From 180 to 360: Ex-Ante Life Cycle Assessment of Circular Snowboard Lifecycles

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From 180 to 360: Ex-Ante Life Cycle Assessment of Circular Snowboard Lifecycles

By

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Executive Summary

Human consumption has driven the earth into an unprecedented environmental crisis, and with the growth of the global middle class, this crisis is expected to worsen. A Circular Economy (CE), a system "restorative by nature" (Ellen MacArthur Foundation, 2013, p. 14), is proposed as a way to mitigate this crisis. However, implementation of circularity principles is challenging for many products, including composites. A snowboard is a typical sports composite; since this sector is severely dependent on the state of the environment, the intention to become more sustainable is increasingly expressed. However, information on the environmental impact of potential circularity interventions is lacking. Life Cycle Assessment (LCA) is the most used and standardized method to evaluate the environmental impact of a product or function over its lifetime. Although LCA's on circular interventions for composites have been performed, studies evaluating circularity measures in the entire lifecycle of the composite are lacking. This study aims to address these knowledge gaps by identifying circular snowboard lifecycle scenarios for 2025 and evaluating these with ex-ante LCA to answer the following research question: "*In what ways could the principles of the circular economy be incorporated into the snowboard lifecycle by design year 2025, and how would this affect the environmental impact?*".

This question was answered with a mixed methods approach. A mixed methods review was first conducted to establish the scenarios evaluated in the LCA. The function of a snowboard was first established for different user archetypes, based on a questionnaire conducted with wintersports participants; afterwards, the main materials used in snowboards were established and the snowboard lifecycle was described based on a sample of 40 brands. The key developments identified in these results were synthesized into scenarios to be evaluated with ex-ante LCA.

Three wintersports archetypes were established: Tourist, Wintersports Enthusiast, and Snowsports Professional. All three archetypes participated in all-mountain snowboarding, although freestyle and off-piste participation was higher for Wintersports Enthusiasts and Professionals. Moreover, the function of the equipment differed amongst the groups; where the Tourist had one do-it-all piece of equipment, the other groups had a "quiver" of specialized equipment for specific conditions and uses. The technical snowboard lifetime was established at around 30 weeks.

A snowboard consists of multiple components that are all made of different materials. Key developments towards more circular materials involved the use of biobased or lower-impact abiotic materials, and removal of toxic substances.

Snowboard supply chains are often intercontinental, with production on one continent and sales all around the world. Materials are produced by a few main suppliers. Snowboards are usually produced by placing a "sandwich" of different material layers and epoxy into a heated press for the epoxy curing time. The snowboard is usually shipped to a distributor by boat or plane. During use, the snowboard is serviced with hot-wax about once a use-week; at the end of life, snowboards discarded with municipal waste are incinerated or landfilled, but indefinite storage and reuse for other purposes are also common options.

Based on these results, six scenarios were devised: Business as Usual (BAU) for 2020, the expected BAU for 2025, and a scenario taking into account the proportion of the current different End-of-Life (EOL) treatment options. Additionally, three circular scenarios were identified (all in 2025): use for the technical lifetime, a focus on biobased materials, and a focus on recycling and recyclability. The goal of the LCA was to compare the circular alternatives with BAU to show the implications of certain circularity decisions on the environmental impact.

The foreground systems were constructed with data from expert consultation and literature sources; for the background system, Ecoinvent 3.6 was used. The scope was limited to any activity that was directly related to or caused by the lifecycle of a snowboard. For characterization, the ILCD 2018 midpoint characterization family was used. Categories evaluated were Climate Change (Biogenic, fossil, Land Use and Land Use Change, and Total), Freshwater and Terrestrial Eutrophication, Freshwater Ecotoxicity, Freshwater Eutrophication, Marine Eutrophication, Terrestrial Eutrophication, Dissipated Water, Land Use, Resource Use, Minerals and Metals, and Resource Use, Energy Carriers.

In the characterization results, it was observed that the expected changes in electricity mix between 2020 and 2025 led to some changes in impact category results (up to 10%). Overall, the technical lifetime-alternative performed best, with an impact reduction of 47-50% compared to 2025 BAU across all categories. The other circular alternatives performed better in certain impact categories and worse in others.

A lifecycle stage contribution analysis was performed. For the BAU alternatives, the largest contributors across all impact categories are material supply and production. The impacts of the other stages (distribution, sales, use, EOL) are limited. The largest contributors to material supply are the PA11-topsheet and the epoxy; for production, this is electricity production. Of the circular alternatives, the technical-lifetime alternative shows a similar picture to the BAU-alternatives, with the same large contributors. For the biobased alternative (A3), the fish glue and the hemp fibers constitute important contributors to the environmental impact. Finally, the recycling-processes in the recycling-focused alternative have considerably higher contributions than the (EOL) waste treatment processes of the other alternatives; it is concluded that, although the recycling of the separated materials leads to avoided burdens, the solvolysis-process as currently modelled has such a large impact that it seems unattractive from an environmental perspective.

Four sensitivity analyses were performed. In a comparison of the current ILCD-results with the ReCiPe Midpoint results, the Marine Eutrophication, Minerals and Metals, and Freshwater Ecotoxicity-categories were found sensitive to the characterization family used; the other results remained relatively consistent. Replacing sea shipping with air shipping leads to significant increases in 5 impact categories (>+5%), with the largest increase for the biobased alternative in Climate Change Total (+74%). Thirdly, the difference between production electricity from the electricity mix and a photovoltaic rooftop installation was evaluated. It was concluded that the production electricity was a crucial determinant of the performance of the recycling-alternative; if this alternative was modelled with the electricity mix, all benefits compared to BAU diminished. Finally, the sensitivity to the substitution multifunctionality treatment was evaluated by comparing it with the Ecoinvent Cut-Off System Model multifunctionality treatment. For most processes and alternatives, the effect of the multifunctionality treatment was limited; however, the results of the reuse of the EOL snowboard for another purpose assumed in the biobased-alternative were severely affected, especially in the Land Use-category.

In the discussion, it was established that the current research was surrounded with large uncertainties due to the use of proxies and the evaluation of emerging technologies. For the BAU alternatives, the effect of this uncertainty on the results should be limited; however, especially the recycling-focused alternative suffers from many assumptions, unproven concepts, and uncertainty about future developments. Moreover, the use of historical (and therefore outdated) data makes the results less representative of 2025. This study's results should therefore be seen as an indication of potential environmental impacts in 2025, that could be used to make sure that the processes realized in 2025 perform better than in this study.

It is concluded that the optimal circularity solution for the snowboard industry requires some more mountains to climb, but that there are promising developments currently going on. Two sure-fix measures to decrease the snowboard lifecycle environmental impact in most categories were identified: sea shipping instead of air shipping, and the use of renewable production electricity. We therefore recommend that industry actors focus on these measures as first steps, before implementing more difficult measures that might be less effective.

Contents

1. Introduction

1.1 Research Background

The linear economy of “take-make-use-dispose” has pushed the earth into an environmental crisis with unsustainable resource consumption, pollution, greenhouse gas emissions, and other unsustainable pressures on the earth’s system (Ellen MacArthur Foundation, 2013). These pressures will only increase as the global middle class grows with an expected three billion people by 2030; to preserve the earth for the future, human impacts need to be brought back to levels within the carrying capacity in the coming decades.

The Circular Economy (CE) is proposed as a strategy to do so. The system of a circular economy is “restorative in intention and design” (Ellen MacArthur Foundation, 2013, p. 14). This means that all activities should be intended to restore ecosystem services and the carrying capacity of the earth rather than eradicate it, for example by minimizing waste, maximizing use of renewable energy and eliminating toxic chemicals. The circular economy aims to close material flow loops, keeping non-biodegradable “technical” nutrients in the economy, while “biological” nutrients are used as effectively as possible and eventually returned to the biosphere (Ellen MacArthur foundation, 2013). This way, economic well-being could in theory be “decoupled” from resource use and other environmental impacts, and the human pressure on the earth’s system could be reduced to a sustainable level.

The philosophy of the circular economy is closely related to that of Industrial Ecology (IE) (Saveedra et al., 2017), which is a field studying material and energy flows with the aim of establishing sustainable production and consumption (Lifset & Graedel, 2015). Since measuring flows and environmental impacts is central to Industrial Ecology, and the circular economy requires measurement of these things (Ellen MacArthur Foundation, 2013; Corona et al., 2019), the research methods developed by IE are vital for an effective transition into a circular economy (Lifset & Graedel, 2015; Saveedra et al., 2017). Life Cycle Assessment (LCA) is one of the core research methods in the IE-field; with this method, the environmental impact of alternatives performing a certain function can be compared over the entire lifecycle (Hellweg & I Canals, 2014). To ensure the sustainability of any circularity efforts, their environmental impact should be evaluated with LCA (Brunklaus & Riise, 2018). Only this way, the CE can contribute to mitigation of the current environmental crisis.

1.2 Problem Statement

The importance of transforming towards a circular economy has been established. At the same time, circularity is hard to achieve for many products. This also holds for composites, consisting of a material “matrix” (often a polymer) reinforced with stronger materials such as carbon or glass fibers (Naqvi et al., 2018). This combination of materials leads to remarkable mechanical properties such as a high strength to weight ratio (Joustra, Flipsen, & Balkenende, 2021). For this reason, composites enable superior performance for various applications, including sports. The volume of fiber-reinforced composites produced is growing rapidly (Meng et al., 2018).

A snowboard is a typical example of such a sports composite application. The sport is heavily dependent on the state of the environment, and the community is showing increasing concern for this matter, which can be seen in the efforts of snowboard brands to adopt more sustainable practices and the involvement in non-for-profit Protect Our Winters (POW) (e.g. Burton, n.d.; Salomon, n.d.; Protect our Winters Canada, n.d.).

However, composites have a few inherent challenges for circular economy implementation. The materials cannot properly be separated, which limits reparability and limits current end-of-life (EOL) treatment practices to incineration or landfilling, wasting an energy-intensive and valuable product (Le Duigou et al., 2011; Douk Snowboards, pers. comm., 2020; Meng et al., 2018). Even if composite materials can be separated, they need to be downcycled into lower-value applications because the quality of the materials decreases during the recycling process (e.g. shortened fibers) or use (e.g. UV-affected plastics).

In the snowboard industry, initiatives towards more circularity are undertaken; factories are installing rooftop PV installations (e.g. SWS, n.d.) or heat pump systems (Capita, n.d.), or using recycled or more biobased materials (e.g. Amplid, n.d.; Arbor, n.d.), and initiatives for reuse at the end of life are becoming more common (e.g. NoK, n.d.). Finally, initiatives towards the recycling of manufacturing waste are also observed (Niche snowboards, n.d.).

However, information on the environmental impact of the snowboard lifecycle and these potential measures is scarce. An eco-efficiency analysis by Walsh and Singh (2009) confirms this, finding that eco-efficiency awareness and marketing in the industry are high, but accounting systems for environmental impacts are lacking. They conclude that the snowboard industry needs standardized measurements and goals for environmental impact mitigation. In an LCA on skis, Luthe, Kägi, and Reger (2013) find that 42% of greenhouse gas emissions result can be attributed to the production phase; another 44% can be attributed to the material supply chain. By swapping out the traditional materials of skis for renewable or greener alternatives they achieve an emission reduction of 27.5% (from 22.6 kg CO_2eq per ski to 16.4 kg CO_2-eq). Apart from these two studies, a large knowledge gap exists. The full lifecycle of a snowboard, including the use-phase, has not yet been assessed, as well as the environmental impact in categories other than global warming. Moreover, the only circularity measure evaluated by Luthe, Kägi, and Reger (2013) is the use of a specific set of alternative materials, leaving the environmental impacts of other interventions, for example the use of alternative production electricity or waste treatment unassessed. Due to this knowledge gap, it is currently not possible to make evidence-based decisions on circularity measures, and thereby ensure effective CE implementation.

The current emergence of circularity initiatives combined with the lack of environmental impact information makes this sector a relevant case study for an Industrial Ecology master's thesis. By evaluating scenarios based on current developments with LCA, snowboard industry actors could receive environmental impact information, enabling them to make evidence-based circularity decisions. This information would also be relevant to the broader composites industry, often using similar materials and production practices. This research could therefore contribute to effective circular economy implementation in the lifecycle of snowboards and other composites and help reduce the environmental impacts of this fast-growing industry.

1.3 Thesis Structure

This thesis is divided into four sections. In *Part I*, a literature review of the context of the research is presented, the research gap is identified, and the research approach and methods are explained. In *Part II*, the foundation for the LCA-study is laid by identifying the function of a snowboard, the most common materials, and the lifecycle structure. This part is concluded with the development of scenarios. In *Part III*, the LCA study is conducted; finally, in *Part IV*, the research is critically discussed and a conclusion is presented.

Part I: Background & Approach

2. Literature Review

In this chapter, a literature review on the theoretical context of this thesis is presented. In the first section, circular economy developments for composites are discussed; afterwards, ex-ante LCA challenges and practices are identified. The chapter is concluded with the identification of the research gap.

2.1 Composites and the Circular Economy

In this section, the implementation of circularity in the field of composites is explored. As explained in 1.2, this is challenging due to the "composite" nature of the products. However, currently, developments to tackle these challenges are taking place throughout the composite lifecycle. In order to address this topic, a short description of a snowboard is first given; afterwards, developments towards more circular composites are described.

A snowboard is a sandwich composite, with a core material and reinforcement fibers glued together into a light but strong construction (Rizov, Shipsha, & Zenkert, 2005). This way, the snowboard consists of around 9 parts, all made of one or more materials such as fiberglass, plastics, and wood, that are united with epoxy resin (Mechanics of Sport, n.d.).

In terms of composite circularity developments, firstly, on the supply chain-side, alternatives to the traditional carbon or glass fiber reinforcements and plastic matrix are often considered. For the reinforcement fibers, biobased fibers such as flax (Le Duigou et al., 2011; Mohareb et al., 2015), hemp, or other plant-based fibers (Oliver-Ortega et al., 2019; Heitzmann et al., 2012) are mentioned, for example because they are renewable and require less processing energy (Le Duigou et al., 2011). The use of basalt fibers is also considered (Torres et al., 2013). Bio-based epoxies and plastics are often mentioned as alternatives to traditional petroleum-based plastics (Torres et al., 2013; La Rosa et al., 2017; Oliver-Ortega et al., 2019; Lacarin et al., 2012; Le Duigou et al., 2011). Finally, epoxy hardeners that facilitate recycling at the end of life are also receiving increasing attention (Post et al., 2020).

Circularity in the use-phase can be established with product service systems (PSS) like lease/rental constructions (Scheepens, Vogtländer, & Brezet, 2016); implementation of these business models depends on the composite application. In the case of snowboards, renting wintersports equipment is relatively common. Since composites usually cannot be taken apart, repairability during use is limited; self-healing polymers could be a solution for certain composites, but fiber repair is impossible for most reinforcement fibers (Tan et al., 2019). In snowboards, only the HDPE base can be repaired by dripping melted HDPE into scratches or holes.

Since the value of composites is in the combination of materials and the structure, the highest-value end-of-life option would be reuse for another purpose (Joustra, Flipsen, & Balkenende, 2021). Currently, the EOL treatment for glass-fiber reinforced composites (GFRP) recommended by the EU is processing in a cement kiln, where the mineral fibers are a feedstock for the cement and the matrix functions as a fuel (Composites UK, n.d.). Because the materials used in GFRP are low-cost, but separating the materials is complex, recycling is currently not economically feasible and therefore not employed on a large scale (Joustra, pers. comm., 2020). However, two recycling methods hold potential for the future: pyrolysis (thermal recycling) and solvolysis (chemical recycling). With pyrolysis, the composite matrix is degraded with high temperatures and the glass fibers are recovered, albeit in a damaged state (Koelega, 2019; Joustra, pers comm., 2020). In solvolysis, the matrix is dissolved by a solvent, allowing the materials to be separated (Yang et al., 2012). However, this process requires toxic chemicals, and the glass fiber quality is likely affected as well as the dissolved matrix and potentially other plastics used in the composite. Thus, both of these recycling processes likely yield products that need to be downcycled compared to their original functions. Therefore, the EOL treatment should be taken into account during product design, so that it results in valuable materials or feedstocks for other products (Joustra, Flipsen, & Balkenende, 2021).

Clearly, implementation of circularity for composites is complex, and it is not straightforward what the environmental impacts of different measures will be. Evaluation with Life Cycle Assessment beforehand is therefore essential to ensure CE implementation that actually mitigates the environmental crisis (Haupt & Zschokke, 2017; Manninen et al., 2018; Corona et al., 2019). This perspective is gaining attention, with various LCA studies evaluating circular alternatives for conventional product systems such as food processing (e.g. Colley et al., 2020), road beds (Deschamps et al., 2018), and reusable pallets (Biganzoli et al., 2018). However, to date, few of these studies have been conducted in the field of composites (La Rosa et al., 2014). Existing studies in the composites sector often compare the status quo with alternative materials (e.g. Hoto et al., 2014; Oliver-Ortega et al., 2019; Lacarin et al., 2012; Heitzmann et al., 2012; Le Duigou et al., 2011; Mohareb et al., 2015). Other studies focus on recycling (e.g. La Rosa et al., 2016); however, none of the studies found evaluate the impact of implementation of circular economy principles on the entire lifecycle.

2.2. Ex-Ante Life Cycle Assessment

In this section, the context of the ex-ante LCA method is described. Life Cycle Assessment (LCA) is the most used and only standardized environmental impact assessment method that covers the entire lifecycle of a product or service (or "function") in multiple impact categories (Hellweg & i Canals, 2014). The method consists of four phases: the goal and scope definition, inventory analysis, impact assessment, and interpretation (Guinée et al., 2002). LCA's can either be attributional or consequential: attributional LCA's "attribute" environmental impacts to a certain alternative and show what proportion of global impacts this alternative causes; consequential LCAs show the environmental impacts that arise from certain decisions, taking into account the entire system affected by a system and hereby broader consequences such as changes in demand (Guinée et al., 2018; Thomassen et al., 2019; UNEP, 2011).

Usually, due to large data requirements, LCA studies are conducted "ex-post" on existing, well-documented systems (Cucurachi, Van der Giesen, & Guinée, 2018). However, changing existing systems is costly and complicated due to lock-in mechanisms, whereas adaptation in an early phase of technology development is relatively easy and can save costs on an economic, social, or environmental level (Arvidsson et al., 2017). This is called the Collingridge dilemma: technology assessment is easy when technologies are mature, but costs of adaptations are high, whereas assessment of early-stage technologies is tough but adaptations are easy (Kudina & Verbeek, 2019). To prevent societal costs, LCA studies should also be conducted before technologies are mature. In such a "prospective" LCA-study, the future environmental impacts of a life cycle are assessed based on scenarios in which different decision alternatives are modelled (Meylan et al., 2018). A prospective LCA is called ex-ante when the technology studied is still in an experimental or pilot phase and future implementation on a larger scale is researched (Cucurachi, Van der Giesen, & Guinée, 2018; Van der Giesen et al., 2020).

The prospective character of such LCA studies leads to additional challenges compared to ex-post LCA studies. Information about the systems studied is often lacking, data is on a lab-scale instead of commercial scale, and the future is hard to predict (Van der Giesen et al., 2020). Moreover, temporal inconsistency of the foreground and background system usually exists, as the background data is usually based on historical databases such as Ecoinvent. Due to the evaluation of lab- or pilot-scale technologies, and modelling in the future, the use of scenarios is essential. These scenarios might rely on learning curves to estimate future environmental impacts and productivity (Arvidsson et al., 2017; Guinée et al., 2018), technological models for manufacturing readiness and technological diffusion (Arvidsson et al., 2017), or other forecasting methods (Hummen & Kästner, 2014). Extensive modelling and complex scenarios could lead to transparency issues, which could affect the implementation of the results by stakeholders (Meylan et al., 2018). In studies involving recycling, the allocation decisions could have a large impact on the results, for example when studying solutions involving waste products of other industries (Hermansson, Janssen, & Svanström, 2019).

2.3. Research Gap

This research gap covered in this research is twofold. Firstly, as indicated in the problem statement, there is only one LCA-study on wintersports equipment (skis) available, in which a specific set of alternative materials is evaluated; environmental impact information for other circularity measures that are now being implemented, such as alternative production electricity, shipping, or waste treatment methods, is lacking. Moreover, in the study by Luthe, Kägi, and Reger (2013), only Global Warming Potential (GWP) was assessed, leaving impacts in other categories unknown.

Secondly, as indicated in 2.1, LCA-studies on more circular composites currently usually focus on one specific circularity element but do not cover the entire lifecycle of the product, although the focus on the entire lifecycle is important to ensure true circularity over the entire lifecycle.

By identifying key circularity developments in the snowboard value chain, extrapolating these into scenarios for the future and evaluating these scenarios with ex-ante LCA, this research aims to bridge these knowledge gaps and give valuable information to actors in both the snowboard and other sandwich composite industries. As the future point of evaluation, 2025 was chosen as the timespan is relatively short and already relevant today, while at the same time giving space for the implementation of technologies that are currently emerging.

The research gap is addressed with the following research question:

In what ways could the principles of the circular economy be incorporated into the snowboard lifecycle by design year 2025, and how would this affect the environmental impact?

This research question will be answered by answering the following four sub-questions:

1. What characteristics does a snowboard need to possess to fulfill its function and what materials are used or could be used in 2025 to establish these characteristics?
2. What do snowboard lifecycles currently look like, and what developments towards more circularity are observed?
3. What scenarios for a more circular snowboard lifecycle in 2025 could be developed?
4. How do these alternative lifecycle scenarios compare in environmental impact?

3. Research Approach and Methods

3.1. Research Approach

For this research, two different approaches were used. The first three sub-questions were answered by employing a mixed methods review; the fourth sub-question was answered with a prospective LCA-model.

In part II, sub-questions 1-3 were answered in a mixed methods review. With this research technique, multiple research methods are combined into one review (Pearson et al., 2015): in this case, analysis of a user sample, literature research, and expert consultation. The review was an iterative process; the results found with one method were used to validate or supplement the results of another. How the methods were combined into an answer to the research questions is explained here; the methods themselves are explained in more detail in the remainder of the chapter.

To answer the first research question on snowboard function and materials, the function of a snowboard was first established based on snowboarder survey results and expert knowledge. For the materials used, an initial review was conducted on both scientific and non-scientific sources such as academic articles, brand catalogues, websites, and books. Afterwards, the websites of a sample of 40 brands were analyzed and the materials they used were fed into a literature table. This table, together with expert consultation, was used to establish the materials most commonly used in snowboards. Based on the results of this mixed methods review, expectations for developments towards 2025 with regards to material use and snowboard function were formulated.

To answer the second sub-question, a supply chain section was added to the brand literature table. By filling out the most important characteristics of the snowboard lifecycles of the forty brands selected, an overview of general lifecycle characteristics was constructed. This overview was supplemented with information from other sources such as magazine articles and video reports. Finally, the use-phase and the End-of-Life-phase were described based on the results of statistical analysis of the wintersports survey dataset. With this information, an overview of the general lifecycle structures of this industry was constructed, followed by a detailed description of every value creation step. Finally, developments towards more circular lifecycles were identified.

Sub-question three was answered by synthesizing the results obtained from SQ1 and SQ2 into scenarios. This was done by identifying the key developments observed in these results and extrapolating these results into scenarios that could be assessed with LCA.

The fourth sub-question was answered using an ex-ante LCA model. First, a zero-alternative was constructed, representing a currently common snowboard lifecycle based on the results of the preceding research. This alternative was translated into a status-quo model for 2025 by extrapolating the most important technologies to the expectations for this time period. Additionally, ex-ante scenarios based on the developments identified in earlier chapters of the research were assessed.

3.2. Mixed Methods Review

Questionnaire and Statistics

To gain insights from the snowboarder population with regards to the snowboard function (SQ1) and their use and End-of-life treatment decisions (SQ2), a web-based questionnaire was conducted. From this dataset, the aim was to obtain statistics that described the use and EOL-phase of a snowboard. The questionnaire was divided in five parts: Winter Sports Experience, Ski Use & End of Life, Snowboard Use & End of Life, Environmental Attitude, and General Demographics. The full survey and design considerations can be found in Appendix A.

The target group for the survey was anybody over 18 that had skied or snowboarded in the past five years. Even though this thesis is about snowboards, skiers were also included to increase the odds of reaching a sufficient sample size. In the US alone, 20 million people participate in snowsports every year (Hagenstad, Burakowski & Hill, 2018). With the Qualtrics sample size calculator, an ideal sample size of 385 people is established (Qualtrics, n.d.); in the end, 388 valid responses were collected.

The survey was available online for a month (12/07/2020 – 11/08/2020). Two different distribution strategies were used. Firstly, the survey was spread through the researcher personal network, with personal Whatsapp messages and by sharing the survey on social media such as LinkedIn and Facebook. This way, an intended form of snowball sampling was achieved (Sarstedt & Mooi, 2019): people forwarded the survey to friends or family in the target group, and it was shared on Facebook and LinkedIn a few times. Apart from the researcher personal network, the survey was also shared in a Snowsports Instructor Facebook group and on three fora where this was allowed: Snowboarding Forum (US-based), Snowheads (UK-based) and WePowder (NL-based). On the fora, especially Snowheads, the survey received quite a bit of attention and stirred up discussion, which likely has led to more responses.

To turn the survey dataset into results, descriptive statistics were used. These include any statistic describing population- or sample parameters, such as the “mean” or average value of a variable and the standard deviation, which is a standardized measure of the average distance of the sample values from the mean (Sarstedt & Mooi, 2019). First, the general population characteristics were identified and checked for self-selection bias, something unavoidable in web-based surveys (Sarstedt & Mooi, 2019). Since ski- and snowboard-answers were captured in different variables, every respondent was “split” into a ski- and a snowboard case (see figure 3.1). This way, both the ski- and the snowboard-values could be aggregated into one variable for e.g. proficiency or equipment ownership. Respondents participating in both sports are represented twice in these variables, once for each sport.

Afterwards, descriptive statistics were used to describe specific groups identified in the population. The analysis was conducted with the SPSS Statistics 27 software and Microsoft Excel; the specific statistics used are explained in more detail with the results in chapter 4. The survey dataset can be found in Confidential Appendix B.

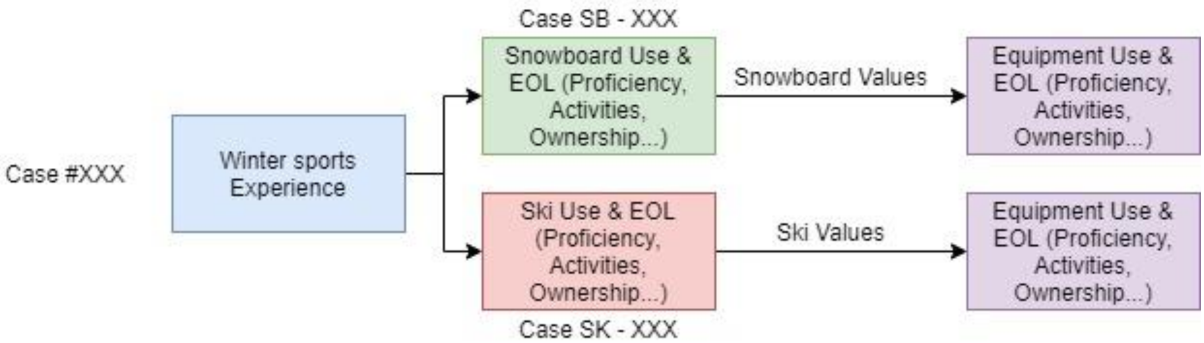


Figure 3.1: Survey snowboard & ski aggregation procedure

Construction of a Brand Sample

Apart from the statistical analysis of use and EOL-practices, industry practices of lifecycles and material use needed to be analyzed in a systematic way. To do so, a sample of brands was constructed. In the initial literature research, it was observed that factories have a very limited online presence or outspoken strategies, whereas brands (or overarching management organizations) report these more clearly. Therefore, the research on life cycle and materials information was focused on brands.

The brand sample was constructed in a number of steps. First, an initial list was constructed based on the personal knowledge of the researcher; next, large webstores such as Blue Tomato and Evo were used to expand the list. All brands that were found this way were based in North America or Europe; in order to increase the geographic coverage, specific searches for Japan (one of the world's biggest snowboarding countries), Oceania and South America were made. However, these searches did not really yield quality results with sufficient material- and lifecycle information. In the end, the sample contained 40 brands with most located in the EU and North America; 1 brand was from Japan.

In an early stage of this research, an interview was conducted with a small manufacturer of snowboards (Douk Snowboards, pers. comm., 2020). During this interview, it became apparent that there is a large difference between smaller, independent brands and larger companies in this market, for example in terms of resources. Therefore, 5 of such brands with small factories were included.

For the analysis, a literature table with all elements to be assessed was created in Excel (see Confidential Appendix F). This table consisted of three categories: a materials section, where used materials were noted per component; a lifecycle section, for notes on lifecycle phases; a sustainability section, where any goals, strategies, or programmes on sustainability were noted. If the information could not be found on the website of the brand itself, a Google search was conducted to obtain information from other sources (e.g. trade magazines); if no info was found, this was indicated in the table. Specifically, the production location was often obtained from sources external from the brand.

After the table had been filled in, the results were quantified by coding the responses and using the "search" function in Excel to identify how many brands used a certain material. This information was then used to quantify e.g. material use or production locations.

Expert Consultation

The results obtained from the brand table were supplemented with the consultation of experts. Over the course of the research, various industry actors or academic experts were consulted via email, skype, or phone (see table 3.1). During the semi-structured interviews, notes were taken; moreover, the interviews with Douk Snowboards, Tobias Luthe, and Behind the Pines were recorded and transcribed. The expert input was used to guide the research direction, validate or supplement literature results and get insights on the developments in their respective fields. For the first three sub-questions, this meant that the knowledge of industry experts was used to validate the results of the literature research. Furthermore, their information was used to establish the sustainability developments in materials and snowboard lifecycle.

Table 3.1: Consulted experts and expertise

Consulted Expert	Expertise
Douk Snowboards (Semi-structured interview)	Small Snowboard Manufacturer
Mark van der Veek (Dry Boards) (Email, semi-structured interview)	Small Snowsurf Manufacturer
Tobias Luthe (Semi-structured interviews)	Owner Grown Skis, Research Scientist in Resilience of Social-Ecological (Mountain) Systems.
Jelle Joustra (Semi-structured interview)	PhD-candidate Circular Design, TU Delft
Behind the Pines (Semi-structured interview)	Snowboard Store (Amsterdam)
Linda Ritzen (Semi-structured interview)	PhD-candidate Industrial Design Engineering, TU Delft
Intersport Kirschner, Snowworld, Sport Klieber (Email)	Ski/snowboard rental companies
Redwood Plastics (Email)	Plastics Distributor
Sander van Dorp (Semi-structured interview)	Experienced Snowboard Teacher

3.3. Ex-Ante LCA

In this section, the ex-ante LCA method of this study is explained. This study differs from the LCA framework specified in the ISO 14040 standard in that it has ex-ante elements. Because of this early assessment of technologies, ex-ante LCAs suffer from additional challenges compared to ex-post studies, such as additional uncertainty, data gaps, and a mismatch between the foreground- and background system (see 2.2). Therefore, additionally to the ISO 14040 standard and the Dutch Handbook for LCA (Guinée et al., 2002), the guidelines proposed by Van der Giesen et al. (2020) will be followed. The procedure is explained below.

The Four Phases of (Prospective) LCA

Goal and Scope

In the goal and scope-phase, the roadmap for the LCA study is drawn by defining the study goal and determining the temporal, geographical, and technological scope as well as the depth the system will be studied in (Guinée et al., 2019). The function, functional unit, and the reference flows of all studied alternatives are also defined in this phase.

The goal and scope of the LCA are based on the results of this study up until this point. For the ex-ante scenarios, the technological scope requires extra considerations, as it needs to be decided what technologies should be extrapolated to the technology levels of 2025, and which ones can be proxied with technology levels available in existing databases. Moreover, to keep the study feasible, it needs to be decided what elements to include, and what items to cut off (Thomassen et al., 2019).

Inventory Analysis

Next, in the inventory analysis, the system to assess for each alternative is modelled by defining system boundaries, drawing flow-charts, and collecting data for each unit process, after which the economic as well as the environmental in- and outflows of these processes are modelled (Guinée et al., 2002). The data for the foreground processes originated from industry or academic experts, website information or catalogues of industry companies, and scientific literature. Snowboard-specific data points were based on expert consultation as much as possible. For the background system, the Ecoinvent 3.6-database was used; if the required process was not available, it was proxied based on academic literature, industry sources, or expert consultation.

The inventory modelling might involve allocation of in- and outflows to several functional flows in case of multifunctional processes. The final result of this step is an inventory table that lists all environmental in- and outflows of the system quantified per functional unit for each reference flow.

To decrease uncertainty, it is attempted to use multiple data points for assumptions, flows, and other model calculations for cross-validation. All calculations and data sources can be found in appendix D.

Impact Assessment

In the Impact Assessment-phase, the environmental impacts associated with the inventory table are "characterized" into distinct environmental impact indicator results based on a selected impact category "family" (Guinée et al., 2002).

Interpretation

Finally, in the interpretation phase, the results and the modelling choices and assumptions are evaluated on validity, consistency, and robustness, and conclusions are drawn. First, a consistency and completeness check are performed. Afterwards, the contribution of relevant elements to the characterization results are explored in more detail. Finally, the robustness of the model to modelling choices and assumptions is evaluated with sensitivity analysis. Due to the higher uncertainty levels of prospective LCA studies, this is an important part of the research.

Part II: Snowboard Materials, Lifecycles, and Future Developments

4. Snowboard Function & Materials

To develop representative scenarios for more circular snowboards, the function of a snowboard and the main materials used need to be understood (SQ1):

> *What characteristics does a snowboard need to possess to fulfill its function and what materials are used or could be used in 2025 to establish these characteristics?*

In this chapter, this question is answered. First, the function of a snowboard is determined for different user groups. Afterwards, the materials used to achieve these functions are discussed. The chapter is concluded with a summary of the main developments in snowboard function and material use.

4.1. Snowboard Function

In this section, the questionnaire dataset is used to establish a profile of different users. First, the sample demographics are discussed to see how representative the sample is of the population; afterwards, user subgroups are described.

In the end, 417 responses were collected. Of these responses, 29 had a completion rate of less than 20%; these were deleted from the sample, leaving a total of 388 responses for analysis. 33% of the respondents indicated to be female, 64% to be male. They originated from 22 countries, mostly from the Netherlands (47%), UK (19%), the US (7%), and Canada (6%). 18 – 30 was the best represented age group with 40% of the sample. The average age was around 38 years.

In terms of snow sports demographics, 74% participates in skiing (n = 287), and 43% in snowboarding (n = 166); 17.5% (68) participates in both. A large number of respondents (40%, 140) was involved in snow sports in a professional context, most of them instructors or coaches (85% of the 40%, 119).

Several indications for self-selection bias of the sample exist. Firstly, recreational users make up 99.5% of the wintersports population in the US (Hagenstad, Burakowski, & Hill, 2018); in this sample, this is about 60%. Secondly, the average recreant in the sample participates in winter sports 2.6 weeks a year, significantly more than the one week a year that is the average for winter sports participants in the Netherlands (CBS, 2016), and this likely also holds for other countries. The sample is therefore probably skewed towards more fanatical participants. Such self-selection bias usually occurs with web-based surveys, since random sampling, where an element of chance is used to obtain the sample, is not possible in a web-based context (Bethlehem, 2009; Sarstedt & Mooi, 2019). However, since the aim of the analysis is to describe different subgroups of the population rather than analyze the entire population, this problem is not expected to affect the results as long as the size of the subgroups is sufficient.

Based on this initial analysis, we can conclude that there are likely two types of recreants in the sample: the tourist, enjoying winter sports for a few weeks a year, and the wintersport enthusiast, with increased participation and fanatism. Next, we have a group of snowsports professionals. The snowboard function for these groups will be analyzed separately in the following paragraphs.

Data Preparation and Interpretation

Before analysis, the data was transformed into a shape that could be analyzed by adapting data formats, converting statements into dummy variables[1], and adding statements for open questions. These alterations are described in Appendix C; all data values can be found in Appendix I (provided separately from this document).

The dataset was first divided in three subgroups: the Tourists, the Wintersports Enthusiasts, and the Snowsports Professionals. The variables used to describe these groups consist of nominal, ordinal, interval, and ratio data.

Nominal data values cannot be ordered on a scale (Sarstedt & Mooi, 2019). Examples of this data type include statement questions such as reasons to buy new equipment, or activities undertaken during wintersports. For these variables, the share of the sample subgroup that has selected a certain answer is reported. The purchasing reasons were aggregated into subcategories (see table C.3).

Ordinal data indicates a value hierarchy, but does not specify the distance between the values (Sarstedt & Mooi, 2019). In this study, skiing and snowboarding proficiency is measured on an ordinal scale. For these variables, the median or middle-value of the subgroup datapoints is reported.

Ordered data with information on the distance between values is called interval or ratio data, where ratio data gives information on an absolute zero point (Sarstedt & Mooi, 2019). Examples of this data type include wintersports frequency or amounts of equipment owned or bought. For these variables, the outliers[2] of each subgroup sample are first identified with the boxplot-function in SPSS. All datapoints that lie further than one interquartile range[3] from the first- or third quartile are excluded from further analysis. Now, the mean and standard deviation are calculated and used to obtain a 95% confidence interval to account for dataset uncertainty. The true mean of the subgroups lies within the lower and higher boundary of this confidence interval with 95% certainty (Sarstedt & Mooi, 2019). The confidence interval statistics were calculated by plugging the variable standard deviation, sample size, and α (1 – 95%) into the CONFIDENCE.NORM formula in Excel (see Microsoft, n.d.). These values were subtracted from and added to the variable mean to obtain the lower- and upper boundaries of the confidence intervals, respectively (see Appendix I).

Snowboard Function for Subgroups

The Tourist

Usually, winter sports tourists in the Netherlands enjoy 1-2 weeks of winter sports per year (CBS, 2016). The Tourist-subgroup was defined as everyone that enjoyed one week of winter sports per year, plus all people that enjoy 2-3 weeks of winter sports with a relaxed attitude. This led to a sample of 170 people, of which 73% skis and 39% snowboards (13% participates in both). The average wintersports participation is 1.25 weeks per year.

Most of these people have a relaxed attitude towards their wintersports experience, preferring to cruise the slopes and enjoy long lunch breaks (68%) or focus on relaxing rather than the wintersports itself (14%). Most of them participate in on-slope skiing or snowboarding (94%) or off-piste (47%); slopestyle tricks (14%), the funpark (7%), ramps/kickers (4%) and backcountry touring

[1] A dummy variable is a binary variable (0 or 1) that indicates whether a certain statement or group is selected (value 1) or not (value 0).

[2] An outlier is a data point that has such a large distance to the other values that it might influence the results substantially (Sarstedt & Mooi, 2019).

[3] The interquartile range (IQR) is the distance between the first quartile (first 25% of the datapoints) and the third quartile (75% of the datapoints) (Sarstedt & Mooi, 2019).

(4%) are less popular. The median participant in this group has an advanced proficiency level and can go down every slope in a controlled manner.

In terms of equipment ownership, 40% rents their equipment and 60% owns it, showing that rental equipment is popular in this group. Almost all people renting their equipment do wintersports 1 week a year (90%), with a 50/50 renting/owning balance for this group; for people participating in wintersports 2-3 weeks per year, the percentage of rented equipment is only 4%, showing that renting is likely only attractive for people participating one week a year.

Equipment owned privately is used for about 1.8 to 2.4 weeks per year for a period of 5 – 7 years, amounting to an average total use-time of 9 – 12 weeks. Most equipment owners have one snowboard/pair of skis (61%); 37% owns more equipment. On average, these equipment owners bought 1 new pair of skis/snowboards in the past five years.

Most people in this group bought new equipment because the old equipment did not fulfill its function anymore (47%), for example because it was running behind in technology (35%) or did not fit their riding style/level (15%). 42% of people reported reasons related to the EOL of previous equipment, such as run-down (26%) or broken equipment (14%), or edges that could not be sharpened anymore (9%). 26% of people bought new equipment because it had something special, such as new technological features (14%) or a cooler/newer look (13%). Finally, 24% of tourists bought additional equipment for a different use and is still using their old equipment.

In conclusion, a snowboard for this group should perform well both on- and next to the slope and should facilitate a little freestyle from time to time, especially because most people only own one piece of equipment (i.e. an “all-mountain” snowboard).

The Winter Sports Enthusiast

The Wintersports Enthusiast is anyone that enjoys 4+ weeks of winter sports per year, or 2+ weeks with a fanatical attitude, and is not involved in snowsports professionally (n = 78). Of this group, 64% (50) participates in skiing, 46% (36) in snowboarding, and 12% (9) in both. On average, this group enjoys 5 - 7 weeks of wintersports per year, with a quite fanatical attitude: most people try to maximize their on-snow time (76%), and a small group spends whole days touring the backcountry (4%). A minority prefers to take it easy, for example by cruising and enjoying long lunch breaks (9%) or focusing on relaxing (4%). The median Wintersports Enthusiast has an expert proficiency level. In terms of activities, off-piste snowboarding/skiing is as popular in this group (83%) as on-piste (82%), and a remarkable 41% reports to go touring in the backcountry. More freestyle oriented activities such as slopestyle tricks (28%), funpark (18%), or jumping ramps (13%) are less popular, but are still undertaken by a considerable share of the group, especially compared to the Tourists.

Virtually everyone in this group owns their own equipment (99%); only 1% rents. Most Enthusiasts own a “quiver” of 3 - 4 pieces of equipment, and have on average bought 2 - 3 pieces of new equipment and 1 piece of secondhand equipment in the past 5 years. This equipment is used between 3.6 to 5.1 weeks per year, for about 4 to 5 years, leading to an average lifetime of 15.3 – 21.4 weeks.

For the Wintersports Enthusiast, additional equipment for a different use is the most important reason to buy new equipment (indicated by 61% of people). 45% of people has bought new equipment due to EOL of their old gear; 43% because the old equipment did not fulfill its function for them anymore, for example because it was running behind in technology (28%) or because it did not fit their riding style/level (17%). 34% reports to have bought new equipment because it had something special, such as new technological features (26%) or looking cooler/newer (11%).

In conclusion, Wintersports Enthusiasts often own a “quiver” with multiple pieces of equipment for different uses or circumstances. This quiver likely consists of a freeride board for off-piste riding, an all-mountain snowboard for on-slope and low-key off-piste riding, and optionally a freestyle-board. They are thus more likely to buy/rent specific snowboards for specific uses.

The Snowsports Professional

In this group, anyone that is involved in snowsports in a professional context without being a professional athlete is included. In the dataset, this groups consists of 140 people, of which 85% (119) works as a snowsports instructor. Other professions include brand sales representative, lift operator, or guide. Of the snowsports professionals, 81% skis, 45% snowboards, and 26% participates in both.

Snowsports Professionals have a mixed wintersports attitude. Firstly, 19% of this group reports spending virtually all of their time on snow teaching others; 53% attempts to maximize their on-snow time, 20% spends their time cruising and enjoying, and 7% prioritizes après-skiing above skiing/snowboarding itself. 1% spends all free time touring the backcountry. In terms of activities, most people ski/snowboard on-slope, but off-piste (79%) and touring (28%) are also popular. Moreover, a high freestyle participation is observed, with 38% doing slopestyle tricks, 25% going into the funpark, and 19% jumping ramps/kickers. The average reported proficiency level is expert.

Snowsports Professionals on average own about 3 pieces of equipment and have bought 2 - 3 pieces of new equipment and 1 piece of secondhand equipment in the last 5 years. On average, their equipment is used between 12.4 to 14.7 weeks per year, for about 3 years, leading to a use-time of about 29 to 36 weeks per set of equipment.

The most important reason to buy new equipment for this group is the EOL of old equipment (70%), because it broke (43%), was run down (47%) or the edges could not be sharpened anymore (19%). 60% has bought additional equipment for a different use; 35% has bought equipment because the old equipment did not fulfill its function anymore, because it was running behind in technology (21%) or didn’t fit the riding style/level (16%). 34% bought equipment because the new equipment had something special: new technological features (22%) or a newer/cooler look (14%). Finally, 7% got free equipment from a sponsorship deal.

The snowsports professional has widely varying demands for their equipment and likely partakes in all these activities on a high level, therefore requiring a good performance of their boards. Like the Wintersports Enthusiast, they therefore own multiple specialized boards for different uses, and an additional older/low key board for teaching (Van Dorp, pers. comm., 2021).

Discussion of these results

A few key points were identified in the wintersports participant “archetypes”.

Firstly, the equipment of every group has a different use-time, increasing with the wintersports involvement. The Tourist uses his equipment for about 9 – 12 weeks, while Snowsports Professional equipment goes up to 29 – 36 weeks. The latter is probably close to the technical lifetime of the equipment, also because the most popular reason to buy new equipment for snowsports professionals is the EOL of their old gear. Since teaching hours are often low-intensity riding (Van Dorp, pers. comm., 2021), the technical lifetime of a snowboard is established at the lower end of the professional confidence interval: 30 weeks.

The amount of equipment owned also increases with involvement; while most Tourists suffice with owning 1 piece of equipment or renting, Wintersports Enthusiasts and Professionals own on average 3-4 pieces.

Finally, for every group, equipment fulfills a slightly different function. While the Tourist has one "do-it-all" (all-mountain) snowboard, the Wintersports Enthusiast and the Professional want specialized snowboards dedicated to specific uses. However, for every group, the all-mountain snowboard is an essential part of the quiver. We therefore focus on the all-mountain snowboard in the remainder of this chapter.

4.2. Snowboard Composition

A snowboard is a sandwich construction of multiple layers that together deliver the desired characteristics (Douk Snowboards, pers. comm., 2020; see figure 4.1). In this section, materials commonly used are discussed, based on the brand sample literature table described in 3.3. The percentages in this chapter represent the number of brands that use these materials rather than the volume of boards they are used in.

Although different types of snowboards might differ in shape or composition, for example in the amount of reinforcement used, the materials used are similar. The all-mountain board described in this section is therefore thought to give a representative overview.

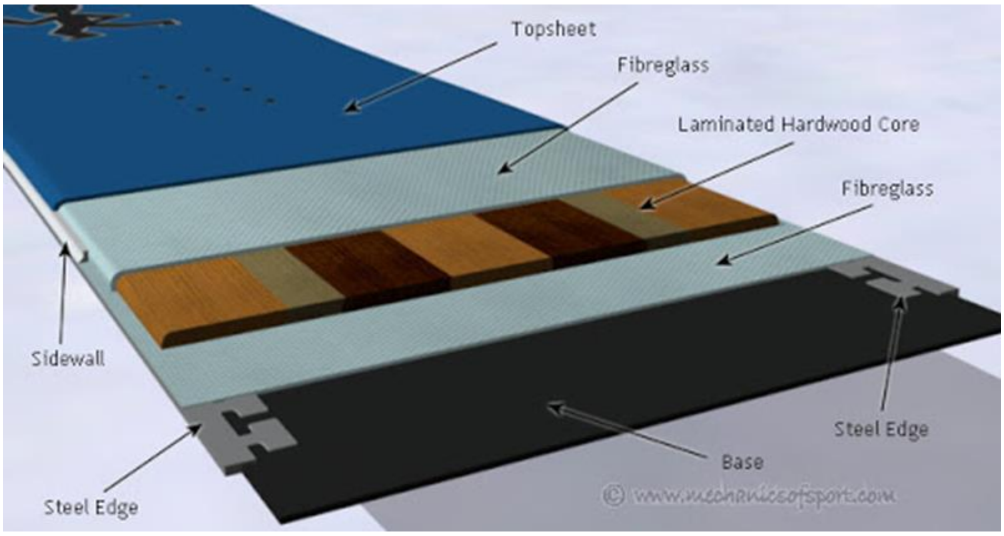


Figure 4.1: Sandwich construction of a snowboard (Mechanics of Sport, n.d.).

