# Screening Life Cycle Assessment comparing One-step and Two-step Injection Molding Compounding using Conservative and Optimistic Scenarios

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This article is dedicated to Univ-Prof. Dr.-Ing. Ralf Schledjewski

*Abstract:* - One-step injection molding compounding (IMC) is an innovative process to manufacture short-fiber-reinforced polymer composites. The aim of combining compounding and injection molding into one process is to enhance component quality and minimize environmental impacts. In this study, a screening Life Cycle Assessment (LCA) is conducted to evaluate and compare the environmental impacts of the IMC process with standard two-step manufacturing. Two scenarios for the IMC are considered, each differing in terms of machinery requirements, energy consumption, and material usage. Mechanically recycled polypropylene and glass fiber are used, and considered in the LCA employing a simple cut-off approach without awarding credits for substituting (primary) materials. The functional unit is the composite produced via the respective process, assuming equal functionality. Inventory data are obtained from initial experiments, literature, and the ecoinvent database. The impact assessment method selected is ReCiPe2016. Results indicate that the environmental performance improvement achieved by the IMC compared to the reference process is minimal in the conservative scenario where energy and material usage can be reduced but machinery usage is increased. However, in an optimistic scenario, the IMC can reduce the impacts of composite manufacturing by 34 %. The contributions at the midpoint level vary, and metal usage and energy consumption are the main contributors in all scenarios. A variation of the energy source for manufacturing shows the dependency of environmental impacts of components produced in both processes on the geographical location of production and its electricity supply. Methodological choices, such as the definition of the functional unit and modeling of recycled materials, have a large influence on LCA results, and alternative options are discussed.

*Key-Words:* - Injection molding compounding, Life Cycle Assessment, recycled fiber-reinforced polymers, recycled glass fibers, recycled polypropylene, scenario analysis.

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## 1 Introduction

Fiber-reinforced polymer (FRP) composites are high-performance materials that can help to reduce negative environmental impacts, e.g. through application in wind power and transport sectors, where they can reduce fuel consumption due to their lightweight potential, [1]. On the other hand, FRP composites are also facing challenges under the sustainability paradigm, such as their reliance on fossil resources for production and processing, limited recyclability at End-of-Life (EoL), and limited availability of functional manufacturing processes for recycled and novel materials, [2], [3]. The development and improvement of a combined injection molding compounding (IMC) process aims to contribute to advancing technological solutions to foster the Circular Economy of FRP composites, as this process is suitable for the usage of recycled glass fibers (rGF) and thermoplastics, such as Polypropylene (rPP). The goal of the improved processing is to decrease material degradation during processing, while simultaneously improving economic and environmental performance of recycling and remanufacturing processes.

The IMC is an innovative process technology for manufacturing different types of fibers, fillers and additives in a thermoplastic matrix by directly connecting a continuously conveying extruder to a discontinuously operating injection molding (IM) machine through a melt pipe and pot, [4]. This connection allows for processing in a single plasticizing process, which can potentially increase composite quality due to reduced degradation of the polymeric matrix and maintained fiber length during processing. Potential economic and environmental advantages are the reduction in processing time, production cost, and machine wear as well as energy savings, [5].

Nevertheless, there remain challenges of the IMC process that need to be addressed to exploit the full potential of the concept, [6], [7]:

- Improvement of the connection between the continuous compounding and discontinuous IM processes,
- Optimised configuration of processing parameters, such as shear energy input and residence time,
- Identification of suitable material combinations and compositions,
- Usage of additives to improve processing of recyclates and component quality.

Research and development aim to address these issues through improvements in machinery conception and process development (especially concerning the connection of the compounder and IM machine), in-line monitoring, formulation of rGF, rPP, and additives, and the analysis of cause-effect relationships.

Environmental advantages associated with the improved processing and the usage of recycled materials are the main motivation for the process development. It is important to verify and quantify these potential environmental sustainability benefits using a suitable methodology such as Life Cycle Assessment (LCA), [8], [9].

