A PRELIMINARY COMPARISON OF ATTRIBUTIONAL AND CONSEQUENTIAL LIFE CYCLE ASSESSMENT AS SPECIFIED IN ECOINVENT V3.0 FOR PACKAGING MADE OF RENEWABLE AND NON-RENEWABLE PLASTIC

By

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ABSTRACT

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The aim of this study was to determine the environmental footprint (EFP) of clamshell packaging containers made of poly(lactic acid), -PLA- a bio-based polymer, and poly (ethylene terephthalate) -PET- a petroleum-based polymer using attributional and consequential life cycle assessment (ALCA and CLCA). The main objective was to determine the EFP of these clamshell packaging containers using the newly developed Ecoinvent V3 database by the Swiss Centre for Life Cycle Inventory, and provided by SimaPro v8.2 applying ALCA and CLCA methods. A functional unit of the study was selected as 1000 clamshell containers of 1 lb capacity. The system boundary was from cradle-to-grave, and the temporal coverage was from 2008 to 2014. IMPACT 2002+ v2.11 midpoint indicator was used as the impact assessment methodology. The EFP for 10 midpoint impact categories for PET calculated according to ALCA were higher than CLCA. For PLA, 11 of 15 midpoint impact categories calculated according to ALCA were higher than CLCA. After normalization, only four midpoint impact categories: carcinogens, respiratory inorganics, global warming and non-renewable energy, were significantly different between ALCA and CLCA. The major differences in the EFP between ALCA and CLCA were the environmental benefit and the resin production stages.

ACKNOWLEDGEMENTS

Most of all, I wish to record my thanks to my parents, for their help and support on both spirit and finance I have received. Without them, I would not be able to finish this research. I wish also to record my appreciation to Dr. Auras, my supervisor, for accepting me, his faith in this project and his patient encouragement over many years. From the outset, he encouraged me in my work, provided me with a lot of details and suggestions for research. Thanks to Dr. Selke for all her valuable inputs and guidance. I could learn a lot about detail procedure for life cycle assessment through LCA group meeting. Also, I wish to express my thanks to Dr. Joshi for his valuable advices. I would like to record my gratitude to the RAA members for their support and encouragement. Thanks to Kang for providing significant contributions. Thanks to all my friends for their encouragement, and for the good time we had. Finally, I would like to send separately gratitude to my wife, Minyoung Kim.

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KEY TO ABBREVIATIONS

ALCA	Attributional life cycle assessment
CLCA	Consequential life cycle assessment
EOL	End of life
ISO	International organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PET	Poly(ethylene terephthalate)
PLA	Poly(lactic acid)
CG	Carcinogens
NCG	Non-carcinogens
RI	Respiratory inorganics
IR	Ionizing radiation
OLD	Ozone layer depletion
RO	Respiratory organics
AEC	Aquatic ecotoxicity
TE	Terrestrial ecotoxicity
TA	Terrestrial acidification / nitrification
LO	Land occupation
AC	Aquatic acidification
AEU	Aquatic eutrophication

GW	Global warming
NRE	Non-renewable energy
ME	Mineral extraction

1. Introduction and motivation

Plastic is one of the most used materials for non-durable goods, packaging and containers due to its low cost, simple manufacturing, and tradeoff between weight and performance properties. Traditional commercially available plastics such as polyethylene, poly(ethylene terephthalate), (PET) and poly(styrene) (PS) are mostly made from petroleum. Increasing concern about the environmental footprint (EFP) of these polymers has created a demand for polymers produced from renewable resources such as thermoplastic starch, poly(hydroxybutyrate-valerate), PHBV, and poly(lactic acid), PLA [1]. A common method to evaluate the EFP of polymers is life cycle assessment (LCA) [2].

LCA is an analytical technique to evaluate the resources consumed and potential effect on the environment and human health by products, services or systems [3]. LCA is mostly conducted according to the guidance of ISO14040/14044, and it comprises four main steps a) goal and scope, b) inventory analysis, c) impact assessment and d) interpretation. The goal of the LCA study defines the main objective of the study and identifies the targeted audience. The inventory analysis step (LCI) deals with data collection, allocations of inputs and outputs, and emissions. The impact assessment phase (LCIA) deals with the conversion of the LCI results to impact indicator results. Finally, the interpretation phase evaluates the results of the LCI and LCIA for the targeted audience. Specially, the LCI phase has been faced with the issue of dealing with multiple input and output allocations [4, 5].

Three types of LCA situation decision support studies have been proposed by the International Reference Life Cycle Data System (ILCD) handbook to solve allocations regarding multiple input and outputs [6]. Situation A generally intends “micro-level

decision support" denoting support immediately or indirectly relevant to inform the acquisition of products, goods or services. Situation B is designated as "meso/macro-level decision support" stating life cycle derived resolution assistance with consequences, which are diversifiable. The concept of situation C is "accounting". Entirely illustrative accounting and documentation of the reviewed system of the past, present or predicted future, and without involving a decision-context would justify possible supplementary consequences on further systems. Situations A and C are mostly known as attributional LCA (ALCA), and situation B is often considered as consequential LCA (CLCA). In ALCA studies allocations of multiple inputs and outputs are handled by different types of allocation methods such as mass, economic, and embedded energy [7]. In the case of CLCA, multiple input and output allocations are generally managed by system expansion.