The main component of a snowboard is the laminated wood core, which consists of strips of wood glued together lengthwise (Mechanics of Sport, n.d.). Commonly used wood species include poplar, paulownia, beech, aspen, and bamboo. The core is the most important determinant of the snowboard's mechanical characteristics (Mechanics of Sport, n.d.).

The core of all-mountain snowboards is often reinforced in specific directions or areas with "lay-ups" of reinforcement materials (e.g. carbon fibers) with epoxy, for example in the shape of woven "stringers", tubes, or plates (e.g. Bataleon Snowboards, n.d.; Rome Snowboards, n.d.; Mechanics of Sport, n.d.). Carbon is by far used the most for these (used by 85% of brands), followed by basalt (31%), Kevlar (19%), bamboo (13%) and flax (9%). Damping lay-ups, intended to reduce vibrations or impact during use (Amplid, n.d.), are also receiving increasing attention; 27% of brands

(11) incorporates some kind of damping into the board. These mostly consist of thermoplastic polyurethane (TPU) poured into channels in the core (5, 45% of damping efforts), or plates under the binding made from cork, glass-fiber, flax fibers, or carbon. This seems to be an emerging development on which consensus has not been reached yet. Lay-up elements often contain combinations of materials and are quite diverse; of the brands that use lay-ups, the majority (59%) reports the use of more than one lay-up material in their collection.

Two layers of fiber reinforcement fabric sandwiching the core add strength and torsional stiffness (Mechanics of Sport, n.d.). These fabrics are usually made of glass fiber (93%), sometimes also with some carbon fibers woven into it (20% of brands) or basalt (2 brands, 5%). Other fibers used for these reinforcement fabrics include carbon (2 brands), basalt (1) or flax (2).

The upper and lower glass-fiber layers are covered respectively by a topsheet and a base. The topsheet often consists of one or more polymers, such as PE, ABS and TPU, or a combination of polyamide-11 (PA11) and polyamide-12 (PA12), which is the most high-quality option (ISOSPORT, 2017a). This material combination has the high UV-resistance, abrasion resistance, and form stability that are needed to withstand snowboarding conditions. For most brands (29, 73%), information on topsheet materials was not available; PA11 and wood veneer were the most mentioned options for brand that did report topsheet materials. Wood veneer needs to be finished to be protected from moisture, for example with lacquer or epoxy (Dry Boards, pers. comm., 2020), or with linseed oil (Luthe, pers. comm., 2020).

Most snowboard bases are made from Ultra High Molecular Weight Polyethylene (UHMWPE) (mentioned by 39 brands, or 98%) or High-Density Polyethylene (HDPE) for cheaper models (mentioned by 14, 35%). UHMWPE is a polyethylene grade with extremely long molecules that is abrasion resistant and experiences minimal friction with snow due to its hydrophobic nature (Vegetti, Radnóczy, & Ossi, 2013; Mechanics of Sport, n.d.). Optionally, graphite is added to higher-end bases (mentioned by 10, 25%) to further decrease the friction with snow. Recycled base content is mentioned by 3 brands. The ink used for topsheet and base graphics is either solvent- or water-based (How to Heat Press, 2019).

At the side of the core, snowboards have sidewalls. Forty percent of brands did not report their sidewall material; for the others, the sidewalls were either UHMWPE (8, 20%), ABS (11, 28%), or polyurethane (PU) (8, 20%). Two brands reported the use of recycled UHMWPE and three recycled ABS. Two brands in the sample used bamboo sidewalls.

All layers are joined together with epoxy resin. This resin consists of two components: the epoxy component and the hardener (Entropy resins, n.d.). Most of these resins are fully based on fossil fuels (81%); 19% of brands reports the use of epoxy with bio-based content. One brand reports the use of a hardener (Recyclamine) that should allow for easy cleavage of the epoxy bonds for recycling (Niche Snowboards, n.d.).

Finally, a steel edge runs around the base, enabling the board to grip the snow (Mechanics of Sport, n.d.). Stainless steel inserts are drilled into the core for the attachment of bindings.

Usually, all-mountain snowboards have medium flex and torsional stiffness, a directional twin-shape (i.e. a tip and tail are symmetrical, with the bindings slightly set back towards the tail), and lay-ups in specific directions.

4.3. Future Developments Towards More Sustainable Materials

Based on these results, a few key developments in material use are identified. Firstly, bio-based materials are becoming more popular. In terms of topsheets, over 30% mentions the use of bio-based materials like wood veneer or PA11; for reinforcement lay-ups, more than 25% of brands mentions the use of bio-based fibers such as flax or hemp, or bamboo elements. Although less common, bio-based fiber reinforcement fabrics are also making their entry as replacement for traditional glass fiber and interests of multiple companies for these materials show potential for growth (e.g. Grown Skis, n.d.; Jones Snowboards, n.d.; Amplid Research Cartel, n.d.). 18% mentions the use of partially bio-based resin. Thus, bio-based materials are rapidly adopted in this industry and are seen as a potential way to make snowboards more sustainable.

A second development towards more sustainable material use are efforts to reduce the environmental impact of abiotic materials. These include the use of alternative materials such as basalt instead of glass- or carbon fibers (31% of brands in lay-ups, 8% as reinforcement fabrics) and the use of recycled plastics for the sidewall (13%) and base (8%). These efforts also include striving for a recyclable snowboard, for example with the use of an easily cleavable epoxy hardener (Jones Snowboards, n.d.; Niche Snowboards, n.d.). This makes the epoxy thermoset recyclable, normally not the case for thermosets, and is therefore a very promising development in composite recycling (Joustra, pers. comm., 2020). To date, only evidence of manufacturing waste separation could be found; how this process would work with an entire snowboard is not yet clear.

The move towards lower-impact abiotic materials is also shown in an increasing focus on removing toxic and harmful components from the lifecycle. Traditionally, various substances that can be toxic and detrimental to human health are used. By some brands, an ambition to remove these substances from the supply chain is expressed, for example with the use of low-VOC epoxy (Mervin Manufacturing, n.d.) and water-based ink (e.g. Niche Snowboards, n.d.), or the elimination of acetone as sidewall finisher (Jones Snowboards, n.d.). Other examples include restricted substance lists (e.g. Burton Snowboards, n.d.) and more general policy on toxic substance elimination (K2 Sports, n.d.). Finally, with the ban on wax containing fluorocarbons in competitions, FIS shows that this is a winter sports-wide development (FIS, 2020).

Finally, a small trend towards snowboards designed for a longer lifetime can be observed. This idea is expressed in two ways: firstly, various brands are implementing damping elements in their snowboards, which could prevent breakages; secondly, some brands report the use of thicker edges that can be sharpened more times (Jones Snowboards, n.d.; Slash Snow, n.d.). Business models that could elongate the lifetime, such as a pass-along program for used gear (Burton Snowboards, n.d.) are also explored.

In conclusion, currently, various developments towards material use that better fits with the circular economy are taking place; bio-based materials are increasingly used, there is a focus on recycling and toxic substance reduction, and the first efforts of design for a longer lifetime are present. These developments are expected to gain ground towards 2025.

5. Snowboard Lifecycles

Apart from materials, the lifecycle is an essential part of the environmental impact of a snowboard. Therefore, the following sub-question was formulated:

> *What do snowboard lifecycles currently look like, and what developments towards more circularity are observed?*

In this chapter, this question is answered with information obtained from literature and analysis of a sample of brands, as well as expert consultations of people working in the industry. First, the most common lifecycle structures are described, followed by a description of the main value-creation phases. The chapter is concluded with developments towards increased circularity in the lifecycle.

5.1. The snowboard lifecycle structure

The snowboard supply chain follows a two-year cycle, where snowboards are designed two years before they are sold. In the first winter season, the boards are designed and a sample order is produced. These samples are distributed amongst the sales agents of each region in the fall, after which the sales season starts. During this winter, stores place their orders for the next winter. At the end of the winter, these orders are passed on to the factories, who manufacture the boards over the summer. Finally, the boards are sold in the second winter season after they are designed.

Snowboard production is often outsourced to factories that produce for multiple brands. Some of these factories are owned by a company managing one or multiple brands, such as Mervin Manufacturing (Mervin Manufacturing, n.d.) or the Mothership (Capita MFG, n.d.); others are independent, such as SWS (SWS Board Sports Industries L.L.C, n.d.) and produce for external

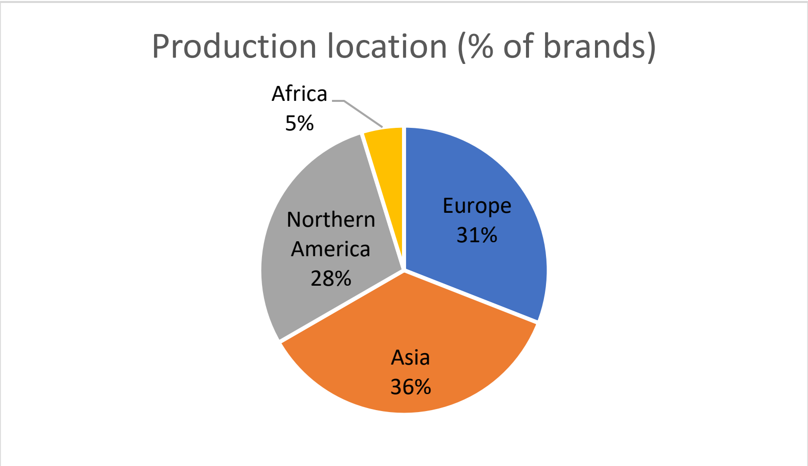


Figure 5.1: division of production locations in percentage of brands

companies only. These factories are located around the world, predominantly in the northern hemisphere (see fig. 6.1); additionally, there are countless small workshops and factories scattered around the world (Douk Snowboards, pers. comm., 2020). Most materials used in snowboards are produced by ISOSPORT in Austria (ISOSPORT, n.d.) and Crown Plastics in the US and Europe (Crown Plastics, n.d.); however, materials might also be supplied by smaller companies, and the wood for the cores is sometimes also sourced locally (e.g. Mervin Manufacturing, n.d.).

Most brands sell worldwide, so after production, the snowboards are shipped around the world. They are sold to retailers through local distributors or sales agents; the snowboard is subsequently sold in a physical store or online, or rented out (see use). For end-of-life snowboards there are no known reverse logistics systems in place, except for warranty cases that might have to be evaluated by the factory. It is therefore expected that snowboards, when discarded, end up with municipal waste.

Based on the information presented above, the lifecycle structure in figure 6.2 is established. Only activities directly related to the production of the snowboard are taken into account. This means that the activities such as design, production of samples, and marketing efforts such as sales events are excluded, since these cannot directly be assigned to one snowboard. These could however be interesting elements for another study to include.

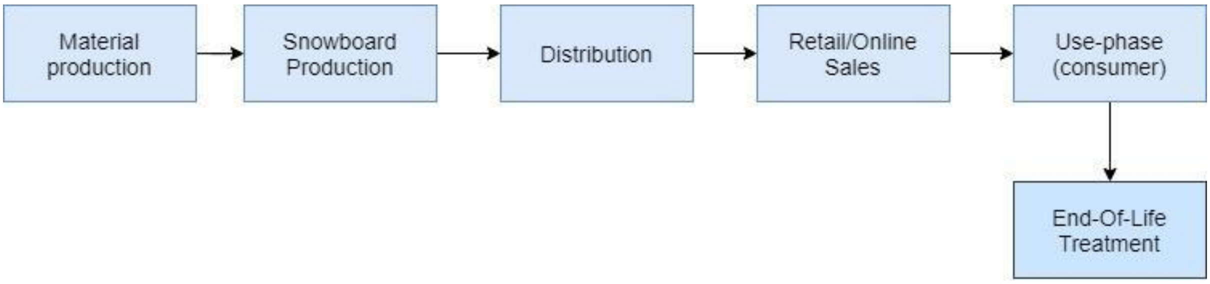


Figure 5.2: Lifecycle structure of a snowboard

Although every snowboard brand might have a different supply chain, all snowboards go through these general value creation phases. Thus, although these phases might look different depending on the brand, the structure will generally be similar to this one.

5.2. Description of the Lifecycle

In this section, the individual value creation activities are described. In the literature table mentioned in the previous chapter (see Appendix F), information about the lifecycles of these 40 brands was also noted. The value creation phase descriptions are based this information, supplemented with other sources such as websites, scientific articles, and expert consultations. These descriptions form the basis of the LCA-study, and therefore require sufficient detail on the processes executed.

Material Production

The feedstocks for the snowboard "sandwich" can be divided in three categories: synthetic ready-made rolls or sheets, the wooden core, and steel parts. These component types are each manufactured differently.

The wooden core of the snowboard is produced by gluing blocks of wood together with PVA-glue and slicing these into thinner, vertically laminated slices (Douk Snowboards, 2016). These slices will be planed, thinned even more, and sanded into the final shape of a core. Veneer topsheets are produced similarly.

The plastic and the reinforcement fabric are delivered to the factory ready-made in sheets or rolls. Except UHMWPE, these plastics are produced through extrusion, where a plastic feedstock such as pellets or powder is fed to an extruder (PaulsenTraining, 2010). In the extruder, the plastic is pushed through a heated barrel by a screw that moves, heats, and pressurizes the plastic. At the end of the extruder, the melted plastic is forced through a die that produces a continuous sheet in the desired dimensions. UHMWPE-bases are produced by sintering, where UHMWPE-powder is compacted in a certain shape and subsequently "sintered" at temperatures within the glass transition range, which is the temperature range during which the material transitions from brittle to rubbery (Hambir & Jog, 1999; Karamanov et al., 2013). During this process, the material crystallizes and is linked together while full liquefaction is prevented. The lower the pressure, the higher the porosity of the base (Barnetson & Hornsby, 1995), which leads to better wax absorption and reduced electrostatic friction.

The steel edges and inserts are ordered ready-made; the edges are cut to the right length for each individual snowboard when they are used.

Snowboard Production

Production of the snowboard starts with the core, which is either ordered ready-made or built at the factory (Isosport, 2017; Mervin Manufacturing, 2020). The core is then cut into the right shape using a mold. Into the core, holes are drilled for the inserts to attach the bindings (Discovery UK, 2018). The sidewalls are also adhered to the core at this stage; ABS and UHMWPE-sidewalls are glued to the core, possibly with a strip of rubber or plywood in between, whereas PU-sidewalls are poured into a mold around the core and left to set (Never Summer Industries, 2019; Mervin Manufacturing, 2020; Douk Snowboards, pers. comm., 2020). If reinforcement lay-ups are used, they are also attached to the core now (Never Summer Industries, 2019).

In the meantime, a sheet of topsheet material has been cut off a roll and adorned with graphics. This is either done with silkscreening, where colors are printed one at a time with the use of a silk screen (Merriam-Webster, n.d.) or sublimation printing, where the ink is printed onto transfer paper and subsequently transferred into the molecular structure of the topsheet material in a heat press (Never Summer Industries, 2019). The ink on the transfer paper is in a solid state and directly converts into a gas (How To Heat Press, 2019). Next, a sheet of P-tex (either UHMWPE or HDPE) for the base is cut into the right shape, and the steel edges are attached to it with superglue (Douk Snowboards, pers. comm., 2020; Never Summer Industries, 2018).

Now, the different layers of the snowboard are assembled, often within an aluminum mold (Mervin Manufacturing, 2020; Douk Snowboards, 2016). The epoxy resin and the hardener component are mixed and applied to every material layer added to the “sandwich”. Before assembly, the wooden core is often impregnated with epoxy to close off the pores and prevent excess absorption of epoxy during curing (Dry Boards, pers. comm., 2020). First, the base is laid out and covered with a sheet of glass fiber fabric. Next, the core is placed on top, followed by another layer of glass fiber. Finally, the topsheet is placed onto the stack and the top of the aluminum mold is put on. This construction is placed into a heated hydraulic press, where the temperature is dependent on the epoxy used (around 80-110 °C) and heated for the required cycle time of the resin.

When the snowboard is removed from the press, excess epoxy and materials are cut off with a bandsaw and the board undergoes finishing treatment, such as polishing the sidewalls, grinding the base, and finally removing the protective foil on the topsheet (Douk Snowboards, 2019). The snowboard can now be subjected to quality control and packaging.

Distribution & Sales

Shipping usually happens by sea or air shipping (e.g. Jones Snowboards, 2018), depending on how urgent the shipment is. Sea shipping is less expensive but takes around 6 weeks; if production delays occur, it might be necessary to use air shipping instead. Once the snowboards have arrived at a distribution location, transport to the point of sales is often outsourced to package delivery companies such as UPS or DHL. Sales might either take place online, which is a growing market, or in a physical store.

Snowboards are also often bought secondhand. Taking the Netherlands as an example, this usually happens through the informal market via private-sales websites such as Marktplaats.nl

(Marktplaats, n.d.) or via secondhand equipment fairs (Kliknieuws, 2019). Some retailers also specialize in secondhand equipment (e.g. 2nd Ride, n.d.), although these often sell used demo boards rather than privately used snowboards. The sales channels for rental equipment are less documented. Expected is that these snowboards follow a similar route to the snowboards for sales, where the boards are first shipped to a local distributor and then transported to the rental site by a package delivery company.

Use

As explained in the previous chapter, snowboards are on average used between 9 and 30 weeks, depending on the type of use. During use, the base of the snowboard is serviced with hot wax about once a week. Usually, the wax is based on hydrocarbons (Toko, n.d.), although alternatives based on for example soybeans are also available (e.g. Ebay, n.d.). This waxing can be done either with a machine or manually; for the best result, manual servicing is preferred. This requires the use of a wax iron to melt the wax and spread it over the base evenly; afterwards, any excess wax is scraped off and the base is finished with a nylon brush (Ski Mag, 2019). Every once in a while, the snowboard edges need to be tuned and sharpened; the frequency of tuning might be everywhere between every week or once every two months, depending on the preference of the user and the type of snowboard.

As established previously, rental snowboards make up a considerable proportion of the market (40% of the tourist-segment). To establish the use-phase of these snowboards, a few rental companies were consulted. Rental snowboards are often used one season (about 3 months, 12-16 weeks) in a western European country (e.g. Austria); afterwards, they are sold to a country in eastern Europe where expected quality and novelty are lower and used until the end-of-life (Intersport Kirschner, pers. comm., 2020; SnowWorld, pers. comm., 2020; Sport Klieber, pers. comm., 2020). It is therefore expected that rental snowboards have a lifetime equal to the expected technical lifetime of 30 weeks. From researcher experience, rental snowboards are often cheaper models; a longer lifetime than for privately-owned snowboards is therefore not expected. Servicing is expected to be the same as for privately owned snowboards.

Finally, secondhand snowboards are also frequently used (see EOL and 4.1), especially by Wintersports Enthusiasts and Snowsports Professionals. This equipment is serviced the same as firsthand equipment; since it is used twice, its lifetime is expected to be the technical lifetime of 30 weeks.

EOL

At the end of life (EOL), there are different options to take care of a snowboard. In the survey, people were asked what they had done with their *previous* snowboard at the end of use. The results are presented in table 6.2. These numbers highlight the importance of secondhand sales once again and indicate that there is likely a large stock of indefinitely stored snowboards that will eventually need to be dealt with.

The number of snowboards sold secondhand after the end of use (56%) is higher than the 18% of snowboards bought secondhand that is reported in 5.1. This might be due to a difference in question formulation: the purchasing question is about secondhand boards bought **in the last five years** while the end-of-use question is about the **previous** snowboard. The first number is thought more representative as this question spans a larger time period and sample.

Table 5.1: EOL Treatment Options

Treatment option	End of (first) Use (n = 63)	End-of-Life (secondhand excluded) (n = 29)
Secondhand sales	56%	-
Municipal waste	6%	14%
Reused for a different purpose	10%	21%
Stored indefinitely	29%	64%

If a snowboard is discarded with municipal waste at the end of life, treatment depends on the location. Incineration is the most common EOL treatment for composites (Yang et al., 2012); however, in some regions these items might also be landfilled or processed in a cement kiln, where the organic parts of the composite function as a fuel and the minerals of the glass fibers as feedstock for the cement (Composites UK, n.d.). Recycling methods are currently being researched, but not yet commercially viable (see 2.1).

In conclusion, there are a few options for snowboards that have reached their end of life, after the snowboard cannot be sold secondhand anymore. Firstly, they might be reused for a different purpose (21%), for example as decoration, as part of a garden fence, or as a shelve. Secondly, they might be indefinitely stored (64%); however, it is likely that at least a portion of these boards eventually ends up elsewhere, for example with municipal waste. Finally, 14% of discarded snowboards ends up with the municipal waste and is likely incinerated or landfilled.

5.3. Sustainability Developments in the Lifecycle

Some developments towards more circularity were observed. Firstly, brands and factories that are becoming more sustainable often start producing their own electricity, usually with photovoltaic installations on factory or office roofs. In the case of the Mothership, a factory owned by Capita Snowboards, the required heating and cooling of equipment is achieved with a heat exchanger system that extracts heat from a neighboring river (Capita MFG, 2015).

As mentioned before, some brands are starting to use cleavable epoxy curing agents (e.g. Niche Snowboards, n.d.). With these epoxy curing agents, a waste stream that usually needs to be incinerated could be separated, and manufacturing waste could be recycled, as well as snowboards that have reached their end of life. Therefore, this is an important development with regards to circularity.

With regards to shipping, brands seem to become more conscious of shipping impacts (e.g. Jones Snowboards) and are trying actively to use sea instead of air shipping. Additionally, it is attempted to cut back on shipping distance by shipping directly to distributors instead of via a central distribution point. Finally, various brands also mention the fact that their materials are sourced locally (e.g. Capita MFG, n.d.; Niche Snowboards, n.d.).

Finally, at the end-of-life, initiatives to give used snowboards another function arise. Some brands have take back programmes (Launch Snowboards, n.d.; Burton Snowboards, n.d.) where boards that can still be used are given another lifetime. Warranty cases are sometimes made into skateboards (NoK Boards, n.d.) or park benches (Bataleon Snowboards, pers. comm., 2019) and are given a new lifetime this way.

6. Scenarios for a Circular Future

To get a picture of the environmental impact that a snowboards lifecycle and potential more circular alternatives have on the environment, the results presented in the previous chapters need to be translated into future scenarios. At the start of the research, the following sub-question was posed:

What scenarios for a more circular snowboard lifecycle in 2025 could be developed?

In this chapter, these scenarios are developed. The key material and lifecycle-findings are first concluded from chapter 4 and 5; afterwards, the key results of the Wintersport Archetypes are discussed. Finally, these findings are translated into scenarios, including an overview of what development is included in what scenario.

Key Developments: Lifecycle and Circularity

From the results presented in chapter 4 and 5, the following key snowboard lifecycle and material characteristics and developments towards more circularity were identified:

- *Global supply chain: most* snowboards have an intercontinental supply chain, where they are sold and used on a different continent than produced. The impact of shipping is receiving increasing attention, leading to a dominant position for sea shipping.
- *Alternative energy:* alternative electricity in the shape of rooftop PV installations is increasingly adopted at snowboard production sites.
- *Different EOL-treatment options:* composites recycling is still a developing field, and increasingly initiatives for other EOL options than incineration or landfilling emerge, such as repurposing.
- *Recycling and recycled materials:* cleavable epoxy and the use of recycled materials open up new possibilities for recycling.
- *Bio-based materials:* the use of bio-based materials for topsheets or fibers is mentioned by more than 25% of all brands. These materials also play an important role in the circular economy.

Wintersports Participant Archetypes

In chapter 4, three wintersports participant archetypes were devised: the Tourist, the Wintersport Enthusiast, and the Snowsports Professional. The following key findings about these archetypes were identified:

- *All-mountain snowboard usage:* all three archetypes participate in multiple different activities, i.e. all-mountain snowboarding.
- *Different equipment use-times and new equipment purchasing reasons:* where a professional on average used their equipment for 29 - 36 weeks, tourist equipment only reaches 9 – 12 weeks of use. Moreover, 70% of professionals bought equipment due to the EOL of previous equipment, compared to 42% of tourists. This indicates that the equipment of Tourists and Wintersports Enthusiasts is likely not as efficiently used as that of the Snowsports Professional.
- *Differences in amount of equipment owned and bought:* stark differences in equipment ownership exists between the archetypes: where 40% of Tourists rents equipment, and equipment owners on average own 1 set of equipment, virtually all Wintersports Enthusiasts and Professionals own equipment, on average 3 – 4 sets. Similar differences exist for the amount of equipment purchased.
- *Secondhand use:* 18% of bought and 54% of end-of-use snowboards were used/sold secondhand, showing that this is a relevant phenomenon in this industry (see 5.2 for an

explanation of this difference). Secondhand equipment was mainly bought by Wintersports Enthusiasts and Snowsports Professionals.

- *Rental snowboards:* 40% of Tourists rent their equipment, showing the important role of product service-systems in this industry. Rental snowboards are expected to be used longer than privately owned snowboards, i.e. for the technical lifetime (see 5.2).

The aim of this study is to evaluate circularity measures that could be implemented by industry actors to improve the environmental impact of snowboard lifecycles. The focus of the scenarios should therefore be on comparing these implementable measures rather than on comparing lifecycles of snowboards used by different archetypes, since the influence of industry actors on what archetype people belong to is limited. For this reason, the scenarios are centered around the lifecycle of one snowboard. Based on the key results listed above, one potential strategy to improve the circularity of the use-phase for one snowboard was identified:

- *Increased use-time:* increasing the use-time of equipment used by Tourists and Wintersports Enthusiasts towards the technical lifetime could potentially improve the environmental impact. This could for example be reached through increasing the volume of equipment rented or sold secondhand.

In order to see if this measure would make sense from an environmental perspective, a lifetime for recreant usage needed to be established for comparison with the technical lifetime of 30 weeks. To this end, the average equipment lifetime for the entire recreant group (Tourist and Wintersport Enthusiast) was calculated: this was 15 weeks (see table C.4).

Based on these observed key points, six scenarios were devised. All scenarios except alternative 2 portray use by the average recreant[4]:

- *Baseline scenario (Baseline alternative AB, 2020):* represents the current status quo with no additional circularity efforts. Represents the current system with the different End-of-Use options (e.g. secondhand use, reuse for another purpose, incineration) identified in the previous chapters, with proportions based on the numbers reported in 5.2 (see 8.1 & Appendix D).
- *Alternative 0 (A0, 2020):* represents the current status quo with incineration as the end-of-life option.
- *Alternative 1 (A1, 2025):* represents the expected status quo of the snowboard lifecycle in 2025 following the identified developments with incineration at the end of life.
- *Alternative 2 (A2, 2025):* represents the expected status quo of the snowboard lifecycle in 2025 with a snowboard that is used for the expected technical lifetime (30 weeks), for example because of secondhand use, use by a professional, or use as rental equipment.
- *Alternative 3 (A3, 2025):* represents the lifecycle of a snowboard mainly made of biobased materials with reuse for another purpose at the end of life.
- *Alternative 4 (A4, 2025):* represents the lifecycle of a snowboard that is centered around recycling and the use of recycled materials.

These scenarios represent the developments observed in the following way:

Table 6.1: Elements Incorporated in the Scenarios

Development/ Characteristic	AB	A0	A1	A2	A3	A4
Global Supply Chain	x	x	x	x	x	x
Bio-based Materials					x	
Alternative Energy					x	x
Secondhand Use	x			x		
Rental Use				x		
Professional Use				x		
EOL-treatment Options	Multiple	Incineration	Incineration	Incineration	Reuse	Recycling
Recycling/Recycled Materials						x

From this table, it can be observed that all key findings are incorporated in one or more of the scenarios. Alternative 2 is the only alternative for which use for the technical lifetime is assumed; the other scenarios are modelled with the average recreant use-time of 15 weeks established above. Alternative 2 is therefore representative of a rental snowboard, a secondhand snowboard, or one used by professionals, as these are all expected to last for the technical lifetime.

Many more combinations of these elements would be possible, but due to the limited scope of this research, a selection had to be made; however, other Chapter 12.

Part III: Life Cycle Assessment

In this section of the thesis, the fourth sub-question is answered: *How do the developed lifecycle scenarios compare in environmental impact?* This question is answered with the use of ex-ante LCA. In chapter 7, the goal and scope of the LCA-study are defined, and the alternatives are introduced. In chapter 8, the inventory analysis is conducted, including the presentation of flowchart and unit-process descriptions. In chapter 9, the results of the impact assessment are presented. Finally, in chapter 10, the results are interpreted and evaluated.

7. Goal and Scope definition

In this chapter, the goal and scope of the LCA study are described in more detail to define the aims and the boundaries of the project.

7.1. Goal Definition

The goal of this study is to compare different types of circular snowboard lifecycles with Business as Usual (BAU), to show what implications certain circularity decisions have on the environmental impact, and to allow people in this and related sectors to make evidence-based decisions. It is therefore important to show how different life cycle phases or decisions affect the environment, which stresses the importance of contribution and sensitivity analysis. The intended audience of this study is actors in the snowboard lifecycle, as well as experts working in or researching other fields of composites or the circular economy.

Since the study is focused on the comparison of environmental impacts over the entire lifecycle of the product, LCA is a suitable method to address this question.

This research is undertaken as a graduation project of the MSc Industrial Ecology at Leiden University/TU Delft. The practitioner has taken an elaborate LCA-course and conducted one such study before. The research is not commissioned; it is supervised and reviewed by Jeroen Guinée, associate professor in the field of LCA at the University of Leiden, Ella Jamsin, assistant professor in Design for Sustainability at the TU Delft, and Ruud Balkenende, professor of Circular Product Design at the TU Delft.

7.2. Scope Definition

This is an ex-ante LCA study. Two baseline alternatives that take place in 2020 are presented, followed by four alternatives that take place in the future (2025). The data used to model the alternatives should be as relevant as possible to these time periods. The demand for the product is not expected to change significantly.

The study is change-oriented, evaluating options that could possibly be implemented in the future by assessing technologies not yet implemented on a commercial scale. The aim is a relatively detailed analysis.

Economic process coverage

For proper assessment from a circular economy-perspective, the entire cradle-to-cradle/cradle-to-grave lifecycle of the snowboard needs to be assessed. It is attempted to follow all economic flows of which the environmental impact should be assigned to the snowboard system to their elementary flows. Due to data gaps, which pose a common problem for ex-ante LCA studies (Thomassen et al., 2019), this was not possible for some flows. Where possible, these flows were proxied with similar activities for which data was available; however, if this was not possible or feasible, they were cut-off (see section 10.3).

Moreover, the question "where should the snowboard system end?" was asked many times during this research. Since this project is about the equipment specifically, only processes directly related to and caused by the lifecycle and the ownership of a snowboard are taken into account. This includes maintenance of the snowboard in the use-phase but excludes elements like holiday transport or ski lift operation. Capital goods like production equipment and buildings are also excluded (see 10.3).

Geographical Scope

Since most snowboards in the world have an intercontinental supply chain, with production on one continent and sales on another (see 6.2), all alternatives in this study have the same lifecycle structure. In this case, production is modelled in China (near Xiahai), a representative production location since about 30% of snowboards is produced in Asia, with materials of most alternatives sourced from Austria, where the biggest supplier is located. The final sales, use, and end-of-life (EOL) is modelled in the Netherlands, predominantly because most survey respondents were from this region and the results might therefore be more representative. Since the results in 6.2 indicate that this could be a representative supply chain, this decision is deemed reasonable.

Technological Scope

Like any LCA study, the activities in this study can be divided in foreground and background activities. Thus, the technologies can also be divided as such: background technologies such as electricity and transport, whose technology levels are determined on an economy-wide scale, and foreground technologies specific to the system, such as adhesives or materials. The approach used for these distinct types of technologies is explained below.

Background Technologies

Since most LCI databases are based on historical data, a challenge for ex-ante LCA studies is to ensure a background system representative of the time of assessment, in this case 2025 (Van der Giesen et al., 2020). Naturally, reviewing and modelling an entire background database representative of 2025 is not feasible. For this reason, it was decided to identify the most important background technologies and focus on extrapolating these to 2025 levels.

An initial version of the snowboard lifecycle was constructed based on the findings in chapters 5 and 6 (alternative 0 in this study). During construction, results for the Climate Change-impact category were calculated regularly for this scenario. From these preliminary results, it was observed that electricity caused a large portion of the Climate Change impact. No other model elements with a similarly large share of impact were identified; it was therefore decided to focus on extrapolating the production electricity mix to 2025.

This 2025 production electricity mix was based on the China Renewable Energy Outlook (NDRC, 2018) and additional literature sources for the details (see Appendix D). However, the coverage of renewable energy technologies in Ecoinvent is limited, for example in the case of wind turbines; in this case, the technology closest to the expected reality was picked based on literature research and expert consultation.

For other background technologies, assumptions were made based on expected developments. In terms of waste treatment, it was assumed that paper and separate thermoplastic streams would be recycled in 2025. For road transport, the most efficient vehicles available in Ecoinvent (Euro 6) were used, as more stringent road vehicle standards are expected in the selected geographical regions (European Commission, n.d.; Climate & Clean Air Coalition, 2018). Since Euro6 and China 6 were already launched in respectively 2013 and 2018, most vehicles should be up to this standard by 2025. China 6 is not available in Ecoinvent, however, because this standard was based on Euro 6, the latter is used as a proxy.

Foreground Technologies

For more system-specific technologies, a different approach was used. For technologies already used on a commercial scale, historical data was used, for example from the Ecoinvent 3.6 database. Emerging or more premature technologies were proxied based on literature sources and/or personal communication, or based on similar Ecoinvent processes if sufficient data was not obtained. All technologies were assumed to be operated on a commercial scale in 2025; however, due to the wide range of technologies that needed to be covered, it did not fit within the scope of the research to apply upscaling approaches such as learning curves or scenarios to these models, although this is common practice in prospective LCA studies (Arvidsson et al., 2017; Tsoy et al., 2020). The technologies were therefore modelled based on the scale of the source. More information on this procedure can be found in 8.2 and in Appendix D.

Environmental Scope

In this study, the ILCD midpoint characterization family published in 2018 will be used, as this is the family recommended by the European Commission (Fazio et al., 2018). The selected impact categories and characterization models are specified in section 9.1. Since part of the alternatives was modelled based on literature sources or expert consultation, and some data was missing, not all relevant elementary flows will be included in the model and some impact categories might be under- or overrepresented. This should be taken into account.

7.3. Function, functional unit, alternatives, reference flows

Function

In the previous chapters, the function of a snowboard has been determined. It was established that most snowboarders, regardless of the subgroup they belong to, participate in all-mountain snowboarding, where they use their snowboard for multiple different activities. This is therefore the function assessed in this research: **“all-mountain snowboarding”**.

Functional Unit

In chapter 6, an average snowboard lifetime of 15 weeks was established for recreational users, with an expected technical equipment lifetime of around 30 weeks. Since the aim of the study is to establish the environmental impact of one snowboard and compare different lifecycles with one another, the following functional unit is proposed: **“all-mountain snowboarding for 15 weeks”**.

Alternatives/Reference Flows

In Chapter 7, six alternative scenarios were introduced. In this section, the reference flows of these alternatives are presented. These are the following:

Baseline Alternatives:

- Baseline Alternative (AB): 15 weeks of all-mountain snowboarding on a conventional snowboard produced in 2020 with an average EOL-treatment mix.
- Alternative 0 (A0): 15 weeks of all-mountain snowboarding on a conventional snowboard with incineration after use

Where AB represents the current system, including a mix of different EOL options, A0 represents the current snowboard lifecycle with the most common EOL treatment for composites (Yang et al., 2012) and is therefore more suitable for comparison with other alternatives that explore other EOL treatments.

Prospective Alternatives (2025):

- Alternative 1 (A1): 15 weeks of all-mountain snowboarding on a conventional snowboard produced in 2025 with incineration after use
- Alternative 2 (A2): 15 weeks of all-mountain snowboarding on a conventional snowboard used for the technical lifetime
- Alternative 3 (A3): 15 weeks of all-mountain snowboarding on a snowboard with a bio-based circular lifecycle
- Alternative 4 (A4): 15 weeks of all-mountain snowboarding on a snowboard with a lifecycle focused on recycling and recyclability

8. Inventory analysis

In this chapter, the alternative systems evaluated in this study are defined. The chapter consists of three sections. The system boundaries and flowcharts of the alternatives are presented first; afterwards, the process data for each unit process is explained. The chapter is concluded with a section on the treatment of multifunctional processes and cut-offs.

8.1. System Boundaries and Flowcharts

In this section, the flowcharts of the alternatives are presented, including a short description of the alternative. The "Substitution"-boxes indicate substitution of a good delivered by a waste treatment, so that the benefits of these goods are included in the snowboard product system. This multifunctionality treatment approach is explained in 8.3, and flowcharts and assumptions can be found in Appendix D. Since the substitution systems both treat waste and produce goods for the foreground system, the flows go both into and out of the system.

Economy-Environment System Boundary

The system boundaries of this study are placed around the entire lifecycle of the snowboard, including the production feedstocks and their supply chains, the use-phase, and end-of-life treatment. The boundary between the economy and the environment is mainly crossed by the environmental extensions of feedstock or waste treatment processes; since the snowboard supply chain processes are not heavy production or chemical processes, limited emissions to the environment occur, and waste flows stay in the economic system and are treated by waste treatment processes. For foreground flows that have a function in other systems, i.e. recycled or recycling flows, a substitution approach is followed. This means that the avoided impact of the product replaced by the recycled product are included in the snowboard system. In the background database, the Ecoinvent cut-off system model is followed (Ecoinvent, n.d.). This is explained in more detail in 8.3.

Baseline Alternative (AB): System Representation 2020

This scenario represents the current representative snowboard system according to the results of this study so far (see figure 8.1). The snowboard is produced with the most common materials reported in chapter 4. A mix of different end-of-use and end-of-life treatment scenarios is included, based on the division of EOL-treatments reported in the survey (see 6.2 and Appendix D for the exact proportions and calculations of the mix).

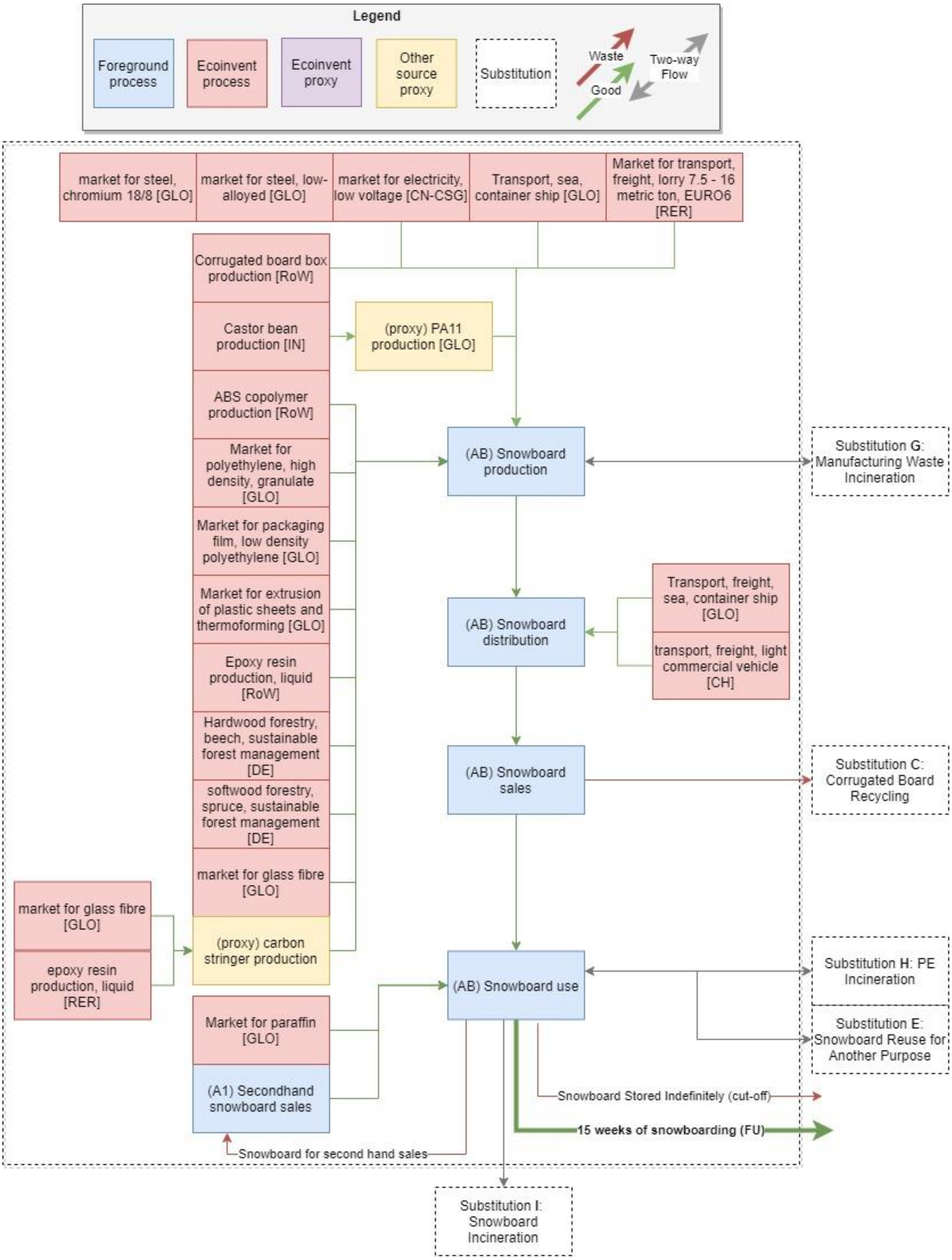


Figure 8.1: Flowchart of the Baseline Alternative (AB)

Alternative 0 (A0): Status Quo 2020

Except for the use-phase and EOL, this alternative is the same as the baseline alternative and therefore represents the status quo of the snowboard lifecycle (see figure 8.2). However, at the end of life, instead of including a mix of options, the snowboard is incinerated, which is currently the most common EOL treatment for composites (Yang et al., 2012). Moreover, no secondhand use is included.

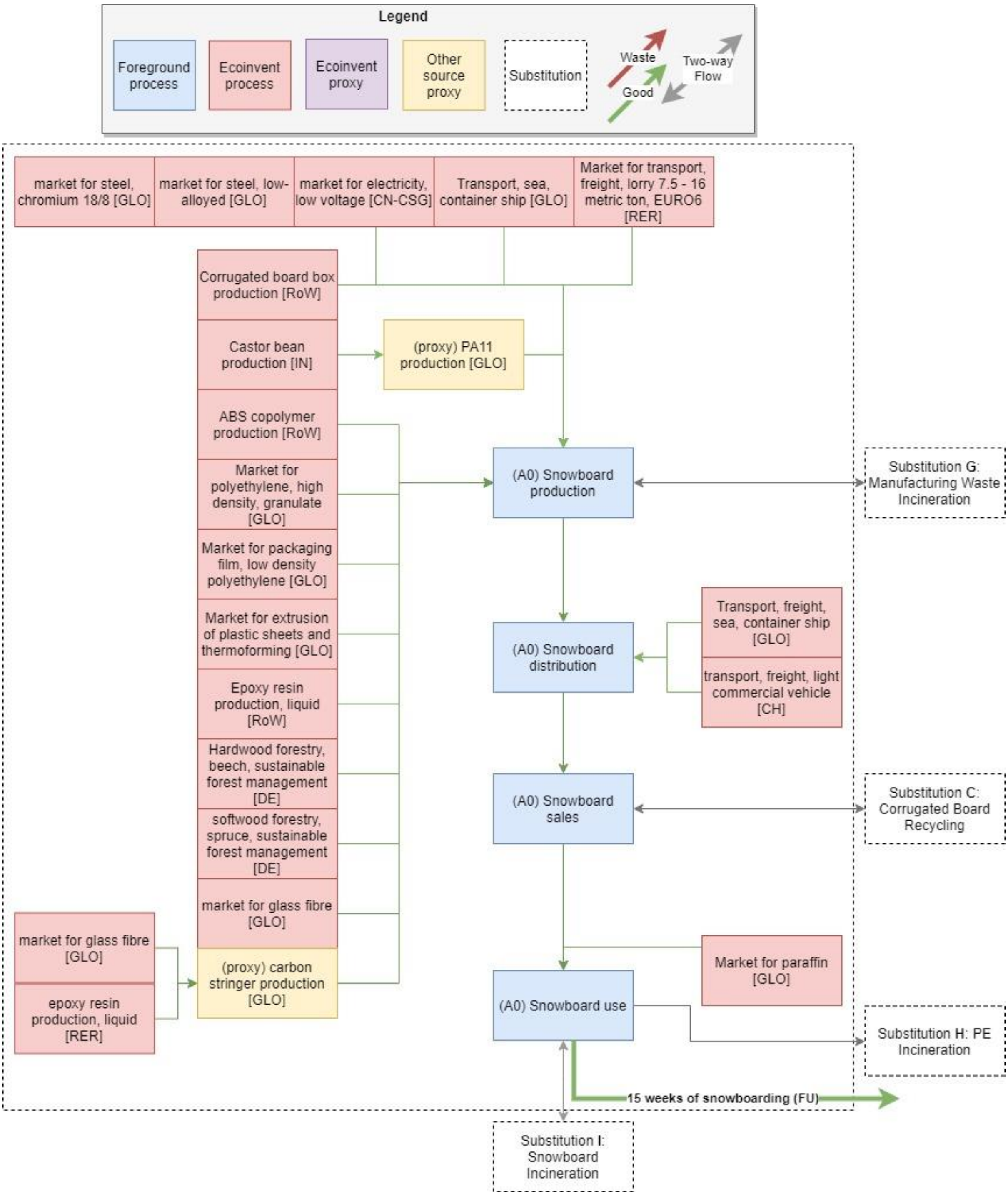


Figure 8.2: Flowchart of Alternative 0 (A0)

Alternative 1 (A1): Status Quo 2025

Alternative 1 is a prospective scenario of the expected status quo snowboard lifecycle in 2025 (see figure 8.3). Radical changes in the snowboard lifecycle are not expected in this period of time; therefore, this alternative is an extrapolation of A0 to 2025. Materials, distribution, use and EOL are expected to remain the same as in A0; however, as specified in the technological scope, the production electricity mix is expected to change and therefore extrapolated to 2025 (see Appendix D).

