Beyond Paper: Exploring the Environmental Impact of Digital Note-Taking

Ecodesign and Life Cycle Assessment

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1 Introduction

In today's world, sustainability has become a growing concern as people become more aware of the environmental impact of their daily choices. With this in mind, it is important to consider the environmental implications of often overlooked practices, such as note-taking during university studies.

On average, every year KU Leuven enrolls about 27000 students for bachelor's studies and another 21000 students enroll for master's programs [1]. By far, these two categories represent the majority of the student population, with a high rate of education continuation from bachelor's to master's. This entire process takes on average 5 years, but can easily be extended further. This translates to hundreds of thousands of lecture attendees per year, each requiring (with varying levels of intensity) a way of capturing all the information being taught in an organized fashion. Throughout the years, the overwhelmingly dominant way of achieving this has been through the reliable, tried-and-tested way: pen and paper. However, with technological advancements, more and more students are making the switch towards digital note-taking, raising the question: is this switch a net-positive in our individual environmental impact?

This paper aims to answer this question to the best degree possible. With this focus, the environmental impact of using multiple notebooks and pens throughout a span of 5 years as a student is compared with the impact of using a tablet with a stencil. This is done through a life cycle assessment (LCA) for the multiple components required in both scenarios, which is conducted in the SimaPro software. By shedding light on the environmental impact of note-taking methods, this investigation aims to contribute to the growing body of knowledge on sustainability and to encourage more sustainable practices in education and beyond.

2 Model Description

The following section contains the description for all models required for the comparison done in this investigation. First, the functional unit used as a comparison point will be discussed in subsection 2.1. After, thorough descriptions for the required models for both scenarios are discussed in subsections 2.2.

2.1 Functional Unit

As a first step, the topic of the functional unit must be discussed. This is a crucial step in the LCA for any product, since its very definition can sway results in a particular way. Therefore, this process was conducted with a large attention to detail in order to provide a neutral comparison between both note-taking approaches. Questions such as *what?*, *how much?*, *how well?*, *where?* and *for how long?* are of special interest, leading to the following functional unit.

Question	Function
What should the note-taking approach do?	Serve for note-taking for university studies with multi-color abilities
How many materials should the approach use?	Enough to provide enough note-taking space for all courses
How well should the notes be taken?	Approach should deliver, readable, organized notes
Where are the notes taken?	At KU Leuven, campus Arenberg
For how long should the approach last?	5 years (bachelor's + master's)

Table 1: Functional unit for comparison between note-taking scenarios.

2.2 Test Case Inventory

Before discussing the effects for each scenario, an inventory for their unit processes must be done. This inventory contains the raw materials involved in the manufacturing process for all components used in the scenario, all processes required for the assembly as well as the transportation involved in the delivery of all physical products. It is worth noting that the materials listed in the following are not an extensive list since the use of the SimaPro software accounts for many often overlooked materials.

Figures 1 and 2 depict a rough representation of the inventory carried out within the SimaPro software for all materials and processes involved in the analog and digital note-taking scenarios, respectively. From these figures, it becomes evident that a large array of raw materials as well as energy intensive processes are required for the manufacturing (and use in the case of the digital scenario) for both scenarios.

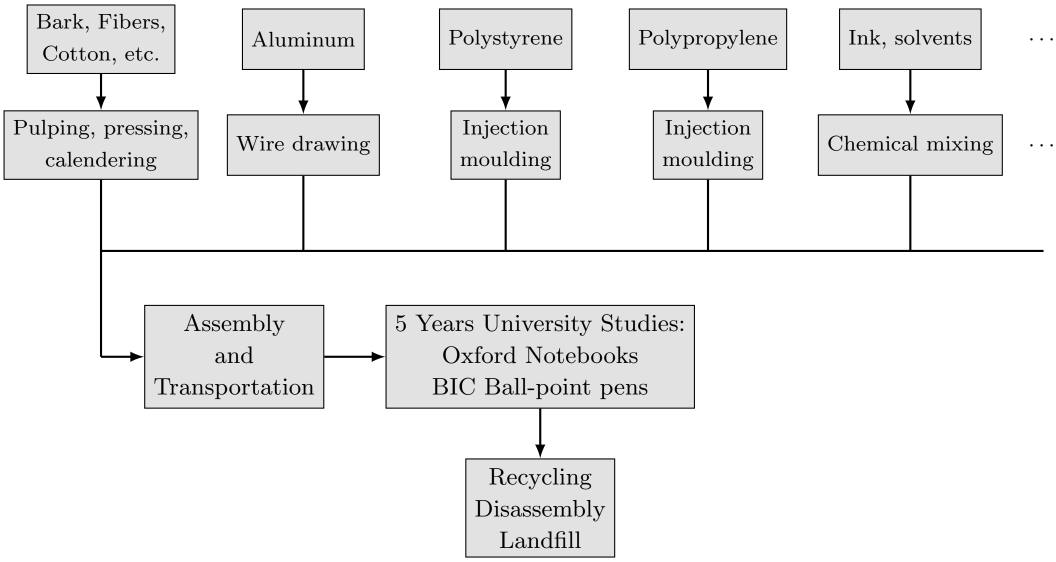

Figure 1: Inventory for analog note-taking scenario.

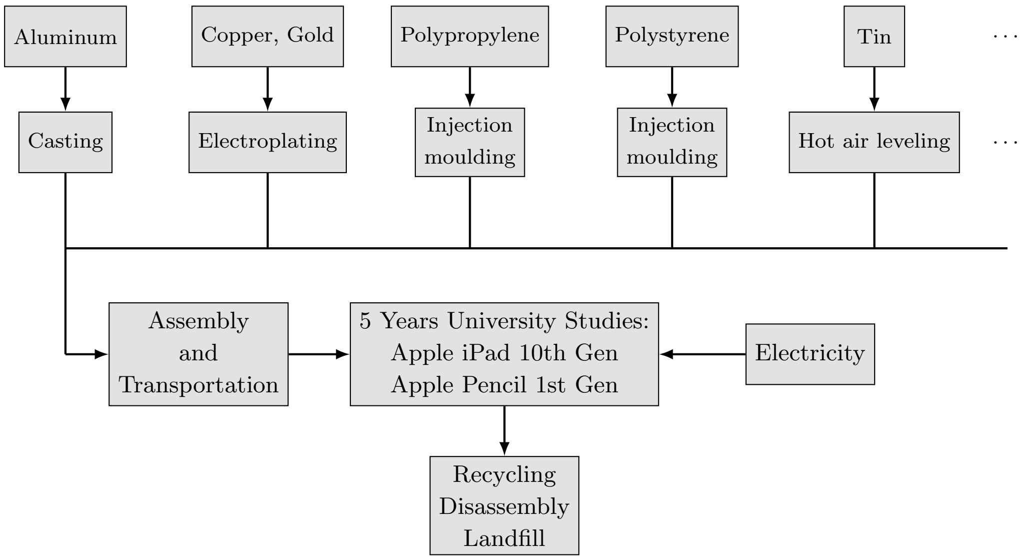

Figure 2: Inventory for analog note-taking scenario..

Moreover, a distinction must be made between the in and outflows for each element in the inventory alongside their sources or recipients. These could come from or go to the ecosphere or the technosphere, where the ecosphere represents the natural environment and the technosphere represents industrial processes. The use of the EcoInvent database alleviates this task from the students which could become very time-intensive. This is because not many processes are straightforward and usually involve multiple inputs and outputs from all sources. Additionally, in many cases multi-functionality within the process raises many issues involving the balance for the responsibility given to the elements involved in the process. This practice involves multiple assumptions and raises many issues for the credibility of the assessment. Fortunately, EcoInvent has these assumptions embedded into its database. Simplified examples for an eco- and technosphere analysis for a single process for both note-taking strategies are given in Figures 3 and 4.

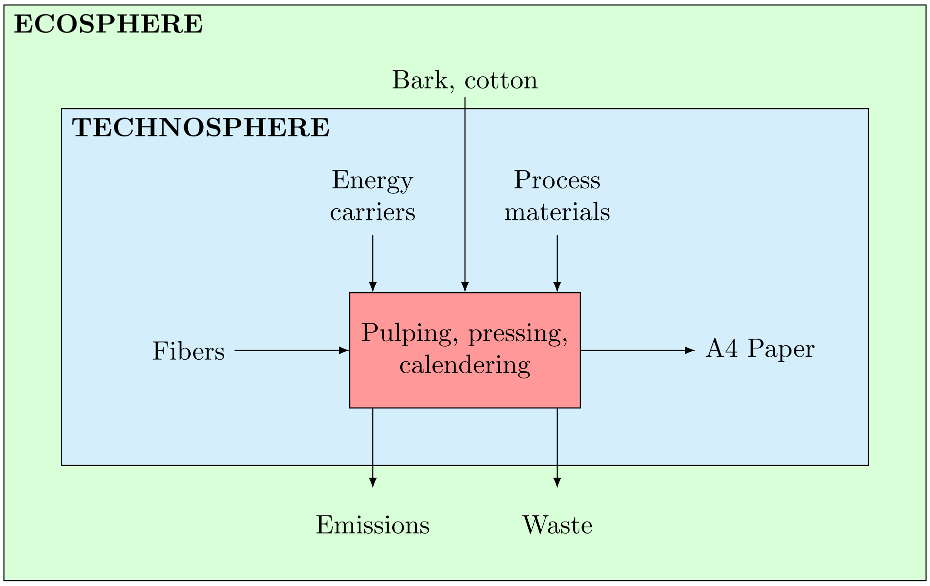

Figure 3: Example for an eco- and technosphere analysis for an individual process for the analog note-taking scenario.