For example, in order to produce 1 kg of crude oil, some amount of petroleum is needed. Simultaneously, natural gas also comes out when crude oil is extracted from petroleum. Therefore, crude oil and natural gas can be represented as multiple outputs from the petroleum process. As shown in Figure 1.1, even if the amount of crude oil is the same between ALCA and CLCA, the emissions of the petroleum calculated by these two methods are not the same due to the different methods of allocation and system expansion. The box with the black dashed line represents the system boundary of the production of crude oil. When the crude oil is extracted from petroleum, natural gas came out as a co-product or multiple outputs at the same moment. The ratio of crude oil to natural gas is the same in ALCA and CLCA. However, the environmental footprint of the required amount of petroleum is not the same because different models are applied to resolve the multiple outputs. In the attributional method, 1.569 kg of petroleum is needed to produce 1 kg of

crude oil, and the impacts are allocated between this product and the 0.728 m^3 of natural gas that is also produced using the relative economic value of the products. In the consequential method, the system expansion approach is used and the 0.728 m^3 of natural gas that is also extracted is considered equivalent to natural gas for market. The environmental footprint of that amount of natural gas is added as a credit (negative values), to the environmental footprint of the crude oil/natural gas system to provide the footprint of the crude oil alone.

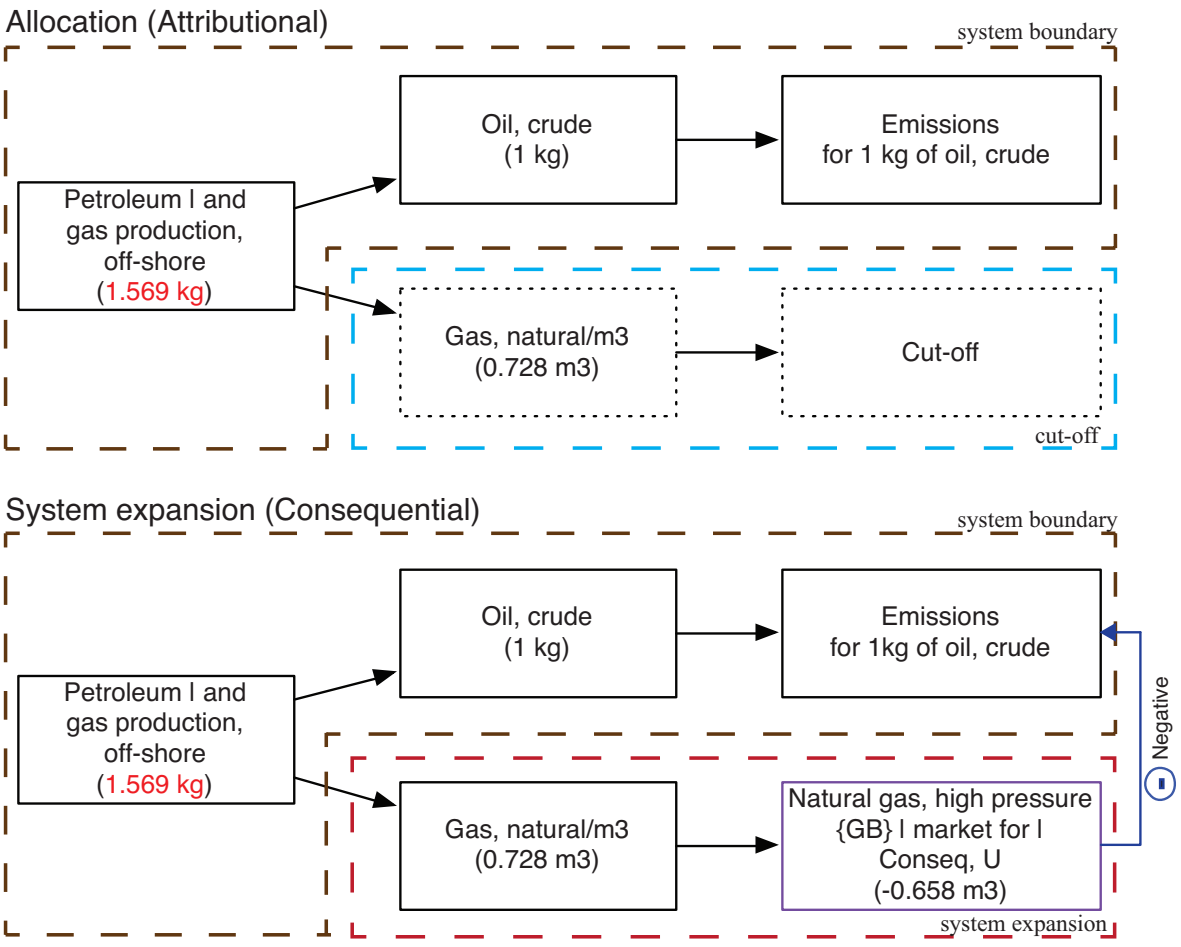

Figure 1.1. Diagram of allocation in ALCA and system expansion in CLCA

Packaging takes up the largest portion of polymers in the market with 37% of all plastics consumed [8]. In recent years, numerous studies have explored the EFP of packaging made from non-renewable polymers such as PET, polypropylene (PP), high-density polyethylene (HDPE) and PS and polymers made from renewable resources such as PLA [9-16]. Most of these studies were conducted using an ALCA approach, and multiple input and output processes were allocated mostly according to mass and economic allocations. For example, in the case of PLA production, the same corn is used to produce starch, ethanol and PLA; however, the LCA of the PLA does not take into consideration that need for a new crop to replace the corn that would have otherwise been used to satisfy the food and ethanol demand. Therefore, this has created a large debate over where and when to apply ALCA and CLCA. Although CLCA has emerged as a technology to evaluate EFP, little research has been conducted on CLCA.

As a step to help to conduct CLCA studies, the Swiss Centre for Life Cycle Inventory released Ecoinvent V3, which is the largest proprietary database about EFP of products and systems [17]. The data have been produced under two main frameworks, economic and system expansion allocations, to facilitate ALCA and CLCA calculations. However, to the best of the author's knowledge, studies comparing these two methods for evaluating EFP using Ecoinvent V3 have not been conducted.