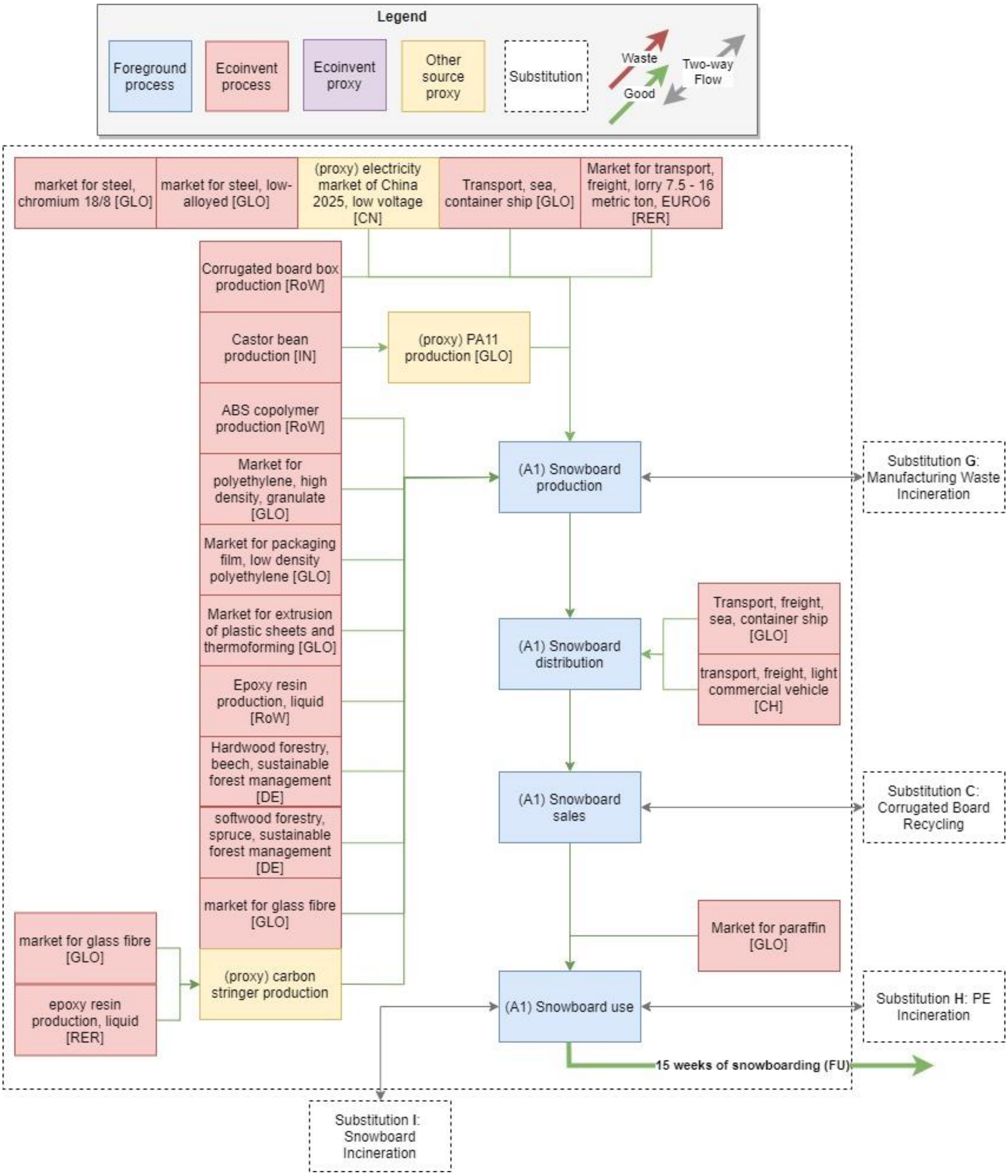


Figure 8.3: flowchart of Alternative 1 (A1)

Alternative 2 (A2): Technical Lifetime

This scenario is the same as A1, except that snowboard is used for the expected technical lifetime of 30 weeks, for example because it is sold secondhand after the first use-time, used by a professional, or as a rental (see figure 8.4). These are all expected to have a similar use-stage in terms of the elements taken into account in this model.

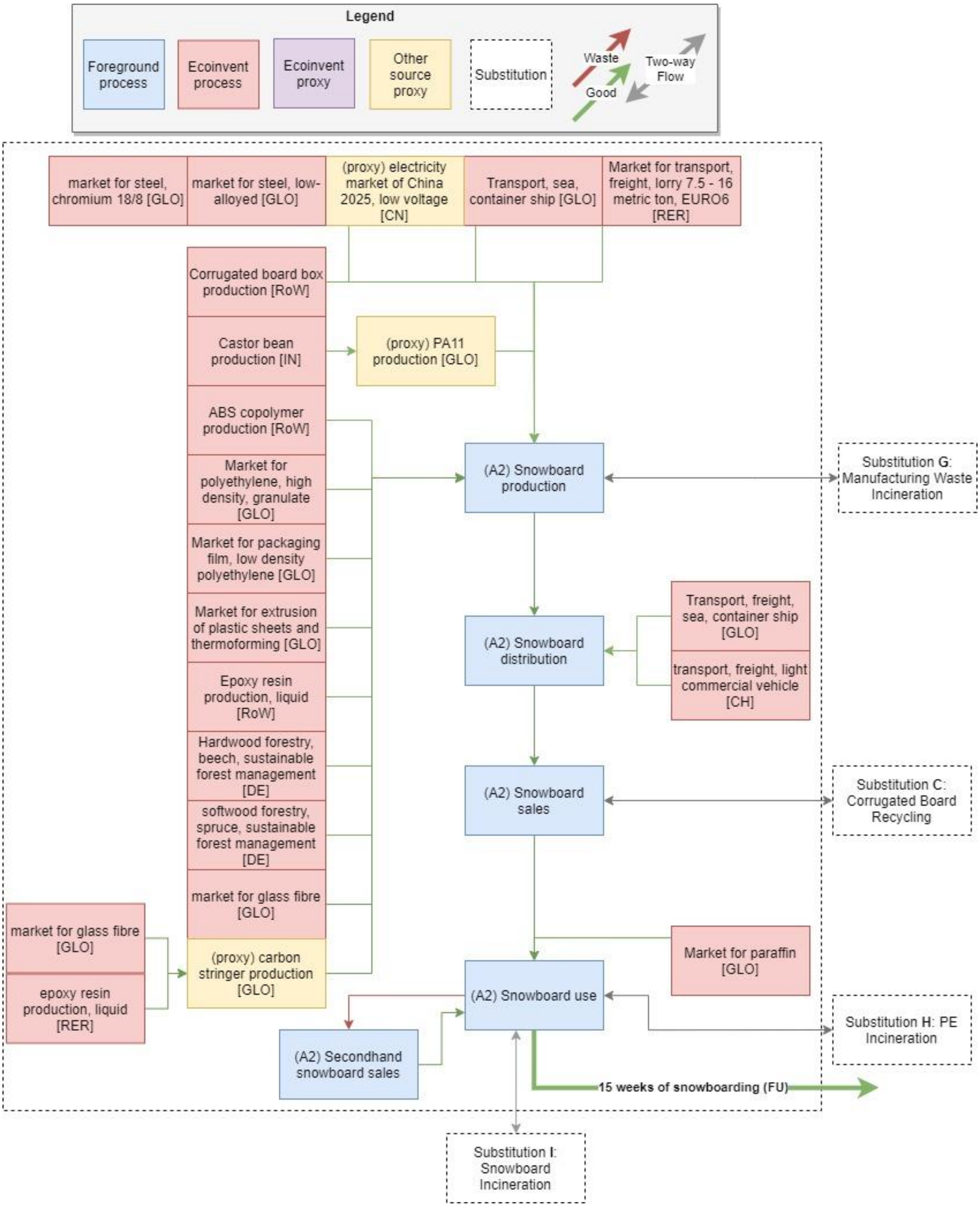


Figure 8.4: Flowchart of Alternative 2 (A2)

A3: Biobased Circularity

This scenario is based on a research project coordinated by researchers of the ETH Zürich, during which a ski is built almost entirely out of bio-based materials. This could be seen as a possible final scenario of the trend towards bio-based material use observed in chapter 6. The ski developed by the ETH Zürich/Grown Ski Labs was translated into a snowboard (see Appendix D).

This alternative differs from conventional snowboard construction methods in many ways (see figure 8.5). Instead of epoxy, the snowboard layers are attached to one another with a mixture of fish glue and tannin powder to waterproof the glue (Luthe, pers. comm., 2020). The topsheet is wood veneer; for the sidewalls, robinia wood is used, as this does not break as easily as some other wood species. The core is made of the same wood species as the other alternatives; for the reinforcement, hemp fibers are used. The wooden parts in contact with the external environment are waterproofed with linseed oil. Finally, although partially biobased UHMWPE is produced by DSM (n.d.), it has not yet been used for applications such as snowboard bases, therefore we assume the UHMWPE to be entirely fossil-based in this scenario. At the end-of-life, the snowboard is reused for another purpose.

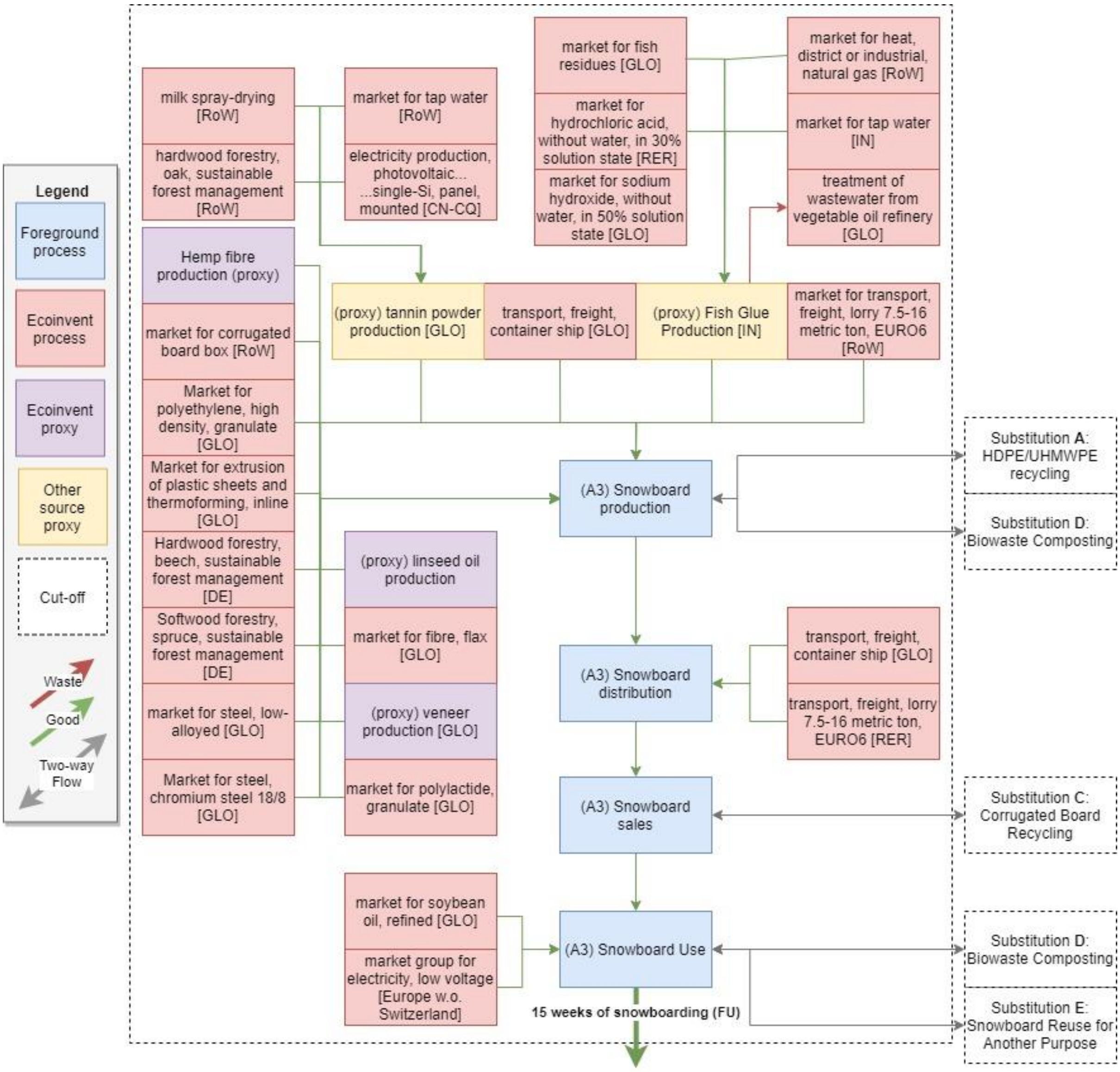


Figure 8.5: Flowchart of Alternative 3 (A3)

A4: Recycling Focus

This scenario is centered around recycling. Recycled materials are used whenever possible, and the use of cleavable epoxy hardener facilitates the recycling of manufacturing waste and the EOL snowboard (La Rosa et al., 2018). The recycling processes are based on three papers by La Rosa et al. (resp. 2014, 2016, & 2018). Since a 25% solution of acetic acid at 70° is used for material separation, the materials used need to be able to withstand these circumstances; moreover, all materials should ideally be recyclable. This leads to a few design changes: since ABS cannot withstand acetic acid (KMAC Plastics, n.d.), the sidewalls are made of UHMWPE. Glass fibers might be affected by the acetic acid

(Owens Corning, 2011) and cannot be remelted into new glass fibers (Ivanitskii & Gorbachev, 2011); therefore, basalt fibers are used for reinforcement in this alternative as these likely have a higher recycling potential (Eutit s. r. o, 2013). Partially bio-based epoxy is used (40%). Except for PA11, all plastics used are assumed to be from recycled feedstock.

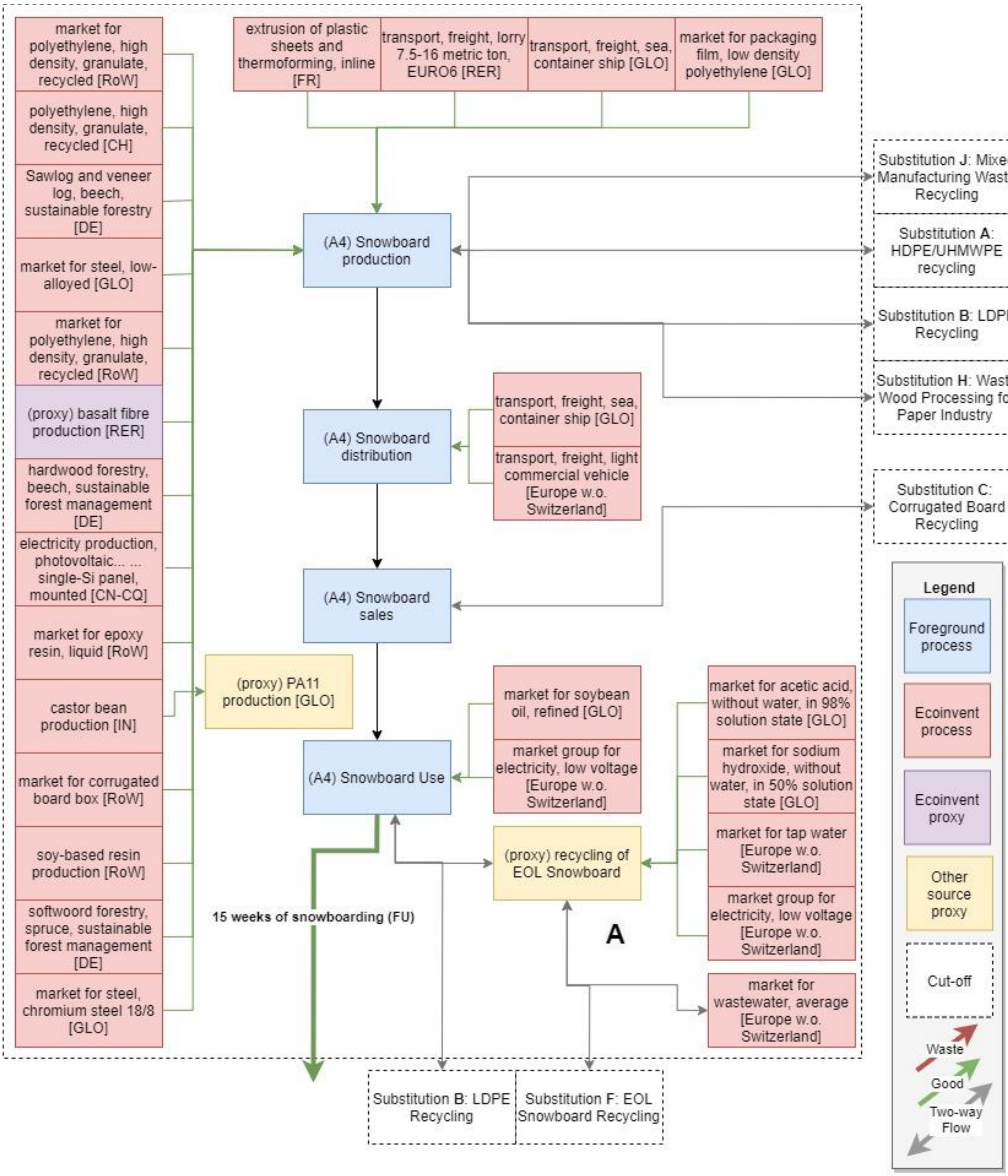


Figure 8.6: Flowchart of Alternative 4 (A4)

8.2. Data Collection and Relating Data to Unit Processes

In this section, the alternatives are presented in more detail. First, the distribution and sales lifecycle phases are presented, as these are the same for all alternatives; afterwards, the lifecycle of each alternative is described. For every process mentioned, a unit process data table with all economic in- and outflows is available in Appendix D, accompanied with clarifications and calculations. This appendix also contains the calculations and process data underlying all proxied background processes.

In tables 10.2 – 10.4, the lifecycles and modelling choices are summarized for all alternatives.

Distribution and Sales

For every alternative in this study, the distribution- and sales processes are the same, because all alternatives are manufactured and sold in the same location (resp. China (near Xiahai) and the Netherlands). These processes are described here.

Distribution: After production, the boards are shipped from the production location in China to a distribution location in Europe (Rotterdam) by container ship. There, the snowboard is transferred to a postal service for transport to the final sales point (in this case assumed to be in the Netherlands). These companies usually employ light commercial vehicles for these distances.

Sales: Upon arrival at the sales point, the cardboard box is discarded for recycling. Other sales impacts such as store electricity are not included.

Table 8.2: Material Characteristics per Alternative

Material Characteristics per Alternative						
	AB	**A0**	**A1**	**A2**	**A3**	**A4**
Element	**System Representation 2020**	**Status Quo 2020**	**Status Quo 2025**	**Secondhand Sales**	**Biobased Circularity**	**Recycling Focus**
Topsheet	PA11/PA12				Wood veneer	PA11/PA12
Base	UHMWPE				UHMWPE	Recycled UHMWPE
Fiber Reinforcement	Glass fibers				Hemp fibers	Basalt Fibers
Lay-ups	Carbon fibers				Flax fibers	Basalt Fibers
Core	Paulownia & Poplar				Paulownia & Beech	Paulownia & Poplar
Sidewalls	ABS				Robinia	Recycled UHMWPE
Sidewall/topsheet finish	acetone				Linseed oil	-
Epoxy	Fossil-based epoxy + curing agent				Fish glue + tannin powder	Partially biobased epoxy (30%) + cleavable curing agent

Baseline Alternative: System Representation 2020

The snowboard in this alternative is produced according to the standard practices described in 5.2. The material layers are produced in Europe (Eisenstadt, Austria) and transported by road to the harbor of Trieste, after which they are shipped to China (Xiahai) by container ship. The materials found most common in Chapter 6 are used (see Table 8.2); the electricity is sourced from the grid at the production location (China, Southern Power Grid region (Ecoinvent CN-SCG)). Manufacturing waste treatment is expected to be municipal incineration with heat recovery. The boards are packaged separately in LDPE foil and into cardboard boxes per 6.

Next, the board is distributed and sold. The use-phase in this alternative is intended to represent the current snowboard system, including the mix of common end-of-use options that was obtained in Chapter 5 (see table 8.4). Before use, the LDPE packaging is discarded. The snowboard is serviced once a week with hot wax as described in 5.2. The snowboard is used for 15 weeks during first use; afterwards, 18% of these boards is sold secondhand and enjoys another 15-week use-time, approaching the technical lifetime. This leads to an average lifetime of 17.7 weeks (see Appendix D for details). The boards that reach their end-of-life (82% of first-use and 100% of second-use boards) are either incinerated (21%), stored indefinitely (57%), or reused for another purpose (21%). For the calculation of these shares, see Appendix D.

Alternative 0: Status Quo 2020

The snowboard in this alternative is produced the same way as in the baseline scenario (see 5.2), with the materials found most common in Chapter 4 (see table 8.2). After production, the snowboard is distributed and sold. At the beginning of the use-phase, the LDPE foil packaging is discarded. The snowboard is used for 15 weeks. Once a week, the board is serviced with a standard hot wax (see 5.2). At the end of use, the snowboards in this scenario are incinerated (Yang et al., 2012) (see also tables 8.2, 8.3, & 8.4, and Appendix D).

Alternative 1: Status Quo 2025

This alternative represents the expected status quo system in 2025 and is therefore strongly based on the first two alternatives. The production method and the materials used are the same as in AB & A0 (see table 8.2 and 8.3); however, the electricity mix of the production country (China) is expected to change significantly towards 2025, thus the production electricity is replaced with a proxy for the Chinese electricity mix of 2025 (see Appendix D). After production, the snowboard is distributed and sold, and at the beginning of the use-phase, the packaging is discarded with municipal waste. The snowboard is used for 15 weeks and incinerated at the end of life.

Table 8.3: Production Characteristics per Alternative

Production Characteristics per Alternative						
	AB	**A0**	**A1**	**A2**	**A3**	**A4**
Element	**System Representation 2020**	**Status Quo 2020**	**Status Quo 2025**	**Secondhand Sales**	**Biobased Circularity**	**Recycling Focus**
Material Production	Eisenstadt (AT) & locally in China (steel parts, epoxy)				Locally, India (Hemp, Flax) & Eisenstadt (AT) (base)	Eisenstadt (AT) & locally in China (steel parts, epoxy)
Production Electricity	Chinese Electricity Mix		Chinese electricity mix 2025		Roof PV installation	Roof PV installation
Mixed manufacturing waste	Cured epoxy, glass fibers, PA11/PA12 (incineration)				Fish glue, tannin powder, hemp fibers (composting)	Cured epoxy, basalt fibers, PA11/PA12 (Recycling, solvolysis)
Separate Manufacturing waste	Wood (incineration), UHMWPE, & ABS (Incineration)				UHMWPE (recycling) & wood (feedstock for other industries)	UHMWPE (Recycling) & wood (feedstock for other industries)

Alternative 2: Secondhand Sales

The snowboard in in this alternative is constructed, distributed and sold according to the status quo; however, it is sold secondhand after the first use and is therefore expected to have a lifetime of 30 weeks, which is close to the expected technical lifetime established in Chapter 4 (see Appendix D for calculations and assumptions). For this reason, this scenario should be representative for snowboard use by snow sports professionals, such as instructors, and for rental snowboards, as both of these snowboard categories are expected to last for about the technical lifetime. At the end of life, the snowboard is incinerated.

Alternative 3: Biobased Circularity

The snowboard in this scenario is produced according to biobased circularity principles, with materials that can be returned to the biosphere safely after use as much as possible (see table 8.2). Except for the base, all materials are biobased. The epoxy is replaced by a mixture of fish glue and tannin powder; this has a different curing cycle than epoxy, curing at room temperature for a longer time (preferably overnight). Furthermore, no printing is used. For these reasons, slightly lower electricity use is assumed (28 kWh instead of 35 kWh for the other alternatives, see Appendix D). Since this scenario requires considerable effort towards cleaner production compared to the baseline, it is expected the electricity would be generated with a rooftop PV installation. The snowboard is packaged in biobased PLA.

After production, the snowboard is distributed and sold: at the start of use, the packaging is discarded for composting with biowaste (Green SXM, 2019). The snowboard is used for the average lifetime of 15 weeks and serviced with soybean-based hot wax once a week. After use, the snowboard is reused with a different function, for example as mattress support, as part of a bench, or in a garden fence.

Table 8.4: Use-characteristics per alternative

Use Characteristics per Alternative						
	AB	**A0**	**A1**	**A2**	**A3**	**A4**
Element	**System Representation 2020**	**Status Quo 2020**	**Status Quo 2025**	**Secondhand Sales**	**Biobased Circularity**	**Recycling Focus**
Lifetime	17.7 weeks	15 weeks		30 weeks	15 weeks	
Servicing - hot wax	Fossil-based wax				Soy-based wax	
Servicing Electricity	EU grid					
End-of-life	Incineration (21%), indefinite storage (57%), reuse for another purpose (21%)	Incineration			Reuse for another purpose	Recycling (solvolysis)

Alternative 4: Recycling Focus

The snowboard in this scenario is designed with a focus on recyclability and recycled materials. This involves the recycling of snowboards at the end of life and manufacturing with solvolysis and thus requires materials that stay intact during this process (see Appendix D). The production process stays the same as described in section 5.2. Production electricity is generated by a rooftop PV installation. The mixed manufacturing waste is recycled with solvolysis instead of incineration. During this process, the crosslinks of the epoxy are broken, causing the epoxy to dissolve in thermoplastic fractions (De la Rosa, 2018). This is done by submerging the manufacturing waste in an acetic acid solution (25%) for three hours at 70°, after which the epoxy thermoplastic is dissolved and the separated materials can be removed from the solution. The thermoplastic is subsequently precipitated by neutralization with sodium hydroxide at room temperature (see also Appendix D). This process is assumed to take place at the snowboard production site.

After production, the snowboard is distributed and sold. Before use, the LDPE packaging of the snowboard is discarded for recycling. The snowboard is used for 15 weeks and serviced with soybean-based hot wax once a week. At the end of life, the snowboard is recollected and recycled with the same solvolysis-process used for manufacturing waste. The separated materials are passed on to the respective recycling industries.

Data Gaps and Proxies

Not all materials and processes used in the alternatives were available in Ecoinvent. For these “data gaps”, it was first attempted to find enough data with literature research or expert consultation to model the required processes; if the data found was insufficient, it was attempted to find a representative Ecoinvent “proxy” that had both a similar function and expected environmental footprint (see table 8.5). For some of these missing materials/processes, these strategies did not yield sufficient results. If these flows were not expected to impact the results too severely, these flows were cut-off (see the cut-off section below).

The technologies used in this study have different Levels of Technological Readiness (TRL; see NASA, 2017). In table 8.6, the most important ex-ante elements of this study are listed. A low TRL, data quality, and the inherent unknowns of the future indicate added uncertainty that should be considered for these activities (see Appendix D for the specifics on each process). The effects of this added uncertainty on the results will be discussed further in the discussion.

Table 8.5: Overview of all materials/processes proxied

Materials/Processes proxied			
Materials		***Processes***	
Element	***Proxied with***	***Process***	***Data source***
PA12	PA11	Basalt fiber production	Based on Ecoinvent data
UHMWPE	HDPE	Veneer production	Based on Ecoinvent data
Recycled UHMWPE	recycled HDPE	Linseed oil production	Based on Ecoinvent data
Carbon fibers	Glass fibers	Hemp fiber production	Based on Ecoinvent data
Paulownia	Spruce	Electricity market 2025	Based on external data
Poplar	Beech	Fish glue production	Based on external data
Robinia	Beech	PA11 production	Based on external data
Biobased epoxy	Soybean polyester resin	Tannin powder production	Based on external data
Epoxy curing agent	Epoxy resin	Carbon stringer production	Based on external data

Table 8.6: Ex-Ante Elements

Alternative	Ex-ante elements	Technological Readiness Level	Data Quality
A1, A2	Electricity Market China 2025	TRL 9: High, technology adopted on large scale.	Medium, historical data from Ecoinvent 3.6 & mix data obtained from Chinese government scenarios
A3	Fish Glue & Tannin powder adhesion	TRL 5: Fully working prototype realized and being tested. Lab-scale composite production.	Medium, proxies based on lab-scale papers. Ecoinvent 3.6 historical data used for model.
A3	Hemp Fiber Reinforcement	TRL 6: Small-scale pilot adoption, small market presence	Medium, data based on Ecoinvent historical data, hemp industry papers, and expert consultation
A4	Solvolysis Recycling (manufacturing waste & EOL snowboards)	TRL 3: proof of concept, inferior prototype tested (carbon fiber epoxy composite), no full-size snowboard tests available	Low, processes based on only one literature source and expert consultation not available.

Cut-offs

Flows were cut-off for two reasons: data gaps and simplicity.

Firstly, for some flows, it was not possible to find enough data to model them with sufficient quality. These data gaps could either be lacking process data, for example due to confidentiality in the case of chemicals, or lacking quantity data or foundations for assumptions. If the impacts of these flows on the results were expected not to be too significant, these flows were cut-off.

Secondly, some flows were left out of the model for the sake of simplicity. These include for example capital goods, such as snowboard production facilities or machinery. These goods are expected to last such a long time that their allocation over all snowboards produced leads to insignificantly small numbers, and therefore it is deemed reasonable to leave them outside the scope of the research. The same holds for samples used for sales to stores (see 5.1) or warranty cases.

The cut-offs are summarized in table 8.7.

Table 8.7: Flows not Followed to the System Boundary

Flow	Process (alternative)	Cut-off reason
[W] Wax discarded with servicing	Snowboard Use (All alternatives)	No data available on waste treatment, out of research scope
[G] Machinery, production facility	Snowboard Production (All alternatives)	No data; marginal amounts per product produced
[G] Sublimation printing	Snowboard production (all except A3)	Electricity included; ink, equipment, transfer paper cut off due to lack of data.
[G] Sample boards and warranty cases	Resp. Sales and Use (all alternatives)	Small amounts on the total volume sold; moreover, samples are often sold after use for sales and then enter the normal lifecycle.
[G] Sales process input requirements	Sales	Store inputs such as lighting, heating, marketing pamphlets etc. Cut-off because marginal amounts can be attributed to one snowboard lifecycle.
[W] Snowboard stored indefinitely	Use (AB)	Cut-off for temporal reasons (stored indefinitely)

8.3. Multifunctionality

Naturally, in this study, multifunctional processes exist. In table 8.7, this issue is explored by listing all foreground activities and their functional flows. A functional flow indicates a function: either the treatment of a waste, or the production of a good. In the end, the model contains 13 multifunctional foreground processes: one production process yielding multiple functional products, and twelve waste treatment processes yielding multiple functions. The environmental impacts incurred by these processes need to be divided over their multiple functions following ISO-standard 14044 (ISO, 2006) and the Dutch Handbook of LCA (Guinée et al., 2002).

Table 8.8: (Multi)functionality of all Foreground Activities. Default assumption for functional flows is that they originate from the process ("out"): if the functional flow goes into the process, this is indicated ("in").

Activity	Alternative	Functional Flows	Multifunctionality?
Snowboard Production	(A0), (AB), (A1), (A2), (A3), (A4)	[G] Finished, packaged snowboard	No
Distribution	(A0), (AB), (A1), (A2), (A3), (A4)	[G] Distributed, packaged snowboard	No
Sales	(A0), (AB), (A1), (A2), (A3), (A4)	[G] Snowboard sold to consumer	No
Use	(A0), (AB), (A1), (A2), (A3), (A4)	[G] Weeks of snowboarding	No
Manufacturing Waste Incineration	(A0), (AB), (A1), (A2)	[W] Mixed Manufacturing Waste (in), [G] Heat	Yes, waste treatment and good production
Corrugated Board Recycling	(A0), (AB), (A1), (A2), (A3), (A4)	[W] Waste corrugated board (in), [G] Recycled corrugated board liner	Yes, waste treatment and good production
PE Incineration	(A0), (A1), (AB), (A2), (A4)	[W] Waste PE (in), [G] Heat	Yes, waste treatment and good production
Snowboard Incineration	(A0), (A1), (AB), (A2)	[W] EOL Snowboard (in), [G] Heat	Yes, waste treatment and good production
Secondhand Sales	(AB), (A2)	[W] End-of-use snowboard (in), [G] Snowboard sold secondhand	Yes, waste treatment and good production
Snowboard Reuse for Another Purpose	(AB), (A3)	[W] EOL Snowboard (in), [G] Snowboard Reused for Another Purpose	Yes, waste treatment and good production
(proxy) PA11 production	(A0), (A1), (AB), (A2), (A4)	[G] Polyamide 11 (PA11), [G] Glycerin, [G] Heptaldehyde	Yes, two by-products are produced
(proxy) carbon stringer production	(A0), (A1), (AB), (A2), (A4)	[G] Carbon stringer	No
(proxy) Electricity Market of China 2025, low voltage	(A1), (A2)	[G] Electricity, low voltage	No
HDPE/UHMWPE Recycling	(A3), (A4)	[W] HDPE for recycling (in), [G] Recycled HDPE	Yes, waste treatment and good production
Biowaste Composting	(A3)	[W] Biowaste for composting (in), [G] Compost	Yes, waste treatment and good production
(proxy) Tannin Powder Production	(A3)	[G] Tannin powder	No
(proxy) Fish Glue Production	(A3)	[G] Fish glue	No
(proxy) Hemp Fiber Production	(A3)	[G] Hemp fiber	No
(proxy) Linseed Oil Production	(A3)	[G] Linseed oil	No

(proxy) Veneer Production	(A3)	[G] Wood Veneer	No
Mixed Manufacturing Waste Recycling	(A4)	[W] Mixed Manufacturing Waste (in), [G] Separated Basalt Fibers	Yes, waste treatment and good production
LDPE Recycling	(A4)	[W] Waste LDPE (in), [G] Recycled LDPE (granulate)	Yes, waste treatment and good production
Waste Wood Processing for Paper Industry	(A4)	[W] Waste Wood (in), [G] Wood Chips for Paper Production	Yes, waste treatment and good production
EOL Snowboard Recycling	(A4)	[W] EOL Snowboard (in), [G] Separated Basalt Fibers, [G] Recycled Steel, [G] Recycled Chromium Steel, [G] Wood Chips for Paper Production, [G] Recycled HDPE	Yes, waste treatment and good production

Firstly, there is one multifunctional process in this study that produces multiple valuable products: the proxy for PA11 production. In the data source, mass-based allocation is used for this process; in order to keep the proxy consistent with the source, the same allocation approach is applied here instead of applying the hierarchy explained below (see Appendix D).

Secondly, the multifunctional waste-treatment processes need to be treated. According to ISO-standard 14044, allocation should be avoided where possible, either by collecting extra data or expanding the systems of all compared alternatives to include all additional functions (ISO, 2006). As waste-treatment activities are inherently multifunctional, the first option is not possible; due to the scope of the alternatives and the wide range of additional functional flows (see table 8.8), system expansion is not feasible. However, the "substitution" approach, where the alternative systems are expanded to include an equivalent product whose burden is avoided because it is assumed to be "substituted" by the product of the waste treatment process is sometimes considered as another way to perform system expansion (e.g. European Commission, 2010), although there is a practical difference between the two: in system expansion, additional functions are added to the system, while in substitution, the avoided impact of the additional function is subtracted (Heijungs & Guinée, 2007). Taking into account these arguments, it is decided to use the substitution approach and carefully evaluate the impacts of this with sensitivity analysis (see Chapter 10). Due to software limitations, the options for other multifunctionality treatment approaches are limited.

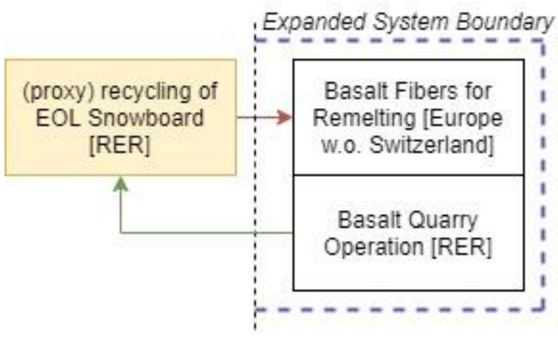


Figure 8.7: Example of the substitution multifunctionality treatment approach used in this study

As an example of this approach, the snowboard recycling process in A4 yields EOL basalt fibers; since these can be remelted into new fibers, they could replace the virgin basalt feedstock. The avoided environmental impacts of the "substituted" virgin basalt are therefore subtracted from the environmental impact of the recycling (see figure 8.7). All processes necessary to turn the waste-treatment product into an equivalent product to the substitute are included. All waste treatment process for which this approach is applied are listed in table 8.9; in Appendix D, each substitution system is described.

Table 8.9: Overview of Multifunctional Processes and Implemented Solutions

Multifunctional Process	Functional Flows Exiting the System	Solution (see Appendix D)
PA11 Production (A0, AB, A1, A2, A4)	[G] Glycerin, [G] Heptaldehyde	Mass Allocation (see Appendix D)
HDPE/UHMWPE Recycling (A3, A4)	[G] Secondary HDPE/UHMWPE	Primary HDPE/UHMWPE (*Substitution A)*
LDPE Recycling (A4)	[G] Secondary LDPE	Primary LDPE *(Substitution B)*
Corrugated Board Recycling (All Alternatives)	[G] Recycled Fluting Medium for Corrugated Board	Virgin Fluting Medium *(Substitution C)*
Biowaste Composting (A3)	[G] Compost	Mineral Fertilizer *(Substitution D)*
Snowboard Reuse for Another Purpose (AB, A3)	[G] Snowboard Reused for Another Purpose	Hardwood Plank *(Substitution E)*
EOL Snowboard Recycling (A4)	(1) [G] Separated Basalt (2) [G] UHMWPE (3) [G] (chromium) Steel (4) [G] Incineration Heat (from mixed thermoplastics)	(1) Primary Basalt Rock (2) Primary UHMWPE (3) Primary (Chromium) Steel (4) Heat (district or industrial) *(Substitution F)*
Manufacturing Waste Incineration (A4)	[G] Incineration heat	Heat (district or industrial) *(Substitution G)*
PE Incineration (A0, AB, A1, A2, A4)	[G] Incineration heat	Heat (district or industrial) *(Substitution H)*
Snowboard Incineration (A0, AB, A1, A2)	[G] Incineration heat	Heat (district or industrial) *(Substitution I)*
Mixed Manufacturing Waste Recycling (A4)	(1) [G] Separated basalt fibers (2) [G] Incineration heat (from mixed plastics)	(1) Primary Basalt Rock (2) Heat (district or industrial) *(Substitution J)*
Waste Wood Processing for Paper Industry (A4)	[G] Wood chips	Wood chips for paper production *(Substitution K)*

Finally, the model was based on the cut-off system model of Ecoinvent 3.6. In this version of the database, the waste treatment burden is fully assigned to the waste-producing system, while the efforts to produce a recycled material are assigned to the system using this material (Ecoinvent, n.d.). Concretely, this means that waste streams in this project are cut off as soon as they become a feedstock for another system. This is thus a different method of multifunctionality treatment to the one used in this study, which could impact the results.

8.4 Results of inventory analysis

The results of the inventory analysis can be found in Appendix E (provided separately from this document).

9. Impact assessment

In this chapter, the environmental impact of the alternatives is quantified and compared. The impact categories relevant to the goal and scope of the study are first identified. Afterwards, the characterization results for the alternatives are presented. Finally, the environmental interventions not included in the characterization models and the economic flows not followed to the system boundary are discussed.

9.1. Selection of Impact Categories and Characterization Models

The goal of this study is "to compare different types of circular snowboard lifecycles with Business as Usual" and "to allow people in this and related sectors to make evidence-based decisions" (see 9.1). The circular economy aims to "decouple" consumption from resource use and eradication of the biosphere (European Commission, 2020; Ellen MacArthur Foundation, 2013). To evaluate the effectiveness of the scenarios in satisfying these aims, the aims should be covered by the impact categories. Moreover, the actors in the snowboard industry often focus on certain impact categories when they present sustainability measures; these should therefore also be included.

Currently, the ILCD 2018 midpoint characterization family is the standard recommended by the European Union (Fazio et al., 2018). This characterization model family will therefore be used. Based on the requirements listed above, the following impact categories are selected:

- **Climate Change – Total (kg CO_2-eq)**
- **Freshwater and Terrestrial Eutrophication (mol H+ eq)**
- **Freshwater Ecotoxicity (CTU)**
- **Freshwater Eutrophication (kg P-eq)**
- **Marine Eutrophication (kg N-eq)**
- **Terrestrial Eutrophication (mol N-eq)**
- **Dissipated Water (m^3 water)**
- **Land Use (points)**
- **Resource Use, Minerals and Metals (kg Sb-eq)**
- **Resource Use, Fossils (MJ)**
- **Carcinogenic Effects (CTUh)**
- **Ionizing Radiation (kg U235-eq)**
- **Non-Carcinogenic Effects (CTUh)**
- **Ozone Layer Depletion (kg CFC-11)**
- **Photochemical Ozone Creation (kg NMVOC-)**
- **Respiratory Effects, Inorganics (disease i.)**

9.2. Characterization Results

In this section, the characterization results for the alternatives are presented. The results are discussed for the impact categories presented in 9.1, for the functional unit (15 weeks of all-mountain snowboarding) (see table 11.1 and figure 11.1; the values in figure 11.1 can be found in Appendix G).

Table 9.1: Characterization Results for 15 Weeks of Snowboarding

	(AB)	(A0)	(A1)	(A2)	(A3)	(A4)
Climate Change Total (kg CO_2-eq)	$3.63 * 10^{1}$	$4.49 * 10^{1}$	$4.15 * 10^{1}$	$2.12 * 10^{1}$	$1.54 * 10^{1}$	$2.34 * 10^{1}$
Freshwater and Terrestrial Acidification (mol H+-eq)	$2.44 * 10^{-1}$	$2.88 * 10^{-1}$	$3.00 * 10^{-1}$	$1.53 * 10^{-1}$	$1.20 * 10^{-1}$	$1.89 * 10^{-1}$
Freshwater Ecotoxicity (CTU)	$4.02 * 10^{1}$	$4.97 * 10^{1}$	$5.01 * 10^{1}$	$2.52 * 10^{1}$	$6.95 * 10^{1}$	$4.78 * 10^{1}$
Freshwater Eutrophication (kg P-eq)	$1.60 * 10^{-2}$	$1.80 * 10^{-2}$	$1.80 * 10^{-2}$	$9.00 * 10^{-3}$	$5.30 * 10^{-2}$	$2.30 * 10^{-2}$
Marine Eutrophication (kg N-eq)	$5.80 * 10^{-2}$	$6.90 * 10^{-2}$	$6.80 * 10^{-2}$	$3.40 * 10^{-2}$	$4.70 * 10^{-2}$	$5.50 * 10^{-2}$
Terrestrial Eutrophication (mol N-eq)	$6.20 * 10^{1}$	$7.37 * 10^{1}$	$7.22 * 10^{1}$	$3.66 * 10^{1}$	$3.22 * 10^{1}$	$5.28 * 10^{1}$
Dissipated Water (m3 water)	$7.92 * 10^{0}$	$9.48 * 10^{0}$	$9.88 * 10^{0}$	$4.92 * 10^{0}$	$2.26 * 10^{1}$	$1.56 * 10^{1}$
Fossils (MJ)	$5.17 * 10^{2}$	$606 * 10^{2}$	$566 * 10^{2}$	$298 * 10^{2}$	$209 * 10^{2}$	$354 * 10^{2}$
Land Use (points)	$8.04 * 10^{2}$	$1.37 * 10^{3}$	$1.51 * 10^{3}$	$7.62 * 10^{2}$	$3.90 * 10^{2}$	$1.34 * 10^{3}$
Minerals and Metals (kg Sb-eq)	$3.52 * 10^{-4}$	$4.20 * 10^{-4}$	$4.67 * 10^{-4}$	$2.30 * 10^{-4}$	$5.27 * 10^{-4}$	$6.82 * 10^{-4}$
Carcinogenic Effects (CTUh)	$1.10 * 10^{-6}$	$1.30 * 10^{-6}$	$1.30 * 10^{-6}$	$7.00 * 10^{-6}$	$1.00 * 10^{-6}$	$1.00 * 10^{-6}$
Ionising Radiation (kg U235-eq)	$2.1 * 10^{0}$	$3 * 10^{0}$	$2.8 * 10^{0}$	$1.6 * 10^{0}$	$1.5 * 10^{0}$	$3.5 * 10^{0}$
Non-Carcinogenic Effects (CTUh)	$2.20 * 10^{-5}$	$2.70* 10^{-5}$	$2.70* 10^{-5}$	$1.30* 10^{-5}$	$-2.00* 10^{-6}$	$2.60* 10^{-5}$
Ozone Layer Depletion (kg CFC-11)	$1.30 * 10^{-6}$	$1.60 * 10^{-6}$	$1.80 * 10^{-6}$	$9.00 * 10^{-7}$	$5.00 * 10^{-6}$	$4.40 * 10^{-6}$
Photochemical Ozone Creation (kg NMVOC-)	$1.30 * 10^{-1}$	$1.50 * 10^{-1}$	$1.50 * 10^{-1}$	$8.00 * 10^{-2}$	$7.00 * 10^{-2}$	$1.10 * 10^{-1}$
Respiratory Effects, Inorganics (disease i.)	$2.30 * 10^{-6}$	$2.80 * 10^{-6}$	$2.50 * 10^{-6}$	$1.30 * 10^{-6}$	$6.00 * 10^{-7}$	$1.10 * 10^{-6}$

In figure 9.1 and 9.2, the characterization results are presented relative to the 2025 baseline (A1), which was scaled to 1. From the differences between the 2020 baseline scenario (A0) and the 2025 baseline (A1) it can be concluded that the developments in electricity mix led to significant changes in some impact categories: Climate Change Total (-8% compared to 2020), Fossils (-7%), Minerals and Metals (+11%), Land Use (+10%), Ionizing Radiation (-8%), and Respiratory Effects, Inorganics (-9%) .

Secondly, the alternative with the extended lifetime (A2) is the only circular alternative consistently performing better than the 2025 baseline across all categories (with about 47-50% lower impact). The only impact category for which a higher impact is recorded is Ionizing Radiation (58% of the 2025 baseline). This indicates that lengthening the lifetime of a snowboard might be one of the most effective ways to decrease its environmental impact.

The other circular alternatives have a more variable impact. The biobased alternative (A3) has a significantly lower impact than A1 in some categories, sometimes up to 75% (Respiratory Effects, Inorganics; see table G.3). In Non-Carcinogenic Effects, this alternative even records a negative impact (-9% of the impact of A1), something that should be addressed further in the interpretation (see 10.3

and 10.4). The same holds for the decreased Land Use and Marine and Terrestrial Eutrophication-impacts compared to A1; due to the use of biobased materials, land use and eutrophication were expected to increase. Finally, the steep increase in Freshwater Eutrophication and Dissipated Water compared to the 2025 baseline also deserves additional attention. In Freshwater Ecotoxicity and Minerals and Metals, the biobased alternative causes a slight increase.