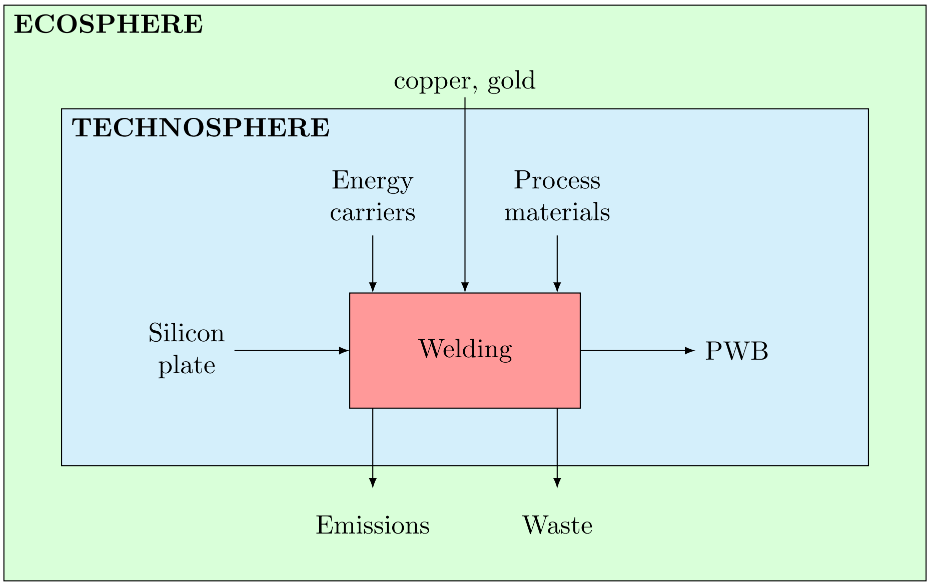

Figure 4: Example for an eco- and technosphere analysis for an individual process for the digital note-taking scenario.

Following this distinction, all pieces of data must be classified as being foreground or background data. For this investigation, this step is facilitated by the use of the EcoInvent database within the SimaPro software. Most of the processes described for each investigation will be taken as background data since their information is widely available in the EcoInvent database and only the top-level assembly definitions are taken as foreground data since they must be explicitly given. A through description for these (sub)assemblies is given in the following section for both note-taking scenarios.

Finally, the system boundaries must be clearly stated. This is a crucial step since it can determine the outcome of an investigation, specifically when comparing multiple test cases. For this investigation, only the materials, processes, transportation and energy required for the manufacturing, use and disposal of both test cases is considered over a period of five academic years. Impacts caused by the manufacturing of the machines involved in the industrial and transportation processes of the material for the investigated test cases are not included.

3 Life Cycle Scenarios

Following the definition for both scenarios to be compared, their life cycles must be described. For this, all materials and processes involved in their material sourcing, processing, manufacturing, assembling, transportation, use and disposal are considered. This was done within SimaPro, with the help of the EcoInvent database. Subsections 3.1 and 3.2 describe each step for the analog and digital scenarios to be compared, respectively. Moreover, subsection 3.3 describes all of the considered case studies for the simulations.

3.1 Analog

For the analog case, traditionally used brands for all materials were considered. This choice required some assumptions to be taken in order to ensure sufficient and realistic amounts for the materials used over a 5 year student career. For this, a small survey of 10 master in mechanical engineering students was conducted. Students were asked how many courses they take on average per academic year as well as how many notebooks and pens they require per lecture. This amounted, on average, to 8 lectures per year using 1 notebook per lecture. Additionally, the students agreed upon using three multi-colored pens per semester (6 per academic year). These results amounted to a total of 40 notebooks and 30 pens used over a span of 5 academic years.

Moreover, traditionally bought and widely available brands were chosen for the notebooks and pens. This led to the choice of BIC ball-point pens and spiraled, 100 page A4 Oxford notebooks.

Assembly

Once the material selection was carried out, the assemblies for the notebooks and pens could be created. For this, the EcoInvent database was used within the SimaPro software to take advantage of the highly detailed accounts available for the impacts of a wide range of materials and assemblies. The following describes all components involved in each of the assemblies.

1. **Oxford Notebook (x40)**

   (a) Wire spiral: For the wire spiral holding the pages and covers together, a low-alloyed steel wire was chosen. This model accounts for the manufacturing of the spirals as well as the sourcing for the steel required to produce all 40 spirals.

   (b) Covers (x2/ea): For the covers, white-lined chipboards (WLC) were chosen. Additionally, their calendering, giving them the typical shiny look, was accounted for.

   (c) Paper (x100/ea): For the notebook pages, 100 gram per square meter (GSM) A4 paper was taken. This is considered standard in many European paper companies and is widely found in many notebook models. Within the SimaPro software, this was modelled using a wood-containing light weight coated (LWC) paper for which all dimensions and densities were accounted for.

2. **BIC Ball-point Pen (x30)** [2]

   (a) Pen barrel: The outer casing for the pen was modelled using polystyrene. Furthermore, this was subjected to a process of injection moulding to account for the energy required for the shaping of the component.

   (b) Pen ink tube and cap: Similar to the pen outer casing, the internal ink tube for the ball-point pen, as well as its calp, were set to be manufactured using injection moulding. However, this was modelled by using polypropylene granulate instead of polystyrene.

   (c) Pen ink: This sub-assembly presented some difficulties since there were no pre-defined modules within the EcoInvent database for the specific type of ink used in ball-point pens. However, a model existed for printer toner which resembles the chemical constitution of pen ink. This required the addition solvent (benzyl alcohol) in order to account for the difference in solubility as well as density between the two types of ink. This mixture was done using a 1:1 ratio between the toner and solvent.

(d) Pen tip: The pen tip sub-assembly required two main components. First the ball-point was taken to be made out of pressed and honed brass. Lacking specific modelling for these manufacturing processes, a general metal product manufacturing model was taken. Moreover, the casing for the ball point was again taken to be made from injection moulded polypropylene.

Transportation

With the goal of accounting for the transportation required for the material to arrive at Belgium, an extensive research on manufacturing plants for both companies (Oxford and BIC) was conducted.

Oxford Notebooks is a daughter company to Hamelin, a French-based company. However, the closest manufacturing plant to Belgium, which is its national provider, is located in the Netherlands outside of Venlo. Therefore, to account for the transportation, a small lorry (> 16 ft) was considered. The impact of this transportation is measured by its total tkm (ton kilometer) which amounted to 4.7815 tkm for the transport of all 40 notebooks (27.48 kg) over the driving distance between the manufacturing plant in Venlo and Brussels (174 km).

In the case for the BIC ball-point pens, it was found that the provider for Belgium was a manufacturing plant in Montevráin, France. Similar to the notebook case, a small lorry was considered with a total of 0.0474 tkm for all 30 pens over the 482 km between the manufacturing plant and Brussels.

Use Case

Considering that this scenario only involved analog components, the use case of it required to additional contributions to its environmental impact. This presented a clear advantage to the digital scenario, which will be discussed in detail in the following section.

Waste Scenario

For the end of life treatment of all components used over the 5 years of study, a disposal scenario was developed. The developed disposal scenario was based on detailed accounts from both Oxford and BIC for their corresponding disposal programs. However, since these programs require of a proper disposal by the end users, it was decided that only 15% of the used materials would find their way to them while the remaining 85% would end up in landfills.

The finalized disposal program consists of the following:

- 80% of the polystyrene from the pens is able to be recycled for further use within BIC manufacturing processes.
- In contrast, the polypropylene from the ball-point pens is not able to be process, leading to most of its mass to be exported to developing countries and end up in massive landfills [2].
- 100% of the brass recovered from the ball-point is recycled.
- 100% of the returned steel from the notebook spirals is made into scrap for further reuse.
- 100% of the papers as well as the covers is able to be turned into recycled paper for further use within Oxford notebooks.
- All remaining materials such as leftover ink in the pen cartridges are disposed of into inert material landfills.

3.2 Digital

The selected tablet for this study is the 10th generation of the Apple iPad along with its compatible 1st generation Apple Pencil. The reason why an iPad was selected is because it is the leading product for tablets and note-taking electronic devices. The 10th generation is the last generation of the regular iPad, which is also the most affordable version. Although a 2nd generation of the Apple

Pencil already exists, it is not compatible with the 10th generation of the iPad, hence the reason why the 1st generation of the Apple Pencil was considered. Although the materials for both the iPad and Apple Pencil are not publicly disclosed, this materials can be approximated considering the total weight of the devices and their functionality. Apple releases environmental reports for their products, where it describes that the aluminum for the iPad comes from recycled material. The other components such as the wiring board, screen and batteries are strictly confidential for the Apple products, therefore, general components for electronic devices were considered in SimaPro. It is important to mention that the transportation for the raw materials is already accounted for in the EcoInvent database from SimaPro.

Assembly

1. **Apple iPad 10th Generation [3]**

   (a) Aluminum casing: To configure this component, a new scrap of aluminum was selected. New scrap refers to aluminum that has been recycled once. Apple specifies in its environmental reports that the housing for their iPad models is made from recycled materials and has a weight of 147g. In SimaPro, the aluminum selected includes manufacturing processes such as, melting, alloying and casting.

   (b) PWB: The configuration of the printed wiring board (PWB) was inspired by the one in the 'Mobile phone tutorial' example elaborated in class, however, it was re-dimensioned according to the specifications for the iPad. The selected PWB in SimaPro describes an unspecified, through-hole mounted PWB used in electronic and electric devices. The overall weight of the PWB is 156g.

   (c) LCD screen: A liquid-crystal display (LCD) screen contains a mirror, glass filter, polarizing screen, liquid-crystal layer, among other components. The selected LCD screen in SimaPro accounts for all the parts that compose an LCD module. The data represents a 15-inch LCD screen, however, a new dimension was specified in the configuration according to the dimensions of the iPad. The LCD screen is the lightest component in the assembly, with a total weight of 15g.

   (d) LiIo battery: Apple uses lithium ion (LiIo) batteries for their products and is the heaviest component from the assembly with 159g. The selected battery in SimaPro describes a rechargeable lithium ion battery pack that includes 14 single cells, a steel casing, a battery management system and the required cables.

2. **Apple Pencil 1st Generation**

   (a) Plastic casing: The casing for the Apple Pencil is made from a lightweight high-gloss plastic. A typical example for a high-gloss plastic is polycarbonate (PC). It is very common to see PC as a casing material in electronic devices, therefore, this material was selected in SimaPro and configured with a total weight of 42g.