To develop a better understanding of the anticipated environmental benefits of the combined process and identify hotspots, this study conducts a screening LCA. The one-step IMC process is compared in two different scenarios to a conventional two-step compounding plus injection molding (IM+C) process to produce a component using rPP reinforced with rGF. The goal of this paper is the depiction of the status quo in IM+C processing and the development of two scenarios (conservative and optimistic) to estimate the environmental impacts of the IMC process. Elaboration at an early stage of the project helps to identify hotspots for environmental performance in the process functioning. Furthermore, methodological choices in LCA, such as the choice of the functional unit and approaches to model recycled materials, are critically discussed.

# 2 Methodology

The goal and scope of the LCA are to determine the potential environmental advantages of the IMC process in comparison to a conventional two-step IM+C process using different scenarios. The scenarios vary according to the key areas expected to be different, namely machinery requirements, energy consumption, and generation of waste. The geographical scope of the LCA for manufacturing is Austria, whereas additional materials are supplied from the European market. While the research activities are performed in Austria with Austrian and German machinery manufacturers, the IMC technology can be used worldwide to produce FRP products.

## 2.1 Functional Unit

The functional unit (FU) constitutes the object investigated and represents the quantified reference unit for inventory data and environmental impacts, [10]. To ensure comparability of different products, the FU needs to include quantitative and qualitative aspects of the object's function(s) concerning: the service provided (what?), extent of the service (how much?), level of quality (how well?), and duration or lifetime of the product (for how long?), [11].

In this screening, LCA, the FU is the injection-molded rGF/rPP component produced in the respective process. The components produced in the two processes have uniform geometrical dimensions and shape (convex hull) and are composed of the same materials. They are expected to provide an equivalent level of functionality.

Nevertheless, there are potential differences in the level of quality provided by the two processes. Previous research showed that Young's modulus of PP nanocomposites manufactured in an IM+C two-step is up to 7 % higher than in the counterpart manufactured using a one-step IMC process, [6]. This is explained by differences in shear energy introduced and by the long residence time of the melt in the non-optimized melt conveying system. Research and process developers aim to solve these shortcomings of the IMC process, and it is expected that in the future, the IMC component will exhibit better mechanical properties than the IM+C counterpart due to the decrease in material degradation during manufacturing.

The adaptation of the FU is one option to account for these differences in LCA. Before undertaking any modification of the FU in a process comparison LCA, it is important to reflect on the cause-effect relationship leading to differences in component quality. It should be analyzed to what extent these differences are a result of processing differences or material-induced variability. Recycled materials are often subject to inherent heterogeneity as a consequence of polymer degradation, cross-contamination with other substances, and variable input streams into recycling from the first life, [12], [13], [14].

Afterward, the FU can be modified by reflecting on the consequences of quality differences during the life cycle of the component in its field of application. Possibilities for quantification in the FU are the inclusion of differences in component lifetime and effects on emissions during the use phase. To make products from the two processes comparable, a modification of component geometry and composition to reach equal mechanical properties is another possibility to redefine the FU. Such a change can be considered in LCA by modeling components at equal strength or stiffness as expressed by Ashby indices, [15], [16]. At the same time, this change does not only require the adaptation of inventory data concerning material inputs but also concerning mold design and energy consumption. The influence of mold and cavity design on energy consumption in IM has been illustrated by [17].

## 2.2 System Boundaries

The cradle-to-gate system boundaries and flow chart for the recycling and two manufacturing schemes are depicted in Fig. 1. The life cycle of the components starts with the collection of the post-consumer polymer waste and post-industrial GFRP waste. The input material is the same in both processes, an rPP from the mechanical recycling of the Austrian post-consumer packaging waste. After packaging waste collection, the size is reduced by shredding and the PP fraction is sorted from the mixed waste using Near-Infrared (NIR) sensors. During the washing step residues are removed before the flakes are extruded and pelletized. The rGF is provided by the size reduction and sieving of post-industrial GF/PP tapes.