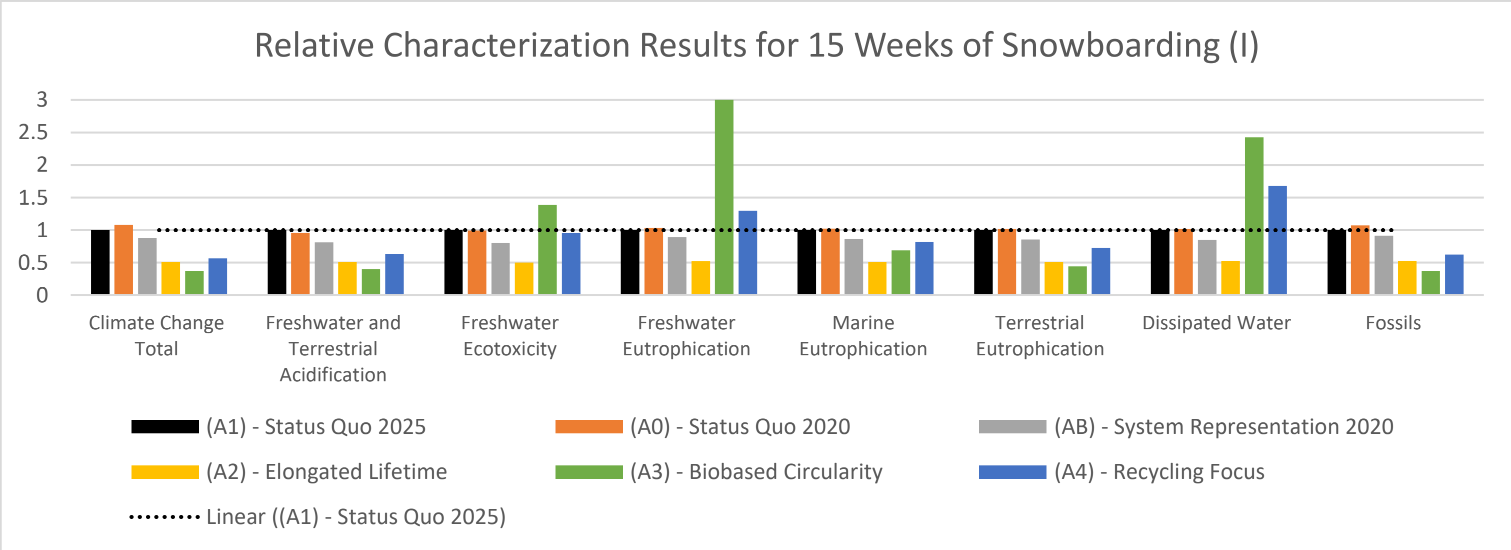
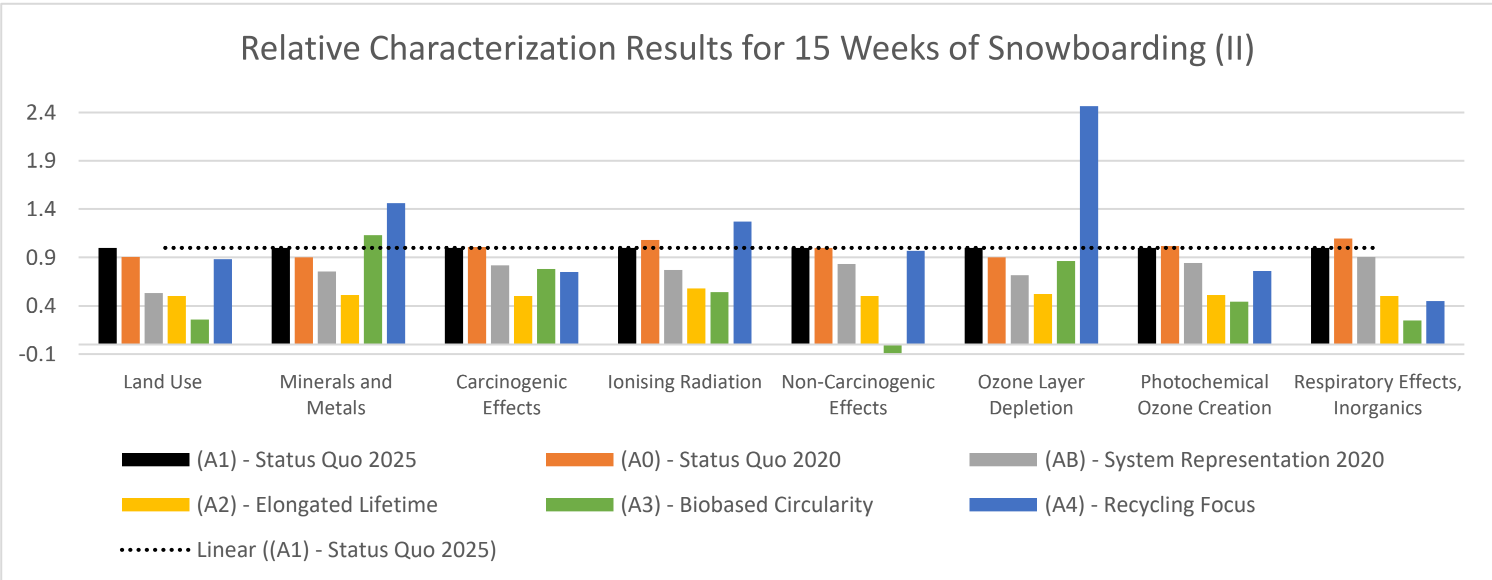


Figure 9.1: Characterization results scaled to the 2025 baseline (A1) (I)

The results of the recycling-focused alternative (A4) follow a similar pattern to the bio-based alternative (A3), although the results are mostly less extreme. It is also observed that this alternative performs similarly to the baseline in Freshwater Ecotoxicity, Marine and Terrestrial Eutrophication, Land Use, and Non-Carcinogenic Effects. Interestingly, the depletion of minerals and metals increases for the recycling-focused alternative. Moreover, Ozone Layer Depletion for A4 is 2.5 times higher than for A1; these results deserve more attention in the contribution analysis (10.3).



9.3. Missing Interventions & Economic Flows

Interventions for which characterization factors are lacking

Unfortunately, a large volume of elementary flows is not covered by the current characterization families. It is unfortunately not possible to extract a list of flows that were not characterized in the current results out of the Activity Browser; however, this is likely the case for some flows in the inventory and should be taken into account. For the ILCD 2018 midpoint characterization family, a list of all elementary flows included in the characterization can be found in Fazio et al. (2018).

Economic flows not followed to the system boundary

In this research, a number of flows were cut off and not followed to the economy-environment system boundary. These flows can be found in section 8.3 (table 8.6). If included, these flows could have an impact on the results; this should therefore be taken into account when interpreting the results of this study.

10. Interpretation

In this chapter, the LCA-study is interpreted. First, the model is checked for consistency and completeness. Afterwards, contribution and sensitivity analyses are conducted.

10.1. Consistency Check

In this section, the consistency of the model with the goal and scope of the study is assessed. The goal of this study was the following: "to compare different types of circular snowboard lifecycles with Business as Usual, in order to show what implications certain circularity decisions have on the environmental impact, and to allow people in this and related sectors to make evidence-based decisions" (p. 34). To this aim, six alternatives were modelled, of which four (A1 – A4) were modelled in 2025 using an ex-ante approach.

Inconsistency between the background system, usually based on historical databases such as Ecoinvent, and the future foreground system is an unavoidable problem for ex-ante LCA studies (Van der Giesen et al., 2020). In this study, this problem was addressed by extrapolating the technologies with the largest environmental impact in the present to 2025 based on scenarios from academic literature (see 7.2). However, the background technology processes themselves were still based on historical (and therefore outdated) data. We therefore have to conclude that an inconsistency between the foreground and background systems exists, and that the use of outdated data will affect the results.

Another source of inconsistency in this study is the difference between the ex-ante alternatives (A1 – A4) and the alternatives in present time (A0 & AB). Especially A3 and A4 include technologies that are not yet employed on a commercial scale. These technologies were not present in the existing Ecoinvent database and had to be modelled based on lab-scale sources (see 8.3). Due to the scope of this study, no or limited scaling to commercial levels was applied. This could lead to an unfair comparison with the commercial-scale technologies used in A0, AB, A1 and A2 with outcomes favorable to the incumbent alternatives. Moreover, the future of emerging technologies is likely more uncertain than the future of the incumbent (Van der Giesen et al., 2020); thus, uncertainty inconsistency also exists between the alternatives. A safety margin should therefore be used when comparing the results for A3 and A4 with the more conventional alternatives.

These challenges affect the consistency with the study's goal and scope and the power of the results. The results of this study should therefore not be seen as definitive, but rather as an indication of the potential comparative environmental impacts of the evaluated technologies under specific circumstances, as Villares et al. suggest (2017, as cited by Van der Giesen et al., 2020). With this information, the involved stakeholders should work to further develop these technologies while taking into account their potential environmental impact hotspots. With iterative LCA-evaluation, this could lead to more effective circular economy implementation.

10.2. Completeness Check

In this section, the study is assessed on completeness for interpretation by looking at data gaps and potential errors in data, assumptions, and modelling choices (Guinée et al., 2002).

Naturally, this study suffers from data gaps. These data gaps exist for various reasons: some activities were confidential, some activities were not (yet) undertaken on a large scale and not available in the Ecoinvent database, and for some activities, any data on quantities was simply missing. In general, data gaps were addressed with the strategy specified in 8.3: where possible, activities were modelled with expert knowledge or literature. If this was not feasible, the activity was proxied with a similar activity for which data was available. Finally, if the data for a representative substitute was also lacking, the flow was cut-off (see 8.3). It was attempted to only cut off flows that would not affect the results too severely; however, since these cut-offs were made because of lacking data, this could not be verified. Both these cut-offs and the proxies could lead to completeness issues.

Especially for the prospective alternatives (1 – 4), and then specifically the ones employing emerging technologies (3 – 4), finding representative data was an issue, also because the required commercial-scale data simply did not yet exist (Van der Giesen et al., 2020). Thus, these processes were modelled with lab-scale data; this inherently has an impact on the completeness of the results. Economic and environmental flows that might occur in larger-scale processes might not be included and vice versa. Moreover, since the future cannot be predicted, both the incumbent and developing technologies in the prospective alternatives might develop or be produced differently in reality (Van der Giesen et al., 2020). This means that the chance on qualitative data gaps, where an input is simply not known and therefore not included (European Commission, 2010), is also higher for these alternatives. The future alternatives are therefore inherently less complete than the historical alternatives.

A few measures were taken to enforce data completeness. First, where possible, the data and modelling choices were evaluated by and sourced from industry experts. This led to a number of significant improvements in the model, for example in the quantity of steel used for the edges. Estimated data was cross-checked with calculation based on different samples (e.g. cardboard packaging). Control cells were built in for the calculations in Excel, and different error-checking rounds of the model in the LCA-software were held to make sure the unit process data was entered correctly.

In a related study on skis by Luthe, Kägi and Reger (2013), a similar degree of completeness is observed. For some elements, such as epoxy hardener, data is simply not available; this was proxied with epoxy resin, like in this study. Luthe, Kägi and Reger also exclude machinery and capital goods and have modelled the production of basalt fibers the same way (2013, p. 612). They find a climate change impact of 45 kg CO_2-eq for a pair of conventional skis, which is close to the 44.9 kg CO_2-eq found for A0 in this study. The other alternatives in this study unfortunately differ too much from their alternatives to compare. Since the snowboard- and ski lifecycle are very similar, and the same is expected for the GWP, this indicates similarity in completeness level of these studies, at least for the BAU-alternatives.

In conclusion, the model suffers from some completeness issues, especially for the future alternatives (1-4). However, as was indicated in the consistency check, the aim of this study is not to draw definitive conclusions on the impact of the alternatives, but rather to indicate potential environmental impacts that should be focused on in the development of the technologies; this aim should not be affected.

10.3. Contribution Analysis

To identify so-called environmental impact “hotspots”, contribution analyses are conducted (Guinée et al., 2002). This can be done in different ways: one could for example research the contribution of elementary flows to the characterization results. In this study, the life cycle stage-approach is taken, where the impact of each lifecycle stage is extracted.

The contribution analysis structure is depicted in figure 10.1. Firstly, every alternative in this study can be divided into the main lifecycle stages Material Supply, Production, Distribution, Sales, Use, and End of Life (EOL); the contributions of these stages will be discussed. Additionally, processes were aggregated into four product categories: Packaging, Production Electricity, Transport, and Waste Treatment. This was done by selecting all in- and outflows of the Activity-Browser model and dividing these into the processes depicted in figure 10.1. In Appendix H (provided separately from this document), the aggregation into these categories is clarified for all foreground economic flows. Moreover, in Appendix H, all values behind figure 10.2 and 10.3 are presented. Table 10.2 is also included in appendix H.

To explore what flows determine the contribution of a certain lifecycle phase or input category, the Sankey-diagram function built into the Activity Browser software is used. A Sankey-diagram depicts how things (e.g. objects, substances, embedded environmental impacts, …) "flow" from one connection to another (SankeyMATIC, n.d.). Unfortunately, these diagrams could not be included in the appendix because they could not be exported from the Activity Browser-software. From the Sankey diagrams, the most important contributors of the system supply chains were identified (e.g. the supply chain of the PA11 topsheet); these results are presented in table 10.2.

The results are presented in absolute values for two reasons. Firstly, this way, the relative size of the life cycle stage impacts can also be compared. Secondly, the substitution allocation method led to negative waste treatment impacts in some cases, which inflated the 100% results and degraded the information power. Graphs depicting the results scaled to 100% are presented in Appendix G.

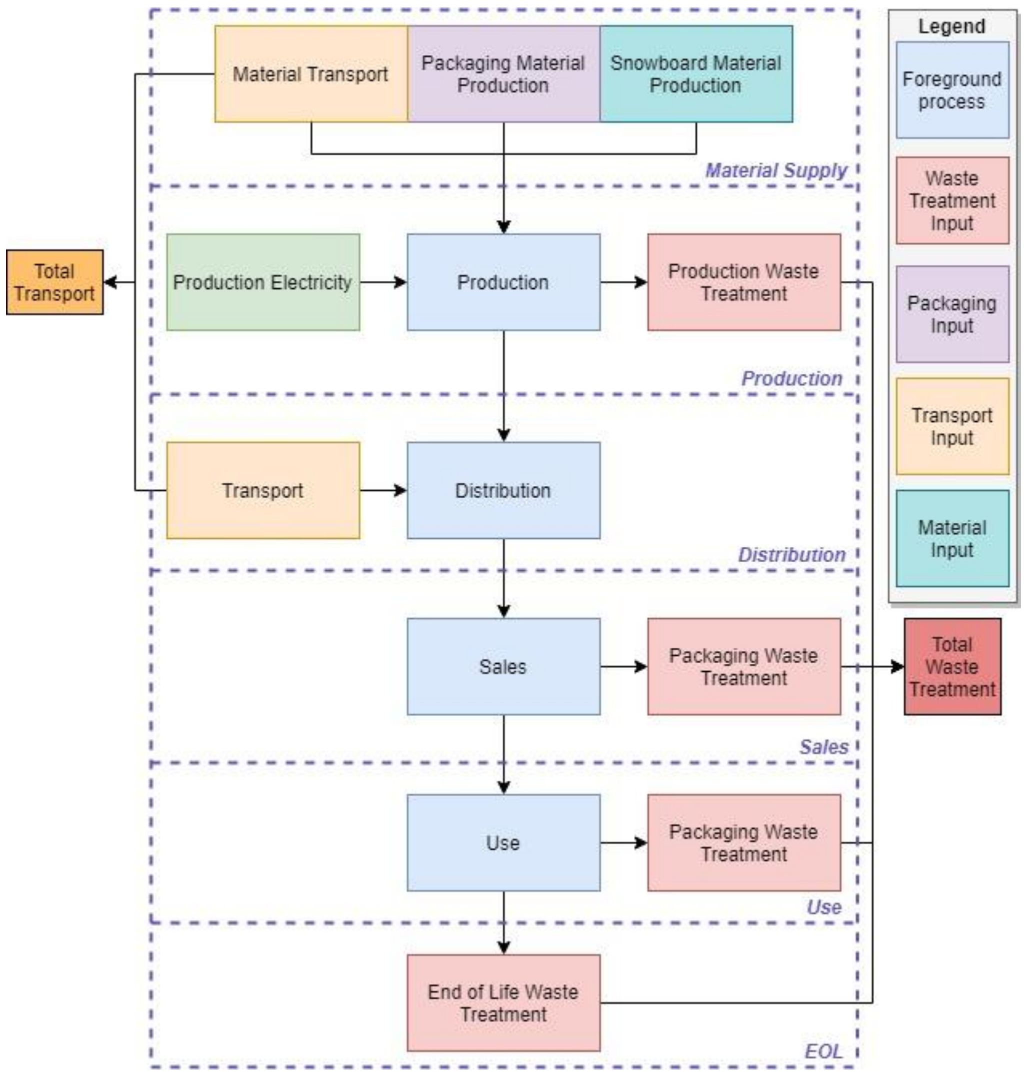


Figure 10.1: Overview of the contribution analysis structure

A few general trends are observed in the contribution results (see figure 10.2 - 10.4). Firstly, the materials supply – and production phase dominate the results, together making up at least 61% of the impact category results for every alternative. The contribution of distribution, sales, use, and EOL treatment is limited; however, in specific cases, the impact of these phases is increased. Looking at the aggregated product categories (figure 10.3), it is observed that packaging barely contributes to the results.

Business-as-Usual (BAU) Contributions

For BAU alternatives A0, A1, and AB, material supply makes up the largest contributor in 10 impact categories (see figure 10.2 & 10.4): Freshwater Ecotoxicity, Freshwater Eutrophication, Marine Eutrophication, Terrestrial Eutrophication, Dissipated Water, Land Use, Minerals and Metals, Carcinogenic Effects, Non-Carcinogenic Effects, and Ozone Layer Depletion. The PA11 topsheet and the epoxy are consistent contributors to these large material supply results (see table 10.2).

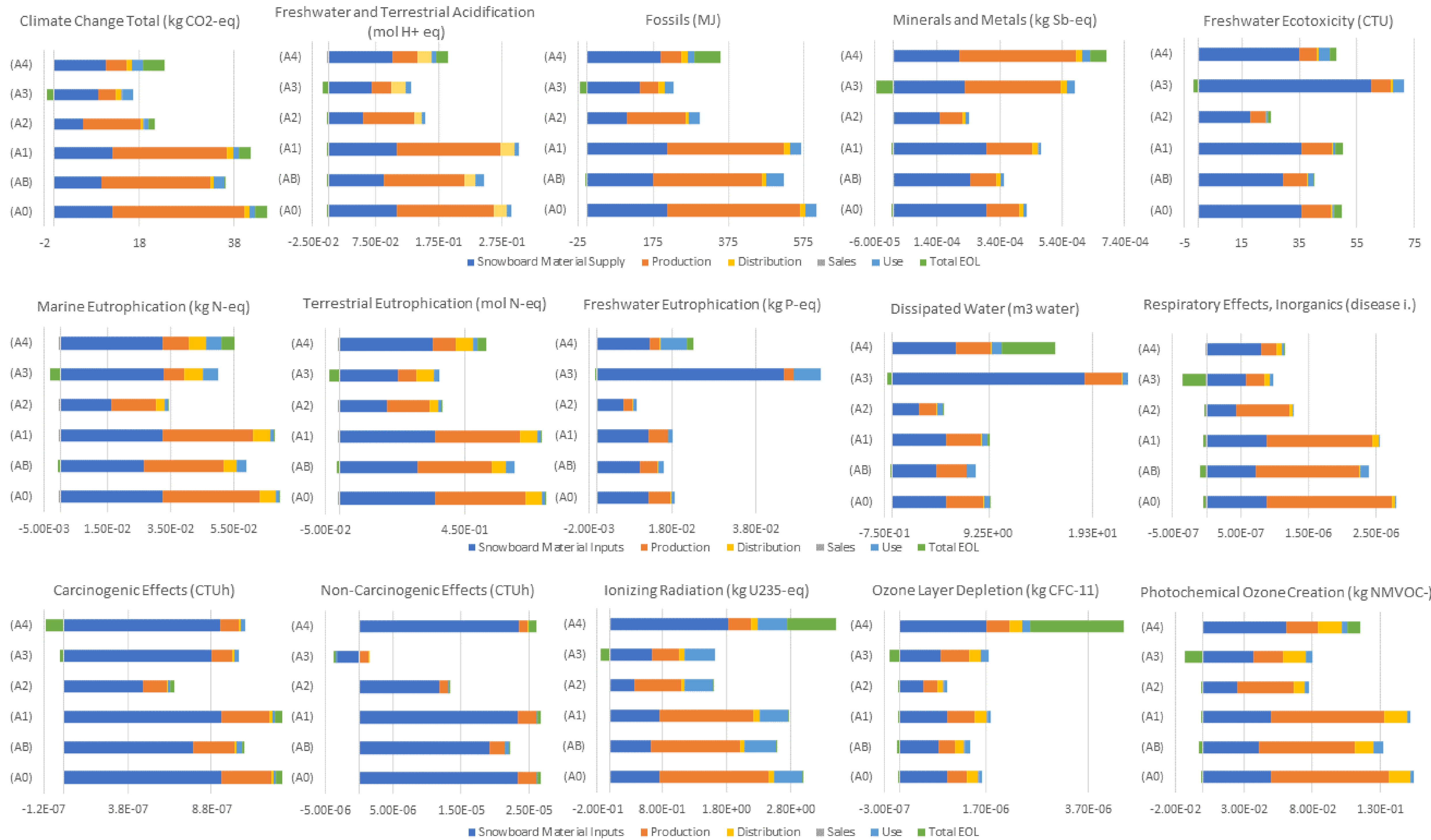
Production has the largest contribution to Climate Change Total, Freshwater and Terrestrial Acidification, Fossils, Ionizing Radiation, Photochemical Ozone Creation, and Respiratory Effects, Inorganics. Looking at the drivers of this large production contribution, we observe that electricity likely makes up the bulk of it, with a minimum contribution of 50% to these categories (see table 10.2). Moreover, the difference between the results for the production-stage (figure 10.2) and production electricity (figure 10.3) is maximum 14% (see appendix H), indicating that production electricity makes up at least 86% of the production impact for AB, A0 and A1 across all impact categories.

Distribution, Sales, and Use have a limited contribution to the results of these alternatives. Distribution contributes 0-3% in most categories, with the largest contribution in Marine and Freshwater Eutrophication (8-9%), Photochemical Ozone Creation (11%), and Ozone Layer Depletion (14%). Sales does not contribute to any impact category except Land Use and Respiratory Effects, Inorganics, where it has a slight "negative" result (-1 – -4%), indicating the "avoided burden" of the cardboard packaging recycling. The Use-phase contributes between 2-6% for all categories except Ionizing Radiation (16 - 19%).

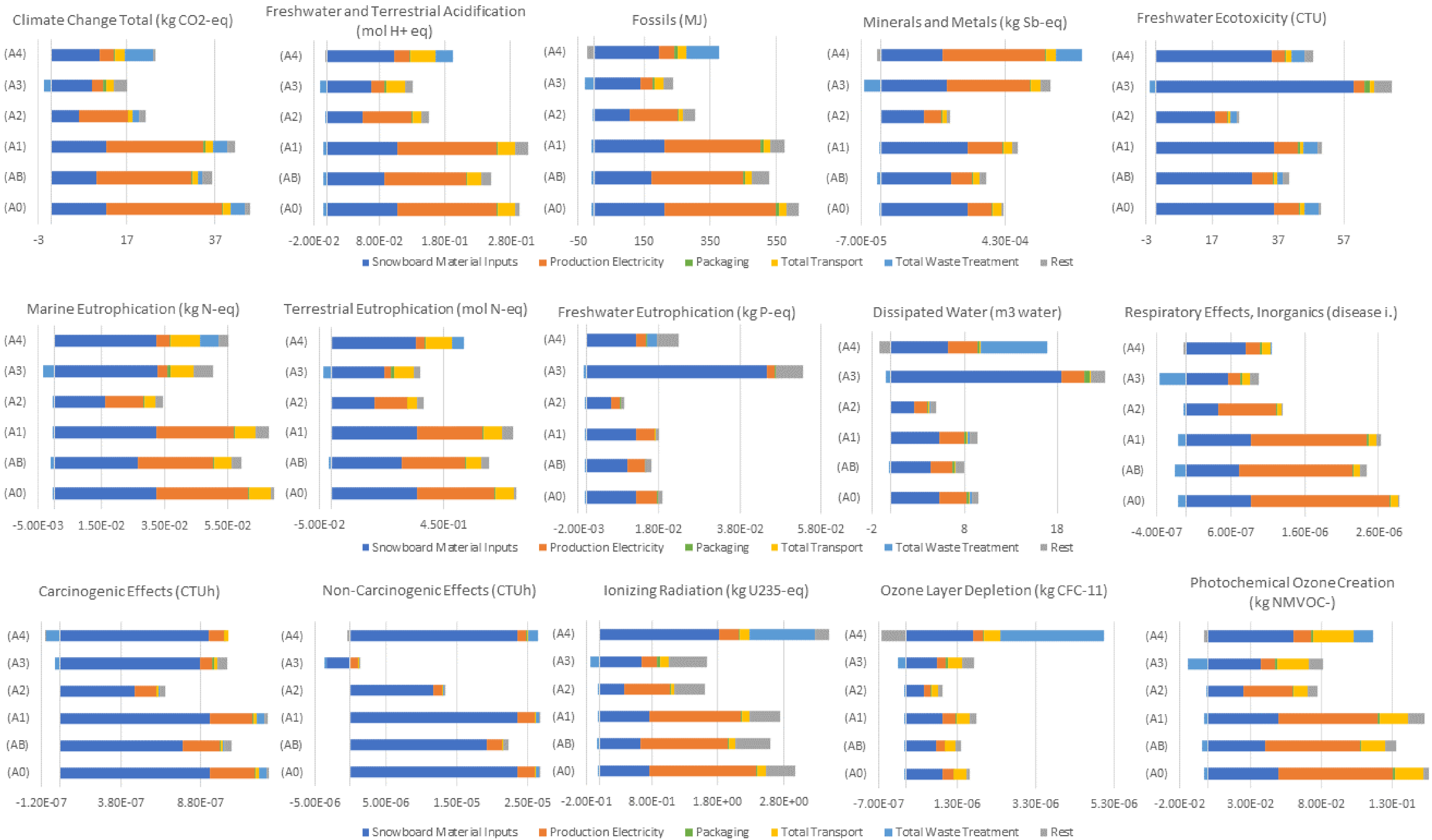
The EOL treatment contributions are negative in some categories due to the inclusion of waste treatment avoided burdens. These impacts are, however, not negative in reality (see 11.1). In the case of the EOL snowboard incineration in AB, A0, and A1, the negative impacts are small (see figure 10.2 and 10.3); however, for the reuse of the EOL snowboard for another purpose, where the snowboard replaces a wooden plank, the negative results reach up to -71% (Land Use) (see figure 10.2, 10.4 and table 10.2). This result is further interpreted in 11.1.

In conclusion, the main hotspots for these alternatives lie in the material supply-stage and the production stage. The material supply-contribution has a few main drivers (see table 10.2): the PA11 topsheet, the wooden core, and the base. For the production phase, the production electricity is the main contributor. These processes therefore deserve attention if the impact of these alternatives is to be decreased.

Figure 10.2 (p. 53): Absolute contributions of life cycle stages to the impact category results (X-axis units in graph titles).
Figure 10.3 (p.54): Absolute contributions of aggregated product categories to the impact category results (X-axis units in graph titles).



Climate Change Total (kg CO2-eq)
Freshwater and Terrestrial Acidification (mol H+ eq)
Fossils (MJ)
Minerals and Metals (kg Sb-eq)
Freshwater Ecotoxicity (CTU)
(A4)
(A3)
(A2)
(A1)
(AB)
(A0)
-2 18 38
-2.50E-02 7.50E-02 1.75E-01 2.75E-01
-25 175 375 575
-6.00E-05 1.40E-04 3.40E-04 5.40E-04 7.40E-04
-5 15 35 55 75
Snowboard Material Supply
Production
Distribution
Sales
Use
Total EOL
Marine Eutrophication (kg N-eq)
Terrestrial Eutrophication (mol N-eq)
Freshwater Eutrophication (kg P-eq)
Dissipated Water (m3 water)
Respiratory Effects, Inorganics (disease i.)
-5.00E-03 1.50E-02 3.50E-02 5.50E-02
-5.00E-02 4.50E-01
-2.00E-03 1.80E-02 3.80E-02
-7.50E-01 9.25E+00 1.93E+01
-5.00E-07 5.00E-07 1.50E-06 2.50E-06
Snowboard Material Inputs
Production
Distribution
Sales
Use
Total EOL
Carcinogenic Effects (CTUh)
Non-Carcinogenic Effects (CTUh)
Ionizing Radiation (kg U235-eq)
Ozone Layer Depletion (kg CFC-11)
Photochemical Ozone Creation (kg NMVOC-)
-1.2E-07 3.8E-07 8.8E-07
-5.00E-06 5.00E-06 1.50E-05 2.50E-05
-2.00E-01 8.00E-01 1.80E+00 2.80E+00
-3.00E-07 1.70E-06 3.70E-06
-2.00E-02 3.00E-02 8.00E-02 1.30E-01
Snowboard Material Inputs
Production
Distribution
Sales
Use
Total EOL


Climate Change Total (kg CO2-eq)
Freshwater and Terrestrial Acidification (mol H+ eq)
Fossils (MJ)
Minerals and Metals (kg Sb-eq)
Freshwater Ecotoxicity (CTU)
Marine Eutrophication (kg N-eq)
Terrestrial Eutrophication (mol N-eq)
Freshwater Eutrophication (kg P-eq)
Dissipated Water (m3 water)
Respiratory Effects, Inorganics (disease i.)
Carcinogenic Effects (CTUh)
Non-Carcinogenic Effects (CTUh)
Ionizing Radiation (kg U235-eq)
Ozone Layer Depletion (kg CFC-11)
Photochemical Ozone Creation (kg NMVOC-)
(A4)
(A3)
(A2)
(A1)
(AB)
(A0)
Snowboard Material Inputs
Production Electricity
Packaging
Total Transport
Total Waste Treatment
Rest

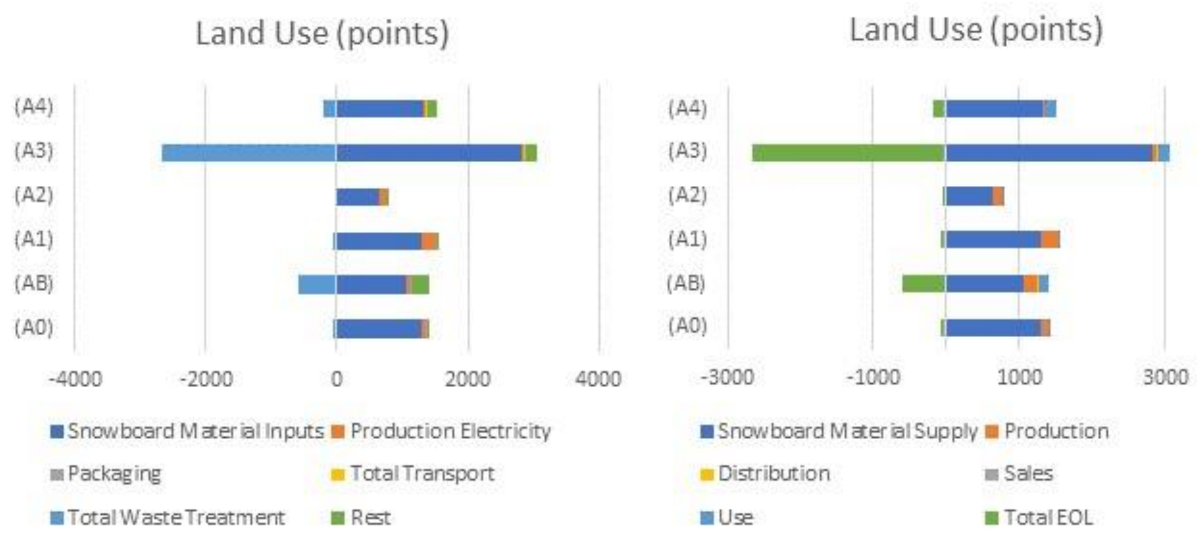


Figure 10.4: Absolute Land Use contributions of aggregated product categories (left) and life cycle stages (right).

Contributions Circular Alternatives

The contributions for the Technical Lifetime-alternative (A2) show a picture similar to the BAU alternatives. Material supply and production make up the largest contribution share in the same categories: material supply in Freshwater Ecotoxicity, Freshwater Eutrophication, Marine Eutrophication, Terrestrial Eutrophication, Dissipated Water, Land Use, Minerals and Metals, Carcinogenic Effects, Non-Carcinogenic Effects, and Ozone Layer Depletion, and production in Climate Change Total, Freshwater and Terrestrial Acidification, Fossils, Ionizing Radiation, Photochemical Ozone Creation, and Respiratory Effects, Inorganics. Like for the BAU-alternatives, the PA11 topsheet and the epoxy are consistent large material supply-contributors (see table 10.2), and production electricity causes most of the production-impact (see Appendix H). The snowboard in A2 has a use-stage twice as long as A1 (30 instead of 15 weeks) and is therefore expected to have a larger use-stage contribution; however, the increase is limited (6% average use-stage contribution for A2, 3% for A1). Ionizing Radiation is an exception to this observation: in this category, use makes up 28% for A2 (14% for A1). This large contribution is due to the electricity used for servicing the board (see table 10.2). The limited use-stage contribution explains why the longer use-time in A2 leads to the large impact reductions observed in 9.2: the other stages determine most of the impact, leading to total impact reductions if the snowboard is used for longer.

Compared to BAU, the contribution analysis of the biobased alternative (A3) yields some interesting results. Firstly, the contribution of the materials-supply stage is larger for every impact category compared to A1, and material supply is now the largest contributor in all categories except Minerals and Metals (see figure 10.2), with a minimum contribution of 43% (Appendix H). The contribution of distribution has also increased, now on average contributing 8% compared to 4% for A1.

A3 has a Freshwater Eutrophication result three times larger than the 2025 baseline (A1) (see figure 10.2), mostly because of the material supply (84%) and use (12%) stages. The production of fish glue is responsible for 70.5% of this impact, specifically the treatment of wastewater originating from this process (69.9%) (see table 10.2). The use-impact in this category is due to soybean wax (10.5%). The material supply-stage also contributes largely to the increase in Freshwater Ecotoxicity (86% material supply-contribution) and Dissipated Water (81%), mainly due to the production of hemp fibers (resp. 62% and 52.3% contribution, see table 10.2).

The use of PV production electricity instead of the electricity mix is responsible for some changes compared to BAU (see figure 10.2 and 10.3). The impact in Minerals and Metals is higher for A3: in this category, production makes up the largest contribution (58%, of which 93% can be attributed to production electricity, see Appendix H), due to the material requirements of the PV panels and the inverter. In the categories Climate Change Total, Freshwater and Terrestrial Acidification, and Marine- and Terrestrial Eutrophication, the switch to PV electricity leads to a significant impact reduction (see figure 10.3). This explains the low Marine- and Terrestrial Eutrophication results observed in 9.2.

Finally, in figures 10.2 - 10.4, numerous "negative" impacts are observed for A3. These occur for two reasons. Firstly, in Non-Carcinogenic Effects, a net negative result is recorded. This result can almost entirely be attributed to the Material Supply-stage, specifically to the Hemp Fibers (-232%, see table 10.2). This result is further interpreted in 11.1. Secondly, in almost all impact categories, a "negative" impact is observed for the A3 EOL waste treatment. This is due to the "avoided burden" of the replacement of a wooden plank by a reused EOL snowboard. Especially land use is affected; a large negative and a large positive result add up to the remarkably low land use result observed in the characterization results. This shows the potentially large effect of the substitution multifunctionality approach (further evaluated in 10.4 and 11.1).

Table 10.1: Overview of the Net Burden of Recycling Activities.

Recycling Activity	Net Avoided Impact ("Avoided Burden")	Net Increased Impact ("Increased Burden")
Basalt Fiber Recycling	All impact categories	-
Chromium Steel Recycling	All impact categories	-
Steel Recycling	All remaining categories	Freshwater Ecotoxicity
Wood Recycling for Paper Production	All impact categories	-
Thermoplastics Incineration	Land Use	All remaining categories
HDPE recycling	All impact categories	-
LDPE recycling	All impact categories	-
Manufacturing Waste Solvolysis	-	All categories
EOL Snowboard Solvolysis	-	All categories

Compared to BAU, the contribution results of recycling-focused alternative A4 differ considerably. The contribution of material supply is higher; except for Minerals and Metals, the production contribution has decreased (average contribution of 16% compared to 38% for A1). In contrast, the waste treatment contribution is higher, with an average contribution of 16% (1% for A1); the high Ozone Layer Depletion results can also largely be attributed to waste treatment (figure 10.3), specifically to the acetic acid and sodium hydroxide solutions used for the manufacturing waste and EOL snowboard processes (resp. 27.25% and 33.7% of the Ozone Layer Depletion impact of A4 according to the Sankey diagram).

Where a negative impact is observed for the A3 waste treatment in almost all impact categories due to "avoided burdens", A4 only shows this in Land Use (-11%) and Carcinogenic Effects (-11%). This suggests that the A4 recycling processes might only increase the impact of the snowboard compared to the BAU incineration waste treatment. To validate this hypothesis, both solvolysis-processes (manufacturing waste and EOL recycling) and the subsequent recycling processes of the separated materials (see Appendix D) were evaluated individually in an LCA. The reuse and recycling of the separated materials led to an avoided burden in almost all impact categories (see table 10.1); however, because of the high impacts of the solvolysis process, the benefits of the material reuse/recycling are undone in all categories except Land Use and Carcinogenic Effects. Thus, the snowboard recycling-process as currently modelled would not improve the environmental impact of the snowboard lifecycle; however, this process was modelled based on a lab-scale paper which could have negatively affected the results (see 11.1).

*Table 10.2: Overview of the main contributors if processes are aggregated into reference products entering the foreground system. The bold numbers indicate the top 3 contributors in the selected impact category. *: Land Use results for A3 and AB were severely affected by the substitution approach (see also figure 10.6).*

	Climate Change Total	Freshwater and Terrestrial Acidification	Freshwater Ecotoxicity	Freshwater Eutrophication	Marine Eutrophication	Terrestrial Eutrophication	Dissipated Water	Fossils	Land Use*	Minerals and Metals	Carcinogenic Effects	Ionizing Radiation	Non-Carcinogenic Effects	Ozone layer Depletion	Photochemical Ozone Creation	Respiratory Effects, Inorganics
A0																
Production Electricity	**58%**	**52%**	**15%**	**28%**	**42%**	**42%**	**31%**	**56%**	**6%**	**20%**	**21%**	**54%**	**10%**	**16%**	**53%**	**68%**
Epoxy	**7%**	5%	**11%**	**6%**	4%	4%	**17%**	**10%**	1%	12%	3%	**7%**	1%	**28%**	**8%**	4%
EOL Snowboard Incineration	**6%**	0%	5%	-1%	0%	0%	2%	-1%	0%	-1%	3%	0%	2%	-1%	-1%	-1%
PA11 Topsheet	5%	**19%**	**35%**	**51%**	**32%**	**32%**	**13%**	2%	**53%**	**14%**	**20%**	3%	**80%**	10%	7%	**13%**
Sea Transport	2%	**11%**	1%	0%	**12%**	**12%**	0%	2%	0%	2%	1%	2%	0%	**12%**	**15%**	1%
HDPE Base	5%	3%	2%	3%	3%	3%	8%	**9%**	0%	4%	2%	4%	1%	4%	5%	3%
Glass Fibers	3%	4%	6%	3%	4%	4%	5%	4%	1%	**24%**	2%	5%	2%	7%	5%	3%
Inserts	2%	2%	10%	2%	1%	2%	2%	2%	1%	8%	**34%**	2%	2%	3%	2%	3%
Electricity (Use)	2%	2%	1%	4%	1%	1%	4%	3%	1%	1%	1%	**15%**	0%	4%	1%	0%
A1																
Production Electricity	**53%**	**50%**	**15%**	**25%**	**36%**	**36%**	**30%**	**51%**	**14%**	**26%**	**20%**	**50%**	**9%**	**18%**	**46%**	**62%**
Epoxy	**8%**	5%	**11%**	6%	4%	4%	**17%**	**11%**	1%	11%	3%	**7%**	1%	**25%**	**8%**	5%
EOL Snowboard Incineration	**6%**	0%	5%	-1%	0%	0%	2%	-1%	0%	-1%	3%	0%	2%	-1%	-1%	-1%
PA11 Topsheet	5%	**18%**	**35%**	**52%**	**33%**	**33%**	**13%**	2%	**48%**	**13%**	**20%**	3%	**80%**	9%	7%	**15%**
Sea Transport	2%	**11%**	1%	0%	**12%**	**12%**	0%	2%	0%	2%	1%	2%	0%	**11%**	**15%**	1%
HDPE Base	5%	3%	2%	3%	3%	3%	8%	**10%**	0%	4%	2%	5%	1%	4%	5%	4%
Glass Fibers	4%	4%	6%	3%	4%	4%	5%	4%	1%	**22%**	2%	5%	2%	6%	5%	4%
Inserts	2%	2%	10%	2%	2%	2%	2%	2%	1%	7%	**34%**	2%	2%	3%	2%	3%
Electricity (Use)	2%	2%	1%	5%	1%	1%	4%	3%	1%	1%	1%	**16%**	0%	4%	1%	1%

	Climate Change Total	Freshwater and Terrestrial Acidification	Freshwater Ecotoxicity	Freshwater Eutrophication	Marine Eutrophication	Terrestrial Eutrophication	Dissipated Water	Fossils	Land Use*	Minerals and Metals	Carcinogenic Effects	Ionizing Radiation	Non-Carcinogenic Effects	Ozone layer Depletion	Photochemical Ozone Creation	Respiratory Effects, Inorganics
AB																
Production Electricity	**59%**	**51%**	**16%**	**27%**	**41%**	**41%**	**31%**	**53%**	***8%***	**20%**	**21%**	**52%**	**9%**	**16%**	**52%**	**67%**
Epoxy	**7%**	5%	12%	5%	4%	4%	**17%**	**10%**	*1%*	12%	3%	**6%**	1%	**27%**	7%	4%
EOL Snowboard Incineration	1%	0%	1%	0%	0%	0%	0%	0%	*0%*	0%	3%	0%	2%	-1%	-1%	-1%
PA11 Topsheet	**5%**	**18%**	**36%**	**48%**	**31%**	**31%**	**13%**	2%	***75%***	**14%**	**20%**	3%	**79%**	10%	**7%**	**13%**
Sea Transport	3%	**16%**	1%	0%	17%	**18%**	1%	3%	*0%*	3%	1%	2%	0%	**12%**	**15%**	1%
HDPE Base	5%	3%	2%	3%	3%	2%	8%	**9%**	*1%*	4%	2%	4%	1%	4%	4%	3%
Glass Fibers	4%	4%	6%	2%	4%	3%	5%	4%	*1%*	**24%**	2%	5%	2%	7%	5%	3%
EOL Reuse for Another Purpose	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	***-70%***	-3%	-1%	-1%	0%	-3%	-2%	-3%
Inserts	2%	2%	11%	2%	1%	1%	2%	2%	1%	8%	**34%**	2%	2%	3%	2%	3%
Electricity (Use)	2%	2%	1%	4%	1%	1%	4%	3%	1%	1%	1%	**14%**	0%	4%	1%	0%
A2																
Production Electricity	**52%**	**49%**	**15%**	**24%**	**35%**	**36%**	**28%**	**49%**	**14%**	**25%**	**20%**	**43%**	**9%**	**18%**	**46%**	**62%**
Epoxy	**7%**	5%	**11%**	6%	4%	4%	**16%**	**11%**	1%	11%	3%	**6%**	1%	**24%**	**8%**	**5%**
EOL Snowboard Incineration	**6%**	0%	5%	-1%	0%	0%	2%	-1%	0%	-1%	3%	0%	2%	-1%	-1%	-1%
PA11 Topsheet	5%	**18%**	**35%**	**50%**	**32%**	**32%**	**13%**	2%	**48%**	**12%**	**20%**	2%	80%	9%	7%	**14%**
Sea Transport	2%	**11%**	1%	0%	**12%**	**12%**	0%	2%	0%	2%	1%	2%	0%	**11%**	**15%**	1%
HDPE Base	5%	3%	2%	3%	3%	3%	8%	**10%**	0%	4%	2%	4%	1%	4%	5%	3%
Glass Fibers	4%	4%	6%	3%	4%	4%	5%	4%	1%	**21%**	2%	5%	2%	6%	5%	4%
Inserts	2%	2%	10%	2%	2%	2%	2%	2%	1%	7%	**34%**	2%	2%	2%	2%	3%
Electricity (Use)	2%	2%	1%	4%	1%	1%	4%	3%	1%	1%	1%	**14%**	0%	4%	1%	1%

	Climate Change Total	Freshwater and Terrestrial Acidification	Freshwater Ecotoxicity	Freshwater Eutrophication	Marine Eutrophication	Terrestrial Eutrophication	Dissipated Water	Fossils	Land Use*	Minerals and Metals	Carcinogenic Effects	Ionizing Radiation	Non-Carcinogenic Effects	Ozone layer Depletion	Photochemical Ozone Creation	Respiratory Effects, Inorganics
A3																
Fish Glue	**24%**	**15%**	**9%**	**70%**	**17%**	**16%**	4%	**20%**	*6%*	**23%**	7%	**15%**	25%	**39%**	**21%**	**26%**
Production Electricity	**16%**	**16%**	5%	4%	7%	9%	**11%**	**18%**	*4%*	**54%**	**8%**	**16%**	**43%**	**14%**	15%	**25%**
Soybean Wax	8%	1%	4%	0%	7%	2%	0%	1%	*38%*	2%	1%	2%	-11%	4%	4%	4%
Sea Transport	4%	**18%**	0%	0%	11%	**18%**	0%	4%	*0%*	1%	1%	3%	1%	8%	**22%**	3%
Hemp Fibers	6%	8%	**62%**	3%	**21%**	11%	**52%**	4%	***134%***	3%	**8%**	3%	**-231%**	5%	9%	13%
Inserts	6%	5%	**8%**	1%	2%	3%	1%	6%	*2%*	6%	**44%**	3%	23%	3%	5%	13%
Linseed Oil	4%	13%	4%	**8%**	**19%**	**21%**	**9%**	2%	*54%*	3%	4%	1%	**53%**	2%	3%	16%
HDPE Base	**14%**	8%	2%	1%	4%	6%	3%	**27%**	*2%*	3%	2%	9%	6%	5%	10%	14%
EOL Reuse for Another Purpose	-9%	-8%	-3%	-1%	-7%	-11%	-2%	-10%	***-676%***	**-10%**	-3%	-9%	-16%	**-13%**	**-19%**	**-54%**
Wood Veneer	0%	0%	0%	0%	0%	0%	0%	0%	*11%*	0%	1%	14%	3%	4%	6%	3%
Wooden Core	0%	0%	0%	0%	0%	0%	0%	0%	***136%***	0%	0%	0%	0%	1%	2%	1%
Electricity (Use)	5%	4%	0%	2%	2%	2%	2%	9%	2%	1%	1%	**30%**	-4%	4%	3%	2%
A4																
EOL Snowboard Recycling	**19%**	10%	**5%**	**7%**	**8%**	6%	**33%**	**19%**	**-11%**	**8%**	-11%	**22%**	**4%**	**42%**	8%	0%
Production Electricity	**13%**	**13%**	**9%**	**10%**	7%	**7%**	**20%**	**13%**	1%	**52%**	**10%**	8%	**5%**	**6%**	**11%**	**17%**
Manufacturing Waste Recycling	**10%**	5%	4%	3%	4%	4%	**15%**	**13%**	1%	6%	3%	8%	1%	**17%**	6%	5%
Sea Transport	4%	**18%**	1%	0%	**15%**	**17%**	0%	4%	0%	1%	1%	2%	0%	5%	**20%**	3%
PA11 Topsheet	9%	**29%**	**37%**	**40%**	**40%**	**45%**	8%	4%	**55%**	**9%**	**27%**	2%	**82%**	4%	**10%**	**33%**
Inserts	4%	3%	**11%**	1%	2%	2%	1%	3%	1%	5%	**46%**	1%	2%	1%	3%	**7%**
Soybean Wax	6%	1%	6%	1%	6%	1%	0%	0%	**11%**	1%	1%	1%	-1%	2%	3%	2%
Wooden Core	0%	0%	0%	0%	0%	0%	0%	0%	**40%**	0%	0%	0%	0%	0%	1%	0%

	Climate Change Total	Freshwater and Terrestrial Acidification	Freshwater Ecotoxicity	Freshwater Eutrophication	Marine Eutrophication	Terrestrial Eutrophication	Dissipated Water	Fossils	Land Use*	Minerals and Metals	Carcinogenic Effects	Ionizing Radiation	Non-Carcinogenic Effects	Ozone layer Depletion	Photochemical Ozone Creation	Respiratory Effects, Inorganics
Electricity (Use)	3%	2%	1%	4%	1%	1%	3%	5%	1%	1%	1%	**13%**	0%	2%	2%	1%

10.4. Sensitivity Analysis

In this section, the sensitivity of the results to modelling choices, assumptions, and data quality is checked to make sure the results are robust enough to be a foundation for decisions (Guinée et al., 2002). The results are first evaluated with another characterization family. Afterwards, the effect of two changes in the model will be evaluated. Firstly, in 5.2, air shipping was identified as an additional popular distribution means; therefore, the changes in impact for this distribution method are evaluated in this section. Secondly, in the contribution analysis, it was found that electricity causes a large share of the impact in numerous impact categories; therefore, the use of rooftop PV (standard in A3 and A4) and the Chinese electricity grid are compared. Finally, the substitution allocation method used to allocate the multifunctional waste-treatment processes in this study is evaluated.