   (b) PWB: The selected printed wiring board in SimaPro is also the one used in the iPad, which describes a PWB used in general electronic devices. The overall weight for this PWB is 5.2g.

   (c) LiIo battery: The configuration of the lithium ion battery for the Apple Pencil is similar to the one described for the iPad. The only difference is the weight of the battery, which for the Apple Pencil is 10.3g.

   (d) Pencil tip: The tip of the Apple Pencil uses a different plastic than the casing. Polypropylene (PP) as granulates was selected for the tips. Although the material for the tip is not publicly disclosed, it is known that it has to be a lightweight plastic where carbon nano tubes have to be embedded to allow conductivity, and PP is usually used for this application. This is the lightest component of the assembly, with an overall weight of 1g.

Transportation

To account for the transportation for the iPad and Apple Pencil, it is crucial to consider the manufacturing plants for these products. Apple manufactures its products in a megafactory located in Shenzhen, China. It was considered that this products will travel from Shenzhen to Rotterdam by transoceanic freight ship, with a total impact of 5.6275 tkm over a total distance of 18,256 km. Then the products are transported by lorry (> 16 ft) from Rotterdam to a retail store in Brussels, with an impact of 0.1045 tkm with a total distance of 149.8 km.

Use Case

In contrast to the analog alternative previously described, the energy required to use the digital components has to be accounted for. The energy required for the iPad and Apple Pencil was taken as whole in SimaPro, since the Apple Pencil is charged with the iPad. The selected scenario in SimaPro is inspired from the use of a laptop, which takes into account a total charge each day for 240 days a year. Considering the energy capacity for an iPad's battery of 29Wh, this equates to a total of 34.8kWh (or 125.8 MJ) over 5 years.

Waste Scenario

The life cycle for the digital alternative also considers a 5-year university study. To assess the waste scenario for the iPad and Apple Pencil, 15% was considered to be properly disposed by the user and 85% will go to landfill. The proper disposal is detailed as follows:

1. 100% of the aluminum used for the housing of the iPad can be recycled.
2. 100% of the lithium ion batteries can be properly disposed.
3. 100% of the printed wiring boards are properly disposed for precious metal recovery.
4. 100% of the polypropylene used for the Apple Pencil tips is correctly discarded.
5. 100% of the waste plastic for consumer electronics, such as polycarbonate is properly disposed.
6. 100% of the LCD screen for the iPad is dismantled mechanically, which includes the manual disassembly of the LCD and shredding of the remaining part.

3.3 Case Studies

In order to allow multiple perspectives for the comparison between both note-taking approaches, multiple scenarios were considered. In the following, the considerations for all scenarios are described in great detail.

Manufacturing only

The first case study considers the environmental impacts of manufacturing an iPad and Apple pencil compared to the materials required for a 5 year academic career. This study does not consider the energy required to charge an iPad. This is done with the goal of decoupling the environmental impact of the use of the iPad from its manufacturing since its impact is fully dependent on the energy source shares offered by the grid, as well as any considerations for local renewable installations such as solar PV roofs. Multiple scenarios with varying renewable energy sources (RES) penetration levels are considered in the remaining case studies.

To manufacture an iPad, the aluminum body, circuit board, and battery must be produced and assembled. This involves the use of considerable amounts of water, chemicals, and energy, which contribute to air, water and soil pollution. For the production of an Apple pencil, the process is similar, except for the body of the pencil, which is made from injection moulding of plastic.

In order to manufacture a paper notebook, wood pulp is used to create the paper. It is well known that the production paper also needs large mounts of water and energy. However, chemicals such as dyes and bleaches are also encountered in the manufacturing process. The production of a pen also involves the use of chemical substances such as the ink and solvent, and to manufacture the barrel, plastic injection moulding is used.

5 years: 0% RES penetration

Once the manufacturing processes are compared independently from their use cases, the energy required to run the digital components is factored in, for which the impact caused by the digital case is expected to increase significantly. Within the SimaPro software, this was set up by introducing a parameter which represents the balance between energy from the national Belgian grid and a local solar PV installation.

In the first use case scenario, this parameter is set to 0%, indicating that the energy is entirely sourced from the EcoInvent database for the Belgian grid mix. This scenario represents the situation where the difference in environmental impact between the digital and analog scenarios is expected to be the most significant.

5 years: 50% RES penetration

Following the case with 0% RES penetration, a case study with a grid mix containing 50% renewables is considered. This translates to a local solar PV installation large enough to deliver half of the required energy to charge the components in the digital case over five years.

5 years: 100% RES penetration

Lastly, a case study is conducted to examine a scenario with 100% solar PV penetration. This particular case represents an idealistic situation where non-renewable energy sources are completely eliminated from the energy mix, and the electronics are exclusively charged at outlets powered by solar PV energy.

4 Results

In this section, the impact assessment for all of the considered test cases from the previous section are developed. With this in mind, two assessments are conducted for each test case.

Initially, a midpoint assessment is conducted to compare the impact of each note-taking scenario across various environmental mechanisms. This assessment is carried out both comparatively and in absolute terms, aiming to not only highlight the differences in impact between the approaches but also provide context regarding the significance of each category. For instance, while the digital scenario may exhibit a five-times greater impact in a specific category compared to the analog case, if the absolute value remains relatively small, it limits the extent of conclusions that can be drawn from this relationship. In this evaluation, all absolute values are expressed in units such as loss of species per year (species.yr), disability-adjusted life years (DALY), or excess costs in 2013 US Dollars. These units represent the damage to the ecosystem quality, damage to human health, and cost increases due to resource scarcity caused by the note-taking approach, respectively.

Following the midpoint assessment, an endpoint assessment is conducted to establish a single-score comparison between the approaches using normalization factors. This comparison step has a higher level of uncertainty compared to the previous assessment since it requires qualitative input to determine normalization factors across all categories. However, the well-established ReCiPe methodology used in this study provides objectivity to these values to the best of our knowledge.

4.1 Manufacturing Impact

As mentioned in the previous section, first, the manufacturing processes for both note-taking approaches are compared. For this, the previously mentioned scenarios including their transportation and waste treatments are considered.

As a first step, their effects per impact category were compared. Figure 5 depicts a relative analysis for the most significant categories between both scenarios while Figure 6 shows the absolute values for all impact categories.

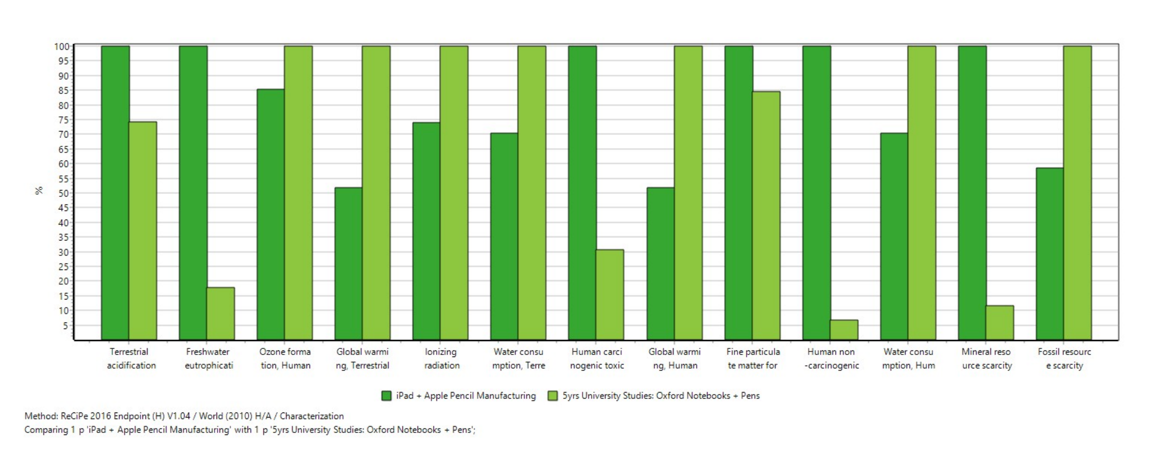

Figure 5: Relative midpoint assessment for the manufacturing of the investigated note-taking approaches per impact category.

This Figure showcases the similarity between the impact for both note-taking scenarios where each case dominates six categories. However, a clear disparity favoring the digital approach can be seen for all categories related with global warming and natural resources. The analog case causes about twice as much global warming on average over the three considered categories and is well above the digital case for scarcity of fossil resources, water consumption and ozone formation. On the other hand, the digital case has a much greater impact in categories involving the damaging of ecosystems such as terrestrial acidification and freshwater eutrophication as well as human impacts (carcinogenic and non-carcinogenic) and scarcity of mineral resources.

Se	Impact category	Unit	iPad + Apple Pencil Manufacturing	5yrs University Studies: Oxford Notebooks + Pens
☐	Global warming, Freshwater ecosystems	species.yr	3,4E-12	6,58E-12
☐	Marine eutrophication	species.yr	8,65E-12	4,37E-11
☐	Water consumption, Aquatic ecosystems	species.yr	1,39E-10	1,99E-10
☐	Marine ecotoxicity	species.yr	3,73E-9	2,79E-10
☐	Terrestrial ecotoxicity	species.yr	5,99E-9	1,17E-9
☐	Stratospheric ozone depletion	DALY	1,16E-8	1,64E-8
☐	Land use	species.yr	1,35E-8	3,18E-7
☐	Ozone formation, Terrestrial ecosystems	species.yr	1,65E-8	1,93E-8
☐	Freshwater ecotoxicity	species.yr	1,71E-8	1,31E-9
☑	Terrestrial acidification	species.yr	5,7E-8	4,23E-8
☑	Freshwater eutrophication	species.yr	1,01E-7	1,8E-8
☑	Ozone formation, Human health	DALY	1,14E-7	1,34E-7
☑	Global warming, Terrestrial ecosystems	species.yr	1,25E-7	2,41E-7
☑	Ionizing radiation	DALY	1,46E-7	1,97E-7
☑	Water consumption, Terrestrial ecosystem	species.yr	3,12E-6	4,44E-6
☑	Human carcinogenic toxicity	DALY	2,72E-5	8,35E-6
☑	Global warming, Human health	DALY	4,13E-5	7,98E-5
☑	Fine particulate matter formation	DALY	5,73E-5	4,84E-5
☑	Human non-carcinogenic toxicity	DALY	0,000251	1,67E-5
☑	Water consumption, Human health	DALY	0,000513	0,00073
☑	Mineral resource scarcity	USD2013	0,461	0,0531
☑	Fossil resource scarcity	USD2013	2,77	4,73

Figure 6: Absolute midpoint assessment for the manufacturing of the investigated note-taking approaches per impact category.