For the consideration of the recycled materials, a simple cut-off approach is chosen. The recycled materials come burden-free from their first life and no credits for the replacement of (virgin) materials are awarded to emphasise on manufacturing processes instead of the materials being recycled. Therefore, the environmental impacts incorporated by the recycled materials are solely related to necessary recycling steps from waste treatment (sorting, shredding, washing, and extrusion) to generate the input material for the IMC and IM+C processes.

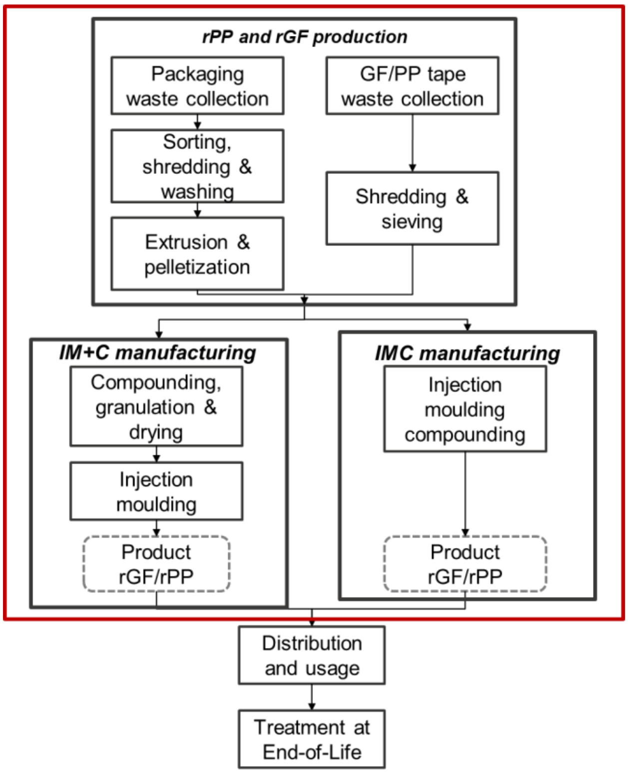

Fig. 1: Flow chart of the IM+C and IMC processing with system boundaries of the LCA (red box)

Using the recyclates, the component manufacturing takes place according to the two described processes for comparison: In the separate IM+C process, the first step is the production of an rGF/rPP granulates using a compounder with a granulation unit. The granulate is dried before further usage to minimize humidity. In the second step, the granulate is used in an IM machine, where the polymeric matrix is melted again and mechanically injected into the mold to obtain the desired component shape. In the alternative combined IMC process, the melt of the compounder is directly conveyed to the IM machine to obtain the final product. The use phase and treatment of the component at EoL are neglected in this study as the focus lies on the manufacturing stage.

## 2.3 Inventory Data

Inventory data describe the type and amount of resources consumed as well as process outputs (products, wastes, and emissions). They can be categorized in three main groups for this study: machinery, energy, and material requirements. Data for modeling the two-step IM+C process are retrieved from preliminary experiments, the ecoinvent v3.8 cut-off database, [18], and literature. Data for the mechanical recycling of the PP from Austrian post-consumer, mixed packaging waste were retrieved from [19], [20], whereas data for GF/PP tape shredding were extracted from [21]. The inputs required for sorting the mixed packaging waste were allocated based on the mass of the different waste fractions according to the waste composition described by [22].

In addition to experimental data for compounding and IM processing, the energy consumption of the IM machine (in the two-step IM+C manufacturing scenario) was modeled according to [23]. Transport between the recycler and manufacturer has been neglected as it is expected to be the same in both manufacturing processes.

For the two scenarios of the IMC process, the inputs are varied about the IM+C process as visible in Table 1. The conservative scenario (IMC-CON) expects an increase in machinery and a moderate decrease in energy and material consumption, whereas the optimistic scenario (IMC-OPT) expects a significant reduction in all three regards.