Sensitivity to Characterization Families

To test to what extent the results are influenced by the chosen characterization family, the model was characterized with the ReCiPe 2016 Egalitarian midpoint family (see RIVM, 2016 for more info). Only impact categories similar to the selected ILCD categories were evaluated; for Land Use, multiple similar categories existed in ReCiPe, of which Agricultural Land Occupation was selected. For Terrestrial Eutrophication, Carcinogenic Effects, and Non-Carcinogenic Effects, no suitable ReCiPe categories to compare with were identified. In table G.3, the compared impact categories are shown. The changes in results were assessed on relative performance compared to the 2025 baseline (A1), since the impact categories of both characterization families differ in units. By ranking the results for each impact category and comparing these ranks, four impact categories with significant changes in alternative relative performance were identified (see figure 10.5; for the values, see Appendix H).

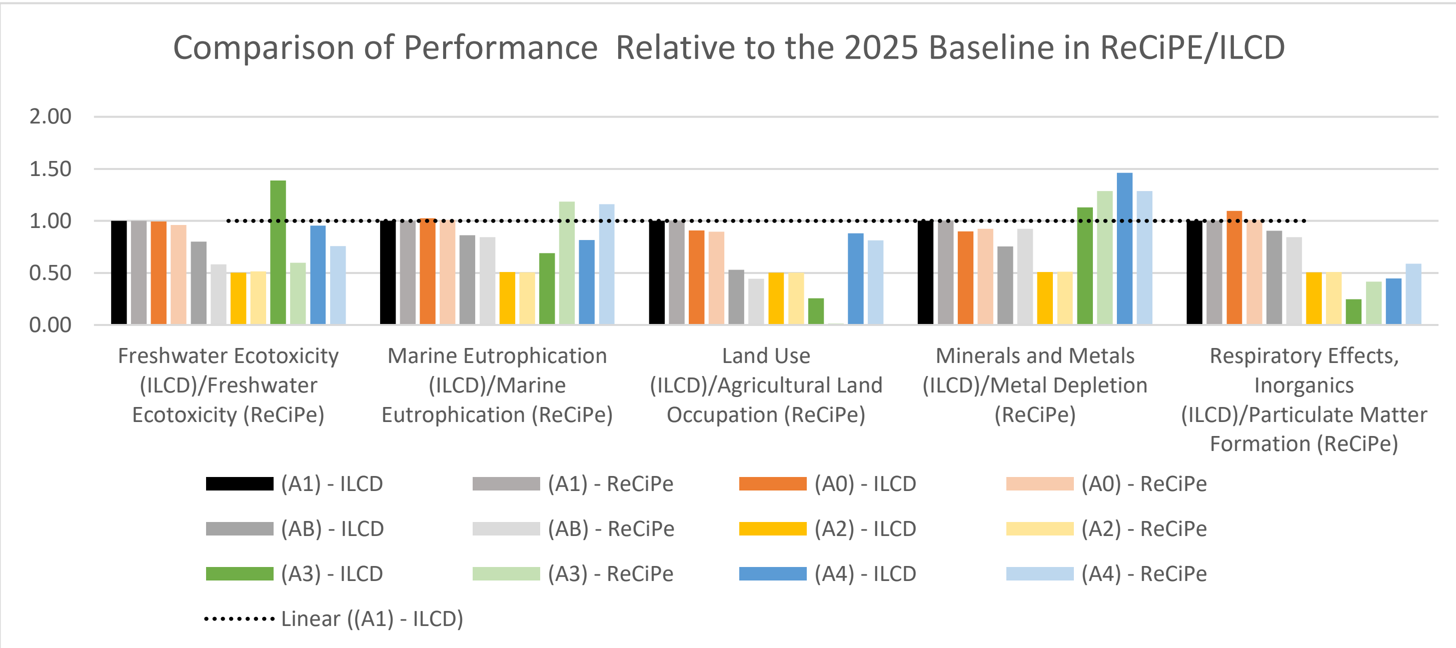


Figure 10.5: Performance scaled to the 2025 baseline (A1) following the ILCD Midpoint Characterization Family (dark colors) and the ReCiPe Egalitarian Midpoint Characterization Family (light colors).

The relative results change significantly in four categories. Firstly, in the ILCD results, the biobased (A3) and recycling-focused (A4) alternative score similarly to or worse than A1 in Freshwater Ecotoxicity; however, in the ReCiPe results, the performance of A3 and A4 is better (resp. 139% and 95% of A1 in ILCD, 60% and 76% in ReCiPe). In contrast, for Marine Eutrophication, the results for A3 and A4 have increased, causing worse performance than the 2025 baseline (A1). Compared to the ILCD Land Use-category, AB performs 16% better relative to the 2025 baseline in the ReCiPe Agricultural Land Occupation category, now performing better than A2. Additionally, the Agricultural Land Occupation impact of A3 is virtually zero compared to A1, and therefore considerably lower than the ILCD Land Use result (26% of A1). In the ILCD-category Minerals and Metals, A4 performs worse than A3; however, in the ReCiPe Metals Depletion-category, they perform similarly. Finally, in the ILCD-category Respiratory Effects, Inorganics, A0 and AB perform worse than in the ReCiPe-category Particulate Matter Formation; interestingly, for A3 and A4 the performance changes in the opposite direction, i.e. worse in the ReCiPe categories.

In conclusion, the results for Freshwater Ecotoxicity, Marine Eutrophication, Land Use, Minerals and Metals, and Respiratory Effects, Inorganics, are sensitive to the choice of characterization family, but the overall results remain relatively consistent.

Sensitivity to alternative modelling decisions/assumptions

Scenario 1 – Distribution by Air

In this scenario, the effects of distribution by plane instead of by containership are evaluated. These options are both often used by snowboard brands (see 5.2). The contribution of distribution by sea shipping to most impact category results is limited, but this might be different for air shipping.

The flight distance is calculated with travelmath.com (n.d.) from Hongkong to Rotterdam, as the airport of Xiahai (original sea shipping origin) is not found by the calculator and Hongkong is quite close. To model the shipping, the Ecoinvent 3.6 process “market for transport, freight, aircraft, long haul” was used. The transport from and to the airport was kept the same; only the sea shipping was replaced.

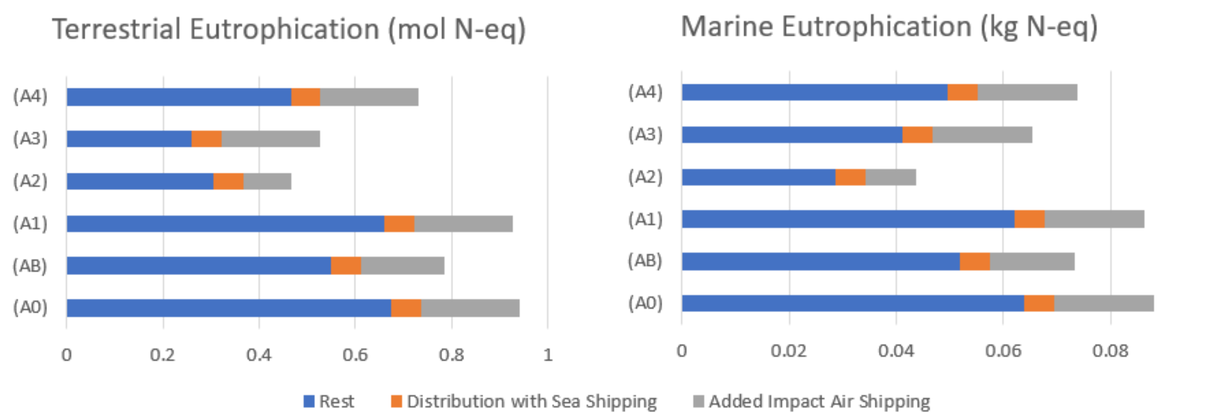


Figure 10.6: Marine Eutrophication and Terrestrial Eutrophication results for Sea and Air Shipping

The implementation of air shipping was found to increase the impact of the alternatives in all impact categories. For this reason, it was decided to show the change in distribution contribution in the graphs. For eight categories, the total impact of all alternatives increased with more than 10%, causing the distribution contribution to increase considerably[5] (see figure 10.6 - 10.8). The starkest impact increase is for Climate Change Total (between 25% increase for A0 and 79% increase for A3;

[5] For A3, an additional two categories increased significantly (Non-Carcinogenic Effects, +50%, and Respiratory Effects, Inorganics, +16%); however, because these categories did not increase significantly for the other alternatives, the graphs are not added here.

see table G.5). Thus, choosing for air shipping can have a significant impact on the environmental impact of a snowboards lifecycle, and the results are quite sensitive to this decision.

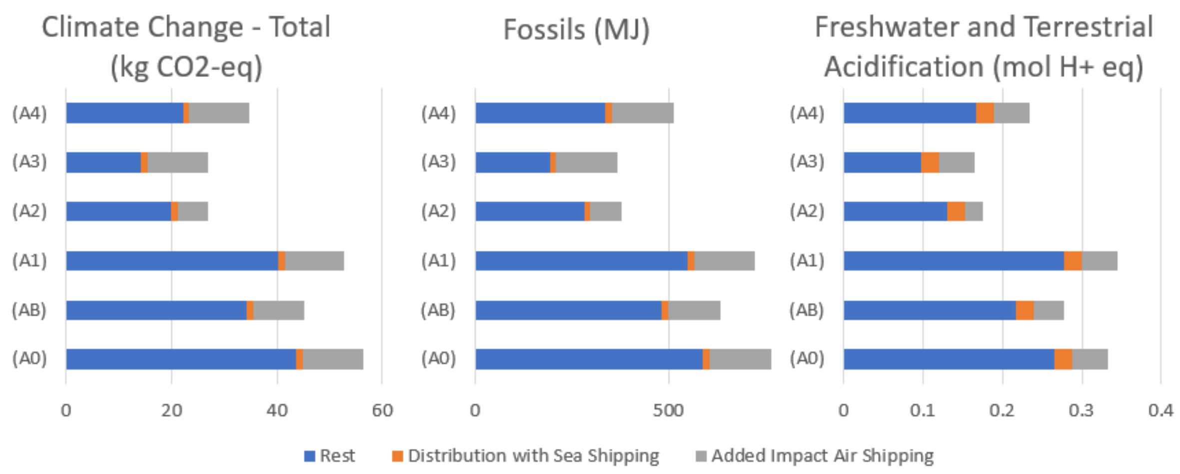


Figure 10.7: Climate Change Total, Fossils, and Freshwater and Terrestrial Acidification results for Sea and Air shipping

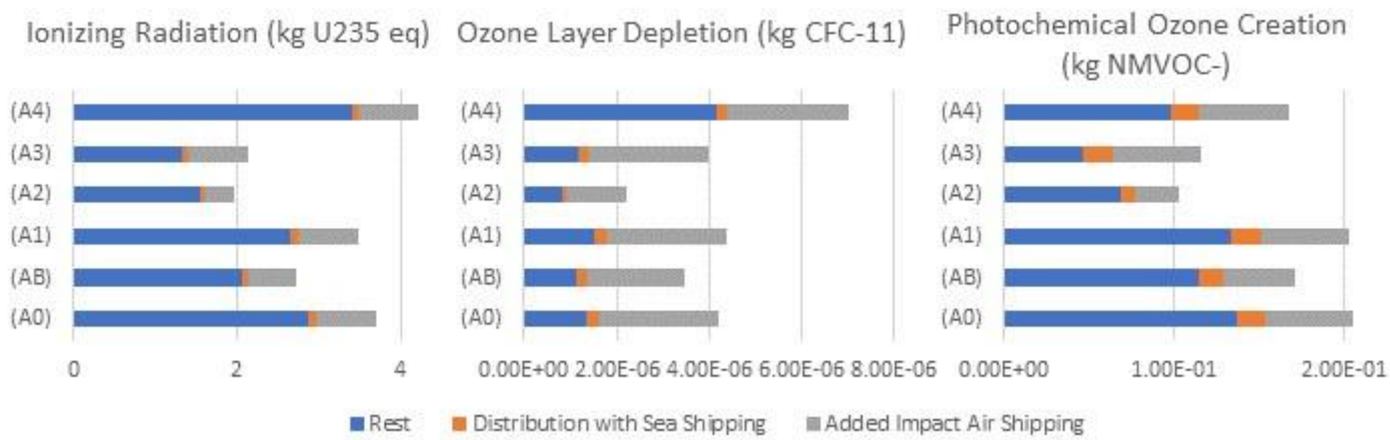


Figure 10.8: Ionizing Radiation, Ozone Layer Depletion, and Photochemical Ozone Creation results for Sea and Air Shipping

Scenario 2 – Production Electricity

In this section, two scenarios for production electricity are evaluated: production location (China) grid electricity (currently used in A0, AB, A1 and A2) and an on-site rooftop photovoltaic (PV) installation (currently used in A3 and A4). PV electricity is a popular measure for snowboard brands to become more sustainable (see 5.3). To see how sensitive the model is to this element, all alternatives were run with both grid- and PV electricity. All categories with more than 10% difference for all alternatives are presented in figures 10.9 – 10.12; for characterization results see table G.3.

The production electricity type has a large impact on the relative performance of the alternatives. If the recycling-focused alternative is modelled with the same production electricity as the 2025 baseline (A1), A4's environmentally favorable performance is diminished completely, sometimes even leading to worse performance than the 2025 baseline. The relative performance of the other circular alternatives (A2 and A3) depends less on the electricity used; these alternatives show improved performance compared to the baseline regardless of the electricity technology used.

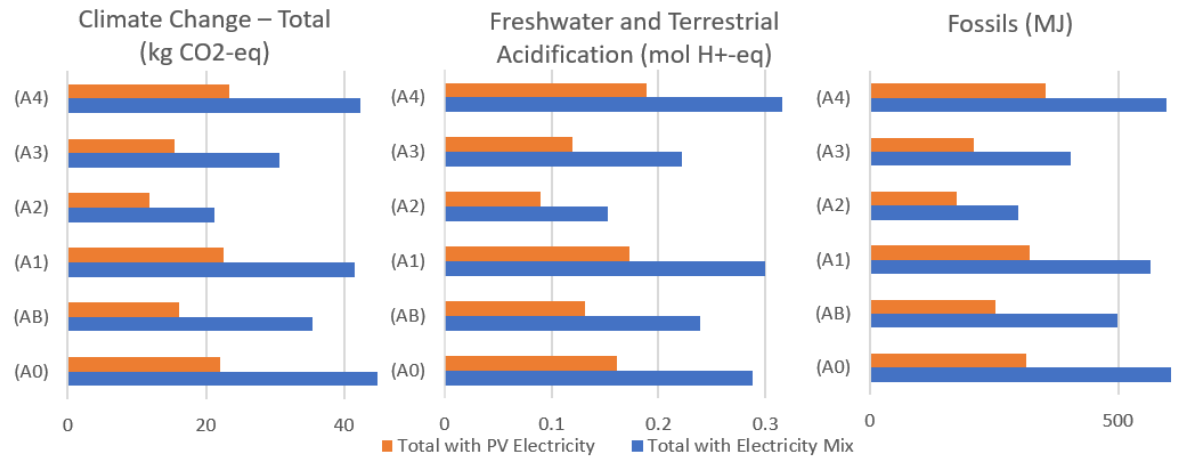


Figure 10.9: Climate Change Total, Freshwater and Terrestrial Acidification, and Fossils results for production with grid electricity and rooftop PV.

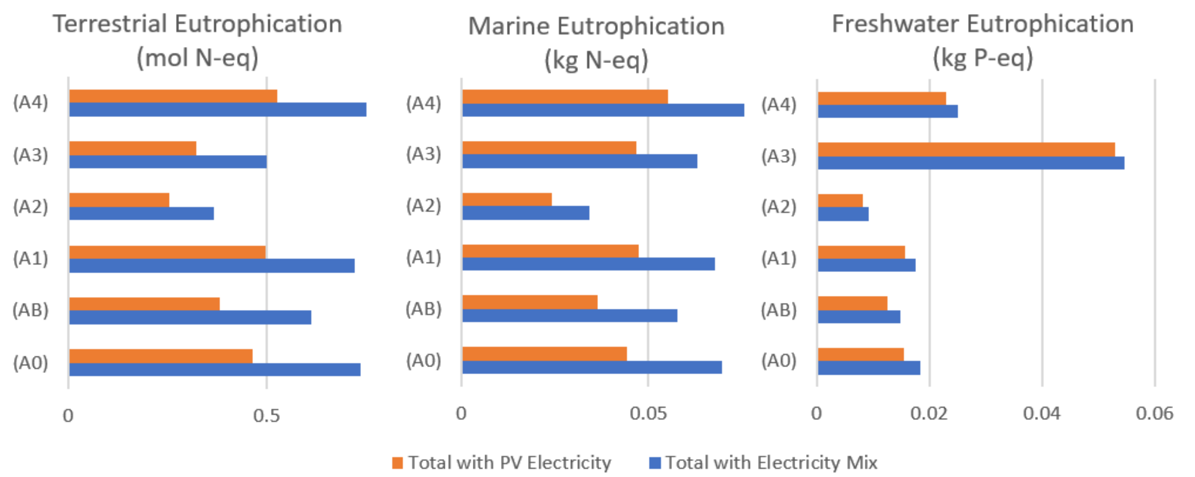


Figure 10.10: Marine Eutrophication, Terrestrial Eutrophication, and Freshwater Eutrophication results for a snowboard lifecycle with PV or grid production electricity.

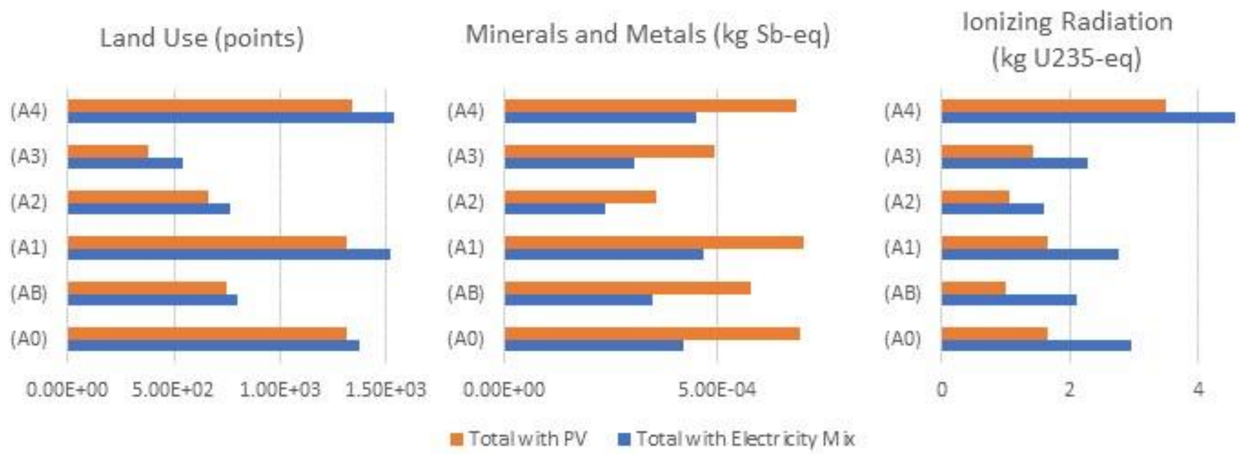


Figure 10.11: Land Use, Minerals and Metals, and Ionizing Radiation results for a snowboard lifecycle with PV or grid production electricity

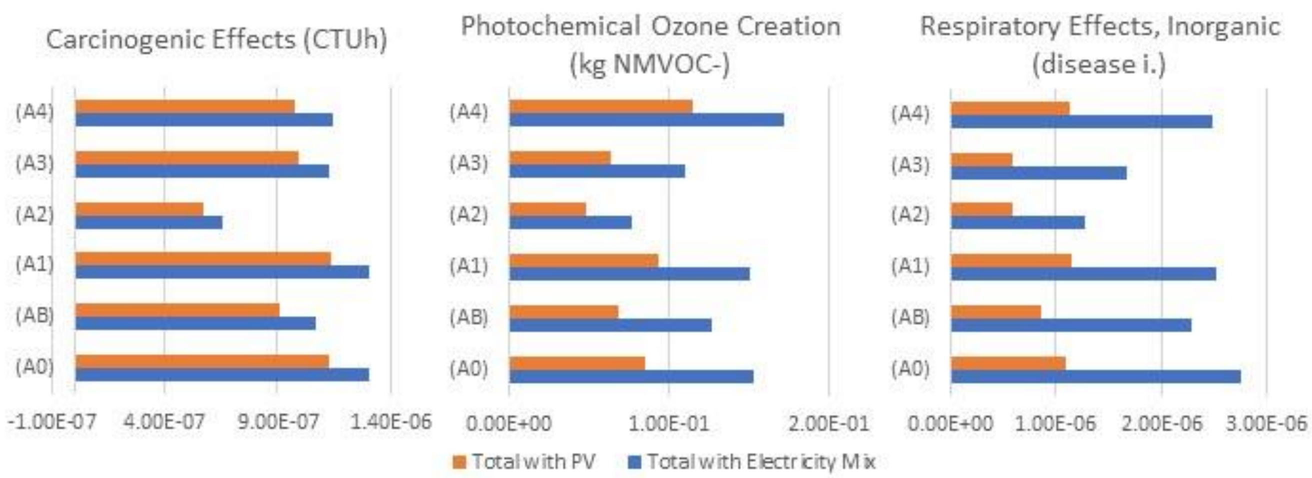


Figure 10.12: Carcinogenic Effects, Photochemical Ozone Creation, and Respiratory Effects, Inorganics results for a snowboard lifecycle with PV or grid production electricity

Looking at the changes in results, we can see that the use of rooftop PV improves the performance drastically in some impact categories, with impact reductions of up to 188% (A3, Respiratory Effects, Inorganics). However, in a few categories, the use of PV means an increase compared to grid electricity. For Dissipated Water (+2 – 4%), this increase is limited; however, for Minerals and Metals Depletion, the impact increases between 49 and 66 percent with the use of PV electricity (see table G.3).

In conclusion, the results are highly sensitive to the production electricity used and should therefore be one of the first areas in which innovations towards more circular snowboards take place if the aim is to improve the environmental performance in most impact categories.

Sensitivity to Multifunctionality Approach

To evaluate the effect of the chosen substitution-approach, the model was also constructed following the principles of the Ecoinvent Cut-Off System Model, where waste products are cut off the moment they become an input to another system, hereby ensuring that products for recycling are freed of the burden of previous cycles and vice versa (Ecoinvent, n.d.). In this case, this means that all substitution elements indicated in the flowcharts of the alternatives are cut off at the system boundary (see Appendix G for an example). The results were scaled to the 2025 baseline (A1) under the substitution multifunctionality treatment that was used throughout this study. In figure 10.13 and 10.14, all impact categories that incurred more than 10% change for an alternative are included; for complete characterization results, see Appendix G. The data behind the graphs is included in Appendix H. The substitution elements are explained in Appendix D.

Land Use is the most affected impact category, with changes above 10% for A3 (+685%), AB (+64%) and A4 (18%). From the Sankey diagrams in the Activity Browser, it is observed the difference for A3 and AB is due to the substitution of a wooden plank for a park bench or fence by the EOL snowboard in the substitution model; when the EOL snowboard is cut off at the end of life instead, A3 even gets the largest land use results by far. Due to the use of biobased materials, this higher land-use result is more in line with the expectations. The increase in land use for A4 (18%) is due to the assumed substitution of wood chips for paper production by the recycled snowboard core and production wood cut-offs. Thus, the land use results are very sensitive to the allocation approach chosen.

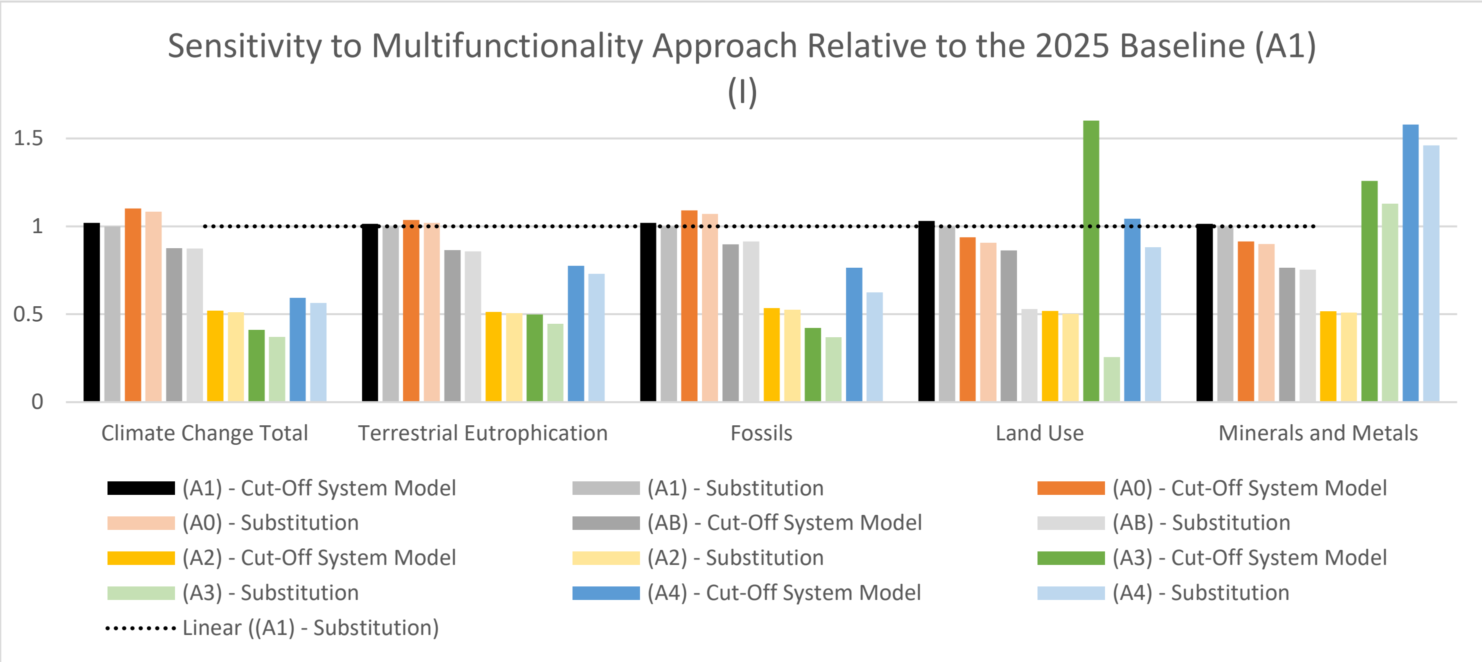


Figure 10.13: Results relative to the 2025 Baseline (A1) under Substitution Multifunctionality Treatment for Substitution (light colors) and the Cut-Off System Model Approach (dark colors).

When looking at the alternatives, A3 is affected most severely, experiencing result changes close to or higher than 10% in 9 of the 10 selected impact categories (see table G.4 and Appendix H). All of these significant changes are due to the way the reuse of the EOL snowboard is modelled. Alternative 0, 1, and 2 are barely affected, with a maximum result change of 5%. Alternative AB is affected in 2 categories: Land Use (63%) and Ionizing Radiation, both attributable to the EOL snowboard reuse. Finally, A4 is affected significantly in four categories: Land Use (18%, explained above), Fossils (22%), Photochemical Ozone Creation (12%) and Respiratory Effects, Inorganics (25%); these changes are predominantly caused by three recycled materials that were assumed to substitute virgin materials in the substitution model and are now cut-off: the recycled base, replacing virgin HDPE, and the steel edges and chromium steel inserts, replacing virgin (chromium) steel.

In conclusion, the chosen substitution allocation approach has an effect on the results for some impact categories and alternatives. The reuse of a snowboard for another purpose, which is an EOL treatment in AB and A3, especially leads to different results for the two allocation approaches. For most impact categories, these differences are limited; however, for Land Use, they are so large that the relative performance of the alternatives is altered. This should therefore be considered in the interpretation of the Land Use results.

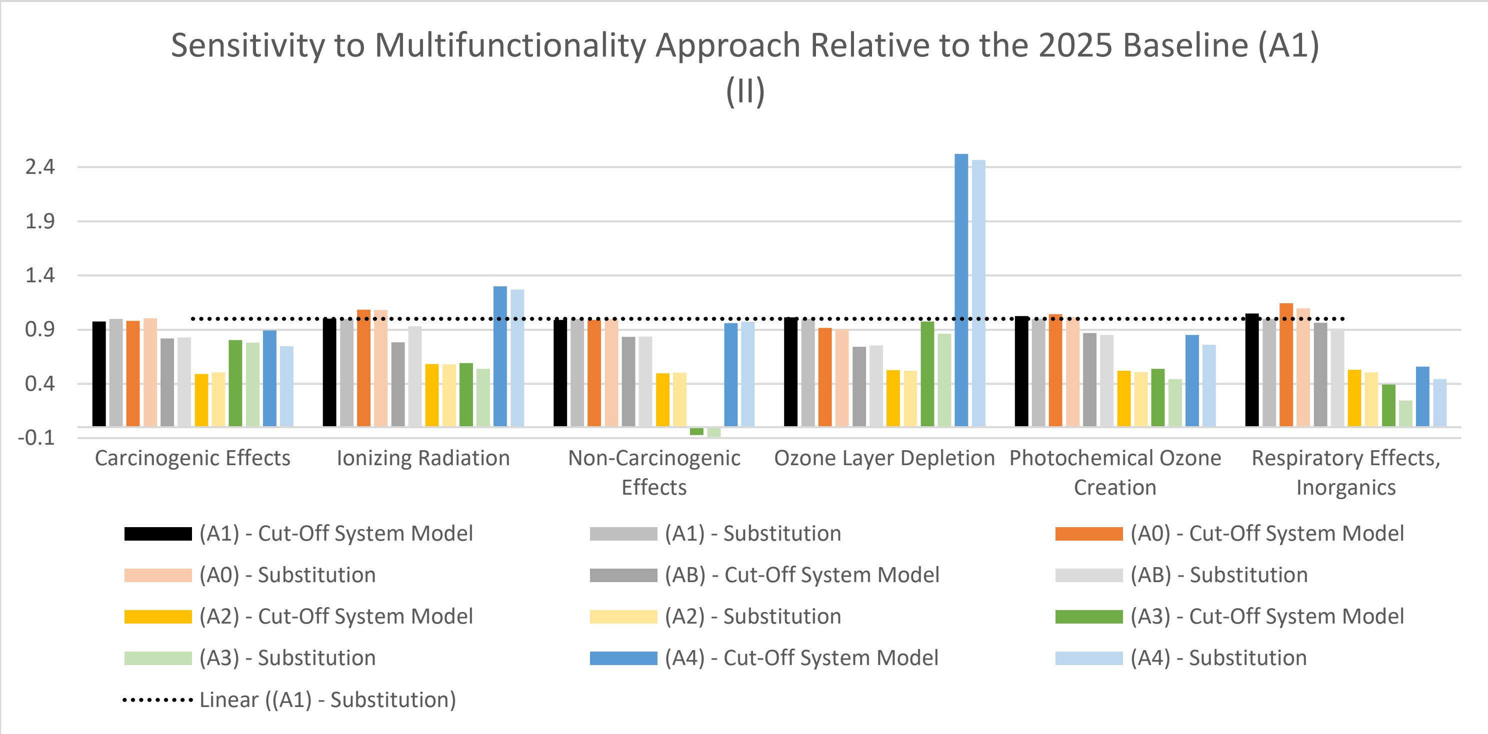


Figure 10.13: Results relative to the 2025 Baseline (A1) under Substitution Multifunctionality Treatment for Substitution (light colors) and the Cut-Off System Model Approach (dark colors).

Part IV: Discussion and Conclusion

11. Discussion

In this chapter, the results obtained in this study are critically discussed. The robustness and uncertainty of the results is first discussed; afterwards, the economic feasibility of the circular alternatives is discussed.

11.1 Research Robustness and Uncertainty

In this section, the results presented in the previous chapter are critically evaluated on validity and robustness.

Wintersports Archetypes Interpretation

In chapter 4, three wintersports participant archetypes were established: Tourists, Wintersports Enthusiasts, and Snowsports Professionals. These archetypes are subject to some limitations that are discussed below.

Firstly, as reported in 4.1, the survey dataset was clearly subject to self-selection bias and not necessarily representative of the wintersports population. By dividing the dataset into three subgroups that represented a certain subgroup of the population, this problem was tackled. However, for calculation of the average equipment lifetime, the sample was only divided into two groups (recreants and professionals), and since fanatical recreants were overrepresented, the recreant lifetime used in this study is likely overstated. This lifetime was calculated in an early stage of the research and could not be adapted anymore in the LCA model. Future research into wintersports equipment lifetime and key determinants for equipment lifetime could deliver valuable insights that could possibly lead to more durable snowboards. Since a longer lifetime was identified as one of the most effective measures to decrease snowboard environmental impact, this could definitely be worth looking into.

A second issue that should be considered is the fact that the established archetypes were based on the responses of both skiers and snowboarders. Although snowboarding and skiing are similar, there are differences between the two. Because one moves sideways with snowboarding, going “backwards” (i.e., moving with the “wrong” leg in front) is easier than on skis, where going backwards actually means going backwards. This makes snowboarding more inviting for freestyle; if the subgroups are split into snowboarders and skiers, freestyle participation is indeed higher for snowboarders in all three subgroups. This illustrates that the inclusion of skiers in the archetypes might affect their representation of snowboarders, and that the importance of freestyle activities could be understated in the established functions. It would have therefore perhaps been better to exclude the skiers from analysis; however, this would have led to very limited sample sizes.

The effect of these limitations on the final research results is expected to be limited; however, the overstated use-time for recreants might mean that the environmental benefits of use until the technical lifetime might be larger than found in this study.

Finally, as explained in chapter 6, the archetypes were not used in the LCA-scenarios, because these were focused on circularity measures that could be implemented by snowboard industry actors. However, the archetypes are a valuable component of this research nonetheless. Firstly, because valuable information on the snowboard use-stage was identified, such as use patterns, equipment ownership statistics, and reasons to purchase equipment. Secondly, because in the end, doing business is about providing value to a customer and capturing value in return (Porter, 2001); by combining the outcomes of the LCA study with the insights that the archetypes provide, concrete recommendations to implement effective circularity measures in a way that suits the archetypes can be given (see 12.2). The archetypes are therefore an essential part of this research.

The Impact of Proxies

In the contribution analysis, some proxies were identified as large contributors. The reliability and robustness of these proxies is discussed in this section.

The PA11 topsheet supply chain had a large contribution to various impact categories for A0, AB, A1, A2, and A4. For this proxy, an eco-profile published by manufacturer Arkema was used (Devaux, Lê, & Pees, n.d.). This paper contained a description of the production processes, stoichiometric ratios of the feedstocks, and the CO_2-eq emissions per kg of produced PA11. Based on this information, a basic model of the PA11-production was constructed with the Ecoinvent database (see Appendix D), in which the main feedstocks and processes were included, but production-related flows such as electricity and emissions were cut-off due to data gaps. In the end, a climate change-result of 7.8 kg CO_2-eq was obtained, which was 1.8 CO_2-eq higher than the 6 kg CO_2-eq reported by Arkema. These differences could be due to various reasons. Firstly, a difference of result due to different characterization models was checked by running the thesis-model with the IPCC GWP 100a characterization model used in the eco-profile. This led to a result of 7.4 kg CO_2-eq and therefore does not explain the entire difference. Another explanation could be the use of different data; while Arkema had exact numbers on their own processes, the model in this thesis had to be build based on Ecoinvent data and the information in the eco-profile. Finally, castor oil production from castor beans yields castor meal as a by-product; Devaux, Lê, and Pees (n.d.) indicate that this is reused as fertilizer, however, they do not explain how they handled this by-product in the model and whether they for example applied substitution or allocation. As discussed before, substitution allocation can have a big effect on results (Heijungs & Guinée, 2007).

Although the climate change impact of the modeled PA11 supply chain is about 30% higher than reported in the source, the model was constructed exactly according to the information provided by Devaux, Lê and Pees (n.d.) and should therefore be reasonably reliable; moreover, even if a 30% reduction of impact is assumed in all impact categories, the contribution of the PA11 topsheet stays considerable. The topsheet in this study is a double-layer PA11 topsheet; however, PA11 is also often used in combination with PA12 (Isosport, 2017); since PA12 is not made of castor beans, the environmental impacts of this material are likely considerably different from the PA11 impact. Data on the impact of PA12 is currently not publicly available; if this impact would be lower, combining the two materials could be a way to reduce the impact of the topsheet, although this could affect the recyclability. Nonetheless, the topsheet deserves some additional thought, and alternative materials or other ways to decrease the impact of this part should be considered.

A number of proxies show considerable contributions to the results for the biobased alternative (A3): hemp fibers, linseed oil, and fish glue. For the production of hemp fibers, a modified proxy of flax fiber production in Ecoinvent was used, since hemp fibers are usually produced with the same process and machinery. For the linseed oil production, the mechanical pressing of soybean oil in Ecoinvent was used as a proxy, since this process is very similar to the linseed oil production process (Seedoilpress.com, n.d.). Like the hemp fibers, the flaxseed feedstock could be sourced from Ecoinvent. These processes are therefore both thought reasonably reliable. Finally, the fish glue production process is based on expert consultation and academic literature sources. As mentioned in 10.1, these sources were on lab scale, and it could therefore be that the impacts of the fish glue were overstated, which is a common problem for ex-ante studies (Van der Giesen et al., 2020). Across all included impact categories, on average 63% of the impact of the fish glue production can be attributed to the wastewater treatment. Thus, if the wastewater production would be reduced on a commercial scale, this could have a large impact on the results. To test this hypothesis, the impact of A3 and the fish glue production is calculated for a production process with 50% less wastewater; although the fish glue production impact decreases with at least 20% for every impact category, the change in results for A3 are limited, with only one impact category changing more than 10% (freshwater eutrophication, -33%); the other categories decrease between 0-7%. Originally, A3 scored 3 times as high for freshwater eutrophication as the 2025 baseline (A1); with halved fish glue wastewater treatment, this drops to 2 times and is thus still double as high as the baseline. The expectation is therefore that, although the fish glue production was modelled on lab-scale data, the effect of this might be limited.

Finally, the solvolysis-processes were identified as large contributors for the recycling-focused alternative (A4). These processes are likely the most uncertain process in this research. Although the intention to use this process for snowboard recycling is expressed (Niche Snowboards, n.d.), the only trial described in literature is the recycling of a carbon fiber-epoxy composite (La Rosa et al., 2018), which is different from a snowboard that is designed to keep moisture out. The snowboard would therefore need to be cut open in some way, requiring more electricity than assumed in the current model. Moreover, the current process was modelled based on lab scale: it is unclear how this process would be scaled up, which increases the uncertainty of how the environmental impact would pan out in reality. Finally, there are a number of uncertainties surrounding the recyclability of the materials afterwards. The process is currently based on the following:

- *The basalt fibers* are not significantly affected by the process (Basalt Fiber Tech, n.d.; Smith et al., 2017) and could potentially be remelted into new fibers (Eutit s.r.o, 2013, see also Appendix D) or reused in lower-value molded composites, similar to recycled carbon fibers (e.g. Cherrington et al., 2012).
- *The PA11-topsheet* might be affected by the recycling solution since PA12 is affected by acetic acid under these circumstances (Nylacast, 2019; chemical resistance data for PA11 was not found) and is therefore assumed to be incinerated; however, if it is not affected, the PA11 could be recycled into secondary material (Arkema, n.d.).
- *The HDPE/UHMWPE base* is unharmed by the process and is assumed to be recycled. Lower-segment HDPE bases could theoretically be recycled relatively easily (Singh et al., 2017). UHMWPE is currently reprocessed from production offcuts, but not recycled at the end of life because external factors like UV-light can cause material degradation and UHMWPE products often have specific quality requirements (Redwood Plastics, n.d.; pers. comm., 2021).
- *The steel edges and stainless steel inserts* need to be extracted mechanically before the recycling process, as they are severely affected by the recycling solution, and are recycled into secondary steel (Tubing China, n.d.; Kahyarian et al., 2017).
- *The retrieved epoxy thermoplastics:* the reclaimed epoxy-thermoplastic depends on what epoxy formulation was used in combination with the Recyclamine epoxy hardener (La Rosa et al., 2018). This might for example be poly(hydroxyamino ether) (PHAE) (La Rosa et al., 2016). It is suggested to use these thermoplastics for other composites molding applications, although this is not common practice. Incineration is assumed in this study, also because the epoxy thermoplastic is expected to be mixed with dissolved PA11.

The uncertainties listed above first need to be addressed before it is possible to properly conclude the environmental impact of this process; the results of this study are a mere indication of the potential environmental impact under the specified assumptions.

The Effect of Multifunctionality Treatment

Another proxy used in A3 that has a large impact on the results is the reuse of the EOL snowboard for another purpose. For all waste treatment activities, substitution was used as a multifunctionality approach (see 8.3); the severe effects of this approach stressed by Heijungs & Guinée (2007) are clearly observed from the contribution and sensitivity results (see 10.3 and 10.4). In the "Reuse for another purpose"- process, the assumption is made that an EOL snowboard replaces a wooden plank, for example in a park bench or fence, and this assumption results in net negative/avoided impacts for this process. For interpretation of these "avoided" impacts, the question is: how real are the avoided burdens in reality? Is the replaced hardwood plank indeed not produced, is the tree not cut down? As Guinée and Heijungs (2007) illustrate, a definitive answer to these questions cannot be given, as this question depends on a hypothetical scenario that could pan out in different ways in reality. The park bench for example might not have been produced had the EOL snowboard not been there, and a wooden plank was thus never substituted. It is thus not guaranteed that the supply of the recovered EOL snowboard truly substitutes the supply of the wooden plank (Vadenbo, Hellweg, & Astrup, 2016). Moreover, market dynamics likely also play a large role in the substitution of resources.

In the sensitivity analysis, it was observed that the substitution multifunctionality treatment only affected A3 and AB significantly due to the EOL snowboard reuse for another purpose. The EOL snowboard recycling in A4 leads to various avoided burdens for almost all recycled materials; however, due to the large impact of the recycling process itself, these do not show up in the results (see table 10.3).

The interpretation of avoided impacts varies in academic literature. Nagle et al. (2020) use the substitution method to evaluate wind turbine waste treatment processes and obtain negative results or "environmental benefits" for EOL turbine blades processing in a cement kiln. They accept these findings without additional discussion of the substitution multifunctionality treatment effect. The same holds for La Rosa et al. (2018) in their assessment of the solvolysis recycling process evaluated in this study, although avoided burdens play a large role in the results.

In conclusion, the only alternatives significantly affected by the substitution multifunctionality treatment are A3 and AB due to the EOL snowboard reuse for another purpose-process. With regards to the interpretation of the avoided burdens, we conclude that these are firstly highly hypothetical, and secondly likely overstated, as is often the case with one-on-one substitution assumptions (Vadenbo, Hellweg, & Astrup, 2016). The reuse of a snowboard instead of a wooden plank might yield environmental benefits, but that it is impossible to decide the size and reality of these benefits based on the current results.

Interpretation of Negative Non-Carcinogenic Effects

In 10.3, a negative result was observed for A3 in the Non-Carcinogenic Effects-category. This result was mostly attributable to the cultivation of hemp fibers. Since consumption of a good usually does not benefit the environment, negative results deserve some additional attention. Looking at the Ecoinvent unit process data for the hemp cultivation-process, negative emissions to soil for the metals zinc, copper, chromium, nickel, lead, and mercury are observed, likely indicating the uptake of these metals by the plant. The emissions of these metals to soil are indeed included in the characterization factors for the Non-Carcinogenic Effects impact category (Fazio et al., 2018). However, whether the use of hemp fibers would cause a positive effect in this category in reality is questionable. Plants can indeed take up contamination from soil and are sometimes used to clean contaminated areas (Gerhardt, Gerwing, & Greenberg, 2017). However, whether these metals stay removed from the environment depends on what happens to the hemp fibers (and the snowboard) at the EOL. In this case, the snowboard was assumed to be reused; as long as the snowboard is not treated in a way that releases the contained metals into the environment (e.g. incineration), this effect might indeed exist. Regardless, the negative impact of A3 in this category (9% of the impact of A1 in this category, see table G.1) is so small that its relevance is limited.

The Ex-Ante Character

In 10.1 and 10.2, a number of issues related to the ex-ante character of this study were identified with regards to the consistency and the completeness of the alternatives and the results. The implications of these problems were already discussed in these sections and therefore do not need to be discussed here. However, it should be stressed that the results of this study can impossibly be representative of the real situation in 2025 due to the use of historical data, uncertainty about the future, and the assessment on lab scale of the emerging technologies. As van der Giesen et al. (2020) state, the results should therefore be seen as an indication of the potential environmental impacts of the scenarios rather than definitive results. This stresses the importance of collaboration between LCA-practitioners and technology developers, and shows that LCA evaluation and technology development should be an iterative process, in which the environmental impact of the technology is repeatedly evaluated.