From Figure 6, the same trend is observed. Terrestrial ecotoxicity caused by the digital case is more than five times larger than for the analog case, whereas the land use for the analog case is an entire order of magnitude larger than the digital case. Nevertheless, these remaining categories are orders of magnitude smaller than the ones described in the previous Figure and must be carefully analyzed as to not allow for the attention to be deviated from the impact categories with the majority of the impact share.

Once the midpoint assessment is conducted, the impact categories can be divided into three main groups based on the recipient for their impacts: the ecosystem, human health and the global resources. Figure 7 showcases a relative comparison per category between both note-taking scenarios.

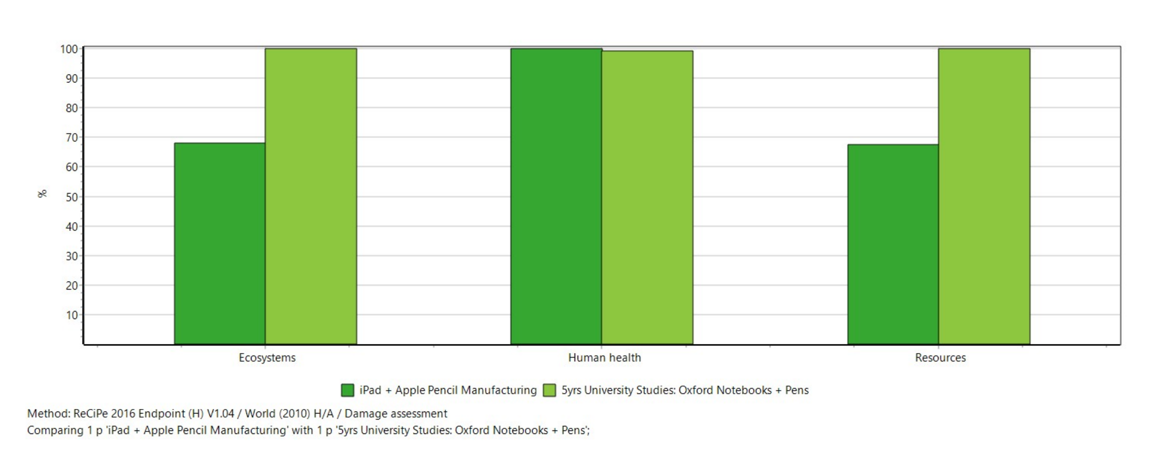

Figure 7: Relative endpoint assessment for the manufacturing of the investigated note-taking approaches.

Based on these findings, it is apparent that both manufacturing processes exhibit a comparable impact on human health, with a slight advantage observed for the digital scenario. However, the analog scenario demonstrates approximately a 40% greater impact on the ecosystem and global resources. This discovery is particularly unexpected, considering the significant manufacturing requirements and intercontinental transportation involved in the digital scenario.

Nevertheless, similar to the midpoint assessment, analyzing the absolute scores for each category is imperative for the context of this difference. Figure 8 depicts the total single score given to the manufacturing for both note-taking scenarios alongside their internal distributions.

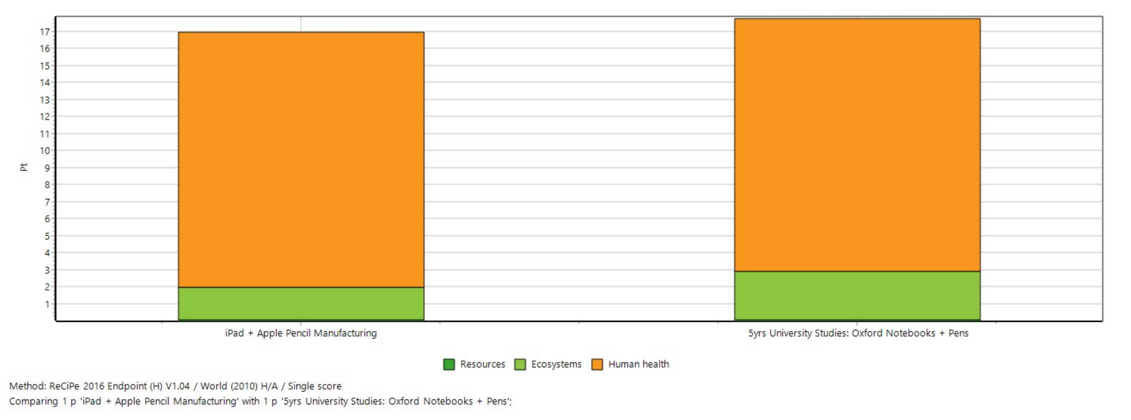

Figure 8: Single score distribution for the manufacturing of the investigated note-taking approaches.

From here, it becomes evident that the impact on human health is the major contributor for both scenarios, with the 40% increase in ecosystem and resource impact for the analog scenario amounting to a surplus of an individual single score point.

4.2 Life Cycle Impact

Once the manufacturing for both note-taking scenarios was compared, the energy required to power the electronics from the digital case are taken into account. As mentioned earlier, three energy source scenarios are considered ranging from 0 to 100% RES penetration for the grid mix. The results for their midpoint and endpoint assessment comparisons are seen in the following.

4.2.1 0% RES Penetration

As expected, the impact for the digital case increases when the energy required to charge and operate the electronics is considered. Figures 9 and 10 showcase the midpoint assessment for both scenarios with 0% RES penetration.

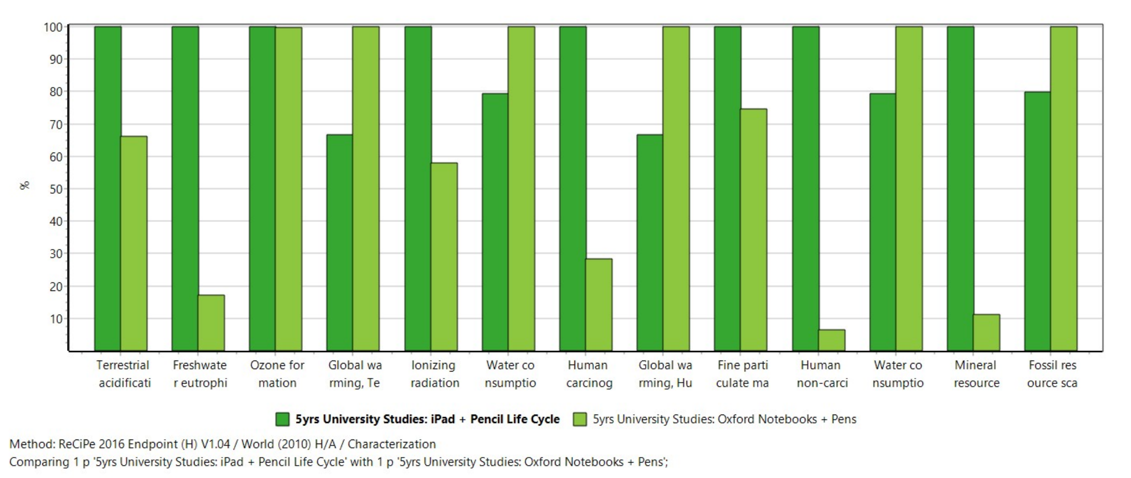

Figure 9: Relative midpoint assessment for a 0% RES penetration scenario.

From Figure 9 it becomes evident that the impact caused by the energy required to run the electronics causes for the digital case to outweigh the impact for the analog case in many categories. This is especially noticeable in the categories for ozone formation, fossil resources and water consumption where increases of approximately 20, 30 and 15% respectively. This is intuitive, since in this case we are considering a grid composed by multiple energy sources. Increases in these categories are attributed to the use of fossil fuel power plants as well as hydropower generation plants.

Se	Impact category	Unit	5yrs University	5yrs University Studies: Oxford
☐	Global warming, Freshwater ecosystems	species.yr	4,39E-12	6,58E-12
☐	Marine eutrophication	species.yr	9,21E-12	4,37E-11
☐	Water consumption, Aquatic ecosystems	species.yr	1,57E-10	1,99E-10
☐	Marine ecotoxicity	species.yr	3,78E-9	2,79E-10
☐	Terrestrial ecotoxicity	species.yr	6,41E-9	1,17E-9
☐	Land use	species.yr	1,43E-8	3,18E-7
☐	Stratospheric ozone depletion	DALY	1,47E-8	1,64E-8
☐	Freshwater ecotoxicity	species.yr	1,73E-8	1,31E-9
☐	Ozone formation, Terrestrial ecosystems	species.yr	1,94E-8	1,93E-8
☑	Terrestrial acidification	species.yr	6,4E-8	4,23E-8
☑	Freshwater eutrophication	species.yr	1,04E-7	1,8E-8
☑	Ozone formation, Human health	DALY	1,34E-7	1,34E-7
☑	Global warming, Terrestrial ecosystems	species.yr	1,61E-7	2,41E-7
☑	Ionizing radiation	DALY	3,41E-7	1,97E-7
☑	Water consumption, Terrestrial ecosystem	species.yr	3,52E-6	4,44E-6
☑	Human carcinogenic toxicity	DALY	2,95E-5	8,35E-6
☑	Global warming, Human health	DALY	5,32E-5	7,98E-5
☑	Fine particulate matter formation	DALY	6,5E-5	4,84E-5
☑	Human non-carcinogenic toxicity	DALY	0,000255	1,67E-5
☑	Water consumption, Human health	DALY	0,000578	0,00073
☑	Mineral resource scarcity	USD2013	0,472	0,0531
☑	Fossil resource scarcity	USD2013	3,78	4,73

Figure 10: Absolute midpoint assessment for a 0% RES penetration scenario.