Thus, the objective of this work was to assess the EFP of packages made from non-renewable and renewable polymers using ALCA and CLCA. Specifically, this study focused on determining the EFP of clamshell packages made of PLA, a bio-based polymer, and of PET, a petroleum-based polymer, using the newly developed Ecoinvent 3.0 LCA database.

2. Literature Review

This chapter presents a basic introduction about the history of LCA. Then, the main phases to conduct LCA are explained. After that, the situation types of LCA studies are explained, and then ALCA and CLCA are discussed. As a particular topic of interest for this work, the allocation and system expansion methods are introduced. Then, the main studies relevant to LCA and packaging are explored, specifically focusing on clamshell packaging, and finally the properties of PET and PLA are discussed.

2.1. Life cycle assessment (LCA)

LCA is an analytical framework to evaluate the resources consumed and effect on the environment and human health by products, services or systems [3]. The first environmental footprint (EFP) study considered to be the birth of LCA was conducted to evaluate the resource needs, emission burdens, and waste flows of diverse beverage bottles by Midwest Research Institute (MRI) for the Coca Cola Company in 1969 [18]. After that LCA emerged in the late 1960s and early 1970s in Europe and the U.S.A [19]. During this decade, standardization processes were challenging due to lack of agreement on methodological issues [20]. During the 1990s, worldwide scientific discussions resulted in the development of the theoretical framework of LCA. During this period, the Society of Environmental Toxicology and Chemistry (SETAC) concentrated its work on the development and harmonization of LCA methods, and the International Organization for Standardization (ISO) was involved in the standardization of the LCA procedures [19]. The first international standard for LCA was produced in 1997.

- ISO 14040 (1997): Environmental management – Life cycle assessment – Principles and Guidelines [3]

ISO 14040 (1997) was revised to improve readability, and applicability, and amalgamated with the previous standards in 2006 [20]. Currently, two international standards provide guidance conducting LCA studies.

- ISO 14040 (2006): Environmental management – Life cycle assessment – Principles and framework [5]
- ISO 14044 (2006): Environmental management – Life cycle assessment – Requirements and guidelines [4]

Basically, LCA is an iterative study with four phases: goal and scope, inventory analysis, impact assessment and interpretation, as shown in Figure 2.1.

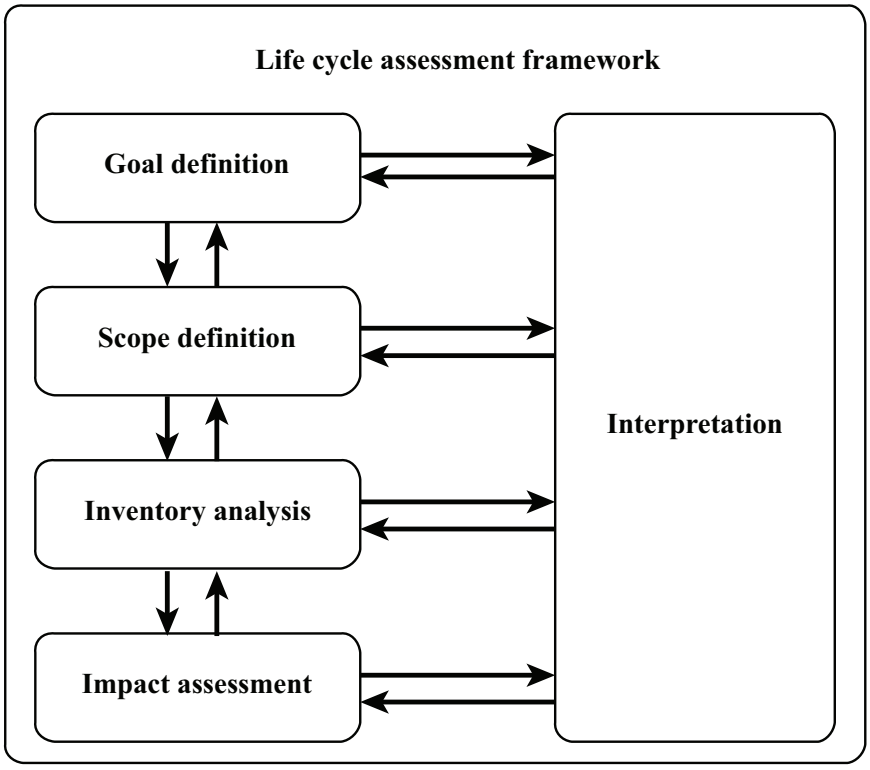

Figure 2.1. Framework for life cycle assessment, adapted from ref [5]

2.1.1. Goal and scope

The goal definition is the first stage in performing an LCA study. In this phase, the goal of the study, the intended use of the application, the reasons for carrying out the study, the initiator and commissioner of the study, the practitioner, the stakeholders and the target audience need to be stated. The goal of the study should be manifested obviously and clearly, not only in respect of what is to be done, but also in respect of the reasons for accomplishing the study.

In the scope definition phase, the temporal, geographical, technological, economic processes, environmental interventions and impact coverage should be determined, justified and reported, in accordance with the goal of the study. Specifically, the practitioner shall consider and describe the following points:

- "The product system to be studied; the functions of the product system or, in the case of comparative studies, the systems; the functional unit; the system boundary; allocation procedures; impact categories selected and methodology of impact assessment, and subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; type of critical review, if any; type and format of the report required for the study" [5]

The scope of the study must be stated adequately and completely to explain the specified goal [21]. In addition, functions of the product system, functional unit and reference flow should be reported in detail. The functional unit quantifies and qualifies those characteristics of the products, system or services. The functional unit plays a center role in any LCA studies because it offers the reference to which all other data in the assessment are normalized. The reference flows are based on an equal number of functional units so that

the alternative products are compared on an equivalent base, thus indicating the real consequences of the possible product replacement [22]. The functional unit of LCA varies with different studies. For example, the functional unit for the assessment of the EFP of tomato ketchup might be 1000 kg of tomato ketchup consumed. While for a study of milk bottles, it might be 1000 L of milk delivered to the consumer.