12. Conclusion and Recommendations

12.1 Conclusion

In this research, potential circular solutions for the snowboard lifecycle were identified and evaluated with prospective LCA to answer the following research question: *In what ways could the principles of the circular economy be incorporated into the snowboard lifecycle by design year 2025, and how would this affect the environmental impact?* To answer this question, the four sub-questions are first answered below:

1. *What characteristics does a snowboard need to possess to fulfill its function and what materials are used or could be used in 2025 to establish these characteristics?*

Based on a wintersports participant questionnaire, three wintersports participant archetypes were established: the Tourist, the Wintersport Enthusiast, and the Snowsports professional. Although all three of these groups participate in all-mountain snowboarding, the function of a snowboard is slightly different to them: where the Tourist wants one do-it-all snowboard, the Wintersports Enthusiast and the Snowsports Professional prefer to have a "quiver" of multiple snowboards specialized for specific circumstances or uses. A technical snowboard lifetime of around 30 weeks was established; moreover, it was identified that snowboards were not used until the technical EOL by Tourists and Wintersports Enthusiasts.

With a mixed methods review, involving the analysis of sources, a sample of 40 brands, and expert consultation, the materials used to establish the functions were identified. It was found that, although snowboard functions differed, the snowboard composition and materials used were usually similar. The most important components include a topsheet (usually PA11), fiber reinforcement (glass fibers), sidewalls (ABS), a wooden core, stainless steel inserts, a steel edge, and a base (HDPE/UHMWPE). Future material developments were also observed: brands were increasingly using bio-based materials, showed effort to increase recycling and decrease the use of toxic substances and design for a longer snowboard lifetime. These developments are expected to gain ground towards 2025.

2. *What do snowboard lifecycles currently look like, and what developments towards more circularity are observed?*

This question was answered with the same mixed methods review as the previous sub-question. It was established that the snowboard lifecycle consisted of five main stages: material supply, production, distribution, sales, use, and End-of-Life (EOL). The supply chain was often international, with production on a different continent than sales and use. As most popular value chain circularity measures, the use of local materials, PV rooftop electricity, and distribution by sea shipping instead of air shipping were identified.

3. *What scenarios for a more circular snowboard lifecycle in 2025 could be developed?*

Based on the key developments identified in the answers to the first two sub-questions, six scenarios were developed. First, three baseline scenarios were devised to represent the current most common practices in the value chain. Two of these scenarios took place in the now (2020; AB and A0); one of the scenarios represented the expected standard practices in 2025 (A1). Next, three more circular scenarios were devised for 2025, based on the findings presented above: one scenario built around use for the technical lifetime (A2), one scenario evolving around bio-based materials (A3), and one scenario focused on recycling and recyclability (A4).

4. *How do these alternative value chain scenarios compare in environmental impact?*

To compare these scenarios in environmental impact, an ex-ante LCA study was conducted. The alternatives were assessed in the following ILCD 2018 midpoint impact categories: Climate Change Total, Freshwater and Terrestrial Acidification, Freshwater Ecotoxicity, Freshwater Eutrophication, Marine Eutrophication, Terrestrial Eutrophication, Dissipated Water, Land Use, Resource Use – Minerals and Metals, Resource Use – Fossils, Carcinogenic Effects, Ionizing Radiation, Non-Carcinogenic Effects, Ozone Layer Depletion, Photochemical Ozone Creation, and Respiratory Effects, Inorganics. From this assessment, it was concluded that using a snowboard for the technical lifetime was the most effective way to reduce the environmental impacts of a snowboard, since most of the environmental impact could be attributed to material supply and production (especially electricity). Solutions focused on the use of biobased materials or on recycling decreased impacts for some characterization categories but increased them in others. Since production electricity was one of the largest contributors, switching to cleaner electricity was identified as one of the most effective measures; moreover, sea shipping was considerably better than air shipping from an environmental perspective.

This research is subject to a number of limitations. As mentioned, the research is subject to large uncertainty due to assessment in the future, the use of historical data, and limited data availability. Moreover, the concept of some technologies (fish glue composites construction, snowboard recycling process) was not yet proven, increasing uncertainty further. The outcomes of this study should therefore not be seen as representative of the real situation in 2025, but rather as indications of the environmental impact if the alternatives are implemented similarly to the current model. Additional research, once more information is available on the actual implementation, is therefore required to establish the effectivity of these solutions in decreasing the snowboard lifecycle environmental impact.

Based on these results, the main research question can be answered: *In what ways could the principles of the circular economy be incorporated into the snowboard lifecycle by design year 2025, and how would this affect the environmental impact?*

There are numerous possible ways to implement more circular snowboard lifecycles in 2025, and the perfect option was not evaluated in this study, as the evaluated scenarios had a lower impact than the 2025 baseline in some categories and higher impacts in others. However, striving for use until the technical EOL was established as an effective circularity measure to decrease the environmental impact of a snowboard lifecycle.

In conclusion, interesting developments are going on towards making the snowboard lifecycle more circular; however, for environmentally effective implementation of the circular economy, there are still some mountains left to climb.

12.2. Recommendations

Industry Recommendations

In this section, recommendations for snowboard industry actors are formulated based on the results of this study. The structure of the snowboard lifecycle is followed.

Materials Supply and Production

For the materials supply-stage, a few interesting results were obtained that should be translated into recommendations for the snowboard industry. Firstly, the PA11-topsheet modelled in this study was consistently one of the largest contributors to the environmental impact results of the BAU alternatives. This material has a considerably high impact across many categories; alternative materials or ways to decrease the use of this material should therefore be considered. The wood veneer used in A3 could possibly be an option, possibly in combination with one layer of PA11 (instead of the two layers modelled in this study) (e.g. Arbor Collective, n.d.) or with a linseed oil coating like in A3. Other materials frequently used for topsheets include ABS/TPU combinations or PA12/PA11: depending on the impacts of these materials, these could also be options.

The epoxy adhesive was a considerable contributor to various categories for the BAU alternatives. The combination of fish glue and tannin powder used in the biobased alternative could be an alternative adhesive. When comparing these two adhesion systems in an LCA, the epoxy performs better in most categories. However, since the epoxy-production process was available in Ecoinvent and the fish-glue production process was modelled on lab-scale data, this is probably an unfair comparison. Moreover, the amount of epoxy required (0.6 kg) was based on a commercial source; the amount of fish glue (1.14 kg) was estimated based on the lab-scale construction of one pair of skis. If the same amounts of epoxy and fish glue are compared, the fish glue does outperform the epoxy. Therefore, it is recommended to further research this adhesion method for snowboards and carefully evaluate the pros and cons and possible applications, because if the production process could become more efficient, the amount of glue used could be reduced, and the adhesion characteristics suffice, this could be a promising alternative to epoxy.

Another large contributor for the BAU alternatives was the glass fiber reinforcement. The hemp and basalt fibers used in A3 and A4 could possibly be used to reduce this contribution. When these fibers are compared in an LCA, it is observed that the hemp fibers perform better in some categories, such as Climate Change and Fossils and Non-Carcinogenic Effects, where it even scores a negative impact, but considerably worse than both basalt and glass in Freshwater Ecotoxicity, Marine, Freshwater, and Terrestrial Eutrophication, Land Use, and Dissipated Water. This presents a trade-off between mitigation of some impacts, and worsening in others; no clear recommendation on the use of these fibers can be given. The basalt fibers perform a little better than the glass fibers in most categories, and a lot better in the Minerals and Metals category. The improved performance of these fibers is mostly due to the single basalt rock feedstock, which allows higher material-to-fiber conversions because production failures can be recycled, which is not possible for glass fibers. Since the mechanical properties of basalt fibers are also similar to glass fibers, and the reinforcement qualities have been proven, this is a promising alternative to glass fibers that should be considered.

Finally, in the contribution analysis (10.3), it was observed that the material supply impact of the biobased alternative was lower than BAU in most cases: however, in Freshwater Eutrophication, Freshwater Ecotoxicity, and Dissipated Water, it was considerably higher. The hemp fibers were the main contributor to two of these categories. This performance of the biobased materials shows promise, and options should be explored; however, many of the materials used have not proven their performance in the modelled applications. For example, wooden or bamboo sidewalls have been used in the past, but tended to break more easily; this would need to be evaluated carefully before implementation on a large scale. It is therefore recommended that industry actors explore the potential of these materials.

In the production stage, the circularity measure most effective from an environmental perspective can be taken: the implementation of a production energy alternative to the grid (e.g a factory rooftop PV installation). Since electricity causes the bulk of all production (and total) impacts for most categories, and the implementation of rooftop PV causes stark reductions in almost all categories, this should be the place to start if circularity is to be implemented by snowboard industry actors. These results were obtained for the Chinese electricity mix; however, in any production country with an electricity mix dominated by fossil fuels, this recommendation would hold.

Distribution and Sales

In this study, it was found that most snowboards had an intercontinental supply chain. The impact of shipping a snowboard for large distances by containership was found limited; however, the impact of air shipping was significantly larger. It is therefore recommended that brands focus on the design- and production planning and actively make sure that there is enough time before the boards are needed to ship the boards by container ship.

Moreover, in the evaluation of the sample of brands, local supply chains were identified as a popular measure to become more sustainable, because extensive shipping is avoided. This measure has limited effectiveness if sea shipping is used in the alternative; however, if a brand would otherwise be air shipping, this is a different story. All in all, it is not the most effective measure that one could take, and moving to a different factory for this reason might not be worth it.

Only a very limited portion of the sales-stage, i.e. the removal of the packaging, was taken into account in this study. It is therefore not possible to make recommendations on circularity measures for this stage; however, this would be a topic worth researching. It is therefore recommended that the environmental impact of store operation is explored and that hotspots are identified. These could be used to come up with effective measures for more circularity in sales.

Use

In the first part of this research, it was concluded that equipment owned by recreants (Tourists and Wintersports Enthusiasts) was likely not used until the technical EOL (see 4.4); moreover, from the LCA study, it became clear that elongating the lifetime of the equipment was one of the most effective strategies to decrease the snowboard lifecycle environmental impact across all impact categories. Therefore, ways to increase the equipment use-time for these two archetypes are explored below.

Firstly, rental equipment performs better because it is used until the technical EOL (see 5.2). However, equipment is usually only rented by Tourists participating in wintersports for one week a year or less (see 4.1), and not by Wintersports Enthusiasts with higher participation (5 – 7 weeks per year). This might be because of the costs; renting a snowboard for a week costs about 105 – 139 euros, which leaves the Wintersport Enthusiast with a yearly cost of 525 – 973 euros for 5 – 7 weeks of rent (Intersport, n.d.; Skiset, n.d.; Sport2000 Rent, n.d.), for which he could also buy a new set of equipment (350 – 850 euros, depending on the equipment quality (e.g. Blue Tomato, n.d.)). Thus, to motivate this group to rent, it should become more financially attractive, for example by making it cheaper to rent equipment for longer, also if it is rented in separate weeks spread over the season. Moreover, renting equipment should become more flexible: Wintersports Enthusiasts often possess a quiver of 3-4 different pieces of equipment for different circumstances or uses, and additional specialized equipment is their most named reason to buy new equipment (see 4.1). A flexible rental program, allowing to trade in equipment in case circumstances for which other equipment is preferrable arise, could fulfill this need. By getting the Wintersport Enthusiast to rent his equipment, the lifetime of his equipment could be increased; moreover, with flexible rental programmes, the possession of multiple pieces of equipment could be prevented. Finally, this could also be economically attractive to rental companies, since these people often participate in wintersports outside the regular holidays.

40% of Tourists already rents their equipment, which is 50% of the tourists participating in wintersports for one week per year: however, of the tourists that participate for 2-3 weeks per year, virtually nobody rents (3%), likely also because of the costs. Discounts for renting equipment more than one week per year could therefore also be a way to increase renting participation.

The use-time of Tourist or Wintersport Enthusiast equipment could also be increased through the promotion of secondhand use, for example with pass-along programmes (Burton Snowboards, n.d.), or second-hand stores (e.g. 2nd Ride, n.d.). Research into the quality of secondhand equipment and the opinions of consumers should give more insight into opportunities in this area.

EOL & Waste Treatment

Three options for snowboard EOL treatment were compared in this study: incineration, repurposing, and recycling through solvolysis. Firstly, although incineration with energy recovery has a very low degree of circularity incineration was shown to have a limited impact; this still held if the energy generated was not taken into account. In contrast, the solvolysis process evaluated in A4 had a large contribution to the results, and the recycling only yielded net "avoided burdens" in two impact categories (Land Use and Carcinogenic Effects), constituting a net impact in all other categories. Based on these results, implementation of this recycling process in its current shape can therefore not be recommended. However, as indicated before, this solvolysis process has currently only been performed on a lab scale; moreover, the concept was not proven yet for snowboards, and many uncertainties exist (see 11.1). For the industry actors, the recommendation is therefore to keep the conversation with epoxy suppliers and waste treatment companies going, and to express the interest into cleaner EOL treatment options that facilitate higher value retention than energy recovery. In 10.3, it was concluded that the recycling of the separated materials did yield "avoided burdens" in almost all categories (see table 10.2); cleaner material separation processes could therefore still be promising for snowboards.

Finally, repurposing a snowboard at the EOL was shown potentially environmentally beneficial during this study. This also is a high-value way to deal with EOL composites, because the structural benefits of the composite are retained (Joustra, Flipsen, & Balkenende, 2021). Increased repurposing of EOL snowboards might be achieved in two ways: either by encouraging individual repurposing projects, such as the construction of garden fences, benches or shelves from snowboards, or by creating business models around repurposed snowboards. The latter is done by NoK, who manufacture skateboards from faulty produced snowboards (NoK Boards, n.d.). This is currently still a small company; however, it would be interesting to see how this product develops, and whether there are other commercially viable ways to reuse EOL snowboards.

In 10.3, it became apparent that the impact of waste treatment for the BAU alternatives was very limited, with the total waste treatment contributions barely visible in figure 10.3 for most categories. Waste treatment should therefore not be the focus of snowboard actor circularity implementation.

Recommendations for Further Academic Research

Apart from recommendations for industry actors, recommendations for future research were also identified.

Firstly, the solvolysis-process as modelled in this study was not found environmentally beneficial and should not be implemented in the current shape. However, this process was modelled on one lab-scale paper and surrounded by countless uncertainties that could have a big impact on the results. For example, if it were possible to recycle the PA11 topsheet, this could make the process more interesting, since the PA11 topsheet is currently a large contributor to the environmental impact results. For other composites containing energy-intensive materials that could potentially be recovered, this could also hold. For this reason, his process deserves more research attention. A first step would be to prove the concept and technology of this process for various types of composites, and to assess the state of the separated materials after recycling. If this shows promise, scenarios for upscaling into a more industrial process should be developed and evaluated with LCA to get a better picture of the environmental impact. Moreover, these scenarios could give an insight in the economic viability of the technology, which is important as composites recycling processes are often not economically viable (Post et al., 2020). Since the Recyclamine epoxy hardener modelled in this study was recently bought by chemicals giant Aditya Birla Chemicals and is offered as a product line on their website (CompositesWorld, 2019; Aditya Birla Chemicals, n.d.), it is essential that the environmental sense of this recycling process is verified before the process is adopted on a large scale.

Secondly, repurposing at the EOL was found potentially environmentally beneficial. However, as explained in 11.1, this result is surrounded by many uncertainties due to material substitution assumptions. In the current model, it is assumed that the EOL snowboard substitutes a wooden plank and therefore decreases consumption; however, in reality, the repurposing might instead cause additional consumption. For this reason, it would be good to evaluate additional repurposing scenarios taking into account market dynamics and potential consumption rebound effects, for example with consequential LCA. Based on this information, it could then be attempted to develop effective repurposing business models that could prevent or decrease the occurrence of consumption rebound effects.

Thirdly, in this research, three wintersports participant archetypes with distinct participation characteristics were established. However, the differences in environmental impact of snowboard use between these archetypes were only researched to a very limited extent in this study. This holds potential for future research, as comparing these archetypes could lead to insights that could complement the results of this study. Moreover, the questionnaire also contained questions on attitude and behavior towards the environment: in the end, these variables were not analyzed. Adding these variables to the archetypes could provide valuable information for the adjustment of specific measurement to specific users and the communication to different user segments.

Fourthly, various recommendations for more sustainable snowboard lifecycles were given in the previous section. However, in this research, only distinct combinations of circularity measurements were evaluated in the scenarios: in reality, more combinations and possibilities exist, and these might be more environmentally beneficial. Many material alternatives were not evaluated; moreover, other experimental technologies, such as combined cork and wood snowboard cores (Anticonf, n.d.), also exist but were left outside the scope of this analysis. The same holds for other repurposing options such as the skateboards sold by NoK, or recycling technologies (pyrolysis or mechanical recycling). In conclusion, it would be good to evaluate additional scenarios with LCA.

Finally, in this study, all snowboard-specific data originated from small-scale manufacturers. This could have affected the representativeness of the results for larger manufacturers. Moreover, due to the ex-ante character of the study, the study suffered from data gaps, was dependent on many proxies and lab-scale data, and a temporal gap existed between the foreground- and background system. This all affects the information power of the results. It is therefore recommended that this or similar studies are repeated during the development of the evaluated technologies and as more data becomes available, to ensure effective circularity implementation from an environmental perspective in the lifecycle of snowboards and other composites.

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Appendix A: The Survey

A.1. Survey Design

The survey consists of four parts:

I. Winter sports Participation
II. Ski Use & End of Life
III. Snowboard Use & End of Life
IV. Environmental Attitude and Action
V. General Demographics

The first part of the survey is about people's average winter sports frequency and experience; this allows for division of the sample based on participation style. People are also asked whether they participate in skiing, snowboarding, or both; this determines what subsequent parts they are directed to (see figure A.1). People that participate in both activities are asked to fill in both dedicated parts. People are also asked whether they own or rent equipment; this question determines what questions will be shown in part II and III.

In these parts, people are asked about the reasons they have purchased new equipment for. These include questions on breakages or other issues. Skis and snowboards are treated separately, firstly because they suffer from slightly different issues, and secondly because people that participate in both activities might do this on a different level or engage in different activities.

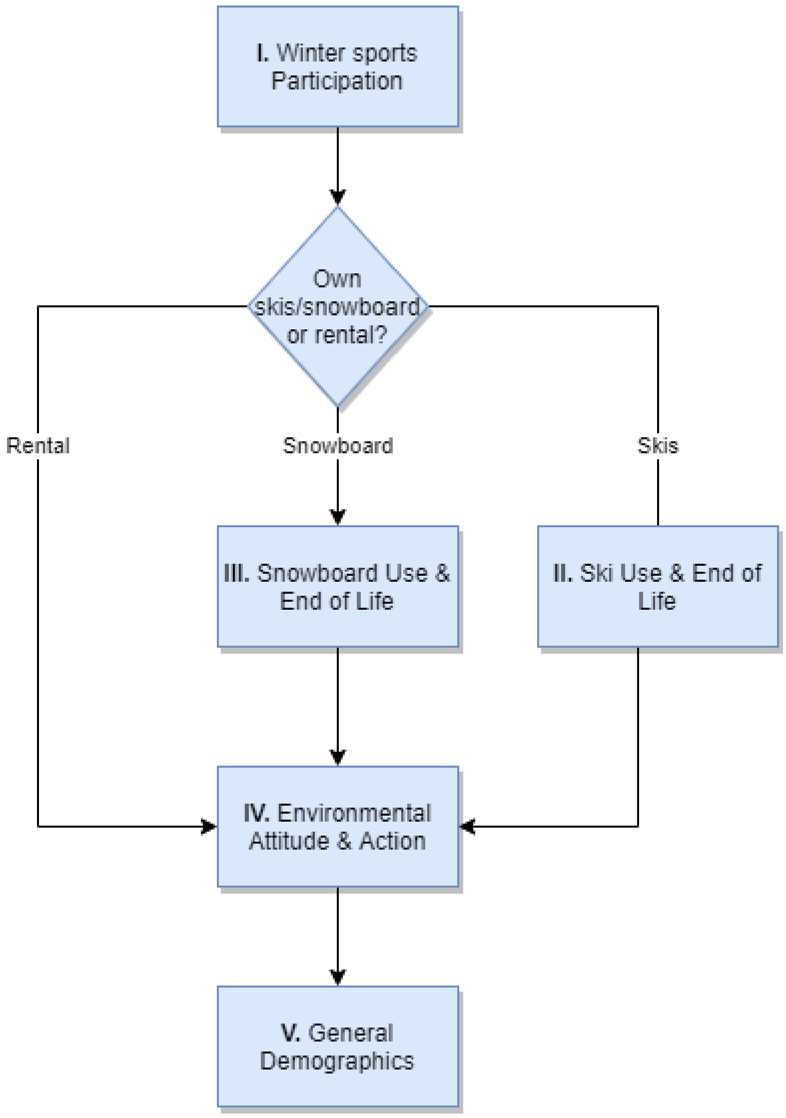


Figure A.1: Questionnaire flow diagram

In the fourth section of the survey, people are enquired about their environmental attitude. The questions are based on a survey by the EU (European Commission, 2008). Since this part is not the main focus of the questionnaire, it is kept short.

In the final, fifth part of the survey, a few questions about general demographics are asked to get a picture of the sample obtained and check whether this sample is representative of the winter sports population.

Overall, most survey questions are based on personal experience of the researcher, obtained from working as a snowboard and ski instructor as well as being a working student at a snowboard brand for a year. The questions about reasons to buy a new piece of equipment and defects were also partially based on consultation of the researcher personal network. In the design of the questionnaire, the attention points raised by Bethlehem (2009) were used. These for example emphasize the importance of short and concise questions, short time frames for recall questions, and avoiding leading questions that stimulate an answer in a certain direction. Apart from ensuring data quality, the aim was also to make the survey as comfortable for the participant as possible, in order to stimulate the completion rate. A built-in tool in the Qualtrics platform was also used for this.

Multiple test and feedback rounds were conducted before the survey was published. The survey was made available in Dutch, English, and German; for each version, an expert in this language was consulted.

A.2. The Survey

Below, the questionnaire is included in English. The questionnaire was also available in Dutch and German; these translations are available upon request.

Start of Block: Intro

Q31 This survey is part of a study on sustainable snowboards/skis and can be filled out by anyone that participates in skiing or snowboarding. The data will be used to model the use and the end-of-life of a snowboard or pair of skis, including use patterns, reasons for discarding the gear, and attitudes on sustainability. It will also be attempted to identify ways to increase ski/snowboard durability. Participation is anonymous and can be withdrawn at any moment. For more information, please feel free to send an email to emmathunnissen@gmail.com.

The survey is available in Dutch, German, and English (see top right)!

End of Block: Intro

Start of Block: Winter Sports Participation

Q1 How often do you usually do winter sports?

1. A few days a year or less (1)
2. 1 week a year (2)
3. 2-3 weeks a year (3)
4. 4-6 weeks a year (4)
5. 6 - 12 weeks a year (5)
6. The full winter season (6)

Q30 What statement describes your winter sports experience best?

7. Relaxing is key; some skiing/snowboarding when there's good weather, and plenty of sun/apfelstrudel/drink breaks (1)
8. I'm comfortably cruising the slopes most of the day, with a good lunch break and maybe a well-earned drink at the end of the day (2)
9. I'm here to do winter sports right? Long lunch breaks are overrated, doing winter sports is what counts! (3)
10. Apres-ski has priority, also during the ski day, but depending on the state of my body I also hit the slopes pretty seriously. (4)
11. Other, namely... (5) ____

Q27 What winter sports do you do? (select all that apply)

1. Skiing (1)
2. Snowboarding (2)
3. Others, namely (3) ____

Q5 Do you own your own equipment? (multiple answers possible)

What winter sports do you do? (select all that apply) = Snowboarding

4. No, I rent/borrow my snowboard (1)

What winter sports do you do? (select all that apply) = Skiing

5. No, I rent/borrow my skis (4)

What winter sports do you do? (select all that apply) = Snowboarding

6. Yes, I own a snowboard (2)

What winter sports do you do? (select all that apply) = Skiing

7. Yes, I own skis (3)

Q4 Are you professionally involved in winter sports in any way (instructor, tour guide, professional skier/snowboarder, rental employee, ...)

12. No, I do winter sports purely for fun (1)
13. Yes, I (sometimes) work as a (2) ____

End of Block: Winter Sports Participation

Start of Block: Ski Use & End of Life

Display This Question:

If What winter sports do you do? (select all that apply) = Skiing

Q2 My skiing level is:

14. Awesome (1)
15. Pretty good, I get down every slope in a controlled manner (2)
16. Intermediate, I get down a red slope in a controlled manner (3)
17. OK, I feel best on a blue slope (4)
18. Beginner (5)

Display This Question:
If What winter sports do you do? (select all that apply) = Skiing

Q3 When I am skiing, I regularly do the following:

8. piste skiing (1)
9. piste tricks (butters, rotations, ollies, ...) (2)
10. jibbing funpark obstacles (3)
11. jumping serious ramps/kickers (4)
12. off-piste (5)
13. touring (as in, walking up the mountain) (6)
14. others, namely (7) ____

Display This Question:
If Do you own your own equipment? (multiple answers possible) = Yes, I own skis

Q6 Is this your first pair of skis?

19. Yes (1)
20. No, I own/have owned other pairs (2)

Display This Question:
If Is this your first pair of skis? = No, I own/have owned other pairs

Q29 How many pairs of skis do you currently have?

I own ... pairs of skis (1)	▼ 1 (1) ... 7+ (7)
Of those, I use ... pairs of skis (2)	▼ 1 (1) ... 7+ (7)

Display This Question:
If Do you own your own equipment? (multiple answers possible) = Yes, I own skis

Q12 In the past 5 years, I got...

... pairs of brand-new skis (1)	▼ 0 (1) ... 9+ (10)
... pairs of second-hand skis (2)	▼ 0 (1) ... 9+ (10)

Display This Question:
If Is this your first pair of skis? = No, I own/have owned other pairs

Q7 Select **all** reasons you've ever had for getting new skis:

15. My skis broke/had a defect (1)
16. My old skis were running behind in technology, which made skiing less enjoyable (3)
17. I wanted new skis that looked cooler/newer (4)
18. My new skis have innovative technological features (5)
19. My new skis have a different type of use; I'm still using my other skis regularly (6)
20. I didn't really need new skis, but I just felt like buying a new pair and am not using my old ones anymore (7)
21. My old skis could not be sharpened anymore because the edges got too thin (9)
22. I lost my ski in the off-piste (11)
23. My old skis were still relatively new, but they didn't fit my skiing style/level (12)
24. My old skis were run down (13)
25. Other, namely (8) ____

Display This Question:

If Select all reasons you've ever had for getting new skis: = My skis broke/had a defect

Q8 Select **all** problems/defects that you have experienced with skis:

26. ski broke near the binding (1)
27. ski broke at the tip (2)
28. Broken edge (3)
29. Loose layers (delamination) at the tip/tail (4)
30. Air bubble in the base/topsheet (5)
31. Dimple in the base/topsheet (6)
32. Hole/deep scratch in the base, letting water into the core (7)
33. Edge coming out/getting loose (8)
34. Binding problem/breakage (9)
35. Other, namely (10) ____

Display This Question:

If Select all reasons you've ever had for getting new skis: = My skis broke/had a defect

Q14 **In the past 5 years**, of my skis with a defect/problem...

... pairs were covered by warranty (1)	▼ 0 (1) ... 7+ (8)
... pairs were NOT covered by warranty (2)	▼ 0 (1) ... 7+ (8)

Display This Question:

If Is this your first pair of skis? = No, I own/have owned other pairs

Q10 How long have you approximately used the **previous** pair of skis?

I have used them for (amount of years) (1)	▼ 1 (1) ... 15+ (15)
for about (amount of weeks) a year (2)	▼ 1 (1) ... 15+ (15)

Display This Question:
If Is this your first pair of skis? = No, I own/have owned other pairs

Q11 What did you do with your **previous** pair of skis?

21. I am still using it (1)
22. I passed them on to someone else/sold them second hand (2)
23. i discarded them with municipal waste (3)
24. They are gathering dust in storage (4)
25. I handed it in for warranty (5)
26. Other, namely (6) ____

End of Block: Ski Use & End of Life

Start of Block: Snowboard Use & End of Life

Display This Question:
If What winter sports do you do? (select all that apply) = Snowboarding

Q28 My snowboarding level is:

27. Awesome (1)
28. Pretty good, I get down every slope in a controlled manner (2)
29. Intermediate, I get down a red slope in a controlled manner (3)
30. OK, I feel best on a blue slope (4)
31. Beginner (5)

Display This Question:
If What winter sports do you do? (select all that apply) = Snowboarding

Q26 When I am snowboarding, I regularly do the following:

36. piste snowboarding (1)
37. piste tricks (butters, rotations, ollies, ...) (2)
38. jibbing funpark obstacles (3)
39. jumping serious ramps/kickers (4)
40. off-piste (5)
41. splitboarding/touring (as in, walking up the mountain) (6)
42. others, namely (7) ____

Display This Question:
If Do you own your own equipment? (multiple answers possible) = Yes, I own a snowboard

Q15 Is this your first snowboard?

32. Yes (1)
33. No, I own/have owned other snowboards (2)

Display This Question:
If Is this your first snowboard? = No, I own/have owned other snowboards

Q30 How many snowboards do you currently have?

I have ... snowboards (1)	▼ 1 (1) ... 7+ (7)
Of those, I use ... snowboards (2)	▼ 1 (1) ... 7+ (7)

Display This Question:
If Do you own your own equipment? (multiple answers possible) = Yes, I own a snowboard

Q18 In the past 5 years, I got...

... brand-new snowboards (1)	▼ 0 (1) ... 9+ (10)
... second-hand snowboards (2)	▼ 0 (1) ... 9+ (10)

Display This Question:
If Is this your first snowboard? = No, I own/have owned other snowboards

Q17 Select **all** reasons you've ever had for getting a new snowboard:

43. My old snowboard had a problem/defect (1)
44. My old snowboard was running behind in technology, which made snowboarding less enjoyable (3)
45. I wanted a new snowboard that looked cooler/newer (4)
46. My new snowboard has new technological features (5)
47. My new snowboard has a different type of use; I'm still using my other snowboard(s) regularly (6)
48. I didn't really need a new snowboard, but I just felt like buying a new one and am not using my old one anymore (7)
49. My old snowboard could not be sharpened anymore because the edges got too thin (9)
50. My old snowboard was still relatively new, but it didn't fit my riding style/level (11)
51. My old snowboard was completely run down (12)
52. Other, namely (8) ____

Display This Question:
If Select all reasons you've ever had for getting a new snowboard: = My old snowboard had a problem/defect

Q19 Select **all** problems/defects that you have experienced with a snowboard:

53. Broken snowboard at tip/tail (1)
54. Snowboard broke at the binding (2)
55. Snowboard broke between the bindings (3)
56. Part(s) of base got loose (diecut delamination) (4)
57. The (top)layer(s) got loose (delamination) (5)
58. A deep scratch/hole through which water reached the base (6)
59. gap between edge and sidewall (7)
60. problems with inserts (8)
61. Air bubble in the base/topsheet (9)
62. Dimple in the base/topsheet (10)
63. Edge coming out/getting loose (11)
64. Other, namely (12) ____

Display This Question:
If Select all reasons you've ever had for getting a new snowboard: = My old snowboard had a problem/defect

Q21 **In the past 5 years**, of my snowboards with a defect/problem...

... snowboards were covered by warranty (1)	▼ 0 (1) ... 9+ (10)
... snowboards were NOT covered by warranty (2)	▼ 0 (1) ... 9+ (10)

Display This Question:
If Is this your first snowboard? = No, I own/have owned other snowboards

Q22 How long have you approximately used your **previous** snowboard?

I have used it for (amount of years) (1)	▼ 0 (1) ... 15+ (16)
for about (amount of weeks) a year (2)	▼ 0 (1) ... 15+ (16)

Display This Question:
If Is this your first snowboard? = No, I own/have owned other snowboards

Q24 What did you do with your **previous** snowboard?

34. I am still using it (1)
35. I passed it on to someone else/sold it second hand (2)
36. i discarded it with municipal waste (3)
37. It is gathering dust in storage (4)
38. I handed it in for warranty (5)
39. Other, namely (6) ____

End of Block: Snowboard Use & End of Life

Start of Block: Environmental Attitude and Action

Q25 Indicate for each statement to what extent you agree

	Strongly disagree (1)	Somewhat disagree (2)	Neutral/don't know (3)	Somewhat agree (4)	Strongly Agree (5)
I think climate change will affect winter sports in the coming decades (1)	40.	41.	42.	43.	44.
Protecting the environment is important to me personally (2)	45.	46.	47.	48.	49.
Economic growth should have priority over environmental protection (3)	50.	51.	52.	53.	54.
I have changed my habits to decrease my environmental impact (4)	55.	56.	57.	58.	59.

Q31 How much would you be willing to pay extra for a more environmentally friendly product?

60. nothing, i think the price should stay the same (1)
61. 1% (this means +€5 on a €500 snowboard) (2)
62. 5% (this means +€25 on a €500 snowboard) (3)
63. 10% (this means +€50 on a €500 snowboard) (4)
64. More than 10% (5)

End of Block: Environmental Attitude and Action

Start of Block: General Demographics

Q26 What is your gender?

65. Male (1)
66. Female (2)
67. Other (3)

Q27 How old are you?

68. 18-24 (1)
69. 25-30 (2)
70. 31-40 (3)
71. 41-50 (4)
72. 51-60 (5)
73. 61+ (6)

X→

Q29 In which country do you currently live?

▼ Afghanistan (1) ... Zimbabwe (1357)

End of Block: General Demographics

Appendix C: Survey data analysis log

C.1. Data Preparation

A few adaptations to the dataset had to be made before analysis. Firstly, for all questions where multiple statements could be selected, dummy variables were created for each statement. If a respondent had selected the statement, the value of the dummy variable was “1”, if the respondent had not selected the statement, “0”. If none of the statements were selected, i.e. the question had not been answered, missing values were assigned to all of the dummy variables.

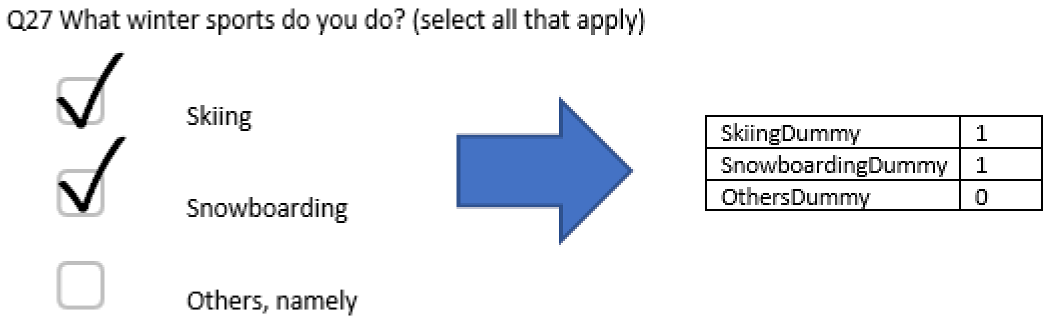


Figure 5.1: Example of conversion to dummy variables

The responses to the “Other, namely…”-option available for some questions were analyzed manually. If these answers fit with an existing answer statement, they were assigned this statement; if an answer did not fit with an existing statement and was at least given 2 times, a new answer statement was added (see table C.1).

The question about their winter sports participation frequency was formulated with categories of unequal size and could therefore not be seen as interval data (Sarstedt & Mooi, 2019); these were converted to numeric values using the means of the categories (see table C.2).

Table C.1: added categories based on "Other, namely..."

Question	Added data category
EOL snowboard & ski	“Reuse for another purpose” “Reuse for another purpose (decoration)” “They were stolen” “I still use them for poor conditions”
Reasons to get new skis:	“I got new skis from a sponsorship deal” (note: also includes brand representatives) “I progressed and needed a better set of equipment” “My skis were stolen” “I increased in length/weight and therefore needed larger skis”
Reasons to get a new snowboard:	“I got a new snowboard from a sponsorship deal” “My old snowboard lost its pop”
Problems/breakages experienced with snowboards:	“Broken Edge” (unfortunately not included as an answer category when it should have been)
Winter sports experience:	“I spend most of my on-snow hours working as a snow sports instructor” “I spend most of my days riding the off-piste/touring”

Table C.2: Transformation of Winter Sports Frequency per Year

Original value	Transformation	New value (weeks)
A few days a year or less	Mean	0.15
1 week a year	Value	1
2-3 weeks a year	Mean	2.5
4-6 weeks a year	Mean	5
6-12 weeks a year	Mean	9
The full winter season	Value	14

Table C.3: Purchasing decision statements aggregated into categories

Statements	Aggregated Category
"My old snowboard/skis had a problem/defect" "My old skis/snowboard couldn't be sharpened anymore" "My old skis/snowboard were run down" "My skis/snowboard were stolen"	Equipment reached EOL
"My old snowboard/skis were running behind in technology" "My old snowboard/skis were still relatively new, but didn't fit my riding style/level" "I progressed and needed a better set of equipment" "I increased in length/weight and needed larger equipment"	Equipment didn't fulfill function anymore
"I wanted new skis/snowboard that looked cooler/newer" "My new skis/snowboard have new technological features" "I didn't really need new equipment, but felt like buying it and am not using my old equipment anymore"	New equipment had something special that I wanted
"My new skis/snowboard have a different type of use; I am still using my other ones regularly"	Multiple pieces of equipment for different uses
"I got new skis/snowboard from a sponsorship deal"	Got new equipment for free

Table C.4: Lifetime in Years & Weeks/Year Usage with outliers excluded

Variable		N	Mean	Std. Deviation	Std. Error Mean
Lifetime in Years	Recreant	144	5.13	2.60	0.22
	Professional	132	2.83	1.48	0.13
Weeks/Year Usage	Recreant	130	2.65	1.62	0.14
	Professional	135	13.54	6.58	0.57

Appendix D: LCA Calculations and Proxies

In this appendix, the LCA calculations are provided. The proxy processes in this study can be divided in two categories: proxies based on Ecoinvent processes, and proxies based on external sources. These will be addressed separately. Afterwards, the calculations underlying all alternatives will be presented.

D.1. Proxies – Adapted From Ecoinvent

The proxies described in the next sections are based on existing processes in Ecoinvent and are only adapted to accommodate the processing of a similar good or service. The adaptations are described per process below.

Basalt Fiber Production

This proxy is based on the Ecoinvent process *Glass Fibre Production [RER]* and is used in A4.

The production of basalt fibers is very similar to the production of glass fibers (Ivanitskii & Gorbatschev, 2011; Jamshaid & Mishra, 2015), except that glass-fiber machines can produce more fibers at a time (Ivanitskii & Gorbatschev, 2011). The processing temperatures are also approximately the same: 1450 °C for basalt (Jamshaid & Mishra, 2015) and 1400 °C for glass fibre (CompositesWorld, 2020), which suggests similar heat requirements. Since basalt fibers can likely be remelted in case of production failure (Eutit s. r. o, 2013), whereas glass fibers cannot, a higher material-to-fiber efficiency is assumed: 1.10 kg material input/kg versus 1.39 kg input/kg fiber for glass fiber (Ecoinvent, 2020).

The biggest difference in the production process is the feedstock; glass fibers are made of different components such as silica, boron oxide, alumina, lime, and magnesia (CompositesWorld, 2020), while basalt fibers only have basalt rock as feedstock, which naturally contains these minerals (Jamshaid & Mishra, 2015).

To create a representative basalt fiber process, the glass-fiber-specific feedstocks (boric acid, alumina, lime, silica sand, clay) were taken out and replaced by basalt as a feedstock. Since boric acid was not required for the process anymore, hydrogen chloride and hydrogen fluoride emissions to the biosphere were removed. As most basalt used for processing comes from Ukraine, the fibers were assumed to be produced in Europe.

Veneer Production

For the veneer production, sawing and planing of the wood is required (Jonny Builds, 2018). There are a few processes in Ecoinvent, of which *sawing and planing, azobe, air-dried [RER]* was the most representative. For the veneer-production process this process was copied and the azobe wood was replaced by oak, as a proxy to replace for example cherry or walnut wood (Grown Skis, n.d.), or ash (Arbor Snowboards, n.d.), since these wood species are not available in Ecoinvent. Oak, a hardwood like the proxied species, is similar to ash.

Linseed Oil Production

The soybean oil production process in Ecoinvent is very similar to the linseed oil production process when comparing the Ecoinvent description with Seedoilpress.com (n.d.); therefore, soybean crude oil production is used as a proxy by replacing the soybeans with flaxseed. The same feedstock-to-oil yield is assumed (2.0168 kg feedstock → 1 kg oil). For refining, the same approach as for the castor oil refining described in the next section is used.

Hemp Fiber Production

Since a hemp fiber production process did not yet exist in Ecoinvent, the process was proxied based on *fibre production, flax, retting [IN]*. The flax feedstock was replaced with Sunn Hemp Production [IN]. Since large amounts of industrial hemp are cultivated in India, it is assumed the fibers are extracted there as well, as this is a two-part process that starts on-site (Sarkar et al., 2015; Global Hemp, 2000). After harvesting, the stems are left to ret, which essentially means rotting until the fibers can be separated from the rest of the stalk easily (Global Hemp, 2000). After retting, the stalks might be transported to a more central location where the fibers are separated from the stem mechanically. This process is very similar to the flax fiber production process, with the same machines. Therefore, the use of flax fiber production is justified, and the material-to-fiber efficiency is kept the same (7.2933 kg of plant/1 kg of fiber).

D.2. Proxies – Based on External References

The proxies described below are proxies for goods and services for which a similar process was not available in the Ecoinvent database. Therefore, these processes were modelled based on external data such as literature, websites, or expert consultations. These are presented below.

Electricity Market China 2025

Since this is a prospective LCA, and electricity mixes are expected to change significantly in the coming years, it was decided to model the electricity mix of production location China in the year 2025. For this model, the Renewable Energy Outlook China 2018 (CREO 2018) (NRDC, 2018) was used as the main source: for missing information, a few other academic literature sources were used.

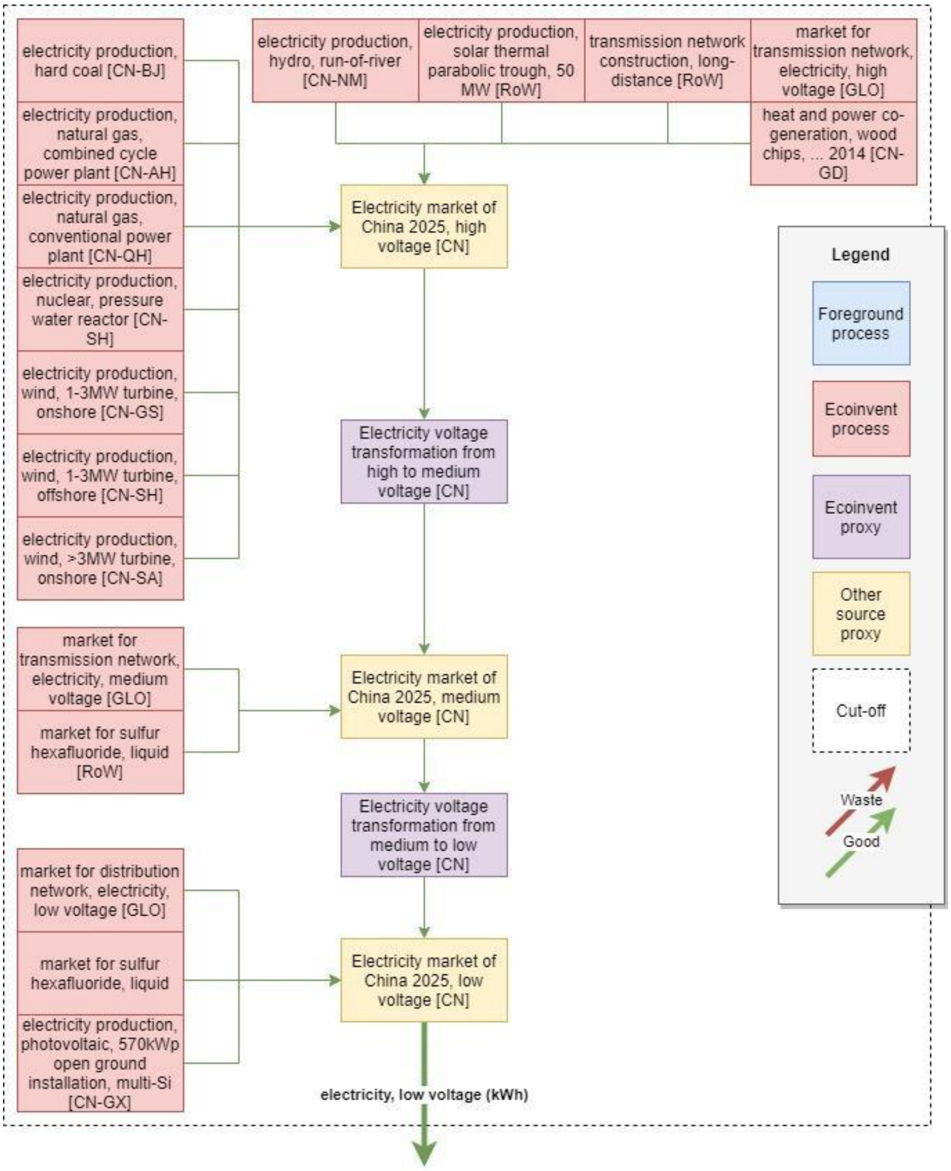


Figure D.1: The electricity market of China in 2025

Determining the Electricity Mix

In the China Renewable Energy Outlook 2018, the following expected electricity mix is presented:

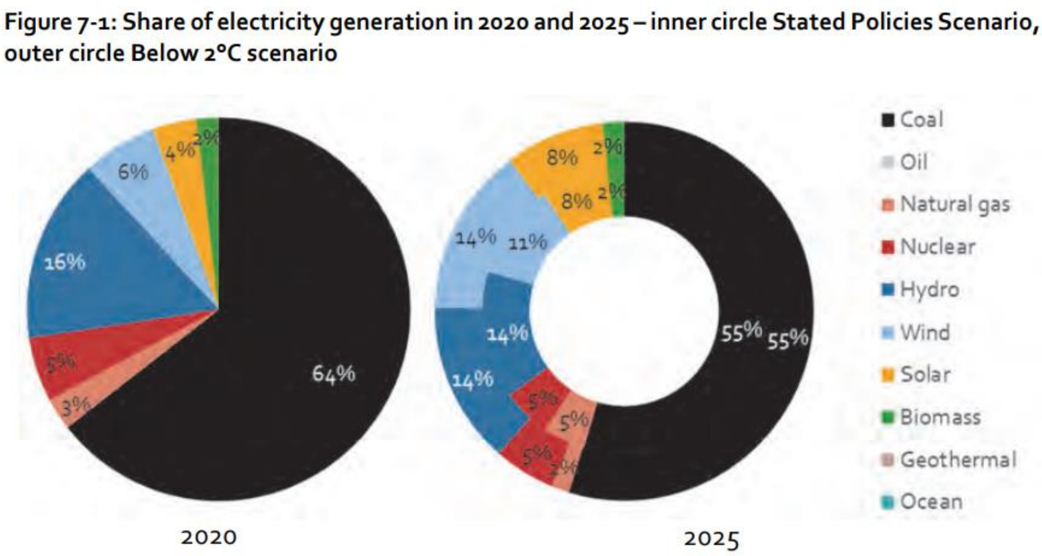


Figure D.2: Expected 2020 and 2025 electricity mix for China (China Renewable Energy Outlook, NRDC, 2018, p. 126).