Analyzing the endpoint assessment for both scenarios in Figures 11 and 12 showcases the impact of the consideration of the energy, which mainly affects the human health category, increasing its single score by approximately 2 eco-points. Moreover, Figure 11 shows that the main driving factor for the increases seen is the water consumption related with effects on human health.

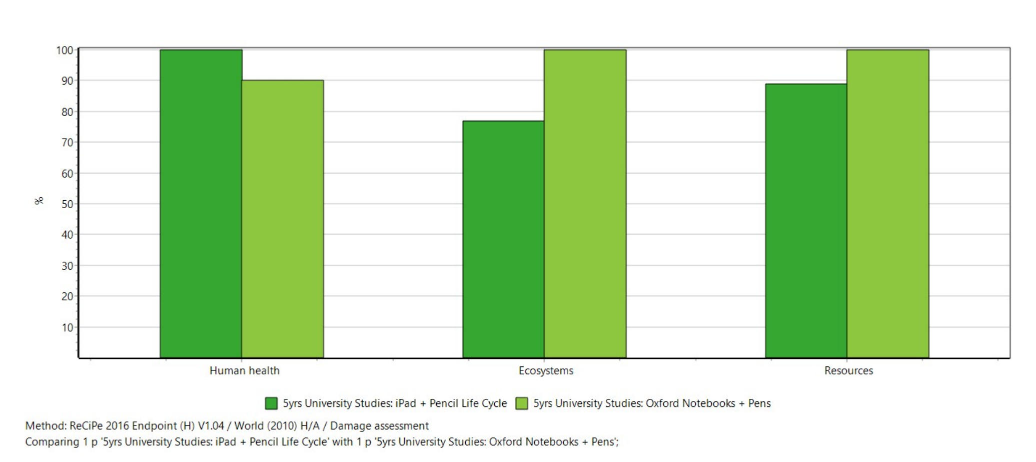

Figure 11: Relative endpoint assessment for a 0% RES penetration scenario.

By comparing the single score for the digital case before and after considering the electricity required to power it, a rise for its single score of 1.8 eco-points is observed (seen in Figure 13). As mentioned earlier, this is driven mainly by an increase in the effects on human health, largely due to its rise in effects for water consumption of about 15% with respect to the manufacturing case.

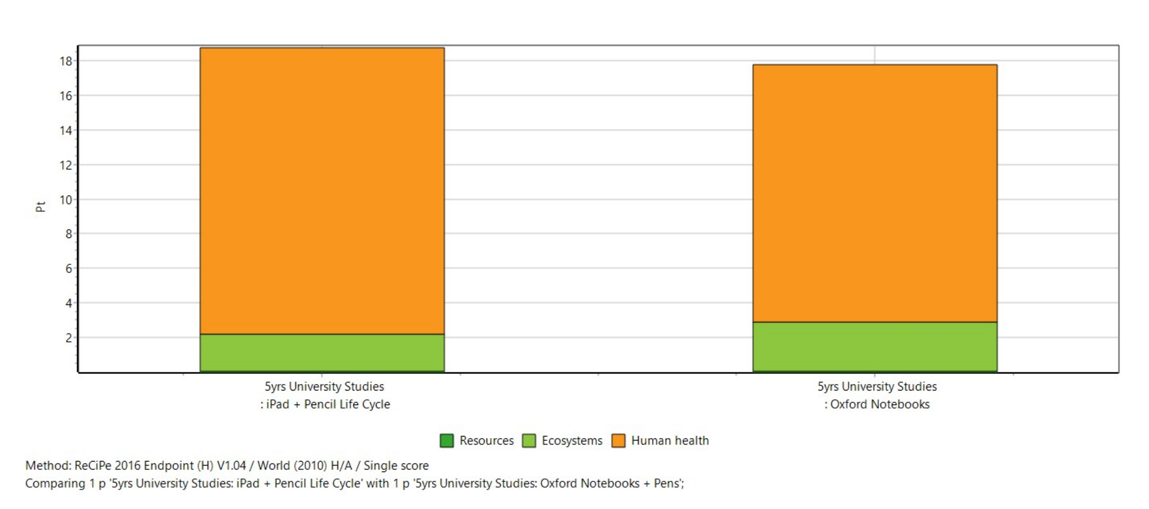

Figure 12: Single score distribution for a 0% RES penetration scenario.

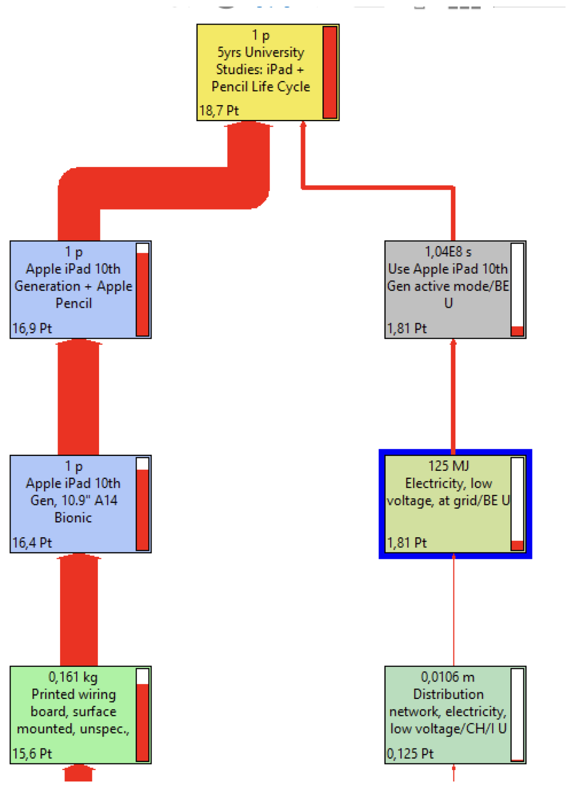

Figure 13: Network for a 0% RES penetration scenario.

4.2.2 50% RES Penetration

The second energy source scenario depicts a 50% RES penetration. Figure 14 shows the relative midpoint assessment for the two note-taking alternatives considered, while Figure 15 depicts the categories considered alongside their absolute midpoint assessment values. The results are similar to those presented in Subsection 4.2.1. Nevertheless, some categories have decreased for the 50% RES in comparison to the 0% RES while others have increased. For instance, the *ozone formation for human health* category had a relative increase of around 6% for the analog case. Similarly, both *global warming* categories considered present a relative increase of 10%. These can be attributed to the reduction in impact for the digital case compared to the 0% RES scenario over these categories. On the other hand, *water consumption* for human health and terrestrial ecosystems presented a relative impact reduction of 7% and 9%, respectively, attributed to an increase for the impact in the digital case with respect to the 0% RES scenario.

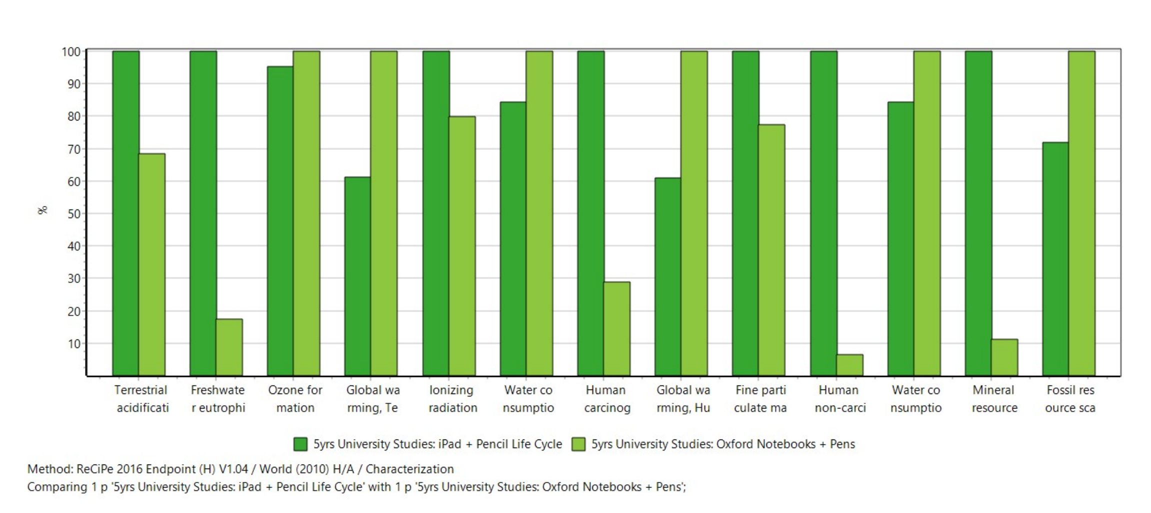

Figure 14: Relative midpoint assessment for a 50% RES penetration scenario.

Se	Impact category	Unit	5yrs University Studies: iPad + Pencil Life Cycle	5yrs University Studies: Oxford Notebooks + Pens
☐	Global warming, Freshwater ecosystems	species.yr	4,02E-12	6,58E-12
☐	Marine eutrophication	species.yr	9,16E-12	4,37E-11
☐	Water consumption, Aquatic ecosystems	species.yr	1,67E-10	1,99E-10
☐	Marine ecotoxicity	species.yr	3,78E-9	2,79E-10
☐	Terrestrial ecotoxicity	species.yr	6,71E-9	1,17E-9
☐	Stratospheric ozone depletion	DALY	1,36E-8	1,64E-8
☐	Land use	species.yr	1,42E-8	3,18E-7
☐	Freshwater ecotoxicity	species.yr	1,73E-8	1,31E-9
☐	Ozone formation, Terrestrial ecosystems	species.yr	1,85E-8	1,93E-8
☑	Terrestrial acidification	species.yr	6,18E-8	4,23E-8
☑	Freshwater eutrophication	species.yr	1,04E-7	1,8E-8
☑	Ozone formation, Human health	DALY	1,28E-7	1,34E-7
☑	Global warming, Terrestrial ecosystems	species.yr	1,47E-7	2,41E-7
☑	Ionizing radiation	DALY	2,47E-7	1,97E-7
☑	Water consumption, Terrestrial ecosystem	species.yr	3,74E-6	4,44E-6
☑	Human carcinogenic toxicity	DALY	2,89E-5	8,35E-6
☑	Global warming, Human health	DALY	4,87E-5	7,98E-5
☑	Fine particulate matter formation	DALY	6,25E-5	4,84E-5
☑	Human non-carcinogenic toxicity	DALY	0,000255	1,67E-5
☑	Water consumption, Human health	DALY	0,000616	0,00073
☑	Mineral resource scarcity	USD2013	0,475	0,0531
☑	Fossil resource scarcity	USD2013	3,4	4,73

Figure 15: Absolute midpoint assessment for a 50% RES penetration scenario.