2.1.2. Life Cycle Inventory (LCI)

The LCI analysis phase defines the product system including the system boundaries, the flow chart with the unit processes, the data gathering steps for each process and the allocations. In this phase, there are a few items that require attention, such as normalization, selection of data sources and data quality requirements, decision-making accounting rules, selections of the processing data, significance analysis, LCI calculation method, and presentation of the LCI results.

2.1.3. Life Cycle Impact Assessment (LCIA)

The step of LCIA is the stage where inputs and outputs of each process are converted to impact indicator results. The LCI analysis is converted to contributions to related impact categories, such as carcinogens, global warming, non-renewable energy, etc. During the LCIA, classification and characterization are compulsory, but normalization, grouping and weighting are selective.

2.1.4. Interpretation

The interpretation phase is the last stage in an LCA study. In this phase, the results of the analysis and all assumptions and considered choices are assessed using a number of evaluation methods. The main steps are evaluation of the results including a consistency check and completeness check, analysis of the results and formulation of conclusions and recommendations. In the analysis of the results step, contribution analysis, perturbation analysis, sensitivity analysis and uncertainty analysis are performed.

2.2. ALCA and CLCA

LCA studies are classified into two main types: attributional and consequential LCA. ALCA offers information about the effects of the processes used to manufacture a product, without consideration of effects on external systems resulting from production of the product. On the other hand, CLCA offers information about the consequences of alteration of product inputs and outputs, which affect both directly and indirectly the life cycle of the product [24]. ALCA and CLCA studies have been gaining momentum to evaluate the environmental footprint of products, services or systems.

To understand the difference between ALCA and CLCA, we need to consider the types of decision-context defining what decision is being made and the reasons for the LCA study. The decision-context is the most important standard to determine the most adequate methods for the LCI modeling framework and the related LCI method approaches to be applied. According to the ILCD handbook, the decision-context of the LCA study shall be categorized through three representative goal situations.

Table 2.1. Arrangement of two main features of the decision-context: resolution aim and kind of consequences in background system or other system, adapted from ref [6]

<table>
<tr><td rowspan="3">Decision support?</td><td rowspan="2">Yes</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A
“Micro-level decision support”</td><td>Situation B
“Meso/macro-level decision support”</td></tr>
<tr><td>No</td><td colspan="2">Situation C
“Accounting”</td></tr>
</table>

Table 2.1 shows the arrangement of two main features of the decision context including resolution intention and type of consequences in the background system or other systems.

Situation A, which is deemed ALCA, is generally called “Micro-level decision support”. Situation A denotes resolution support directly or indirectly relevant to inform the acquisition of products, goods or services, which are already for sale in the market or anticipated to go into the market. The marginal consequences in this small scale are not sufficient to overcome the beginning and initiate wide-ranging consequences in the market. The most related keywords of “Situation A” LCI / LCA studies are “decision support” corresponding to “product comparison,” “comparative assertion,” “product advance development,” “product development,” “product design,” weak point analysis,” “product benchmarking,” etc.

Situation B considered as CLCA is designated as meso / macro-level decision assistance. This situation B states life cycle based decision assistance with consequences which will through industry systems alter portions of the remainder of the economy by having extensive structural results. The most relevant examples of situation B are “strategy

analysis," "policy development," "policy information," "concept development," "pervasive technologies," and similar concept and often combined with "raw material / energy / XY basis / technology" etc.

The main keyword to distinguish between situation A and situation B is the magnitude of the study. In other words, the standard for deciding between situation A and B is whether the investigated resolution entails extensive consequences in the operated apparatus or capacity exterior to the foreground system of the investigated method which takes place through demand and supply in the market.

The concept of situation C is "Accounting". Entirely illustrative accounting and documentation of the reviewed system of the past, present or predicted future, and without involving a decision-context would explain possible extra consequences on other systems. Situation C differentiated two sub-cases, situation C1, which is accounting with other, and situation C2, which accounts excluding interactions with other systems.

2.2.1. ALCA

ALCA is also called "accounting", "retrospective", or "descriptive". ALCA evaluates the system as it is or was. It aims to evaluate the possible environmental impact, which can be charged to a product or system through its life cycle.

2.2.2. CLCA

During the past two decades, CLCA has emerged as a method appropriate to evaluate the environmental footprint of a product system [25]. CLCA is conducted to inform from the consequences of decision and changes [26]. In order to understand CLCA,

knowledge of marginal processes or marginal technology is required. The definition of marginal technologies is the technologies literally influenced by the small alterations in demand generally investigated for the future, in comparison of life cycle assessment. Also, it gives the premier indication of the real consequences of a decision [27]. Also, according to the ILCD handbook, consequential modeling is to identify and model all activities in the background system of a system as a consequence of decision made in the forefront system.

2.2.3. Allocation and system expansion methods

When in an LCA study more than one product is produced in a process, it is crucial to partition the environmental footprint from the process between the product and the co-product. It is not simple to set apart the environmental impacts between the products. Allocation and system expansion approaches are orthodox resolutions for partitioning the environmental impacts between multiple products, such as natural gas and crude oil.