In figure D.2, the expected electricity mix in 2020 is compared with the expected electricity mix in 2025 under two scenarios: the scenario following the policies formulated in the Chinese Five Year Plans, and a scenario following a more stringent path that complies with the Paris aim to keep global warming below 2°. In this project, the proportions of different technologies in the Chinese electricity market were modelled based on the expectations under the current policies (inner circle of the right graph).

Electricity Market Structure

In Ecoinvent, electricity markets are organized in a hierarchy: for every region, a high-voltage, medium-voltage, and low-voltage market is available. All large-scale electricity generation technologies are inputs to the high-voltage market; since photovoltaic electricity generation is a lower-voltage technology, this technology enters the market at the low-voltage level. The electricity moves downwards through the levels; for every market level, a transformation step is included where the losses of the system are included. Additionally, for every step, an input of a transmission/distribution network, construction, and sulfur hexafluoride is included (see figure D.1). The input processes and their quantities were all based on existing Chinese electricity markets in Ecoinvent.

Inventory & Calculations

High voltage

- All calculations were based on the document presented above. Additional assumptions/calculations for flows include the following:
- *Transmission network, construction, & sulfur hexafluoride:* numbers copied from existing Ecoinvent Chinese electricity markets
- *Natural gas (5%):* it is assumed that the plants already existing in 2020 are conventional power plants (0.02 kWh); however, as increasing the natural gas share towards 2025 is to decrease GHG emissions, it is expected that the newly constructed powerplants are CCP plants (0.03 kWh).

- *Wind (11%):* almost half of the capacity installed in 2025 already existed in 2017 (CREO 2018). The average rated capacity of installed wind turbines in 2011 is 1.45 MW, and most of these turbines are onshore (China-Britain Business Focus, 2020); therefore, it is assumed that all turbines installed before 2017 are 1-3 MW wind turbines. According to CREO, 18% of new capacity will be installed offshore. Finally, it is expected that all newly installed onshore turbines will be bigger than 3 MW, since almost exclusively larger wind turbines are constructed nowadays (Roelofs, pers. comm., 2020).
- *Solar (8%):* Currently, 99% of solar energy in China is PV; currently concentrated solar power is being developed so 0.1 kWh concentrated solar power (high voltage) & 0.07 kWh PV is included (low voltage).
- *Electricity output:* the output of the process is 0.93 kWh as solar PV is a low-voltage technology and thus enters the electricity market in the low-voltage state (see figure D.1 & 2).

(proxy) Electricity Market China 2025 (High Voltage)

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] electricity production, natural gas, combined cycle power plant (kWh)	0.03	**[G] Electricity, high voltage (kWh)**	0.93
[G] electricity production, natural gas, conventional power plant (kWh)	0.02		
[G] electricity production, nuclear, pressure water reactor (kWh)	0.05		
[G] electricity production, hydro, run-of-river (kWh)	0.14		
[G] electricity production, wind, 1-3MW turbine, onshore (kWh)	0.05		
[G] electricity production, wind, 1-3MW turbine, offshore (kWh)	0.02		
[G] electricity production, wind, >3MW turbine, onshore (kWh)	0.04		
[G] transmission network, long-distance (km)	3.17E-10		
[G] transmission network, electricity, high voltage (km)	6.58E-09		
[G] electricity production, solar thermal parabolic trough, 50 MW (kWh)	0.01		
[G] electricity production, hard coal	0.55		
[G] heat and power co-generation, wood chips, … 2014 (electricity, high voltage) (kWh)	0.02		
Environmental Flows - In		*Environmental Flows - Out*	
Environmental Flow	Value	Environmental Flow	Value
		Dinitrogen monoxide (kg)	5E-06
		Ozone (kg)	4.16E-06

Transformation

For transformation, the existing rate in Ecoinvent for Chinese electricity markets is copied.

(proxy) electricity voltage transformation from high to medium voltage

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] Electricity, high voltage (kWh)	1.0054	**[G] electricity, medium voltage (kWh)**	1

Medium voltage:

- *Transmission network, construction, & sulfur hexafluoride:* numbers copied from existing Ecoinvent Chinese electricity markets

(proxy) Electricity market of China 2025, medium voltage

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] transmission network, electricity, medium voltage (km)	1.86E-08	**[G] electricity, medium voltage (kWh)**	1
[G] sulfur hexafluoride, liquid (kg)	1.60E-07		
[G] electricity, medium voltage (kWh)	1		
Environmental Flows - In		*Environmental Flows - Out*	
Environmental Flow	Value	Environmental Flow	Value
		Sulfur hexafluoride (kg)	1.60E-07

Transformation: based on existing Ecoinvent transformation processes.

(proxy) electricity transformation from medium to low voltage

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] electricity, medium voltage (kWh)	1.0239	**[G] electricity, low voltage (kWh)**	1

Low voltage:

- *Transmission network, construction, & sulfur hexafluoride:* numbers copied from existing Ecoinvent Chinese electricity markets
- *Photovoltaic:* Low-voltage technology. 99% of solar electricity is PV in China, therefore almost all of it is modelled as PV.

(proxy) Electricity market of China 2025, low voltage

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] electricity, low voltage (kWh)	0.93	**[G] electricity, low voltage (kWh)**	1
[G] distribution network, electricity, low voltage (km)	8.74E-08		
[G] sulfur hexafluoride, liquid (kg)	9.09E-09		
[G] electricity, low voltage (photovoltaic) (kWh)	0.07		
Environmental Flows - In		*Environmental Flows - Out*	
Environmental Flow	Value	Environmental Flow	Value
		Sulfur hexafluoride (kg)	9.09E-09

Fish Glue Production

Fish glue is produced from collagen in fish skins. Due to extensive fishing, fish skins are an abundant waste product in different parts of the world (Chandravanshi, Chowdury, & Nath, 2019; Sampaio et al., 2017). To produce the glue, the collagen needs to be extracted from the skin and made water-soluble. This is done in a process that can be divided in three main steps: washing & cutting, soaking in an alkaline and acidic solution, and evaporation of excess liquid (see figure 1).

Process description

In the first rinsing step, the skin is rinsed with tap water and cut into small pieces (Akter et al., 2011; Chandravanshi, Chowdhury, & Nath, 2019; Manjula, Jayamanne, & Thushari, 2015).

Afterwards, the fish skin is soaked in an alkaline solution of 0.2% (w/w) sodium hydroxide for 24 hours, as this concentration and treatment time was found to yield the best glue in terms of time to tack and strength (Manjula, Jayamanne, & Thushari, 2015). The alkaline solution extracts the fats from the fish skin and causes the skin to swell; after the soaking, the solution is discarded, excess swollen skin is removed, and the remainder is washed. Since the fats carry the odor of the skin, this step also functions as odor removal (Akter et al., 2011). Next, the skin is neutralized with a hydrochloric acid solution with the same concentration for 24 hours. This step is concluded with another washing of the product. In the third step, double the volume of the fish skin product is added in distilled water and the mixture is heated to 60 degrees in a thermally insulated reactor (Sampaio et al., 2017). The mixture is kept on this temperature for 6 hours; afterwards, the mixture is heated to 90 degrees until excess water has evaporated, leaving an end product with 45-50% moisture content (Chandravanshi, Chowdhury, & Nath, 2019).

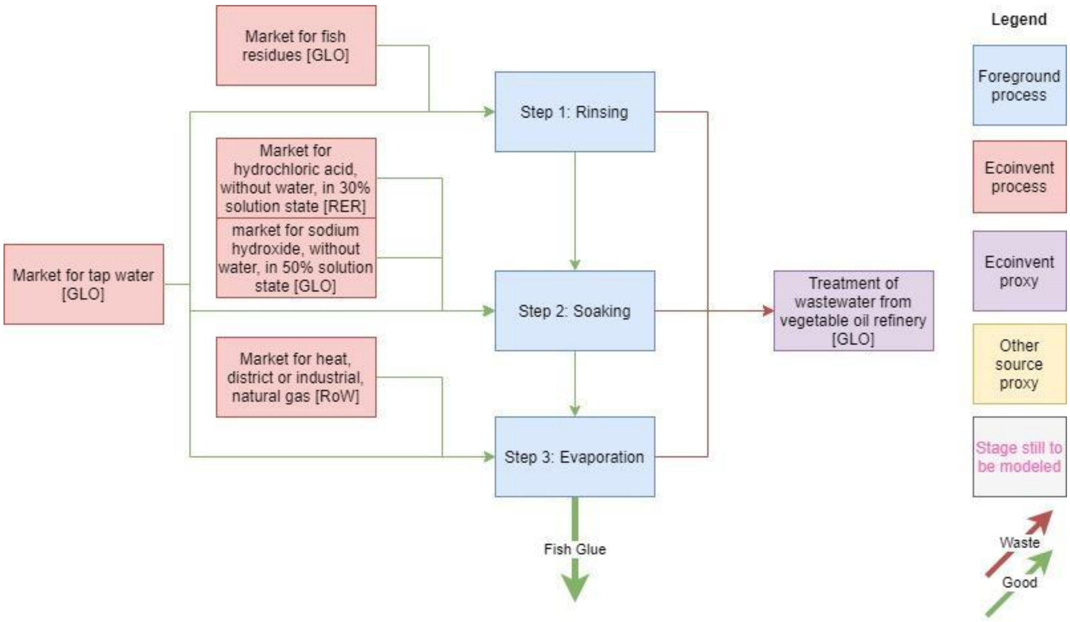


Figure D.3: Flowchart of fish glue production, divided in the three main steps

Unit Process Data

In table 1, the process data is presented. No direct relevant biosphere exchanges of the process were identified.

(proxy) Fish Glue Production

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] Fish residues (skin) (kg)	4.843	**[G] Fish glue (kg)**	1
[G] NaOH (kg)	0.022	[W] Wastewater (l)	145.287
[G] HCl (kg)	0.022		
[G] Heat (MJ)	8.080		
[G] Tap water (l)	182.040		

Table D.2: Cut-offs – flows not taken into account in the process

Cut-offs

Element	Description
Electricity	- Electricity of stirring & cutting not incorporated (no data)
Heating	- Only heating up to desired temperature incorporated (assumption of isobar heating); heat losses over the period of the process not incorporated (data for assumptions lacking)
Waste flows	- Waste flows such as swollen removed skin not taken into account; only the fish skin components dissolved in the waste water are taken into account
Transportation	- No transportation of feedstocks/products taken into account
Packaging	- Currently packaging of transported fish skins not taken into account; packaging of other feedstocks also not taken into account
Equipment	- Process equipment not taken into account (assumed to have such a long lifetime that it can be neglected)
Distilled water	- Not available in Ecoinvent; therefore tap water assumed

PA11 Production

Polyamid-11 (PA11) is produced from castor oil extracted from castor beans (Devaux, Lê, & Pees, n.d.). The French company Arkema is the main producer of this material. There is limited information available on the production of PA11, therefore this proxy is based on an eco-profile published by Arkema only (Devaux, Lê, & Pees, n.d.). This eco-profile only discloses on the carbon footprint of the PA11. Luckily, the castor bean feedstock is available in Ecoinvent, allowing for the inclusion of impacts downstream in the supply chain. Additional feedstocks include methanol, hydrogen bromide, and ammonia; since the methanol is recycled in the process, and the hydrogen bromide, only the ammonia input is included.

The production of PA11 from castor beans starts with the extraction of castor oil, either by crushing or chemical extraction (Devaux, Lê, & Pees, n.d.). The oil is refined afterwards and transported to the PA11-monomer production plant. Here, the ricinoleic acid in the oil undergoes five transformation steps to the PA11-monomer through reactions with respectively methanol, which is recycled in the process, hydrogen bromide, and ammonia.

Inventory & Calculations

This process is proxied in the following way:

- The castor bean feedstock is available in Ecoinvent.
- Soy-bean oil production through mechanical extraction is also available in Ecoinvent; this process is used as a proxy for the oil extraction. Since the oil content of the seeds is nearly 50% (Devaux, Lê, & Pees, n.d.), a seed-to-oil yield of 48% is assumed. From the other 52% of

the castor beans, castor meal is produced, which can be used as animal feed or fertilizer (Feedipedia.org, Devaux, Lê, & Pees, n.d.). This meal is cut-off. Other than replacing the soybean feedstock with castor beans, the process is left the same (process used: *soybean meal and crude oil production, mechanical extraction [RoW]*). This process is a coproduction process of soybean meal and soybean oil, and the in- and outputs are therefore divided between these two products. Only the in- and outputs allocated to the oil are incorporated in this proxy.

- After extraction, the oil is refined. This is proxied with *soybean oil refinery operation [RoW].* The same crude-oil-to-refined oil as in the original process (1.0363 kg of crude to 1 kg of refined) is maintained. The original process is a multifunctional process: only the portion that is allocated to the refined oil is included.
- After refining, PA11 monomer production takes place. The molecular formula of the castor bean feedstock is the following: $C_{57}H_{104}O_9$ (Devaux, Lê, & Pees, n.d.; Pubchem, n.d.). This has a molar weight of 932.61 g/mol. The PA11 monomer (11-aminoundecanoic acid), molecular formula $C_{11}H_{23}NO_2$, has a molar weight of 201 g/mol. Based on the process description of Devaux, Lê, and Pees (n.d.), we obtain a stoichiometric ratio of feedstock to monomer of 1:3, which means that 932.61 grams of feedstock equals 603 grams of final monomer, or a feedstock-to-final product ratio of 65%. It is assumed this yield stays the same for the polymerization step.
- As mentioned before, there are 3 production feedstocks: methanol, which is recycled, boric acid, which might also be recycled as it is extracted from the process chemical in the same shape, and ammonia, which is a part of the final product. Since methanol is recycled and boric acid is not available in Ecoinvent, only the ammonia feedstock is included. The stoichiometric proportions of ammonia (NH_3, molar weight 15 g/mol) to feedstock are 1:3, which means that for every 932.61 grams of feedstock, 45 grams of ammonia need to be added.
- In the process, two valuable by-products are produced: glycerin and heptaldehyde (Devaux, Lê, & Pees). The in- and outflows of the production processes need to be allocated to these three products. The allocation approach of the eco-profile is followed, where the flows are allocated based on produced mass. To do so, the mass of the byproducts needs to be calculated.

Product	Molar weight (g)	Stoichiometric ratio to feedstock	Kg produced per kg PA11
PA11-monomer	201	3:1	1
Glycerin ($C_3H_8O_3$)	92	1:1	0.05086
Heptaldehyde ($C_7H_{14}O$)	114	3:1	0.18905

- These calculations lead to the following amount of total produced mass per kg of PA11-monomer: 1.2399. All inflows were subsequently allocated based on this ratio, meaning that total amount of castor bean feedstock x was divided by 1.2399 to get the amount allocated to the PA11-monomer. This finally leads to the following inventory table:

(proxy) PA11 production

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] Castor oil, refined (kg)	1.2474	**[G] Polyamide 11 (kg)**	**1**
[G] ammonia, liquid (kg)	0.060187		

In this inventory, it becomes apparent that a lot of production elements are cut-off. Monomer production electricity is not included, as well as castor bean and oil transport, the feedstock of hydrogen bromide, and any required production wastewater treatment. These were cut off due to lack of data. However, the Arkema eco-profile indicates a Global Warming of 6 kg CO_2-eq: this global warming is widely exceeded by this proxy with 7.8 kg CO_2-eq. This is probably due to the use of different data to model the process reported by Arkema, as they probably have internal data and for this proxy needs to be resorted to Ecoinvent.

Tannin Powder Production

Tannins are naturally present in plants and are therefore extracted from wood or woody particles (tannins.org, n.d.). In Italy, tannins are usually extracted from chestnut and Aleppo oak. The wood first needs to be stored and air-dried; subsequently, the wood is chipped and immersed in boiling water in an autoclave. The tannins are extracted and dissolved into the water in this process. Next, the thick, brown liquid obtained needs to be purified, firstly by cooling the solution to room temperature to precipitate impurities; next, the tannin is spray dried to a powder form. The wood residues can be dried for use in biomass power generation.

To turn this description into an inventory, the following assumptions/calculations were made:

- 10% woodchip-to-tannin yield (Panzanella et al., 2019).
- Water required: 1:5 woodchip-to-water (Hoyos-Martinez et al., 2019), half of the water is evaporated during boiling and is recovered.
- Electric heating for 2 hours, 5% heat loss per hour, water on boiling point, only heating of the water calculated.
- The spray drying is proxied with the spray drying of milk in Ecoinvent.

(proxy) tannin powder production

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] Tap water (kg)	20	**[G] Tannin powder (kg)**	1
[G] electricity, low voltage (kWh)	4.502		
[G] spray-drying of milk (kg)	2		
[G] Wood chips, wet, measured as dry mass (kg) (oak)	10		

Carbon Stringer Production

In snowboards, ready-made mats of carbon fibers glued together in a certain direction are used. The production of these stringers was approximated based on information from Dry Boards provided during personal communication (2020). Because carbon fibers are not in Ecoinvent, glass fibers were used as a proxy. The stringers were modeled on the scale of 1 meter of stringer, with 2.5 cm width. Based on the density of glass fibers used in the production of Dry Boards, the mass required per 1m stringer was calculated.

(proxy) Carbon stringer production

In		Out	
Economic Flow	Value	Economic Flow	Value
[G] glass fibre (kg)	0.15	**[G] Carbon stringer (m)**	1
[G] epoxy resin, liquid (kg)	0.014341		

D.3. Alternatives – Calculations per Flow

Calculations relevant for all alternatives

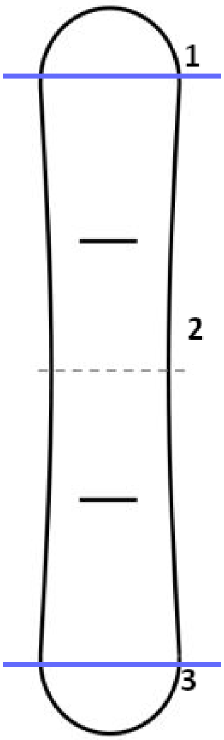


Figure D.4: Snowboard divided in three sections (Snowboarding Profiles, 2019).

Snowboard surface

The snowboard surface is estimated based on the dimensions of the 2020 Burton Custom 154 (Burton, n.d.). By dividing the snowboard surface in three regions, namely the tip and tail, both in the shape of a circle segment, and the "body" of the board, which has the shape of a rectangle with two circle segments cut out (see figure D.4). Afterwards, the surfaces of these sections were estimated using basic geometry, based on the dimensions provided by Burton.

Production used materials & waste

Snowboard materials are often delivered in rolls, sheets and blocks and subsequently cut to the right size. This leads to off-cuts that do not have another use in the snowboard building process and are going to waste. In order to calculate what amount of the materials goes to waste, and what amount ends up in the snowboards, different methods were used. For the sheet materials, the surface of the sheet was estimated using the Isosport materials catalogue (2017) and personal communication with an industry actor (Dry Boards, 2020). By subtracting the estimated surface of the snowboard, the surface lost to off-cuts was calculated. This was 23% of the total sheet surface. For the wooden core blocks, information supplied by Douk Snowboards (pers. comm., 2020) on the dimensions was used. The epoxy losses were assumed to be the same as the sheet material losses.

Production waste streams

In the production waste streams, a distinction can be made between single-material waste flows, that could be separately collected, and mixed waste streams, that are cut off after the epoxy is cured and therefore cannot be separated easily anymore.

Separate waste streams:

- Wood chips/sawdust/core block cut-offs (contain wood and small quantities PVA-glue
- Cut-offs of sidewall material (ABS or UHMWPE)
- Base material cut-offs
- Steel edge cut-offs

Mixed waste

- Cured epoxy resin
- Fiber reinforcement fabric
- Tip fillers (ABS/PE)

- Topsheet cut-offs

Distribution

(AB) distribution (also A0, A1, A2, A3, A4)

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G] Finished, packaged snowboard	1	**[G] Snowboard for sale to consumer**	1
[G] Transport, freight, sea, container ship	60.210		
[G] transport, freight, light commercial vehicle	0.338		

(AB) Sales (also A0, A1, A2, A3, and A4)

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G] Snowboard for sale to consumer	1	**[G] Snowboard sold to consumer**	1
		[W] Corrugate board recycling	0.199

Baseline Alternative (AB)

Production

(AB) Snowboard production

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G} Acrylonitrile-butadiene-styrene copolymer (kg)	0.278	[W] Manufacturing waste incineration (amount of snowboards)	1
[G] Glass fibre (kg)	0.628	**[G] Finished, packaged snowboard**	1
[G] Electricity, low voltage (kWh)	35		
[G] packaging film, low density polyethylene (kg)	0.066		
[G] packaging film, low density polyethylene (kg)	0.039		
[G] Extrusion of plastic sheets and thermoforming, inline	1.152		
[G] Epoxy resin, liquid (kg)	0.6		
[G] Sawlog and veneer log (m3)	0.002		
[G] Corrugated board box (kg)	0.199		
[G] transport, freight, sea, container ship (ton km)	46.711		
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	1.488		
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	0.036		
[G] Polyamide 11 (PA11) (kg)	0.264		
[G] polyethylene, high density, granulate (kg)	0.610		
[G] steel, chromium steel 18/8 (kg)	0.200		
[G] steel, low-alloyed (kg)	0.220		
[G] carbon stringers (m)	1		
[G] Sawlog and veneer log (m3)	0.002		

- *[G] ABS Copolymer (kg):* Calculated based on the density reported by Dielectric Manufacturing (n.d.) and the dimensions reported by Douk Snowboards (pers. comm., 2020) and The Ski Lab (n.d.).
- *[G] Glass Fibre (kg):* two layers (one below the core, one above). Density of the glass fibre fabric and the dimensions of the roll are based on personal communication with Dry Boards (2020).
- *[G] Electricity, low voltage (kWh):* based on the estimated electricity use per board by Douk Snowboards.
- *[G] Packaging film, low density polyethylene (1):* based on the surface calculations above. The number in the table represents a LDPE film going all around the snowboard once.
- *[G] Packaging film, low density polyethylene (2):* protection film for the topsheet during production, in order to prevent e.g. scratches. Discarded after production (*[W] waste polyethylene*)
- *[G] Extrusion of plastic sheets and thermoforming, inline:* all plastics that are produced through extrusion added together: ABS + HDPE + PA11.
- *[G] Epoxy Resin, liquid:* data based on personal communication with Douk Snowboards (2020).
- *[G] Sawlog and Veneer Log:* based on dimensions provided by Douk Snowboards on the amount of wood used per core. Half proxied with spruce, half with beech, since usually Paulownia in combination with poplar is often used; however, these are both not in Ecoinvent, but fast-growing species such as spruce should be a good proxy (Luthe, pers. comm., 2020). Since hardwood is often also used, beech and spruce are both used as proxies.
- *[G] transport, freight, sea, container ship:* as Isosport in Austria (Eisenstadt) is the main supplier of snowboard materials, it is assumed the materials originate there, while production is assumed to take place in China (near Xiahai). The materials are assumed to be shipped to the factory by container ship; the distance is calculated using the tool Seadistances.org (Trieste – Xiahai, 14,125 km). The weight for shipping consists of all materials added up together.
- *[G] Transport, freight, lorry 7.5 – 16 metric ton, EURO6 (1):* transport Eisenstadt – Trieste (distance determined with Google Maps).
- *[G] Transport, freight, lorry 7.*5 *– 16 metric ton, EURO6 (2):* transport approximated from Xiahai to hypothetical production location (250 kms).
- *[G] Polyamid-11 (PA11):* based on roll surface data from Dry Boards (pers. comm., 2020), density and thickness based on the Isosport PA11/PA12 topsheet (2017). Since PA12 is not in Ecoinvent and some brands use PA11-only topsheets, the topsheet is proxied to be entirely PA11.
- *[G] Polyethylene, high density, granulate:* Material requirements for the base, based on the roll size reported by Dry Boards and the density and thickness reported by Isosport (2017). The HDPE is used as a proxy for the superior UHMWPE, which is unfortunately not in Ecoinvent and cannot be modelled based on the sources available. However, bases are also made of HDPE for cheaper boards; this model can be considered representative for these bases.
- *[G] steel, chromium steel 28/8:* inserts. Based on data from Dry Boards.
- *[G] steel, low-alloyed:* steel edges. Based on data from Dry Boards.
- *[G] carbon stringers:* based on data from Dry Boards.
- *[W] Waste plastic, mixture:* consists of cured epoxy and offcuts of layers that were not cut to size before going into the snowboard press. These consist of tip fillers (ABS), fiber

reinforcement (Glass fiber), and topsheet material (PA11). The mass of this mixed epoxy “lump” is calculated based on the material roll surface – the board surface (23%, 77% goes into the snowboard).

- *[W] Waste wood, untreated:* offcuts of the core, based on data from Douk Snowboards. Sent to incineration.
- *[W] Waste polyethylene:* consists of offcuts of the base and the LDPE protection foil. Incinerated.
- *[W] Waste glass:* proxy for waste glass fiber incineration. Quantity based on the roll surface reported by Dry Boards minus the estimated board surface. Incinerated.

Use

(AB) Snowboard Use

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G] Snowboard sold to consumer	1	[W]EOL snowboard, municipal incineration	0.213
[G] Paraffin (kg)	0.25	[W]EOL snowboard, stored indefinitely (cut-off)	0.574
[G] Snowboard bought secondhand	0.18	[W]EOL snowboard, reused for another purpose	0.213
[G] Electricity, low voltage	2.213	[W] Secondhand snowboard for sale	0.18
		[G] weeks of snowboarding (reference flow)	17.7
		[W] LDPE foil for incineration (kg)	0.066
		[W] Wax discarded with servicing (kg) (cut-off)	0.125

- ***Weeks of snowboard use (FU):*** SB Lifetime: 15 weeks (survey). Technical lifetime is probably around 30 weeks and second-hand lifetime is not assumed to be different from new lifetime. Therefore 18% secondhand input Output lifetime use process: 15 + 0.18*15 = 17.7 weeks
- *Snowboards sold secondhand:* There are two questions that inquire about secondhand sales: the question “what did you do with your last pair of skis/snowboard” and the question “How many second-hand snowboards/skis did you buy in the last 5 years”. These yielded different results: 53% had sold their old snowboard/skis secondhand, while only 18% of the bought snowboards were secondhand. Since the latter question inquired about all equipment bought in the last 5 years this is seen as a more accurate measure; therefore, this number is used (0.18 kg). Initially, the proportions of the EOL-options were the following:

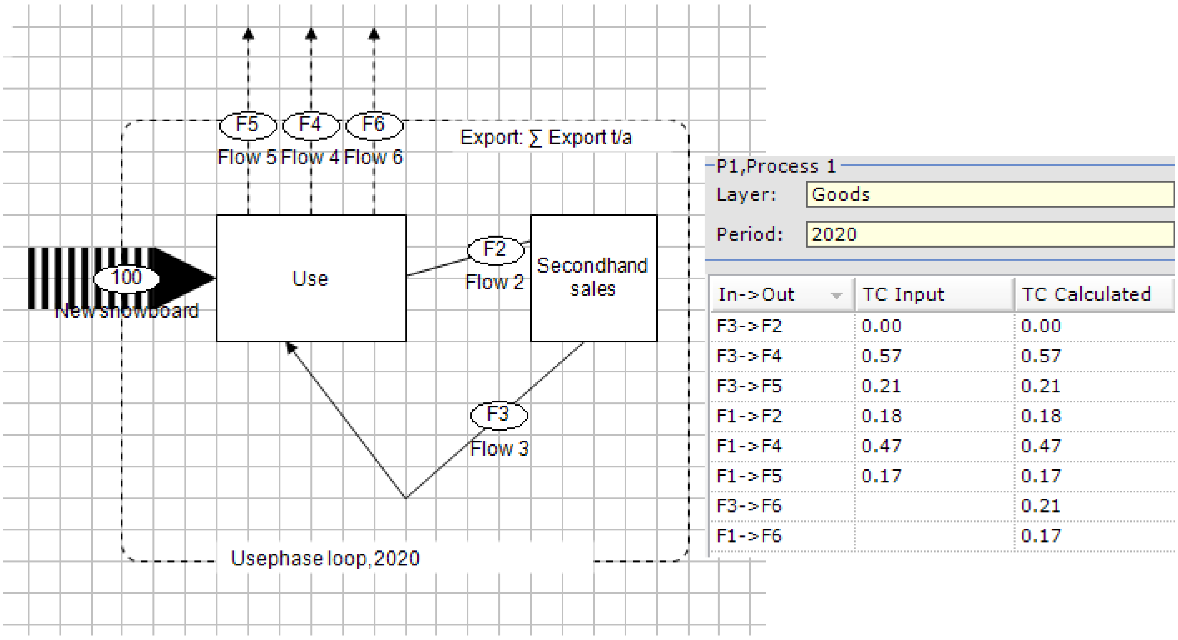
EOL treatment (n = 66)	**%**
Municipal waste	6%
Sold secondhand	53%
Stored indefinitely	27%
Reused for a different purpose	10%

  - In this table, municipal waste, indefinite storage, and reuse for a different purpose make up 47% of the responses. However, if secondhand sales were only 18%, these options would together make up 82%, which is a multiplication factor of 1.744. This leads to the following balance:

EOL treatment (n = 66)	**%**
Municipal waste	17%

Sold secondhand	18%
Stored indefinitely	47%
Reused for a different purpose	17%

- This is the balance of end-of-use options for snowboards in the first lifetime. However, the secondhand snowboards loop through the use-phase another time, and are assumed to have reached their technical lifetime afterwards; thus, they cannot be used another time and have to be allocated to one of the other EOL options. Taking the option of secondhand sales out of the equation and scaling the other options to 100% leads to coefficients of respectively 21.3%, 57.4%, and 21.3%.
- With these two equations in mind, the Mass Flow Analysis-program STAN was used to solve for the entire system. In the picture below, F1 represents the inflow of new snowboards, and F3 represents the inflow of secondhand snowboards into the use-phase.



- *EOL snowboard, municipal incineration:* see above (0.2133 kg)
- *EOL snowboard, reused:* see above (0.2133 kg)
- *EOL snowboard, stored:* see above (0.5744 kg)
- *Waste polyethylene:* packaging of new snowboard, same as mass of packaging in production (0.0798 kg)
- *Paraffin:* amount of wax for 17.7 weeks of use, based on absorption of base materials*2 since excess wax is always used (0.249 kg)

Incineration

See EOL Snowboard Incineration.

Alternative 0 (A0)

See Production (AB) and the general Distribution, Sales and Incineration section above.

Use

(A0) Snowboard use (also A1)

In / *Out*

Economic Flow	Value	Economic Flow	Value
[G] Snowboard sold to consumer	1	**[G] weeks of snowboarding (reference flow)**	15
[G] paraffin (kg)	0.211	[W] Wax discarded with servicing (kg) (cut-off)	0.106
[G] Electricity, low voltage (kWh)	0.350	[W] Waste LDPE for incineration(kg)	0.066
		[W] Waste snowboard for incineration	1

- *[G] paraffin:* proxy for snowboard wax. Based on the maximum wax absorption of an UHMWPE-base (Isosport, 2017) times two, as waxing is always done with excess wax that is scraped off after the treatment. The snowboard is serviced once for every use week.
- *[G] Electricity, low voltage:* electricity required for 10 minutes of wax iron use per service (Energids, n.d.).

Outflows

- *[G] weeks of snowboarding:* based on the expected lifetime for the recreant population (see Chapter 5).
- *[W] Wax discarded with servicing (cut-off):* wax that is not absorbed by the base.
- *[W] Waste LDPE for recycling, collected:* LDPE packaging foil that is discarded at the beginning of use.
- *[W] Waste snowboard for incineration:* the snowboard is incinerated after use.

Alternative 1

This alternative represents a conventional lifecycle with incineration at the EOL (A0) translated to 2025. To this end, a change in production had to be made; other than that, the lifecycle is the same as in A0.

Production

(A1) Conventional Snowboard Production 2025 (also A2)

In / *Out*

[G] transport, freight, sea, container ship (ton km)	46.711	[W] Manufacturing Waste Incineration (amount of snowboards)	1
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	1.488	**[G] Finished, packaged snowboard**	1
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	0.036		
[G] Acrylonitrile-butadiene-styrene copolymer (kg)	0.278		
[G] Glass fibre (kg)	0.628		
[G] Chinese Electricity Market 2025	35		
[G] packaging film, low density polyethylene (kg)	0.066		
[G] packaging film, low density polyethylene (kg)	0.039		
[G] Extrusion of plastic sheets and thermoforming, inline	1.152		
[G] Epoxy resin, liquid (kg)	0.6		
[G] Sawlog and veneer log (m3)	0.002		

[G] Corrugated board box (kg)	0.199		
[G] Polyamide 11 (PA11) (kg)	0.264		
[G] polyethylene, high density, granulate (kg)	0.610		
[G] steel, chromium steel 18/8 (kg)	0.200		
[G] steel, low-alloyed (kg)	0.220		
[G] carbon stringer (m)	1		
[G] Sawlog and veneer log (m3)	0.002		

All production flows except the electricity are the same as AB:

- *[G] Electricity, low voltage:* based on data obtained from Douk Snowboards. Instead of the general electricity market, the electricity is modelled with the expected Electricity market of China 2025.

See Incineration for the EOL treatment.

Alternative 2

This scenario explores the changes in environmental impact if the snowboard is sold secondhand and is used two times, reaching the expected technical lifetime (see Chapter 5). For the stages Production until Sales, see A1 and AB.

Use

(A2) Snowboard use

In / *Out*

Economic Flow	Value	Economic Flow	Value
[G] Snowboard sold to consumer	1	**[G] weeks of snowboarding (reference flow)**	30
[G] Paraffin (kg)	0.423	[W] Wax discarded with servicing (kg) (cut-off)	0.211
[G] Electricity, low voltage (kWh)	3.750	[W] Waste LDPE for incineration	0.066
		[W] EOL snowboard for incineration	1

The use-phase is similar to the one of A1, except that the snowboard is used for 30 weeks instead of 15 weeks since it enjoys a second lifetime. All servicing in- and outflows (*paraffin, electricity,* and *wax discarded with servicing*) are therefore multiplied by 2 compared to A0. Since the secondhand sales does not require additional in- or outflows, secondhand sales processes were not added; instead, the use-time was adapted to 30 weeks. At the end of life, the snowboard is incinerated.

Alternative 3

Alternative 3 represents a snowboard lifecyle where efforts are directed towards circularity with a focus on biomaterials.

Production

(A3) snowboard production (biobased)

In / *Out*

Economic Flow	Value	Economic Flow	Value
[G] fish glue (kg)	1.140	[W] biowaste for composting (kg)	0.396

[G] fibre, hemp (kg)	0.801	[W] Wood for use in other industries (kg)	0.40 3
[G] polyethylene, high density, granulate (kg)	0.610	[W] waste HDPE for recycling, collected (kg)	0.14 0
[G] extrusion of plastic sheets and thermoforming, inline (kg)	0.698	**[G] finished, packaged snowboard**	1
[G] sawlog and veneer log, hardwood, meaasured as solid wood under bark (cubic meter)	0.002		
[G] steel, low-alloyed (kg)	0.220		
[G] steel, chromium steel 18/8 (kg)	0.200		
[G] sawlog and veneer log, hardwood, measured as solid wood under bark (cubic meter)	0.002		
[G] tannin powder (kg)	0.060		
[G] linseed oil, crude (kg)	0.137		
[G] electricity, low voltage (kWh)	28.00 0		
[G] sawlog and veneer log, hardwood, measured as solid wood under bark (cubic meter)	0.000		
[G] transport, freight, sea, container ship (ton km)	10.67 0		
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	0.833		
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	0.939		
[G] fibre, flax (kg)	0.131		
[G] fish glue (kg)	0.014		
[G] wood veneer (cubic meter)	0.008		
[G] polylactide, granulate (kg)	0.088		
[G] Corrugated board box (kg)	0.199		

- *Material input calculations*: the material input requirements were based on ski data; to translate this to a snowboard, the data was multiplied with the surface change from ski to snowboard. The surface of the Grown TheOnly (Grown Skis, n.d.) was estimated with the method described above.

Flows:

- *[G] fish glue*: fish glue combined with tannin powder replaces epoxy in this alternative. The amount of glue is estimated to be 1.5 times more than for skis.
- *[G] fibre, hemp*: based on ski data (Luthe, pers. comm., 2020).
- *[G] polyethylene, high density, granulate:* based on the numbers for UHMWPE bases in the Isosport catalogue (2017) (proxy).
- *[G] extrusion of plastic sheets and thermoforming, inline:* the base is extruded as if it were a HDPE base; in reality, UHMWPE bases would be sintered so this is a proxy. The PLA packaging film is also extruded.

- [*G] sawlog and veneer log, hardwood, … (beech) (1):* for the core, a hardwood (beech) and a softwood (spruce) are used as a proxy for paulownia and poplar (not available in Ecoinvent). Both of these represent half of the core. Core dimensions: Douk Snowboards (pers. comm., 2020).
- *[G] steel, low-alloyed:* steel edges (Dry Boards, pers. comm., 2020).
- *[G] steel, chromium steel 18/8:* steel inserts for binding connection (Dry boards, pers. comm., 2020).
- *[G] sawlog and veneer log, hardwood, … (2):* Robinia wood sidewalls, proxied with beech (Lute, pers. comm., 2020).
- *[G] tannin powder:* added to the fish glue to waterproof it. 5% of the fish-glue weight (Luthe, pers. comm., 2020).
- *[G] linseed oil, refined:* used to protect the wooden parts in contact with the outside environment. The wood is oiled with about four layers of linseed oil. Quantity based on regular wood varnish required per m2, and then multiplying with 4 layers.
- *[G] electricity, low voltage:* There's no printing in this scenario, and the glue cures at room temperature; therefore, the electricity usage is assumed to be 28 kWh instead of the 35 kWh used for the other alternatives.
- *[G] transport, freight, sea, container ship (1):* Since this alternative involves fewer ready-made components, it is assumed that only the base is produced in Europe and needs to be shipped overseas. Distance Trieste – Xiahai obtained from seadistances.org.
- *[G] transport, freight, sea, container ship (2):* transport of the hemp fibers from India (Kolkata) to Xiahai overseas (seadistances.org), since India is a big producer of hemp fibers (Sarkar et al., n.d.).
- *[G] transport, freight, lorry 7.5 – 16 metric ton, EURO6 (1), (2) & (3): (1)* waste transport, assumed to be 50 km, (2) transport of the base from the Xiahai harbor to the hypothetical production location (250 km, (3) transport of the base from Eisenstadt to Trieste for shipping (450 km).
- *[G] fibre, flax:* used for the lay-up reinforcements. Mass calculated on the lay-up dimensions and flax fibre fabric weight provided by Dry Boards (pers. comm., 2020).
- *[G] fish glue:* the amount of fish glue used to attach the lay-ups.
- *[G] Wood veneer:* used for the topsheet. Dimensions: personal communication with Dry Boards (2020).
- *[G] polylactide, granulate:* PLA packaging film that the board is sold and shipped in. Mass based on density and surface of packaging film wrapped around the snowboard one time.
- *[G] corrugated board box:* box for shipping, packaged per 6 snowboards. Mass based on the mass of three sample cardboard boxes that were subsequently scaled to the size of 175x35x15, which is the max shipping size at DPD and is therefore the expected size.
- *[W] biowaste:* consists of waste fibers and waste glue resulting from production. The waste is composted, since it only contains biodegradable materials; waste quantities are based on the estimated amount of material going to waste in snowboard production calculated before (23%).
- *[W] Wood for use in other industries:* Wooden waste is assumed to be used in other industries, for example biomass energy generation or paper production. Calculated based on the average dry density of the wood species used and the expected waste volume (23%).
- *[W] Waste HDPE for recycling, collected:* material cut off the base, collected for recycling (23% of base material used).

Use

(A3) Snowboard use

In Economic Flow	Value	*Out* Economic Flow	Value
[G] Snowboard sold to consumer	1	**[G] weeks of snowboarding (reference flow)**	15
[G] Soybean oil, refined (kg)	0.211	[W] Wax discarded with servicing (kg) (cut-off)	0.106
[G] Electricity, low voltage (kWh)	1.875	[W] Snowboard for reuse with another purpose	1
		[W] biowaste for composting (kg)	0.088

EOL

Alternative 4

Production

(A4) Snowboard Production (abiotic recycling)

In Economic Flow	Value	*Out* Economic Flow	Value
[G] transport, freight, sea, container ship (ton km)	48.494	[W] waste HD polyethylene for recycling, collected (kg)	0.14
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	1.544	[W] LDPE for recycling	0.039
[G] transport, freight, lorry 7.5 - 16 metric ton, EURO6 (ton km)	0.172	[W] snowboard manufacturing waste recycled (kg)	0.350
[G] polyethylene, high density, granulate, recycled (kg)	0.253	[W] Waste wood, untreated	0.28
[G] polyethylene, high density, granulate, recycled (kg)	0.610	**[G} Finished, packaged snowboard**	1
[G] sawlog and veneer log, hardwood, measured as solid wood under bark (m3)	0.002		
[G] electricity, low voltage (kWh)	35		
[G] Polyamide 11 (PA11) (kg)	0.264		
[G] packaging film, low density polyethylene (kg)	0.066		
[G] packaging film, low density polyethylene (kg)	0.039		
[G] extrusion of plastic sheets and thermoforming, inline (kg)	1.127		
[G] epoxy resin, liquid (kg)	0.369		
[G] polyester resin, unsaturated (kg)	0.246		
[G] corrugated board box (kg)	0.199		
[G] steel, chromium steel 18/8 (kg)	0.200		
[G] steel, low-alloyed (kg)	0.220		
[G] basalt fibre (kg)	0.638		
[G] Sawlog and veneer log, softwood, measured as solid mass under bark (m3)	0.002		
[G] basalt fibre	0.153		

- *[G] Transport, freight, sea, container ship:* transport of 3.17 kg of materials from Trieste – Xiahai (distance: seadistances.org).

- *[G] transport, freight, lorry 7.5-16 metric ton, EURO6:* material transport from Eisenstadt (material production location) to Trieste to be sea-shipped to the snowboard factory
- *[G] polyethylene, high density, granulate, recycled:* material for the sidewalls. Dimensions: Douk Snowboards, pers. comm., 2020.
- *[G] polyethylene, high density, granulate, recycled:* material for the base (Isosport, 2017).
- *[G] sawlog and veneer log, … bark (1) & (2):* together proxy the snowboard core, each 50/50 (see also AB).
- *[G] electricity, low voltage:* based on an estimation by Douk Snowboards (pers. comm., 2020), see also AB.
- *[G] Polyamide 11:* topsheet (Isosport, 2017, see also AB)
- *[G] packaging film, low density polyethylene (1) & (2):* resp. snowboard packaging and the protection sheet of the topsheet (see AB).
- *[G] extrusion of plastic sheets and thermoforming, inline:* extrusion of sidewalls (UHMWPE proxied with HDPE), base (idem), and the topsheet (PA11).
- *[G] epoxy resin, liquid:* since partially bio-based resins are increasingly used, in this case it is assumed that 70% is fossil-based (Entropy Resins, n.d.). Amount of resin: Douk Snowboards (pers. comm., 2020).
- *[G] polyester resin, unsaturated:* proxy for the 30% biobased content of the resin (in reality based on pine resin).
- *[G] corrugated board box:* box for snowboard shipping from factory to distribution center/store.
- *[G] steel, chromium steel 18/8:* chromium steel inserts (Dry Boards, pers. comm., 2020).
- *[G] steel, low-alloyed:* steel edges (Dry Boards, pers. comm., 2020).
- *[G] basalt fiber:* since basalt is stronger than glass fibers (Inman, Thorhallson, & Azrague, 2017), it is expected that the lowest-density basalt fabric supplied by Isosport would suffice (600 g/m2) since most glass-fiber fabrics used have a density of 600 g/m2 (Dry Boards, pers. comm., 2020).
- *[G] basalt fibre (2):* basalt fibers for reinforcement stringers.
- *[W] waste HD polyethylene for recycling, collected:* cut off material of the UHMWPE base.
- *[W] waste LDPE for recycling, collected:* topsheet protection film for recycling.
- *[W] snowboard manufacturing waste for recycling:* mixed waste stream of cured epoxy with reinforcement fibers and topsheet material (PA11). This waste is recycled by dissolving the epoxy and hereby separating the materials (see below).

Manufacturing Waste Recycling

- *[G] acetic acid & [G] tap water:* solution for recycling (dissolves the epoxy matrix). Tap water proxies distilled water.
- *[G] sodium hydroxide:* used to neutralize the recycling solution and precipitate the dissolved epoxy thermoplastic.
- *[G] electricity, low voltage (kWh):* electricity needed for stirring and heating of the recycling solution.
- *[W] wastewater, average:* neutralized recycling solution
- *[W] Basalt fibers for recycling:* fibers extracted from the separated manufacturing waste for recycling.
- *[W] Recovered thermoplastics for incineration:* epoxy broken into thermoplastic fractions, plus PA11 topsheet damaged by the separation process. Assumed to be incinerated due to unknown monomer composition.

- *[W] Waste HD Polyethylene for recycling:* PE base to be recycled.

All data for this process was sourced from La Rosa et al. (2014, 2016, 2018).

(proxy) snowboard manufacturing waste recycling

In		Out	
Economic Flow	Value	Economic Flow	Value
acetic acid, without water, in 98% solution state (kg)	2.287121	wastewater, average (m^3)	0.015463
sodium hydroxide, without water, in 50% solution state (kg)	1.509626	Waste basalt fibers for recycling (kg)	0.418466
tap water (Europe w.o. Switzerland) (kg)	15.46295	Recovered thermoplastics for incineration (kg)	0.39352
electricity, low voltage (kWh) (CN-CQ)	0.598094	waste HD polyethylene for recycling, collected (kg)	0.014796
Snowboard manufacturing waste for recycling (kg)	0.350	PA11 for recycling (kg)	0.173218

Materials affected by the solvolysis process:

Material	**Affected by process conditions (25% acetic acid solution, 70°)**
UHMWPE/HDPE	Not affected
ABS	Severely affected at the temperature of the process (70°) and the acid concentration. Likely comes out of the process in a damaged shape and likely partially dissolves in the solution.
PA11	No data found, but might be affected since PA12 is only "partially resistant" to acetic acid (Nylacast, 2019).
Wood	The wood is affected; however, acetic acid is a common pretreatment for e.g. biorefineries or the paper industry (Chi et al., 2017). Part of the wood might dissolve in the solution.
Glass Fibers	Affected by higher concentrations (80%, 50 degrees); whether the glass fibers are also affected with lower concentrations remains a question
Basalt Fibers	Expected to only be affected marginally based on Basalt Fiber Tech (n.d.) and Smith et al. (2017)

Use

(A4) Snowboard use

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G] Snowboard sold to consumer	1	**[G] weeks of snowboarding (reference flow)**	15
[G] Soybean oil, refined (kg)	0.211	[W] Wax discarded with servicing (kg) (cut-off)	0.106
[G] Electricity, low voltage (kWh)	1.875	[W] LDPE for recycling	0.066
		[W] EOL snowboard for recycling, collected	1

EOL – Snowboard Recycling

- *[G] acetic acid & [G] tap water:* solution for recycling (dissolves the epoxy matrix). Tap water is proxies distilled water.
- *[G] sodium hydroxide:* used to neutralize the recycling solution and precipitate the dissolved epoxy thermoplastic.
- *[G] electricity, low voltage (kWh):* electricity needed for stirring and heating the recycling solution.
- *[W] wastewater, average:* neutralized recycling solution
- *All other waste flows:* materials for recycling extracted from the snowboard by the separation process (see recycling process above).