Table 1. Variation of process input and output of the IMC process scenarios about the IM+C reference process

| | IMC-CON | IMC-OPT |
|---|---|---|
| Machinery usage | 110 % | 50 % |
| Electricity | 90 % | 67 % |
| Heat (natural gas) | 90 % | 67 % |
| Heat (other) | 90 % | 67 % |
| Water | 10 % | 2 % |
| Processing waste | 80 % | 50 % |

### 2.3.1 Machinery Usage

The usage of machinery in the IMC process can potentially be reduced as the granulation and drying units after compounding become redundant. An additional machinery effort is needed to connect the compounder to the IM machine through the (heated) melt pipe and melt pump. The design of the IM machine remains the same in the one-step and two-step processes as the plasticizing unit and screw are still used to convey and inject the melt into the cavity. In the optimistic scenario, overall requirements are still reduced in the IMC whereas the conservative scenario assumes the overall demand for machinery is increased compared to the IM+C process.

### 2.3.2 Energy Consumption

Energy usage can be divided into thermal energy and electricity consumption for the main drive (motors etc.), electrical heating, and auxiliary equipment. Similar to machinery requirements, the energy consumption of the granulation and drying unit and partially from the IM machine can be reduced in the IMC scenario. Even when taking into consideration the additional consumption for the heating of the melt pipe and melt pump, there is still a net decrease in energy consumption expected in the conservative scenario.

The electricity consumed is provided by the average market mix of electricity in Austria at a low voltage level. To depict alternative energy scenarios, supply from the Swedish grid serves as an exemplary low-emission supply with an emission factor for electricity consumption of 0.033 t $CO_2$e/MWh, and Poland gives exemplary results for manufacturing in a country relying on fossil fuels to generate electricity with 0.796 t $CO_2$e/ MWh, [24]. The shares of different energy sources to produce electricity in the three countries, [25], are visible in Fig. 2.

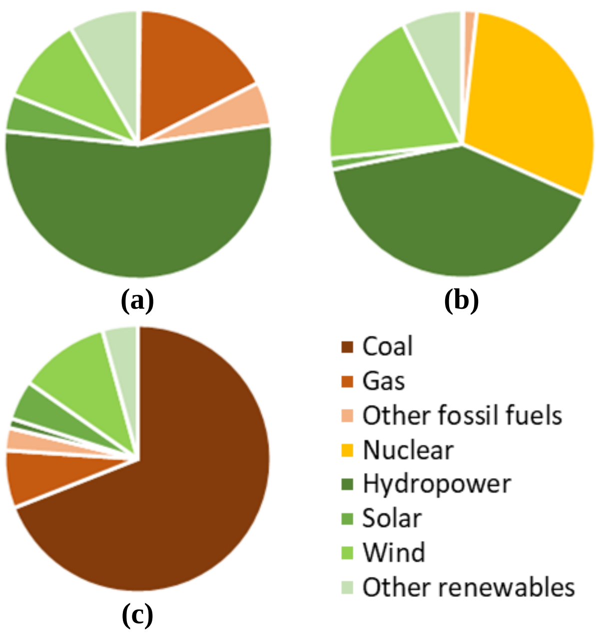


Fig. 2: Electricity mixes of Austria (a), Sweden (b) and Poland (c), [25]