The relative endpoint assessment per impact category of the 50% RES scenario for the note-taking methods is shown in Figure 16. In contrast with the 0% RES scenario, the *ecosystems* and *human health* impacts are higher for this case, with 6% and 2% reductions, respectively. However, the *resources* category decreased by 8% for the 50% RES scenario. These results indicate that, between the 0% RES scenario and the 50% RES scenario, an increase for the ecosystem and human health impacts from part of the digital case are experienced, alongside a decrease in the impact over resources.

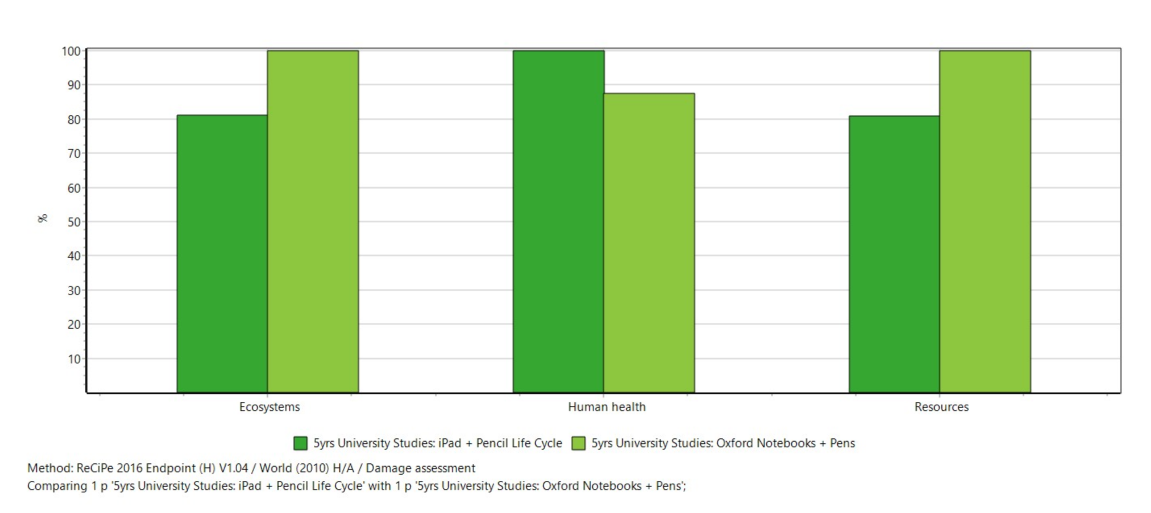

Figure 16: Relative endpoint assessment for a 50% RES scenario.

By analyzing the total single score given for the 50% RES scenario for both note-taking options in Figure 17, it can be observed that the *human health* category has the biggest impact over the *ecosystem* and *resources* categories for the analog and digital note-taking approaches. Moreover, an increase for the single score given to the digital case is observed. This was not expected since, in general, a higher RES results in lower impacts. However, for this application, it seems that the increase in water consumption between both scenarios (0.000578 DALY for 0% RES and 0.000616 DALY for 50% RES) is the driving factor for this increase as in every other human health factor, the 0% RES scenario shows larger values. Nevertheless, the impact of this increased water consumption results in an increase of about 0.6 (seen in Figure 18) ecopoints for its single score rating in the human health category.

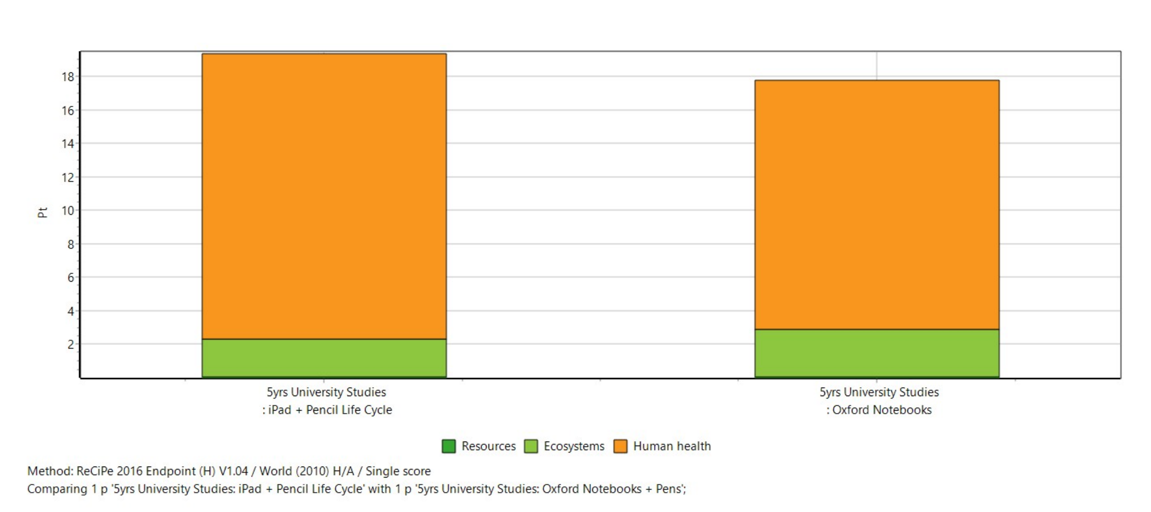

Figure 17: Single score distribution for a 50% RES penetration scenario.

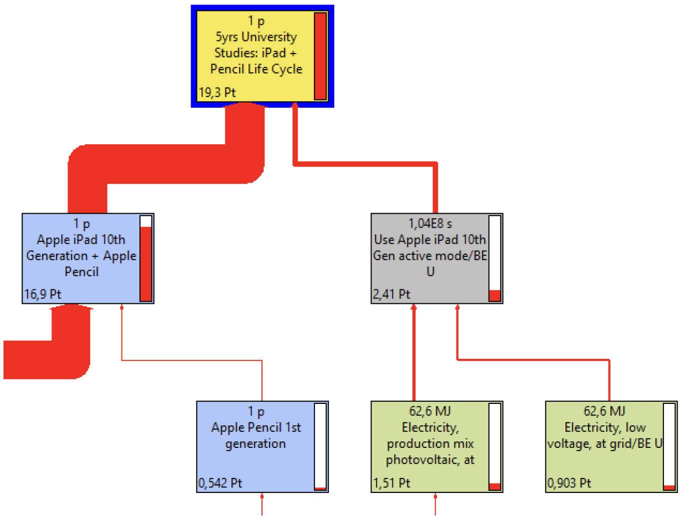

Figure 18: Network for a 50% RES penetration scenario.

4.2.3 100% RES Penetration

The last energy scenario consists of defining a 100% RES penetration to charge the digital note-taking method, which means that all the energy comes from renewable sources. Figure 19 shows the relative midpoint assessment for both note-taking methods, and Figure 20 the relevant impact categories alongside their absolute midpoint assessment. Since now the energy sources are completely renewable, it would be logical to expect a lower impact in some categories from the digital alternative. In contrast to the 50% RES, the *ozone formation* for human health, and *global warming* categories present a relative increase for the analog alternative, meaning that a decrease for the digital scenario was experienced. The *ozone formation* decreased 5%, while the *global warming* for terrestrial ecosystems and human health presented the largest change, with a 10% decrease each. This means that the digital note-taking alternative contributes less to global warming than the analog option, according to its midpoint assessment. On the other hand the *water consumption* impact stayed relatively the same for the 100% RES penetration scenario.

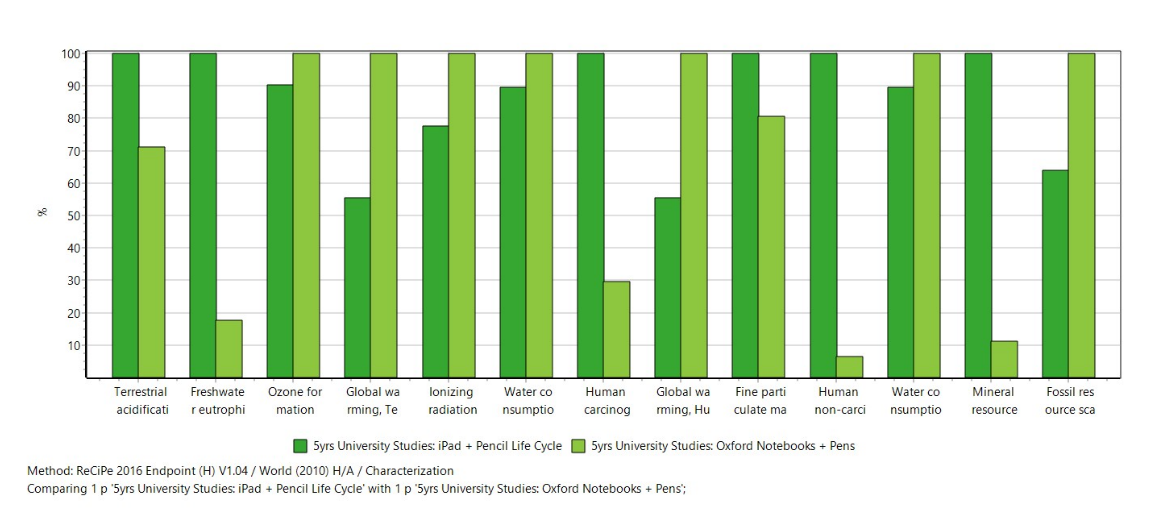

Figure 19: Relative midpoint assessment for a 100% RES penetration scenario.