However, the LCA practitioner needs to be heedful to choose between allocation and system expansion methods because the selection of the approaches has enormous influence on the results of the LCA. These two approaches for partitioning the environmental impacts between the main product and co-product are part of two methods for deciding the LCI modeling framework.

Allocation is the function to separate the input or output flows of a process between the analyzed system and other products generated from the same activity based on a given ratio. Allocation is the conventional approach of the ALCA method. According to ISO 14044, allocation should be avoided as much as possible using separation of the unit

process into two or more sub-processes and collection of the input and output data associated to sub-processes, or expansion of the product system [4].

System expansion is defined as a methodology to expand the system boundaries to avoid the need for allocation. System expansion is usually applied for the consequential LCA method. Joanna *et al*. applied system expansion to evaluate the waste management in the study of LCA of Swedish semi-hard cheese [28]. Franklin Associates also used system expansion for recycling.

2.2.4. Application for packaging

A large number of LCA studies for food or food-packaging containers are reported, especially for beverage bottles [29-32]. Quantis analyzed LCA of drinking water alternatives and consumer beverage consumption [32]. Christopher *et al*. compared the LCA of bottled versus tap water systems with different types of bottles [31]. Various LCA studies about carbonated soft drinks, beer or other beverages were published or reported [33-38]. Most of these studies reported that PET had a lower environmental impact for beverage packaging when compared to other materials such as aluminum and glass.

Madival *et al.* compared the environmental profile of PLA, PET and PS clamshell containers using LCA methodology, and they reported that the main contributions of the environmental burden for all the containers were the resin production and the transportation stages in the study [39]. Brandon *et al.* focused on the end-of-life management of clamshell containers made of EPS foam, PET, PS, PP and PLA. They determined that PET had the highest pre-consumer impacts, and PLA had the potential to be the lowest-carbon alternative [40].

Studies evaluating the end of life management, especially recycling or energy recovery are used to evaluate reducing the environmental footprint or to promote recycling. Firas *et al.* reviewed a number of published and reported papers related to recycling of PET with different recycling technologies. They concentrated on contamination during recycling process and methods to increase the molecular weight of recycled PET [41]. Anke *et al.* focused on recycling and recovery of post-consumer plastic solid waste in Europe [8]. Franklin Associates reported the LCI of 100% postconsumer HDPE and PET recycled resin from postconsumer containers and packaging in 2010 [42]. Recycling of PLA also has been gaining awareness. Fausto *et al.* investigated the LCA of PLA and PET bottles for drinking water. They concluded that the use of renewable resources had a positive impact on the PLA bottles compared with PET bottles, but this advantage was counterbalanced by usage of pesticides, use of land, and use of water to produce raw materials. The data for PLA recycling is assumed using the efficiency of PET recycling due to lack of data [30].

2.3. Clamshell packaging

Clamshell packaging was the most widely used type of plastic container for fresh produce in 2012 [43]. These containers are the predominant packaging for strawberries, blueberries, raspberries, and grape tomatoes due to their benefits such as reclosability, stackability, and reduced labor requirements for stores, as well as protection of contents during shipping. Demand for plastic containers for fresh produce grew from $716 million in 2007 to $1.0 billion in 2012. Furthermore, consumption of plastic containers in fresh produce packaging is forecast to increase 4.8% per year through 2017 – the fastest rate

among the product segments – to $1.3 billion [43]. This trend will drive growth in clamshells in a number of applications.

2.3.1. Polymers

2.3.1.1. Poly(lactic acid), PLA

PLA is produced from agricultural crops such as corn, sugar cane and starch. PLA is basically made through the synthesis of lactic acid monomers. At first, PLA was manufactured and used mostly for medical applications because of its expensive price. Recently, high molecular weight PLA can be compounded at a lower price through the lactide ring opening polymerization technology. Therefore, PLA resin can be used for packaging applications [44]. PLA has medium gas-barrier properties and is impervious to oils. It is brittle and stiff, with mechanical properties similar to PS with mediocre heat and impact resistance and can be manufactured by sheet extrusion, injection molding, blow molding, thermoforming and film forming. PLA is considered safe for food contact, so it can be used in fresh produce containers or disposable cups. The main applications for PLA are thermoformed and extruded food containers and bottles. The density of PLA is 1.24 – 1.30 g/cm^3 [45]. The end-of-life scenario for PLA is mainly through landfill and composting. However, recycling can be a practicable route when PLA packages are low in contaminants. PLA has been recovered by chemical recycling [46].

2.3.1.2. Polyethylene terephthalate (PET)

PET is a thermoplastic resin produced from ethylene glycol and dimethyl terephthalate or terephthalic acid. PET is a clear polymer with good gas barrier

characteristics and chemical resistance. It is tough, and it can tolerate relatively high exposure temperatures during use (below 60 C). It can be fabricated by injection-molding, sheet extrusion, blow-molding, thermoforming and film forming. PET is safe for food contact. The density of PET is 1.38 – 1.40 g/cm^3. PET is manufactured by the condensation reaction between ethylene glycol and terephthalic acid or by the transesterification reaction between ethylene glycol and dimethyl terephthalate [47].

2.3.2. Applications

Vegetables are the principal application for fresh produce packaging, accounting for 50 % of produce packaging demand in 2012 [43]. Packaging for fruit applications represented 37 % of fresh produce packaging. Fresh fruit packaging demand grew from $1.3 billion in 2007 to $1.8 billion in 2012 [43].