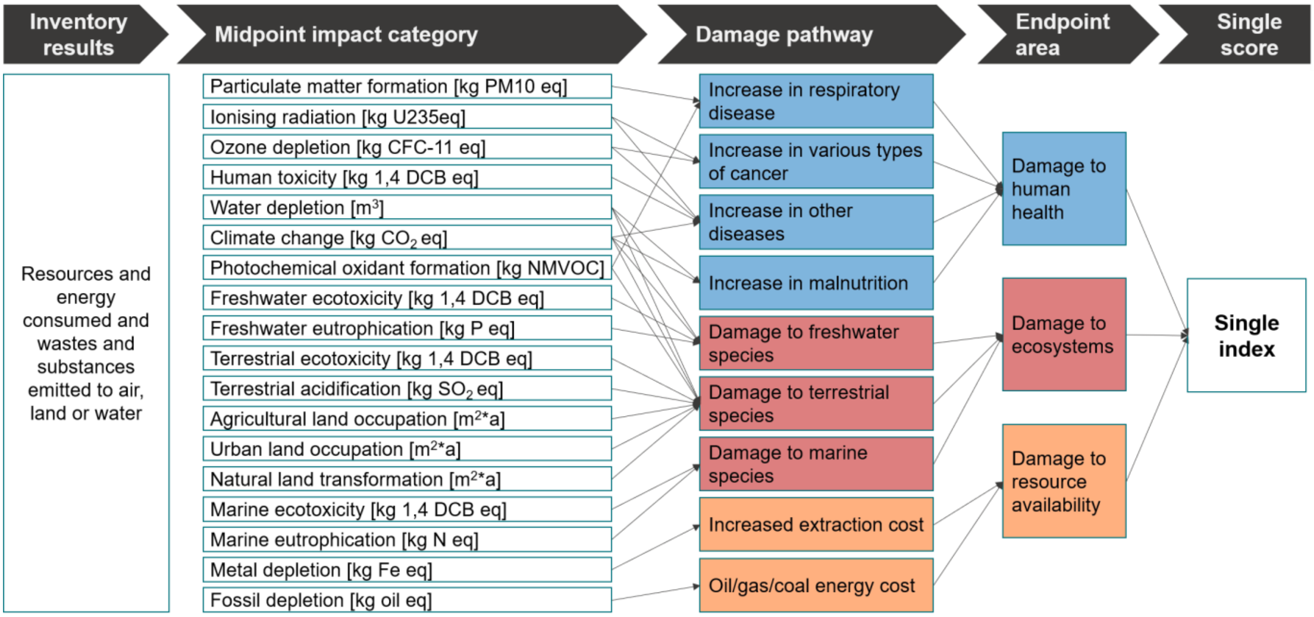


Fig. 3: Overview of ReCiPe2016 methodology for LCIA from inventory results to midpoint impact categories and endpoint areas (Based on [26])

### 2.3.3 Material Requirements

The material origin and blend ratio are the same in all analyzed processes. In the optimistic and conservative scenario, it is expected that processing wastes (purging and lumps) in the IMC are reduced in comparison to the IM+C process. Material input quantities are also expected to be reduced as a consequence of the reduced waste occurrence.

## 2.4 Impact Assessment Method

The Life Cycle Impact Assessment (LCIA) determines the influence of the mass and energy flows described in the inventory on the environment. ReCiPe2016, [26], (as implemented in the ecoinvent version 3.8) has been chosen due to its significance in LCA research, [27], [28]. At the endpoint level, the aggregated single score allows for easy comparison of results while the differentiation into 18 midpoint impact categories enables a more detailed analysis.

The functioning of the ReCiPe2016 method is depicted in Figure 3. The midpoint level uses characterization factors that represent the environmental flow (e.g. greenhouse gases emitted to air). At endpoint, flows are translated into effects on the life of the earth using endpoint characterization factors, which provide more relevant and comprehensive information on damage caused by environmental flows to human health, ecosystems, and resource availability. At the midpoint level, the LCIA results in “a score list with different environmental effects”, [26]. These effects are independent of each other concerning their impact pathways and affected areas of protection. They contribute to the endpoint score through a set of normalized rules.

Furthermore, ReCiPe2016 offers the possibility to choose among three perspectives that represent value choices regarding the parameters of the assessment, such as time horizon, included effects, and uncertainty. The hierarchist perspective has been selected as it provides a balance of the three proposed perspectives. The LCA was conducted using OpenLCA v2.0 software, [29].

# 3 Results

The results of the impact assessment using ReCiPe2016 endpoint level are depicted in Fig. 4.