Se	Impact category	Unit	5yrs University Studies: iPad + Pencil Life Cycle	5yrs University Studies: Oxford Notebooks + Pens
☐	Global warming, Freshwater ecosystems	species.yr	3,65E-12	6,58E-12
☐	Marine eutrophication	species.yr	9,1E-12	4,37E-11
☐	Water consumption, Aquatic ecosystems	species.yr	1,78E-10	1,99E-10
☐	Marine ecotoxicity	species.yr	3,77E-9	2,79E-10
☐	Terrestrial ecotoxicity	species.yr	7,02E-9	1,17E-9
☐	Stratospheric ozone depletion	DALY	1,26E-8	1,64E-8
☐	Land use	species.yr	1,4E-8	3,18E-7
☐	Freshwater ecotoxicity	species.yr	1,73E-8	1,31E-9
☐	Ozone formation, Terrestrial ecosystems	species.yr	1,75E-8	1,93E-8
☑	Terrestrial acidification	species.yr	5,95E-8	4,23E-8
☑	Freshwater eutrophication	species.yr	1,03E-7	1,8E-8
☑	Ozone formation, Human health	DALY	1,21E-7	1,34E-7
☑	Global warming, Terrestrial ecosystems	species.yr	1,33E-7	2,41E-7
☑	Ionizing radiation	DALY	1,53E-7	1,97E-7
☑	Water consumption, Terrestrial ecosystem	species.yr	3,97E-6	4,44E-6
☑	Human carcinogenic toxicity	DALY	2,83E-5	8,35E-6
☑	Global warming, Human health	DALY	4,42E-5	7,98E-5
☑	Fine particulate matter formation	DALY	6,01E-5	4,84E-5
☑	Human non-carcinogenic toxicity	DALY	0,000254	1,67E-5
☑	Water consumption, Human health	DALY	0,000653	0,00073
☑	Mineral resource scarcity	USD2013	0,477	0,0531
☑	Fossil resource scarcity	USD2013	3,02	4,73

Figure 20: Absolute midpoint assessment for a 100% RES penetration scenario.

Figure 21 shows the endpoint assessment of 100% RES scenario for the note-taking methods considered. The impact in *human health* and *resources* dropped 4% in for the analog alternative if compared to the 50% RES scenario. On the other hand, the ecosystem impact increased 4% for the digital case.

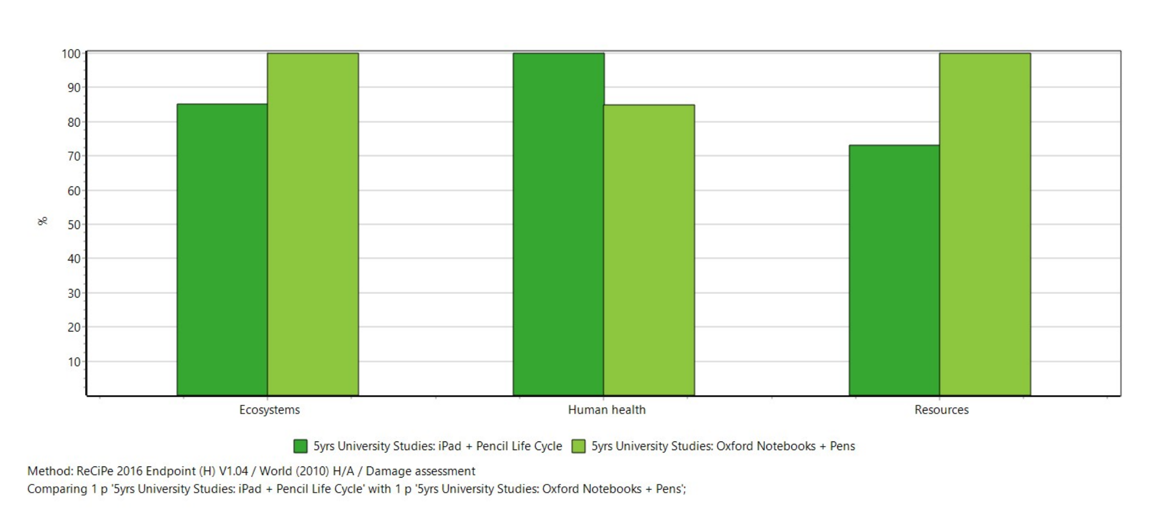

Figure 21: Relative endpoint assessment for a 100% RES scenario.

Figure 22 shows the total single score given for the 100% RES energy scenario. Comparing these results to the ones seen for the 50% RES scenario, an absolute increase can be seen for the single score for the digital scenario. Again, this is attributed to the effects of water consumption on human health, given that all other categories are actually lower, similar to the last case. This increase in water consumption accounts for approximately a 0.6 point increase between both scenarios, seen explicitly in the impact network in Figure 23.

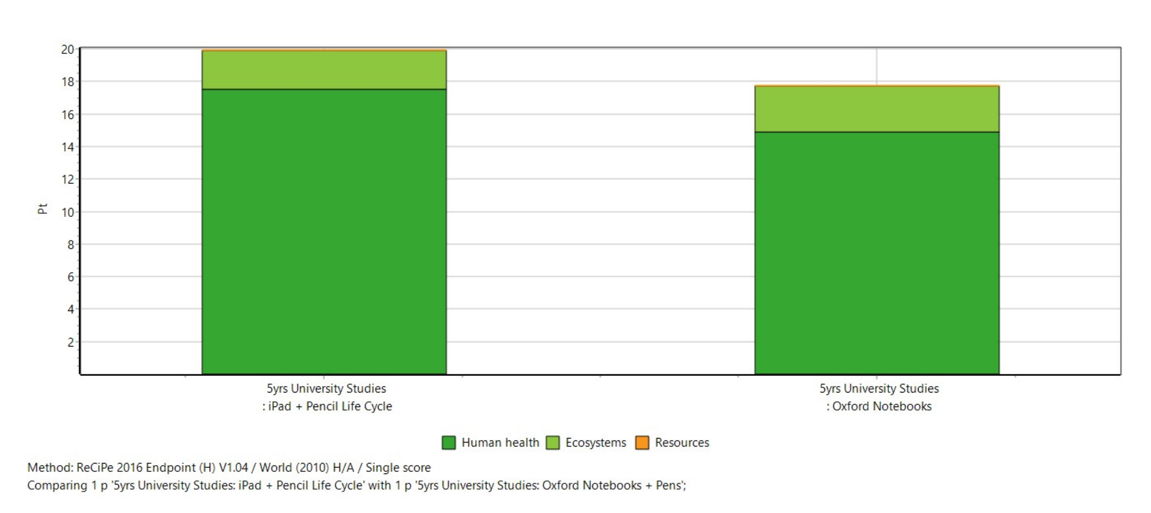

Figure 22: Single score distribution for a 100% RES scenario.

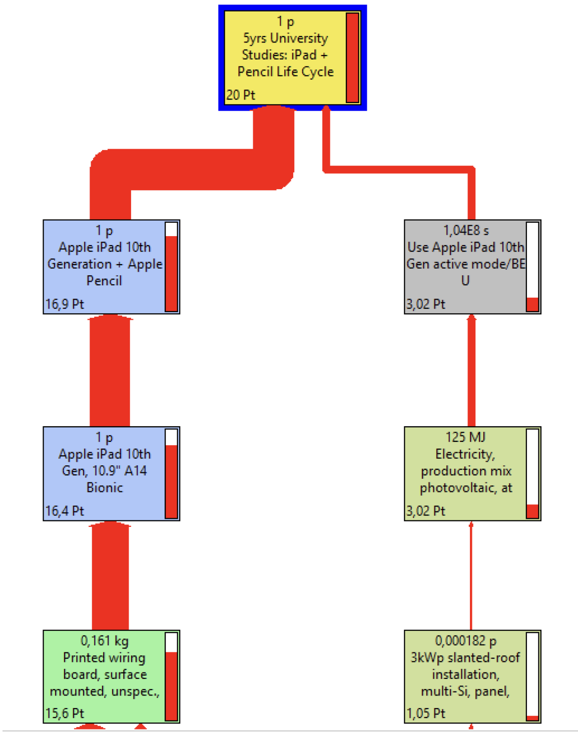

Figure 23: Network for a 100% RES penetration scenario.

4.2.4 Extra: 100% Wind Penetration Case

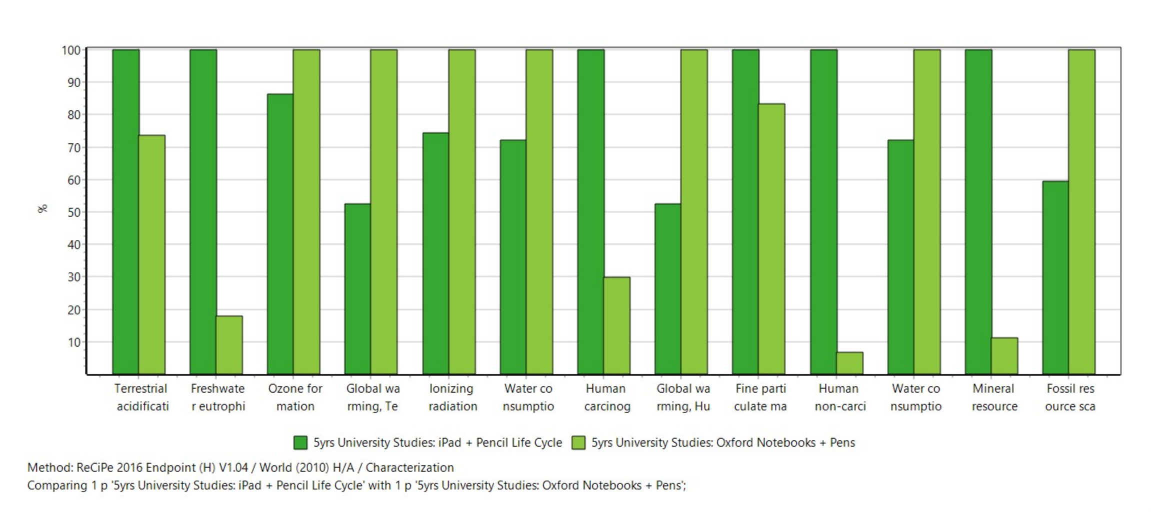

Figure 24: Relative midpoint assessment for a 100% wind penetration scenario.