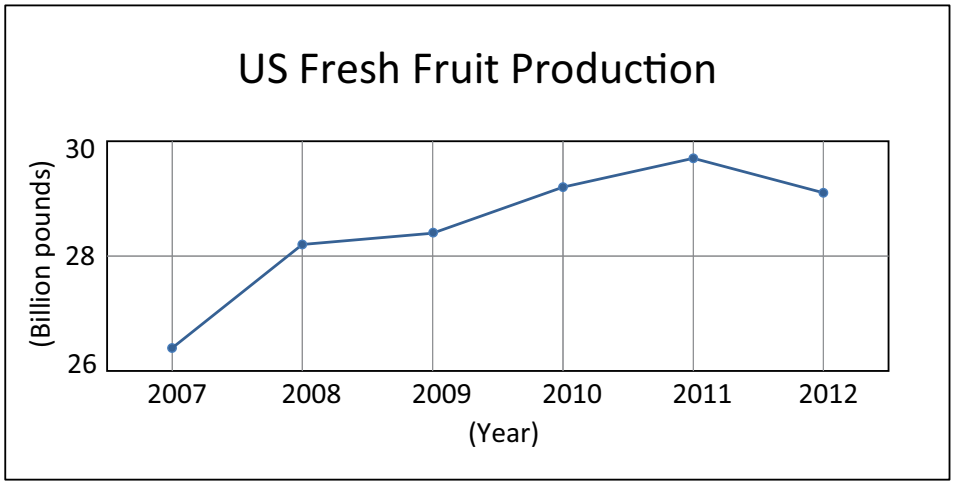

Figure 2.2. Fresh fruit production in the US, adapted from ref [43]

shows fresh fruit production in the United States from 2007 to 2012. The major applications for fresh fruit packaging are berries, apples, and citrus fruit, which together accounted for over 60% of demand in 2012. During the past two decades, packaging for berries has significantly switched from molded pulp and plastic baskets to clamshell containers. Plastic containers, especially clamshell containers, are by far the main packaging type for berries considering strawberries, blueberries, raspberries, and blackberries. Clamshell packaging is beneficial to protect fruits from bruising. Also, it is stackable so that containers can be seen uniformly for displays unlike open top baskets. Moreover, clamshells reduce store labor costs because they can be already packed in display-ready packaging [43]. There are several articles on the LCA of clamshell container packaging as stated above.

Part of this work has been presented as a poster presentation titled "*A preliminary Attributional and Consequential LCA comparison of PLA, PET, and PS clamshell for the Packaging of Strawberries*," Soohyung LEE, Woranit MUANGMALA, Rafael AURAS, Susan E. M. SELKE, DongHo Kang. October 6-8, 2014, XIV LCA conference, San Francisco, US. The poster was awarded 2nd place in the graduate student competition.

3. Goal and scope of the study

3.1. Goal

The goal of this study is to determine the environmental footprint of a bio-based polymer and a petroleum-based polymer used for packaging applications, using ALCA and CLCA. Specifically, this study focused on determining the environmental footprint of clamshell packages made of poly(lactic acid), PLA, a bio-based polymer, and poly(ethylene terephthalate), PET, a petroleum-based polymer. The work is targeted to the plastic industry, especially the consumer clamshell industry, to researchers conducting LCA, and the general public interested in the LCA of bio-based and petroleum based polymers. The study is conducted as an academic exercise, and it is not aimed as a public comparative assertion.

3.2. Scope

The scope of this study is from cradle-to-grave. The entire process was included, from the extraction of crude oil for PET resin manufacturing, corn growing and harvesting for PLA manufacturing, extrusion and thermoforming for clamshell packaging production, transportation, distribution, consumption and end-of-life.

3.2.1. Functional unit

The functional unit of this study was considered as one thousand clamshell containers of 1 lb capacity each, for the packaging of strawberries.

3.2.2. System boundaries

This work concentrates on the determination and comparison of the EFP between PLA and PET clamshells using ALCA and CLCA methodologies. The following processes are considered: extraction of crude oil for PET resin manufacturing, corn growing and harvesting for PLA manufacturing, the extrusion and the thermoforming process for the clamshell packaging production, the transportation, distribution and end-of-life of the clamshell packages. The consumption stage is excluded due to the lack of data. The entire studied system boundaries are shown in Figure 3.1 and Figure 3.2.

In total, five phases are included in the system boundary: resin production, intermediate processes, transportation, waste treatment and environmental benefit.

