a higher aSOS is given. Similarly, the FCE methods favor those value chain products that are largely consumed in a nation, implying that value chains that have a better economic performance in relationship to the national performance would be assigned higher SOS, within and between countries. An objection to only using economic-based downscaling approach is that it would give higher pollution allowances to industries and value chains with greater economic performance, thus hindering the development of value chains with lower economic profits (e.g., establishing value chains). Similarly, as discussed by [57], these economic-based downscaling approaches express the "ability to pay", or the economical affluences which a nation, value chain, and individuals may have. Therefore, their use could hamper the development of less wealthy societies. Moreover, the different results between GVA and FCE method at an industry and value chain level raises questions on which economic indicator should be used for the PB downscaling. The GVA represents the value of the goods produced by the value chain, however, it excludes the degree of societal demands. On the other hand, the FCE includes the societal demands by representing a measurement of a nation's expenditure on a particular product or service. Agreeing with Hjalsted et al. [57], the FCE approach could give unproportioned value to non-essential products, which can result in contradictory strategies, as given preference over essential needs. Moreover, both methods exclude the degree of national income and the current world's development inequality. As for the GF approach, favoring the value chains, industries, nations with higher emissions gives greater developing allowance to systems with higher contribution of emissions. Thus, less incentive is given to improve environmental efficiency [58]. Moreover, all studied methods fail to include population well-being, which can be an essential proxy to help reward value chains that provide higher levels of well-being and simultaneously lay within PB [59]. One step to achieve a more inclusive distribution method is to involve how value chains services aid other societal needs—hence, attempting to grasp other societal challenges. Similar findings were highlighted by Ryberg et al. [25], who stressed the need for going beyond only using economical added utility of a product to people (e.g., GVA and FCE) as a downscaling indicator. A further research question on the impact of sharing principles is related to the effect of different national aSOS on the global strategies that companies could execute. A step further in developing sharing principles is to involve the opinion of relevant stakeholders (e.g., industry and society) as this can help add knowledge on current and new possibly downscaling approaches.

As for the limitations of the present study, assumptions on market data were necessary as detailed market data on the different wood panels available in each country were not available. As presented in the prior discussion, market data directly impact the results of the partitioning principles, hence the relevance of obtaining more detailed data. Further research that integrates different LCA on wood panels, and gathers concise market data (e.g., FCE for oriented strand boards) can address this limitation. Concerning the application of the PB-LCA framework, a limitation is related to land-system change category where it was assumed that the only land transformation occurred was to temperate forest. Such assumption hinders the estimation of the environmental impacts on other land systems. This limitation could be addressed by, for instance, including regional aSOS related to the land system category [60].

5. Conclusions

This study contributes to the state-of-the-art of the PB-LCA framework by adding to the effort of making the PB-LCA framework relevant for strategic decision-making at a value chain level as it helps to understand the implication of applying currently used downscaling methods to two countries. The study outcomes highlight the importance of comparing different sharing principles to understand the overall performance of a value chain. With our case study design, we carved out the effects of the different partitioning principles by contextualizing one value chain in two different economies. Switching between economic and emission-based downscaling will inevitably lead to different policy designs among and within nations. For the GVA and FCE-based methods, particularly affected are countries where the low economic contribution of existing value chains results in smaller aSOS. Such effect raise concerns on how such sharing principles could lead to strategies that perpetuate inequalities, as more prosperous value chains (or economies) would be assigned a greater SOS, which can be also seen as a larger development allowance. Thus, while approaches and recommendations for downscaling exist and are applicable, there is still a need for further research into improvement of the approaches to resolve issues about just assignment of SOS and moving toward consensus approaches to avoid results being shaped by value-based choices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13030461/s1. The supplementary material details the data and calculations used in this study. SM1 summarizes most of the data used for the LCA and PB-LCA calculations. SM2 presents a summary of the PB downscaling as well as the results from the PB-LCA. References [48,61] were cited in supplementary materials.

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