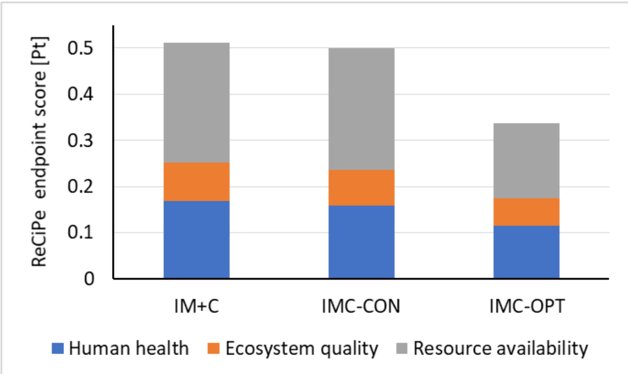


Fig. 4: ReCiPe2016 endpoint results of the IM+C reference process and the two IMC scenarios

The IMC process modeled employing conservative assumptions leads to a marginal improvement of approximately 2 % in environmental performance compared to the reference two-step process. On the other hand, environmental impacts from manufacturing via IMC can potentially be reduced by around 34 % using optimistic assumptions. Nevertheless, it is important to disaggregate these results to have a more complete and differentiated understanding of the advantages and drawbacks of the IMC process in both possible scenarios.

Next to the absolute amount of impacts at the endpoint level, a change in environmental impacts at the midpoint level and consequently, a change in the type of environmental endpoint area can be observed. As depicted in Fig. 4, the IMC-CON process exhibits a larger absolute amount in the endpoint area “damage to resources availability” than the IM+C process (0.25 and 0.26 Pt respectively). The reason for this shift in environmental impacts is visible in Fig. 5, which shows the normalized midpoint impacts for the 18 ReCiPe2016 midpoint categories. The elevated usage of machinery in the IMC-CON scenario requires additional materials (mainly metals) for constructing the connecting parts between the compounder and IM machine, which leads to a comparatively higher metal depletion. On the other hand, even in the conservative scenario, more than 5 % of environmental impacts can be reduced compared to the reference two-step process concerning freshwater and marine eutrophication, ionizing radiation, water depletion, and climate change.

The global warming potentials over 100 years (GWP100) of IM+C, IMC-CON, and IMC-OPT are 3.86, 3.56, and 2.64 kg $CO_2e$ per piece manufactured in the respective processes. The main contributors to climate change in all three scenarios are emissions from direct energy consumption (electricity and heat) responsible for over 50 % of the GWP100, and incineration of the processing waste which accounts for up to 16 % of the overall GWP100.

While the IMC process in the optimal scenario leads to a reduction of environmental impacts in all midpoint categories, there are differences in the magnitude of the change: Impact categories where IMC-OPT has a very large potential to reduce environmental impacts compared to the IM+C reference are metal depletion (reduction of 51 %) and terrestrial ecotoxicity (reduction potential of 42 %). The latter is mainly a result of the reduction in processing waste for incineration.

Next to differences in the environmental performance of the two compared processes as a result of the chosen LCIA method (and level of aggregation), potential benefits associated with the usage of recycled materials and location of production are discussed as they have a large influence on LCA results.