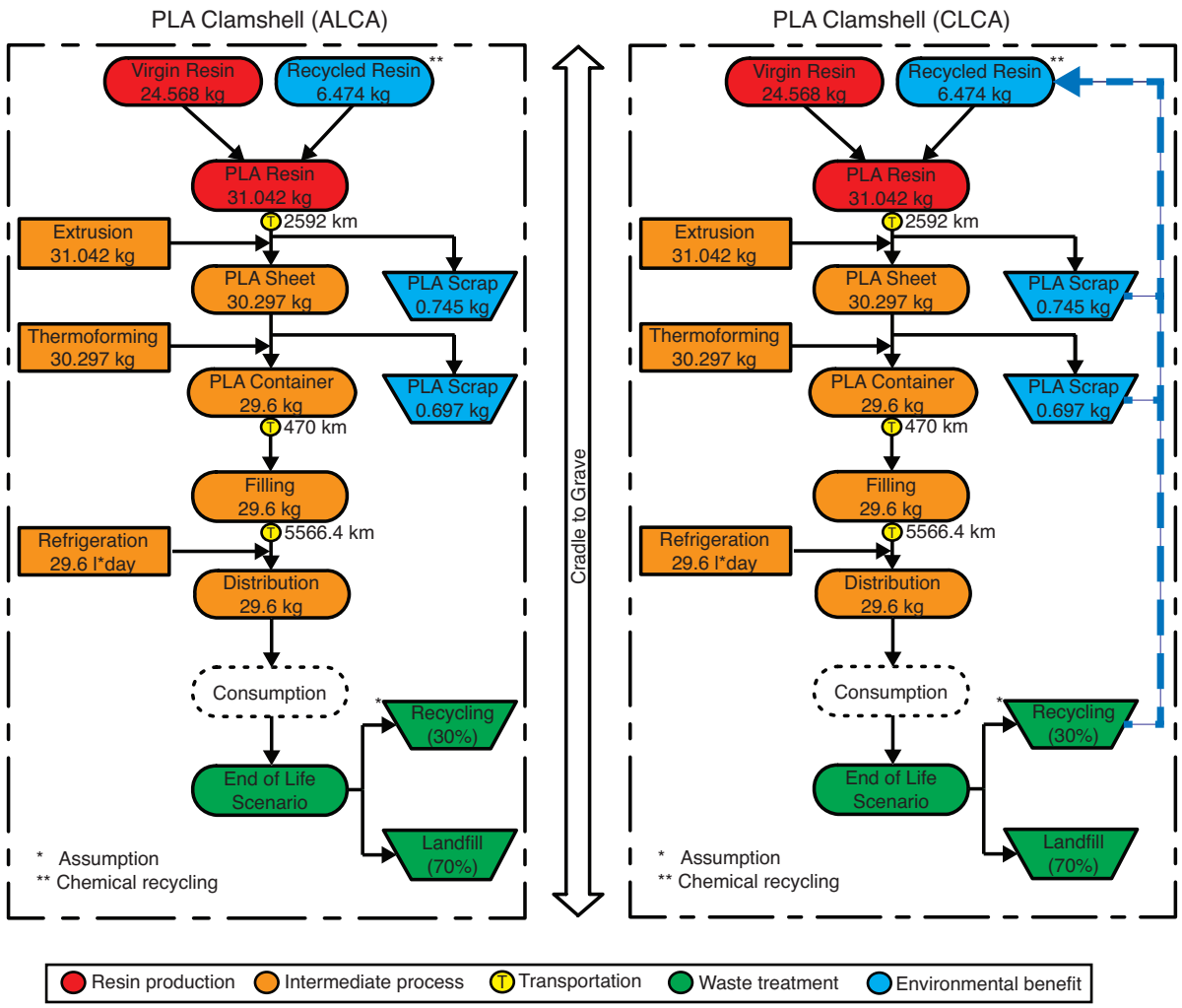

Figure 3.1. PLA clamshell container system boundary in ALCA and CLCA

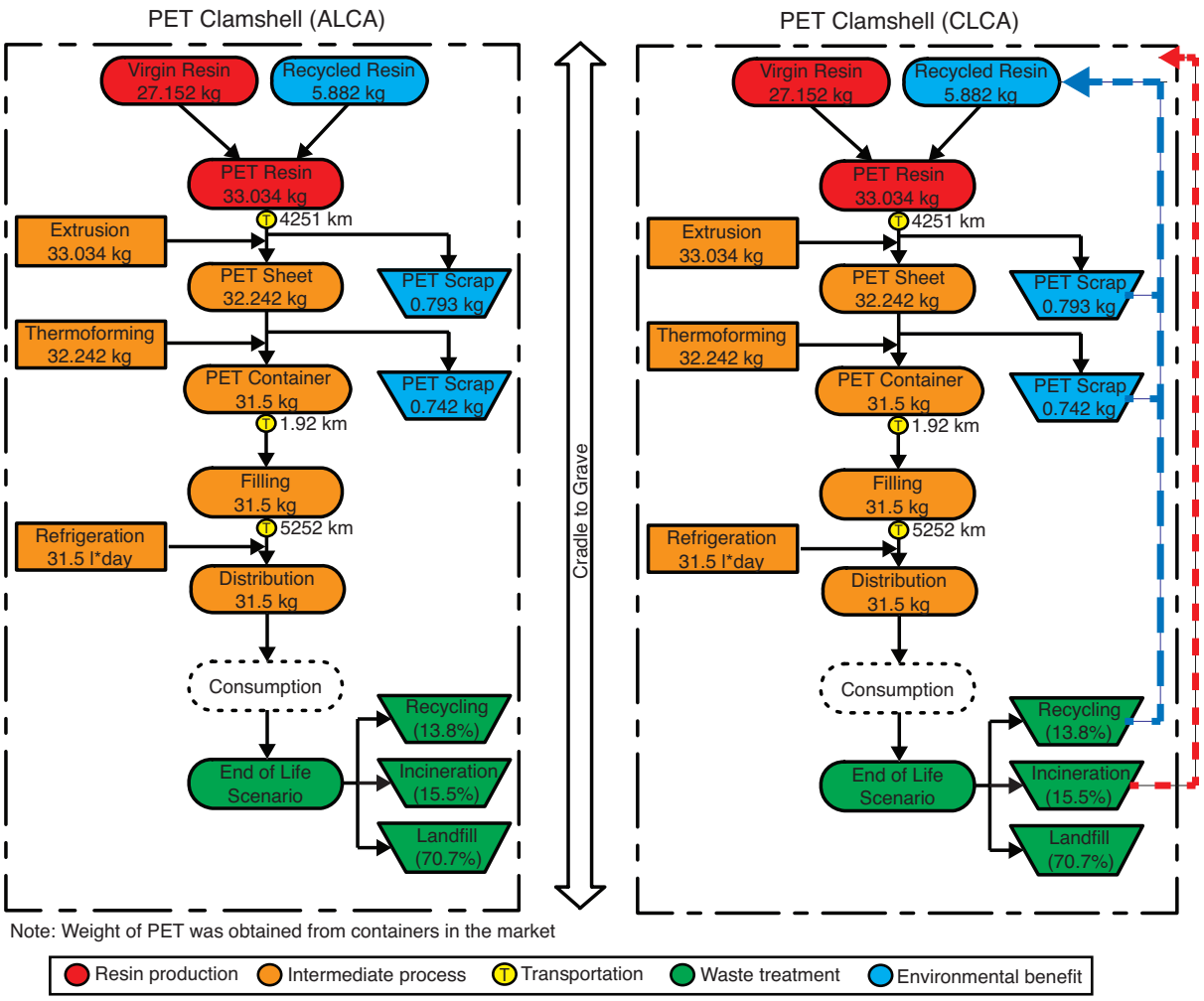

Figure 3.2. PET clamshell container system boundary in ALCA and CLCA

3.2.3. Software and data collection

SimaPro version 8.2 from the Swiss Centre for Life Cycle Inventories was used for this LCA study. This version of SimaPro software is newly released with the Ecoinvent version 3 database and subdivide into attributional and consequential approaches [17]. Most of the data in this study is from the Ecoinvent database. Detailed information concerning data sources is provided in chapter 4, life cycle inventory.

3.2.4. Cut-off criteria

In this study, 1% of the cumulative mass and the total EFP of all the inputs and outputs in each process is applied as a cut-off criterion due to the large number of inputs and outputs in the LCA study.

3.2.5. Allocation and system expansion

Allocation and system expansion methods are used in this LCA study. Especially, the allocation method is utilized in ALCA and the system expansion method is utilized in CLCA as shown in Figure 1.1.

3.2.6. Temporal and technology representativeness

The temporal representativeness for most technology in this study is from 1995 to 2012. The study is conducted under the guidance of ISO 14040 and 14044 [4, 5].

3.2.7. Life cycle impact assessment methodology and impact categories

In order to quantify and compare the EFP from the inventories, IMPACT 2002+ version 2.11 was used. The LCIA methodology IMPACT 2002+ advanced a practicable implementation of the combined midpoint / damage-oriented procedure [48]. In order to cover the important emissions, the following fifteen impact categories were chosen in this study.

- Carcinogens
- Non-carcinogens
- Respiratory inorganics

- Ionizing radiation
- Ozone layer depletion
- Respiratory organics
- Aquatic ecotoxicity
- Terrestrial ecotoxicity
- Terrestrial acidification / nitrification
- Land occupation
- Aquatic acidification
- Aquatic eutrophication
- Global warming
- Non-renewable energy
- Mineral extraction

Normalization included as a step in IMPACT 2002+ was used to provide an overall understanding of the relative emissions of every model with respect to the emissions of an average European citizen. Normalization shows the scale of the impact can be compared to a reference value. After normalization, only four categories were fully assessed due to their differences: carcinogens, respiratory inorganics, global warming and non-renewable energy.

3.2.8. Data quality requirements and assumptions

The data quality requirements met those specified in ISO 14044. The Ecoinvent 3 database in SimaPro software was used as the primary source for the life cycle inventory. Some of the assembled data are from the LCA Food DK library, and the US LCI and BUWAL databases. Moreover, some literature data and calculated data from the literature