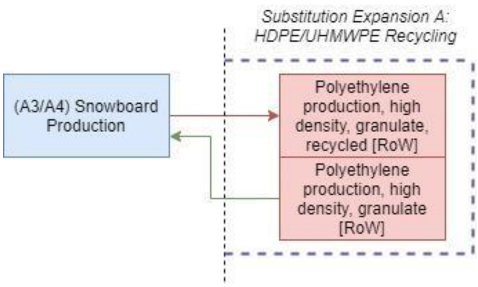
All data for this process was sourced from La Rosa et al. (2014, 2016, 2018).

(A4) EOL Snowboard Recycling w. Solvolysis

In		*Out*	
Economic Flow	Value	Economic Flow	Value
[G] acetic acid, without water, in 98% solution state (kg)	2.014	[W] wastewater, average (m3)	0.042
[G] sodium hydroxide, without water, in 50% solution state (kg)	1.330	[W] waste basalt fibers for recycling (kg)	0.644
[G] tap water (Europe w.o. Switzerland) (kg)	41.986	[W] recovered thermoplastics for recycling (kg)	0.666
[G] electricity, low voltage (kWh) (Europe w.o. Switzerland)	0.636	[W] waste HD polyethylene for recycling, collected (kg)	0.665
[W]EOL Snowboard for recycling, collected	1	[W] waste wood, for use in other industries (kg)	1.285
		[W] Steel for recycling (kg)	0.420

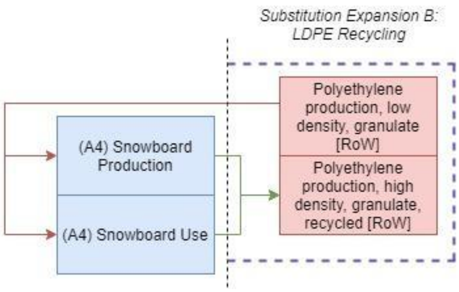
D.4. Multifunctionality: Substitution

In this appendix, the substitution multifunctionality treatment of waste-treatment processes is explained. All processes are treated with a system expansion involving substitution in order to include the function of the recycled materials.



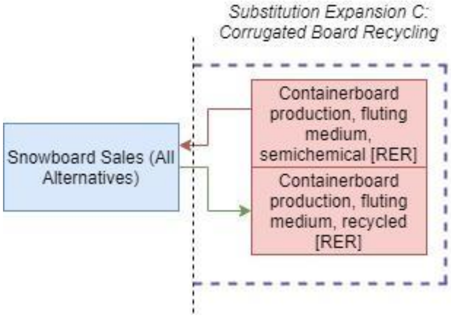
Substitution A: HD/UHMW-PE Recycling

To include the avoided impacts of the recycling of HDPE/UHMWPE (proxied by HDPE in this study), the system is expanded with the recycling supply chain minus the production of virgin HDPE. The recycling efficiency of the Ecoinvent process (1.0632 kg of granulate to 1 kg of PE) is maintained.



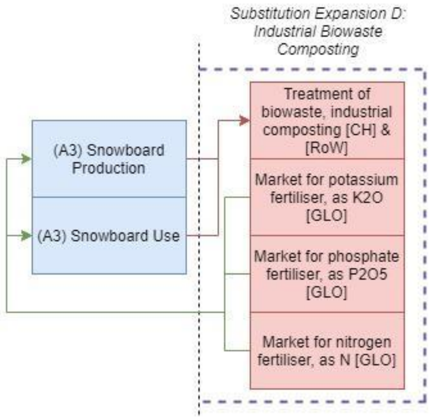
Substitution B: LDPE Recycling

LDPE recycling is not available in Ecoinvent: the recycling of HDPE is therefore used as a proxy. The system is expanded with recycling to granulate, since the subsequent steps would be the same for both recycled and virgin LDPE granulate.



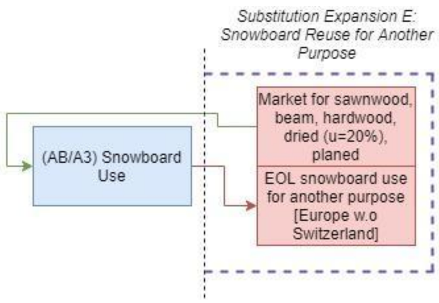
Substitution C: Corrugated Board Box Recycling

It is assumed that the corrugated board box is recycled into fluting medium, which is the medium between the two layers of paperboard in corrugated board that keeps the material light and strong (The Balance, 2019). In the original Ecoinvent 3.6 recycling process, 1.0921 kg of paper feedstock is converted into 1 kg of fluting medium; this rate is maintained. Since the cardboard packaging is discarded at the salespoint in the EU, processes from this region are used.



Substitution D: Biowaste Composting

Composting is inherently a waste treatment activity, and an alternative substitute therefore needs to be found to model the avoided impact. The product found closest to compost is fertilizer. From the “nutrient supply from compost”-process in Ecoinvent 3.6, the quantities of potassium, nitrogen, and phosphorus per kg of compost were extracted. These were used to calculate the quantity of fertilizer substituted by the compost.

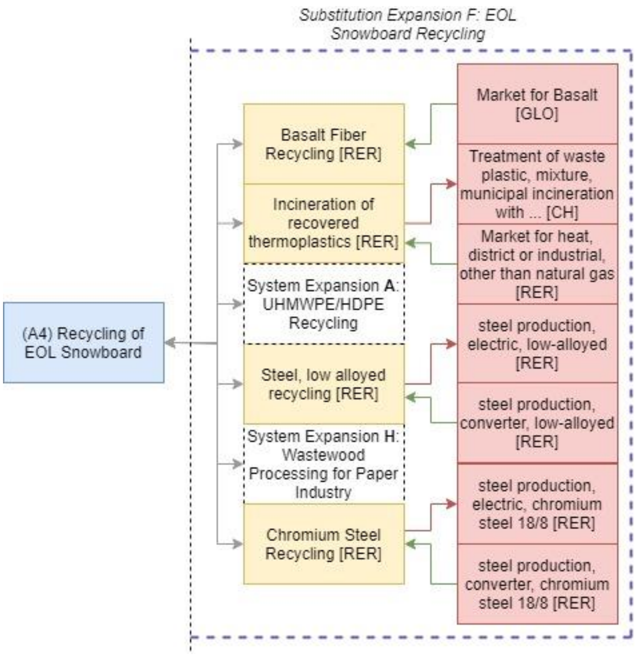


Substitution E: Snowboard Reuse for Another Purpose

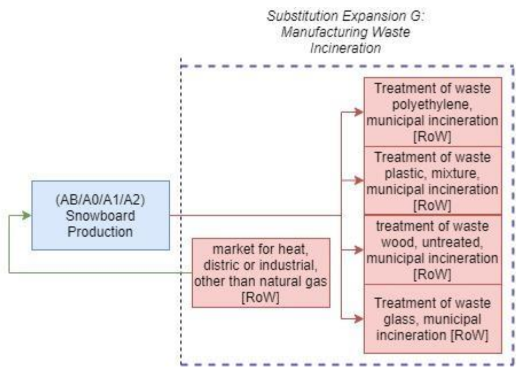
At the EOL, snowboards are sometimes used for another purpose, such as in a garden fence, a bench, or a shelve. This means that the snowboard replaces another material, in these cases probably hardwood with a coating since this is often used for these purposes. In terms of volume, a plank of 3 centimeters thick, 25 centimeters wide, and 156 centimeters long (approximately the dimensions of a snowboard, except the thickness) is assumed.

Substitution F: EOL Snowboard Recycling

From the EOL Recycling process, six different materials are extracted: basalt fibers, mixed thermoplastics, UHMWPE, wood, steel, and stainless steel. These materials each need a different treatment. The basalt fibers are assumed to be remelted into new fibers (Eutit s.r.o., 2013) and therefore substitute virgin basalt with an expected efficiency of 95%. The mixed thermoplastics have been dissolved and precipitated in the recycling process and consist of different polymer fractions; since there is no data available on the composition (La Rosa et al., 2018), incineration is assumed. From the incineration, heat substituting generic district heating from sources other than natural gas results. The UHMWPE is recycled (proxied with HDPE recycling; see A). The wood is assumed to be dried and chipped and then used as a feedstock for paper production, substituting chips from virgin sources. Finally, the steel and the chromium steel are recycled into secondary (chromium) steel, substituting primary material (in the case of steel, scrap; in the case of chromium steel, carbon steel, chromium and nickel, as it already consists of the desired composition). For all processes, the efficiencies used in the original Ecoinvent 3.6 data are maintained.



Substitution G: Manufacturing Waste Incineration



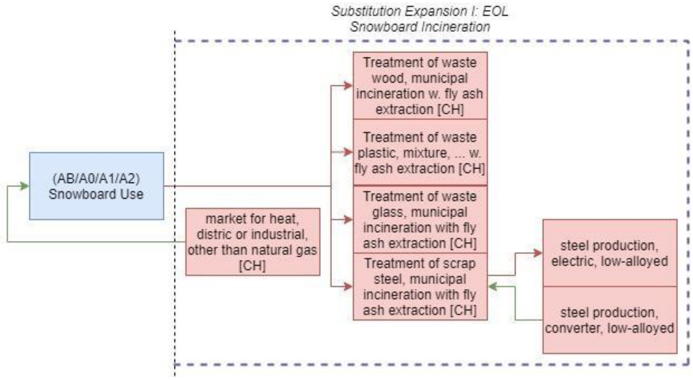
The incineration of manufacturing waste consists of two main waste streams: base off-cuts and protection foil (PE), and mixed materials (mixed plastics, glass fibers, and wood). From the incineration, heat results. This heat is assumed to substitute generic district- or industrial heating from all sources other than natural gas (see the flowchart). The electricity produced by the incineration is cut off as this is not expected to enter the grid and another suitable proxy is not available. The amount of heat produced is calculated based on the Ecoinvent 3.6 incineration process data.

Substitution H: Polyethylene Incineration

See manufacturing waste incineration above. The PE is incinerated; generated heat is assumed to replace generic district or industrial heat from sources other than natural gas. The electricity resulting from incineration is cut off.

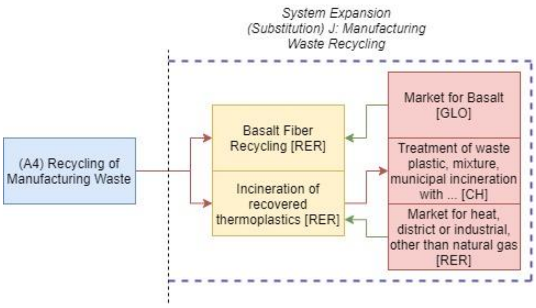
Substitution I: Snowboard Incineration

The EOL snowboard is assumed to be incinerated as a whole. It consists of four types of material: wood, various plastics, glass fibers, and steel (see the flowchart). From the incineration of wood, plastic, and glass, heat results; this heat is assumed to substitute generic district or industrial heat

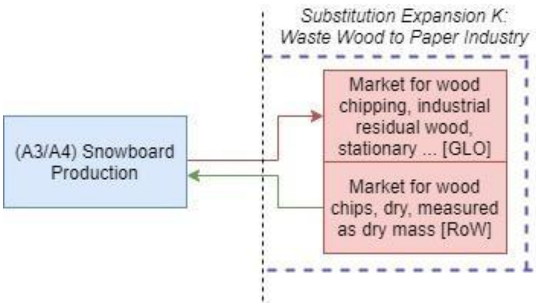


from other sources than natural gas. The incinerated steel is extracted from the incineration slag, sorted, and compressed with a yield of 0.47 kg steel for every kg steel incinerated following the Ecoinvent process data. The steel scrap is assumed to be recycled into secondary steel with a conversion rate of 90.5% and therefore assumed to substitute 0.42 kg of primary steel. Since the production processes of primary and secondary steel differ slightly, the production processes into low-alloyed steel are included in the system.

Substitution J: Mixed Manufacturing Waste Recycling



From the solvolysis of mixed manufacturing waste, two main material streams originate: basalt fibers and mixed thermoplastics. The mixed thermoplastics are incinerated (see also F); the basalt fibers are remelted into new fibers and therefore replace virgin basalt.



Substitution K: Waste Wood Processing for Paper Industry

By chipping waste wood, it becomes a valuable feedstock to the paper industry and thereby substitutes wood chips from primary sources.

Appendix G: Supplements to LCA Characterization and Interpretation

Table G.1: Characterization Results scaled to the 2025 baseline (A1).

Normalized to A1	(A1)	(A0)	(AB)	(A2)	(A3)	(A4)
Climate Change Total	1	1.08	0.86	0.51	0.37	0.56
Freshwater and Terrestrial Acidification	1	0.96	0.80	0.51	0.40	0.63
Freshwater Ecotoxicity	1	0.99	0.80	0.50	1.39	0.95
Freshwater Eutrophication	1	1.04	0.84	0.52	3.00	1.30
Marine Eutrophication	1	1.03	0.85	0.51	0.69	0.82
Terrestrial Eutrophication	1	1.02	0.85	0.51	0.45	0.73
Dissipated Water	1	1.02	0.81	0.53	2.43	1.68
Fossils	1	1.07	0.88	0.53	0.37	0.62
Land Use	1	0.91	0.53	0.50	0.26	0.88
Minerals and Metals	1	0.90	0.74	0.51	1.13	1.46
Carcinogenic Effects	1	1.01	0.82	0.51	0.78	0.75
Ionizing Radiation	1	1.08	0.77	0.58	0.54	1.27
Non-Carcinogenic Effects	1	1.00	0.83	0.50	-0.09	0.97
Photochemical Ozone	1	1.02	0.84	0.51	0.44	0.76
Respiratory Effects, Inorganics	1	1.10	0.91	0.51	0.25	0.45

Table G.2: Sensitivity results for changing distribution from sea to air shipping

Impact Category	(A0)	(AB)	(A1)	(A2)	(A3)	(A4)
Climate Change Total (kg CO2-eq)	+25% (4.49 * 10^{1} to 5.63 * 10^{1}).	+27% (3.55 * $10^{1}$to 4.51 * 10^{1}).	+28% (4.15 * 10^{1} to 5.29 * 10^{1}).	+27% (2.12 * 10^{1c} to 2.69 * 10^{1}).	+74% (1.54 * 10^{1} to 2.68 * 10^{1}).	+49% (2.34 * 10^{1} to 3.48 * 10^{1}).
Freshwater and Terrestrial Acidification (mol H+-eq)	+16% (2.88 * 10^{-1} to 3.32 * 10^{-1}).	+16% (0.24392.88 * 10^{-1} to 0.2772.88 * 10^{-1}).	+15% (3.00 * 10^{-1} to 0.345 * 10^{-1}).	+15% (1.53 * 10^{-1} to 1.75 * 10^{-1}).	+37% (1.20* 10^{-1} to 1.65* 10^{-1}).	+24% (1.89* 10^{-1} to 2.33* 10^{-1})
Freshwater Ecotoxicity (CTU)	+5% (4.98 * 10^{1} to 5.21 * 10^{1}).	+5% (3.98 * 10^{1} to 4.18 * 10^{1}).	+5% (5.01 * 10^{1} to 5.24 * 10^{1}).	+5% (2.52 * 10^{1} to 2.64 * 10^{1}).	+3% (6.95 * 10^{1} to 7.18 * 10^{1}).	+5% (4.78 * 10^{1} to 5.01 * 10^{1}).
Freshwater Eutrophication (kg P-eq)	+1% (1.83 * 10^{-2} to 1.85 * 10^{-2}).	+1% (1.49 * 10^{-2} to 1.51 * 10^{-2}).	+1% (1.77 * 10^{-2} to 1.78 * 10^{-2}).	+1% (9.3 * 10^{-3} to 9.3 * 10^{-3}).	0% (5.31 * 10^{-2} to 5.32 * 10^{-2}).	+1% (2.3 * 10^{-2} to 2.31 * 10^{-2}).
Marine Eutrophication (kg N-eq)	+27% (6.94 * 10^{-2} to 8.81 * 10^{-2}).	+27% (5.76 * 10^{-2} to 7.34 * 10^{-2}).	+28% (6.77 * 10^{-2} to 864 * 10^{-2}).	+27% (3.43 * 10^{-2} to 4.37 * 10^{-2}).	+40% (4.68 * 10^{-2} to 6.55 * 10^{-2}).	+34% (5.52 * 10^{-2} to 7.39 * 10^{-2}).
Terrestrial Eutrophication (mol N-eq)	+28% (7.37 * 10^{-1} to 9.41 * 10^{-1}).	+28% (6.13 * 10^{-1} to 7.85 * 10^{-1}).	+28% (7.22 * 10^{-1} to 9.26 * 10^{-1}).	+28% (3.66 * 10^{-1} to 4.68 * 10^{-1}).	+63% (3.22 * 10^{-1} to 5.26 * 10^{-1}).	+39% (5.28 * 10^{-1} to 7.31 * 10^{-1}).

Dissipated Water (m3 water)	+2% (9.48 to 9.69).	+2% (7.50 to 7.68).	+2% (9.31 to 9.52).	+2% (4.92 to 5.02).	+1% (22.6 to 22.82).	+1% (15.61 to 15.83).
Fossils (MJ)	+26% (6.07 * 10^{2} to 7.65 * 10^{2}).	+27% (4.99 * 10^{2} to 6.33 * 10^{2}).	+28% (5.66 * 10^{2} to 7.25 * 10^{2}).	+27% (2.98 * 10^{2} to 3.77 * 10^{2}).	+76% (2.09 * 10^{2} to 3.68 * 10^{2}).	+45% (3.54 * 10^{2} to 5.12 * 10^{2}).
Land Use (points)	0% (1.37 * 10^{3} to 1.38 * 10^{3}).	+1% (7.96 * 10^{2} to 8.01 * 10^{2}).	0% (1.52 * 10^{3} to 1.52 * 10^{3}).	0% (7.62 * 10^{2} to 7.65 * 10^{2}).	+2% (3.89 * 10^{2} to 3.96 * 10^{2}).	0% (1.34 * 10^{3} to 1.34 * 10^{3}).
Minerals and Metals (kg Sb-eq)	+1% (4.20 * 10^{-4} to 6.90 * 10^{-4}).	+1% (3.50 * 10^{-4} to 5.80 * 10^{-4}).	+1% (4.70 * 10^{-4} to 7.00 * 10^{-4}).	+1% (2.40 * 10^{-4} to 3.50 * 10^{-4}).	+1% (3.40 * 10^{-4} to 5.30 * 10^{-4}).	0% (4.50 * 10^{-4} to 6.80 * 10^{-4}).
Carcinogenic Effects (CTUh)	+1% (1.31 * 10^{-6} to 1.32 * 10^{-6})	+1% (1.07 * 10^{-6} to 1.08 * 10^{-6})	+1% (1.30 * 10^{-6} to 1.31 * 10^{-6})	+1% (6.60 * 10^{-7} to 6.60 * 10^{-7})	+1% (9.90 * 10^{-7} to 1.00 * 10^{-6})	+1% (9.70 * 10^{-7} to 9.80 * 10^{-7})
Ionizing Radiation (kg U235-eq)	+24% (2.97 to 3.70)	+29% (2.12 to 2.74)	+26% (2.75 to 3.48)	+23% (1.60 to 1.96)	+51% (1.42 to 2.14)	+21% (3.50 to 4.22)
Non-Carcinogenic Effects (CTUh)	+5% (2.67 * 10^{-5} to 2.79 * 10^{-5})	+5% (2.22 * 10^{-5} to 2.32 * 10^{-5})	+5% (2.67 * 10^{-5} to 2.80 * 10^{-5})	+5% (1.34 * 10^{-5} to 1.41 * 10^{-5})	+50% (-2.55 * 10^{-6} to -1.28 * 10^{-6})	+5% (2.59 * 10^{-5} to 2.72 * 10^{-5})
Ozone Layer Depletion (kg CFC-11)	+162% (1.61 * 10^{-6} to 4.21 * 10^{-6})	+173% (1.28 * 10^{-6} to 3.49 * 10^{-6})	+146% (1.79 * 10^{-6} to 0 4.39 * 10^{-6})	+140% (9.30 * 10^{-7} to 2.23 * 10^{-6})	+186% (1.40 * 10^{-6} to 4.01 * 10^{-6})	+59% (4.40 * 10^{-6} to 7.01 * 10^{-6})
Photochemical Ozone Creation (kg NMVOC-)	+34% (1.53 * 10^{-1} to 2.06 * 10^{-1})	+35% (1.27 * 10^{-1} to 1.71 * 10^{-1})	+35% (1.51 * 10^{-1} to 2.03 * 10^{-1})	+34% (7.67 * 10^{-2} to 0.1.03 * 10^{-1})	+82% (6.35 * 10^{-2} to 1.16 * 10^{-1})	+46% (1.15 * 10^{-1} to 1.66 * 10^{-1})
Respiratory Effects, Inorganics (disease i.)	+3% (2.76 * 10^{-6} to 2.85 * 10^{-6})	+4% (2.28 * 10^{-6} to 2.36 * 10^{-6})	+4% (2.52 * 10^{-6} to 2.61 * 10^{-6})	+4% (1.27 * 10^{-6} to 1.32 * 10^{-6})	+16% (5.80 * 10^{-7} to 6.80 * 10^{-7})	+9% (1.12 * 10^{-6} to 1.22 * 10^{-6})

Table G.4: Sensitivity analysis results for production with CN grid electricity and rooftop PV electricity

Impact Category	(A0)	(AB)	(A1)	(A2)	(A3)	(A4)
Climate Change Total (kg CO2-eq)	-51% (44.91 to 21.98).	-55% (35.47 to 16.04).	-46% (41.48 to 22.53).	-45% (21.22 to 11.75).	-50% (30.57 to 15.41).	-45% (42.37 to 23.42).
Freshwater and Terrestrial Acidification (mol H+-eq)	-44% (0.29 to 0.16).	-45% (0.24 to 0.13).	-42% (0.3 to 0.17).	-42% (0.15 to 0.09).	-46% (0.22 to 0.12).	-40% (0.32 to 0.19).
Freshwater Ecotoxicity (CTU)	-7% (49.8 to 46.3).	-7% (39.84 to 36.87).	-7% (50.09 to 46.66).	-7% (25.24 to 23.53).	-4% (72.25 to 69.5).	-7% (51.18 to 47.75).

Freshwater Eutrophication (kg P-eq)	-15% (0.02 to 0.02).	-16% (0.01 to 0.01).	-12% (0.02 to 0.02).	-11% (0.01 to 0.01).	-3% (0.05 to 0.05).	-8% (0.03 to 0.02).
Marine Eutrophication (kg N-eq)	-36% (0.07 to 0.04).	-37% (0.06 to 0.04).	-30% (0.07 to 0.05).	-30% (0.03 to 0.02).	-26% (0.06 to 0.05).	-27% (0.08 to 0.06).
Terrestrial Eutrophication (mol N-eq)	-37% (0.74 to 0.47).	-38% (0.61 to 0.38).	-31% (0.72 to 0.5).	-31% (0.37 to 0.25).	-36% (0.5 to 0.32).	-30% (0.75 to 0.53).
Dissipated Water (m3 water)	+ 2% (9.48 to 9.68).	+ 2% (7.5 to 7.68).	+ 4% (9.31 to 9.62).	+ 4% (4.92 to 5.11).	+ 1% (22.3 to 22.6).	+ 2% (15.24 to 15.61).
Fossils (MJ)	-48% (606.58 to 316.03).	-49% (498.57 to 252.35).	-43% (566.08 to 322.58).	-41% (297.85 to 176.1).	-48% (404.02 to 209.22).	-41% (597.01 to 353.51).
Land Use (points)	-4% (1374.43 to 1313.81).	-6% (795.77 to 744.4).	-13% (1514.97 to 1316.32).	-13% (762.07 to 662.74).	-29% (548.21 to 389.29).	-13% (1534.76 to 1336.11).
Minerals and Metals (kg Sb-eq)	+ 65% (0.00042 to 0.00069).	+ 66% (0.00035 to 0.00058).	+ 50% (0.00047 to 0.0007).	+ 49% (0.00024 to 0.00035).	+ 55% (0.00034 to 0.00053)	+ 52% (0.00045 to 0.00068).
Carcinogenic Effects (CTUh)	-14% ($1.31 * 10^{-6}$ to $1.13*10^{-7}$).	-15% ($1.07 * 10^{-6}$ to $9.11*10^{-7}$)	-13% ($1.30 * 10^{-6}$ to $1.13*10^{-7}$)	-13% ($6.57 * 10^{-6}$ to $5.73 *10^{-7}$)	-12% ($1.13 * 10^{-6}$ to $9.95 *10^{-7}$)	-15% ($1.14 * 10^{-6}$ to $9.73 *10^{-7}$)
Ionizing Radiation (kg U235-eq)	-44% (2.97 to 1.65).	-53% (2.12 to 1.00).	-40% (2.75 to 1.66).	-34% (1.60 to 1.05).	-38% (2.29 to 1.42).	-24% (4.59 to 3.50).
Non-Carcinogenic Effects (CTUh)	-5% ($2.67 * 10^{-5}$ to $2.54 * 10^{-5}$).	-5% ($2.22 * 10^{-5}$ to $2.11 * 10^{-5}$).	-5% ($2.67 * 10^{-5}$ to $2.54 * 10^{-5}$).	-5% ($1.34 * 10^{-5}$ to $1.28 * 10^{-5}$).	-62% ($-1.57 * 10^{-6}$ to $-2.55 * 10^{-6}$).	-5% ($2.72 * 10^{-5}$ to $2.59 * 10^{-5}$).
Ozone Layer Depletion (kg CFC-11)	+1% ($1.61 * 10^{-6}$ to $1.62 * 10^{-6}$).	+1% ($1.28 * 10^{-6}$ to $1.29 * 10^{-6}$).	-3% ($1.79 * 10^{-6}$ to $1.73 * 10^{-6}$).	-3% ($9.30 * 10^{-7}$ to $9.03 * 10^{-7}$).	-3% ($1.44 * 10^{-6}$ to $1.44 * 10^{-6}$).	-1% ($4.45 * 10^{-6}$ to $4.40 * 10^{-6}$).
Photochemical Ozone Creation (kg NMVOC-)	-45% (0.153 to 0.0846).	-46% (0.127 to 0.0684).	-38% (0.151 to 0.0931).	-38% (0.0767 to 0.0479)	-42% (0.110 to .0.0635).	-33% (0.172 to 0.115).
Respiratory Effects, Inorganics (disease i.)	-61% ($2.76 * 10^{-6}$ to $1.09 * 10^{-6}$).	-62% ($2.28 * 10^{-6}$ to $8.64 * 10^{-6}$).	-54% ($2.52 * 10^{-6}$ to $1.15 * 10^{-6}$).	-54% ($1.27 * 10^{-6}$ to $5.86 * 10^{-7}$).	-65% ($1.68 * 10^{-6}$ to $5.81 * 10^{-7}$).	-55% ($2.49 * 10^{-6}$ to $1.12 * 10^{-6}$).

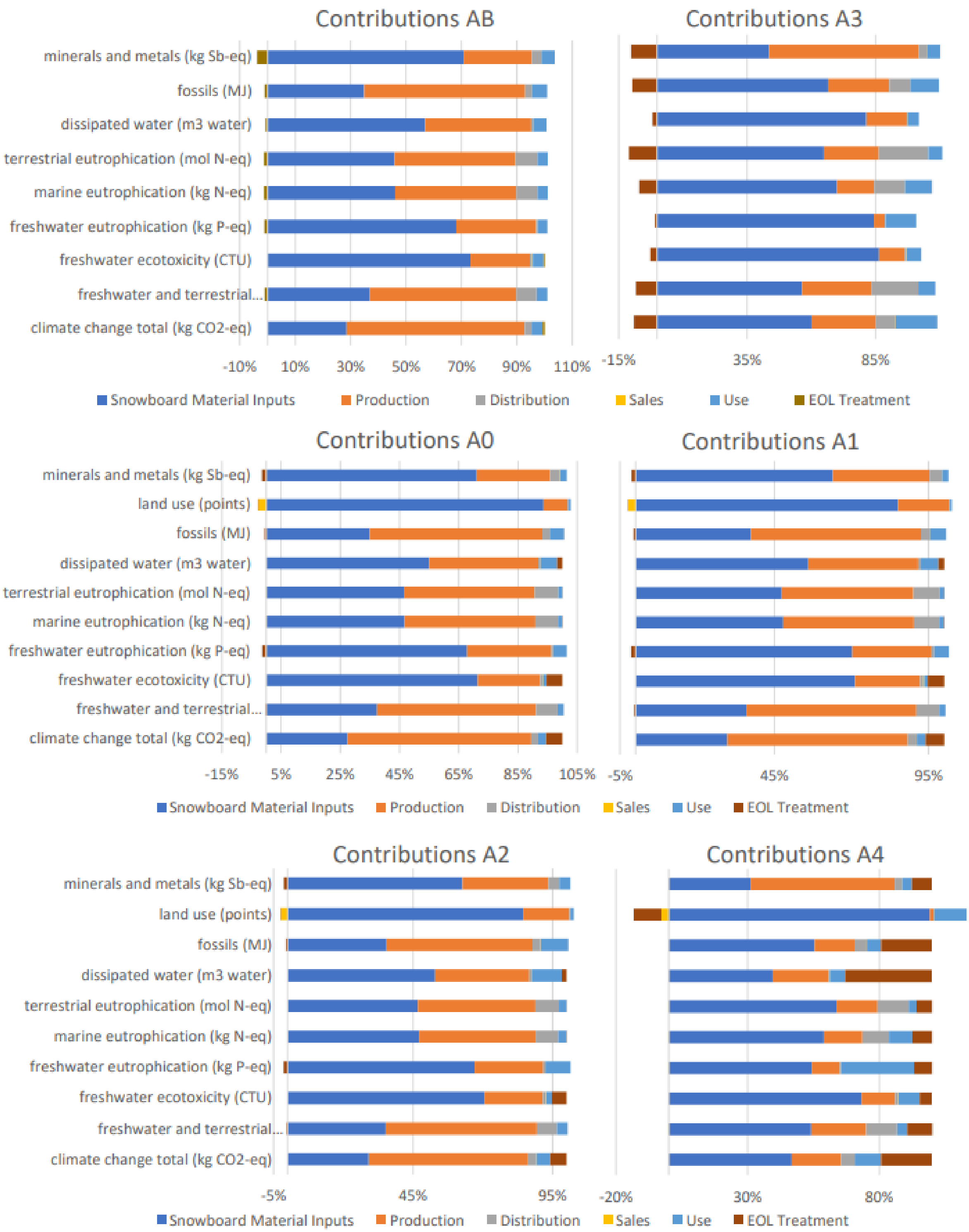


Figure G.1: Contribution of the Life Cycle Phases to the Impact Category Results, scaled to 100%.

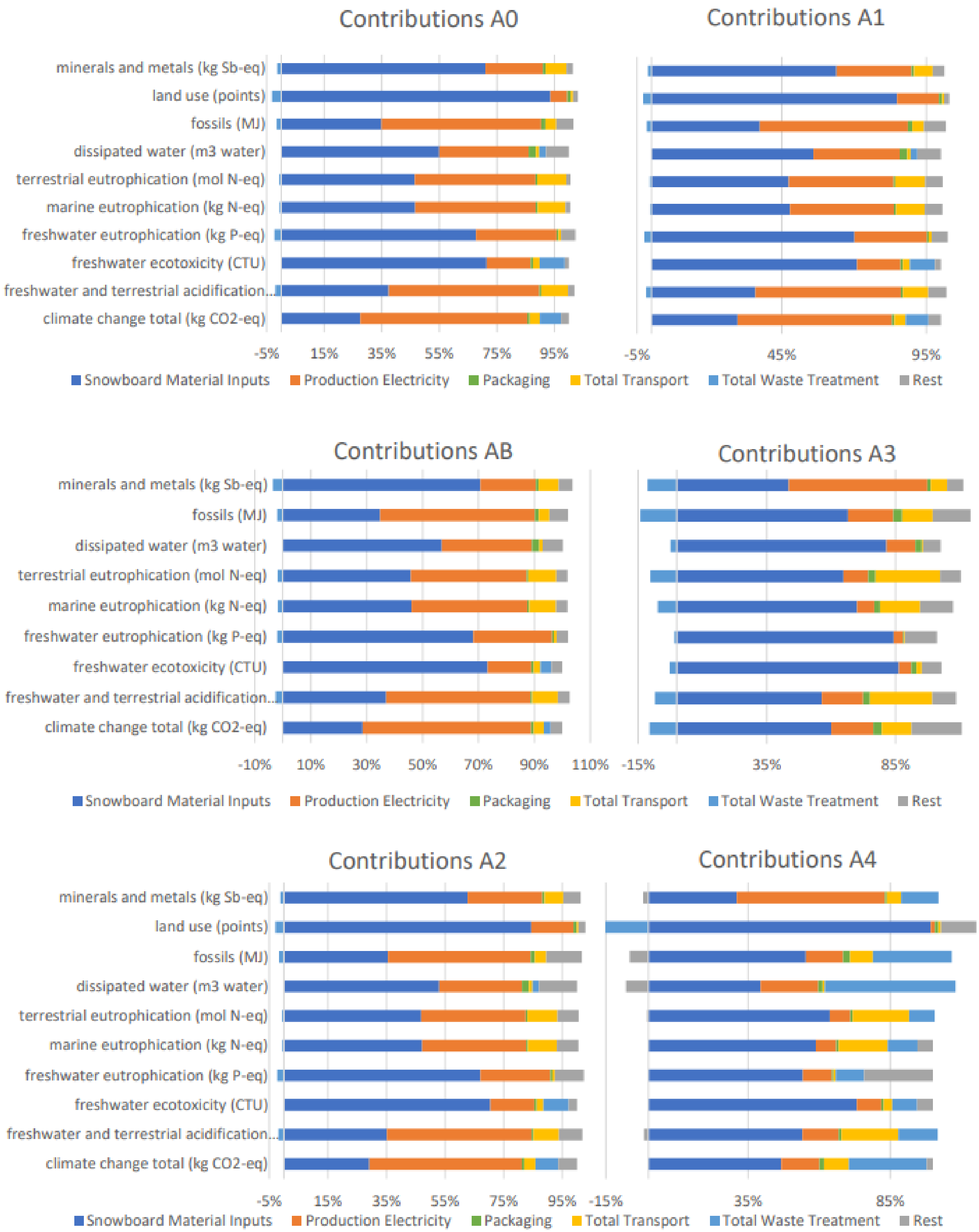


Figure G.2: Contribution of Economic Input Categories to the Impact Category results.

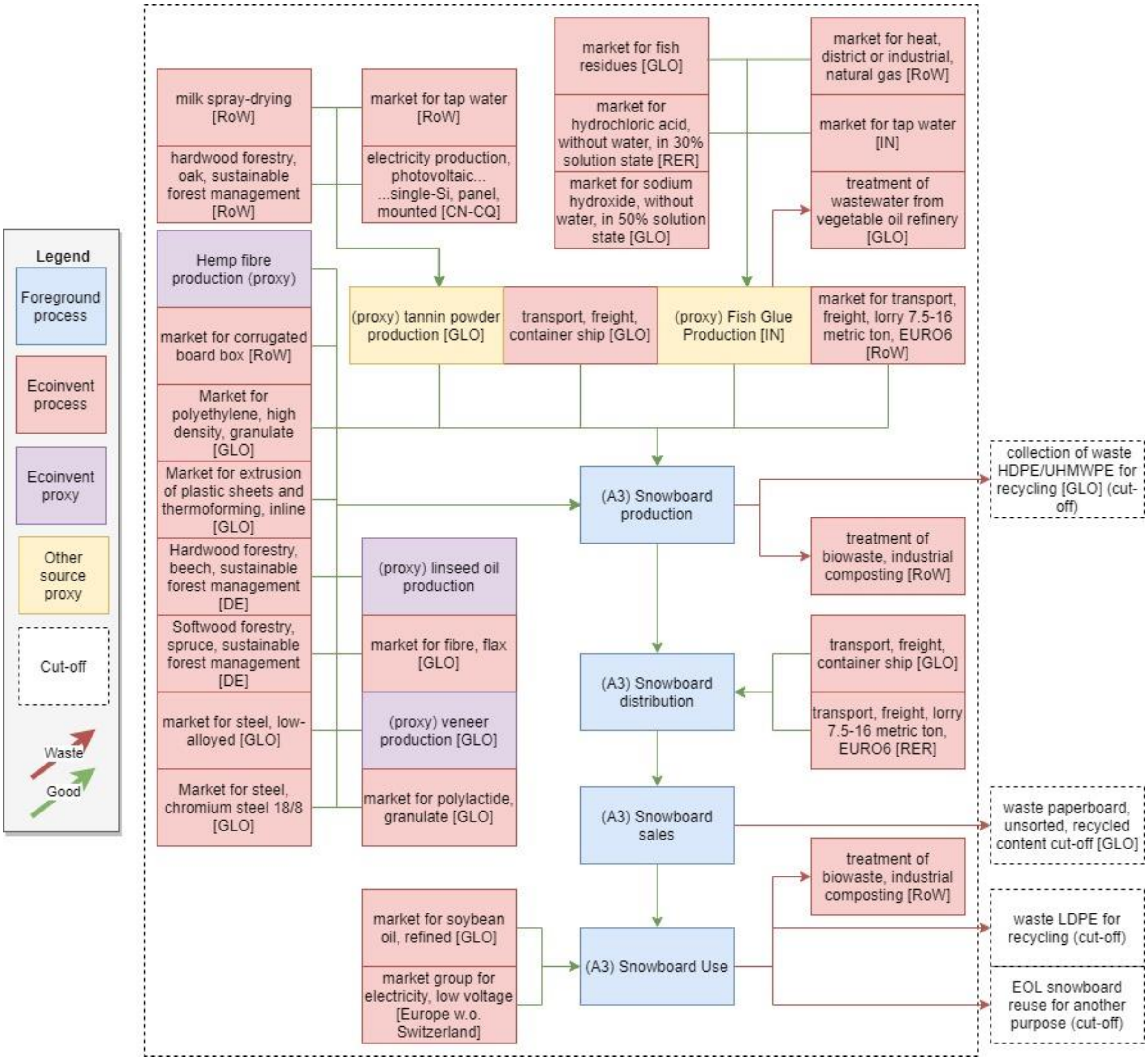


Figure G.3: Cut-Off System example: flowchart of A3 with waste products entering other systems cut off.

Table G.5.: Sensitivity analysis results for substitution allocation (first number) and the Ecoinvent Cut-Off Model allocation approach (second number)

Impact Category	(A0)	(AB)	(A1)	(A2)	(A3)	(A4)
Climate Change Total (kg CO2-eq)	+2% (44.9 to 45.7).	+2% (35.5 to 36.3).	+2% (41.5 to 42.3).	+2% (21.2 to 21.6).	+11% (15.4 to 17.1).	+5% (23.4 to 24.6).
Freshwater and Terrestrial Acidification (mol H+-eq)	+2% (0.288 to 0.294).	+2% (0.239 to 0.246).	+2% (0.300 to 0.307).	+2% (0.153 to 0.156).	+9% (0.120 to 0.131).	+9% (0.189 to 0.205).
Freshwater Ecotoxicity (CTU)	-1% (49.8 to 49.3).	+1% (39.8 to 40.1).	-1% (50.1 to 49.6).	-1% (25.2 to 25.0).	+3% (69.5 to 71.4).	+3% (47.7 to 49.0).
Freshwater Eutrophication (kg P-eq)	+3% (0.0183 to 0.0188).	+2% (0.0149 to 0.0152).	+3% (0.0177 to 0.0181).	+2% (0.00925 to 0.00949).	+1% (0.0530 to 0.0536).	+4% (0.0230 to 0.0239).

Marine Eutrophication (kg N-eq)	+2% (0.0694 to 0.0705).	+2% (0.0576 to 0.0588).	+2% (0.0677 to 0.0687).	+2% (0.0343 to 0.0349).	+7% (0.0468 to 0.0503).	+5% (0.0552 to 0.0580).
Terrestrial Eutrophication (mol N-eq)	+1% (0.737 to 0.748).	+2% (0.613 to 0.625).	+1% (0.722 to 0.733).	+1% (0.366 to 0.371).	+12% (0.322 to 0.360).	+6% (0.528 to 0.560).
Dissipated Water (m3 water)	+1% (9.47 to 9.56).	+2% (7.50 to 7.62).	+1% (9.31 to 9.40).	+1% (4.92 to 4.96).	+2% (22.6 to 23.2).	+7% (15.6 to 16.7).
Fossils (MJ)	+2% (607 to 618).	+2% (499 to 509).	+2% (566 to 577).	+2% (298 to 303).	+14% (209 to 239).	+22% (354 to 433).
Land Use (points)	+3% (1374 to 1420).	+64% (796 to 1307).	+3% (1515 to 1560).	+3% (762 to 785).	+685% (389 to 3057).	+18% (1336 to 1582).
Minerals and Metals (kg Sb-eq)	+2% (0.000420 to 0.000427).	+3% (0.000346 to 0.0003567).	+1% (0.000467 to 0.000473).	+1% (0.000238 to 0.000241).	+11% (0.000527 to 0.000587).	+8% (0.000682 to 0.000737).
Carcinogenic Effects (CTUh)	-2% (1.28E-06 to 1.31E-06).	-1% (1.08E-06 to 1.07E-06).	-2% (1.30E-06 to 1.27 E-06).	-2% (6.57E-07 to 6.42E-07).	+3% (1.02 E-06 to 1.05 E-06).	+19% (9.73E-07 to 1.16E-06).
Ionizing Radiation (kg U235-eq)	0% (2.97).	-16% (2.56 to 2.16).	0% (2.75 to 2.76)	0% (1.60 to 1.60).	+10% (1.48 to 1.63).	+2% (3.50 to 3.57).
Non-Carcinogenic Effects (CTUh)	-1% (2.67E-05 to 2.64 E-05).	0% (2.23 E-05).	-1% (2.67 E-05 to 2.64 E-05).	-1% (1.34 E-05 to 1.33 E-05).	+17% (-2.37E-06 to -1.96E-06).	-1% (2.59 E-05 to 2.57 E-05).
Ozone Layer Depletion (kg CFC-11)	+2% (1.61E-06 to 1.64E-06).	-2% (1.35E-06 to 1.32 E-06).	1% (1.79E-06 to 1.81E-06).	1% (9.29E-07 to 9.43E-07).	+13% (1.54E-06 to 1.74E-06).	+2% (4.40E-06 to 4.50E-06).
Photochemical Ozone Creation (kg NMVOC-)	3% (1.53E-01 to 1.57E-01).	+2% (1.29E-01 to 1.31E-01).	+3% (1.51E-01 to 1.55E-01).	+3% (7.67E-02 to 7.87E-02).	+21% (6.70E-02 to 8.12E-02).	+12% (1.15E-01 to 1.28E-01).
Respiratory Effects, Inorganics (disease i.)	+4% (2.76E-06 to 2.88E-06).	+6% (2.29E-06 to 2.49E-06).	+5% (2.52E-06 to 2.64E-06).	+5% (1.27E-06 to 1.33E-06).	+59% (6.23E-07 to 9.90E-07).	+25% (1.12E-06 to 1.41E-06).

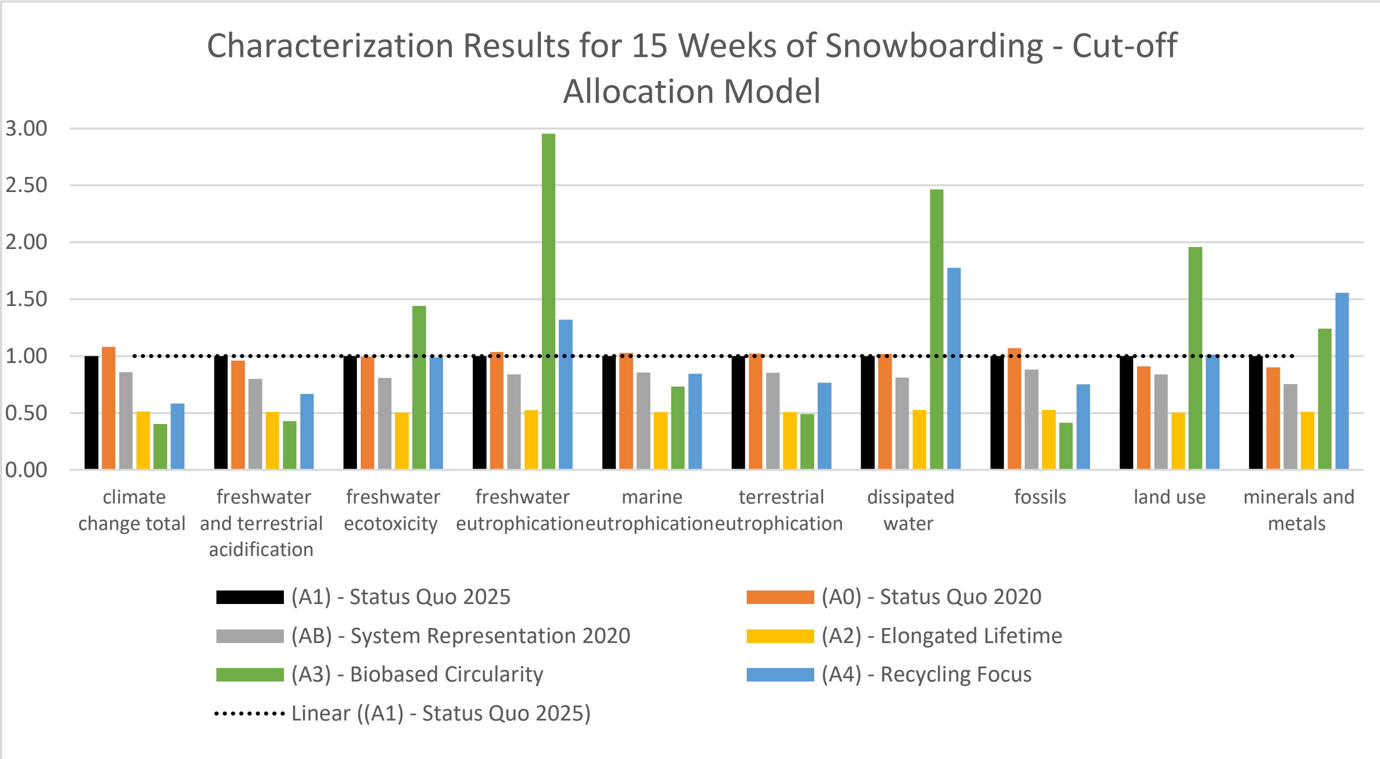


Figure G.4: Characterization results for 15 weeks of snowboarding following the cut-off system model of the Ecoinvent database