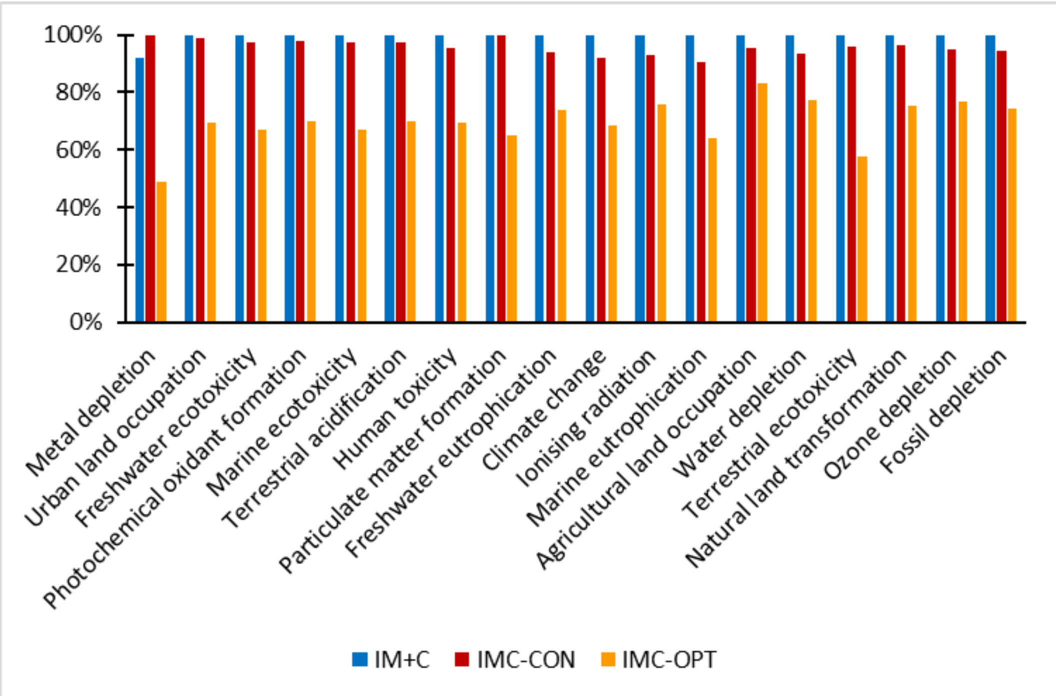


Fig. 5: Normalised results of the ReCiPe2016 impact categories at the midpoint level for the three manufacturing process models

### 3.1 Substitution of Primary Materials

The consideration of substitution effects includes avoided burdens for amounts and types of materials being replaced by the recycled ones in the LCA. Credits for substitution offer also another option to integrate component differences derived from the manufacturing processes into LCA (as discussed in Chapter 2.1): A component with superior material properties can potentially replace a more advanced material type at a higher material quality ratio (quality of the ingoing secondary material compared to quality of the material being substituted).

There exist several methods to model recycling in LCA, [30], [31], [32]. The majority of methods differ in how they consider and allocate impacts among multiple material life cycles (and applications) and how they answer the following question: Do the recycled materials replace another material and if yes, which material and at what quality? The answer is case-specific and depends on the suitability of the different modeling approaches for the field of application. Various parameters, such as type and processability of the materials, material functionality and homogeneity, economic performance, market availability, and environmental impacts play an important role in determining type and quality ratio for materials substituted. Fig. 6 provides some examples of different types of materials and levels of functionality that can theoretically substitute each other. For example, recycled and virgin FRP composites can be used to replace parts manufactured using aluminum and steel in the automotive sector, [33], [34]. In many cases, recycled thermoplastics, such as PP, are expected to replace a virgin thermoplastic but with a decrease in functionality, [14], [35], [36].

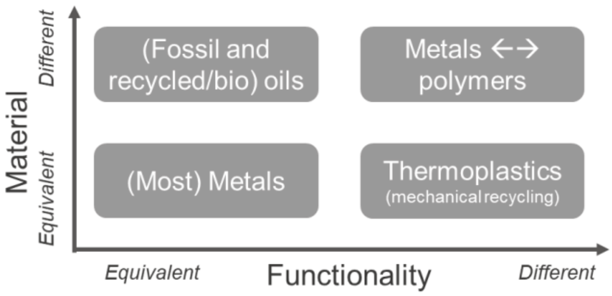


Fig. 6: Examples of materials being substituted with recycled ones considering material type and functionality

In this LCA, no credits for substitution have been awarded because the focus is on comparing the manufacturing processes and not the materials used. Nevertheless, rPP can potentially replace its virgin counterpart (with a decrease in mechanical properties and adaptation of processing parameters) and rGF can replace short virgin GF or another type of filler.

### 3.2 Location of Production

As visible in Fig. 7, the energy provision at the place of production plays an important role when assessing the overall environmental performance of the IM+C and IMC processes. In comparison to production in Austria, production in a country with an electricity mix provided in large parts by renewable energy (such as Sweden) can decrease ReCiPe2016 endpoint scores by up to 16 %. On the other hand, production using an electricity mix relying on fossil fuels (such as in Poland) leads to an increase of up to 41 % compared to the respective production process in Austria.