Se	Impact category	Unit	5yrs University Studies: iPad + Pencil Life Cycle	5yrs University Studies: Oxford Notebooks + Pens
☐	Global warming, Freshwater ecosystems	species.yr	3,45E-12	6,58E-12
☐	Marine eutrophication	species.yr	8,73E-12	4,37E-11
☐	Water consumption, Aquatic ecosystems	species.yr	1,43E-10	1,99E-10
☐	Marine ecotoxicity	species.yr	3,73E-9	2,79E-10
☐	Terrestrial ecotoxicity	species.yr	6,11E-9	1,17E-9
☐	Stratospheric ozone depletion	DALY	1,17E-8	1,64E-8
☐	Land use	species.yr	1,4E-8	3,18E-7
☐	Ozone formation, Terrestrial ecosystems	species.yr	1,67E-8	1,93E-8
☐	Freshwater ecotoxicity	species.yr	1,71E-8	1,31E-9
☑	Terrestrial acidification	species.yr	5,74E-8	4,23E-8
☑	Freshwater eutrophication	species.yr	1,01E-7	1,8E-8
☑	Ozone formation, Human health	DALY	1,16E-7	1,34E-7
☑	Global warming, Terrestrial ecosystems	species.yr	1,26E-7	2,41E-7
☑	Ionizing radiation	DALY	1,47E-7	1,97E-7
☑	Water consumption, Terrestrial ecosystem	species.yr	3,2E-6	4,44E-6
☑	Human carcinogenic toxicity	DALY	2,79E-5	8,35E-6
☑	Global warming, Human health	DALY	4,18E-5	7,98E-5
☑	Fine particulate matter formation	DALY	5,81E-5	4,84E-5
☑	Human non-carcinogenic toxicity	DALY	0,000251	1,67E-5
☑	Water consumption, Human health	DALY	0,000526	0,00073
☑	Mineral resource scarcity	USD2013	0,48	0,0531
☑	Fossil resource scarcity	USD2013	2,81	4,73

Figure 25: Absolute midpoint assessment for a 100% wind penetration scenario.

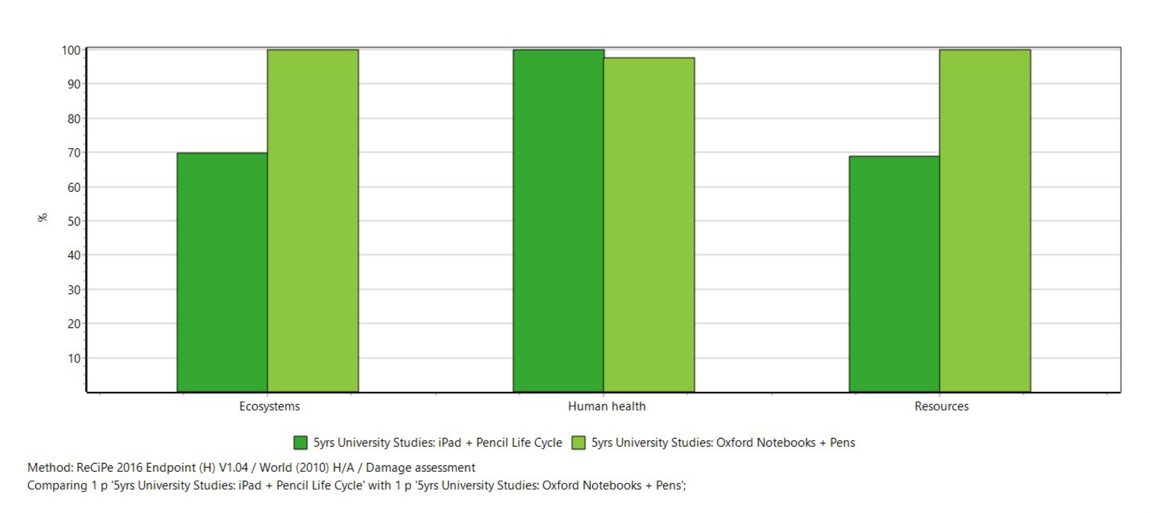

Figure 26: Relative endpoint assessment for a 100% RES scenario.

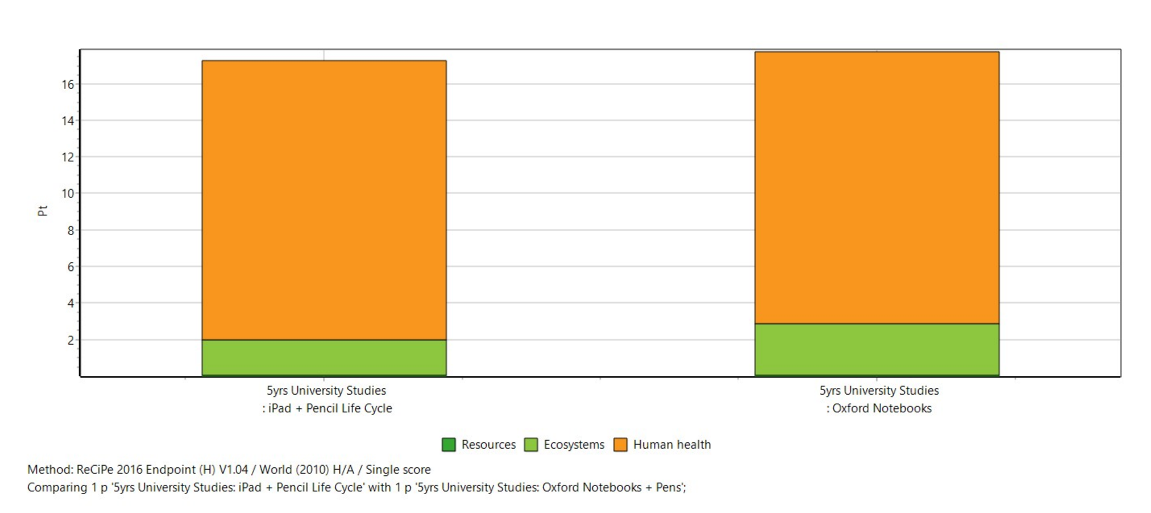

Figure 27: Single score distribution for a 100% wind scenario.

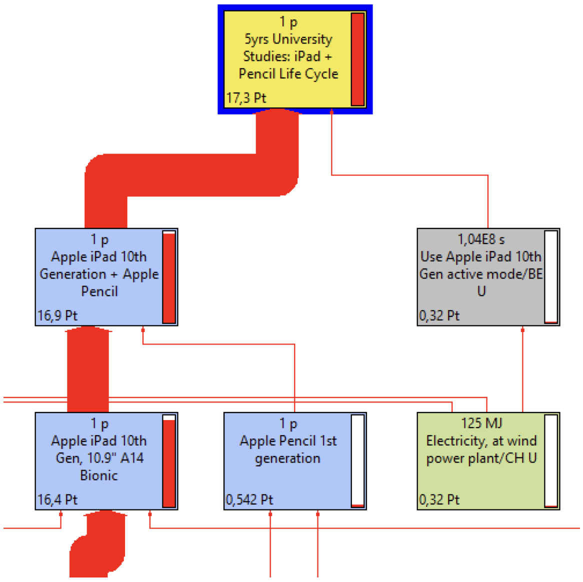

Figure 28: Network for a 100% wind penetration scenario.

Based on these results we can see in Figure 24 that the *water consumption* for the wind case is less than the one from the solar case, having a difference of 22%. This can also be verified in Figure 26, where the impact on *human health* is almost the same for both note-taking alternatives. On the other hand, the *ecosystems* and *resources* categories decreased 18% and 5% respectively. Finally, the single score for the wind scenario decreased around 3 eco-points, making it more beneficial than the analog case.

5 Conclusions

Two different note-taking approaches were considered for the LCA of a 5-year university study period presented in this report. First, an *analog* alternative is defined, which consists on using a number of Oxford paper notebooks and BIC ball-point pens. Furthermore, a *digital* alternative that describes the use of an iPad and Apple Pencil for note taking is defined. The models were thoroughly described, giving the functional unit and their inventory. The latter consists on the materials and manufacturing processes used for their fabrication, while the former answers questions such as *what?, where?, how many?, how well?, for how long?*.

The life cycle scenarios for each note-taking alternative were also defined, which consisted in the assemblies, use case, transportation and waste scenarios. For the Oxford notebooks, it was determined that he closest manufacturing plant is located in the Netherlands, while the BIC pens are manufactured in France. The Apple products come all the way from its megafactory in China, which travel by freight ship to Rotterdam. It was determined that for both cases, 15% of the materials find a proper end-of-life, while the remaining 85% ends up in landfill.

The case studies for the LCA considered only the manufacturing of the products, a 0% RES penetration, 50% RES penetration, and 100% RES penetration. The results were presented for each of the scenarios previously mentioned. It was determined that for the manufacturing scenario, the digital alternative has less overall impact than the analog option. Nevertheless, this analysis did not consider the energy required to charge the Apple products. For the remaining three scenarios, the analog products showed less overall impact than the digital products, regardless on how much energy comes from renewable sources. However, at its largest point (100% renewable) the total single score for both scenarios only differ in 3 eco-points. Considering that the electronics used in the digital scenario can also be used for different activities outside university work, it can be said that this scenario represents a viable option as an alternative for paper note-taking.

When comparing all RES penetration scenarios, a trend for an increasing single score was established. Namely, this was experienced in the human health category, showcasing slight increases between all three scenarios. By comparing their midpoint assessments, it was seen that, for all categories affecting human health, only an increase in the impact on human health due to water consumption was present. For all remaining categories, the impact on human health decreased as the RES penetration increased. The increase for the single score can be attributed to the weight factors given to the water consumption, as it is the main driver for their single score.

References

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