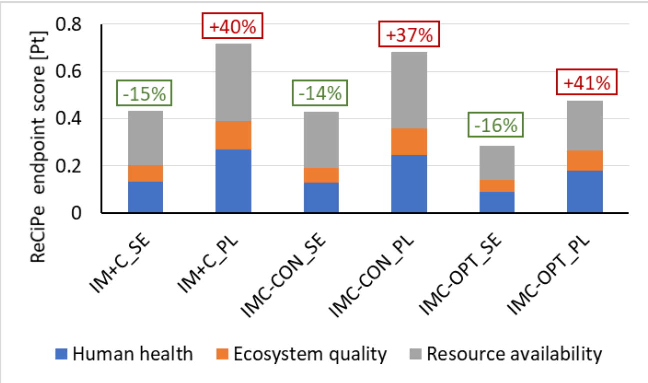


Fig. 7: ReCiPe2016 endpoint results of the IM+C reference process and the two IMC scenarios for production in Sweden (SE) and Poland (PL) including change in endpoint impacts compared to production in Austria

Given the reduced contribution of energy provision to the overall score for production in Sweden (20 to 30 % of total impacts), the benefits of the combined process in the conservative IMC scenario become less pronounced: With 0.429 Pt, the impacts of the IMC-CON in Sweden are marginally lower than the IM+C reference production with 0.433 Pt. Besides energy provision, the metals used for construction and waste treatment (incineration of processing waste) are the main levers of improvement and emphasize the need for a circular economy of waste metals and (post-industrial) plastics.

Due to the differences in electricity provision, there is also a change of impacts at the midpoint level. For example, ionizing radiation contributes 0.2% to the total score for production in Sweden, while the contributions in Poland (0.02 %) and Austria (0.03%) are much lower. Nuclear energy provision in the Swedish electricity mix is the main reason for this difference. Similarly, the GWP100 per process varies significantly as visible in Table 2. While this leads to different absolute Greenhouse Gas emission abatement potentials, the relative magnitude when replacing the IM+C process with the IMC process is similar for all locations (up to around 32 %).

Table 2. GWP100 for the IM+C, IMC-CON, and IMC-OPT processes assuming usage of electricity provided by the Austrian, Polish, and Swedish grids

| **Process** | **Country** | **GWP100 [kg $CO_2$e]** |
|---|---|---|
| IM+C | Austria | 3.86 |
| | Poland | 5.87 |
| | Sweden | 3.04 |
| IMC-CON | Austria | 3.56 |
| | Poland | 5.36 |
| | Sweden | 2.81 |
| IMC-OPT | Austria | 2.64 |
| | Poland | 3.98 |
| | Sweden | 2.09 |

# 4 Conclusion

Reflecting on the initial research question, the IMC process can lead to a potential improvement in environmental performance compared to the two-step IM+C process. This benefit depends mainly on the additional effort required to connect the two machines and energy consumption. Contributions to midpoint categories vary, which results in effect-specific hotspots. Generally, metal usage and energy consumption are the main levers to improve the environmental performance of the IMC processing.

The three-step procedure for the evaluation of energy consumption demonstrated in this paper is recommended to compare the processes and draw meaningful conclusions regarding their environmental performance: i) The separate analysis of the amount of energy consumed in the inventory stage compares processes' energy efficiency and potential optimization measures for further process development. Future research should verify the presented assumptions by collecting inventory data for both, the two-step reference scenario as well as in the one-step IMC manufacturing. ii) Investigating the dependency on location of production and type of energy provision, puts the contribution of energy consumption to overall impacts into perspective. iii) The consideration of multiple impact categories allows for a holistic picture of environmental damages associated with manufacturing. It also helps to identify potential shifts from one impact category to another when changing process characteristics and also location of production.

The role of awarding credits in LCA for avoiding burdens of (virgin) material use through substitution with recycled ones has a potentially large influence on LCA results. Whether and to what extent the inclusion of these credits is appropriate and realistic for the field of application of processes and components should be subject to future research. Furthermore, the options of adapting the FU (as well as inventory data) should be investigated to incorporate potential differences in component quality as a result of the change in component manufacturing.

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**Conflict of Interest**

The authors have no conflicts of interest to declare.