were used in this study. As for geographical coverage, all materials, manufacturing processes, and energy data is for the U.S. Most of the unit processes used in this study in the literature were based on data from Europe. Technological coverage data for most materials and processes were generally industry average.

Evaluation of the data is very crucial since data quality has a great influence on the final results. It is complicated to evaluate all-inclusive data quality and conduct a reliability check on the data reported from a number of literature references and databases; nevertheless, consistency and completeness checks for mass and energy balance results were conducted. More detailed information about the consistency check and completeness check is provided in chapter 6.1.

4. Life cycle inventory (LCI)

4.1. Resin production

The resin production stage includes virgin resin production and recycled resin manufacture, which produces PET and PLA resins. The life cycle inventory data for resin production of PET and PLA was obtained from the Ecoinvent v3 databases in SimaPro software. Data for PET resin production covered all the processes from cradle to gate including extraction and production of crude oil to produce the resin. Data for PLA resin production also included all the processes from cradle to gate including corn growing, harvesting, and starch and lactic acid production.

Table 4.1 shows the inputs and outputs for PET resin production. Flow values are for production of 1 kg of PET resin.

Table 4.1. Input/Output flows for 1 kg of PET according to the Allocation Default method (Economic) Values for Consequential are the same

Input	Amount	Unit
Transport, freight, sea, transoceanic ship <GLO>| market for | Alloc Def, U	5.248E-01	tkm
Transport, freight, lorry, unspecified <GLO>| market for | Alloc Def, U	4.504E-01	tkm
Transport, freight, aircraft <GLO>| market for | Alloc Def, U	7.600E-03	tkm
Transport, freight train <US>| market for | Alloc Def, U	8.944E-02	tkm
Water, unspecified natural origin, GLO	1.630E-04	m^3
Water, cooling, unspecified natural origin, GLO	6.400E-03	m^3
Ethylene glycol <GLO>| market for | Alloc Def, U	3.340E-01	Kg
Nitrogen, liquid <GLO>| market for | Alloc Def, U	2.980E-02	kg
Purified terephthalic acid <GLO>| market for | Alloc Def, U	8.750E-01	kg
Chemical factory, organics <GLO>| market for | Alloc Def, U	4.000E-10	p
Steam, in chemical industry <GLO>| market for | Alloc Def, U	9.400E-01	kg
Hazardous waste, for underground deposit <GLO>| market for | Alloc Def, U	-9.000E-05	kg
Waste plastic, mixture <GLO>| market for | Alloc Def, U	-2.310E-03	kg
Municipal solid waste <GLO>| market for | Alloc Def, U	-8.800E-04	kg
Average incineration residue <GLO>| market for | Alloc Def, U	-4.000E-04	kg

Table 4.1 (cont'd)

Heat, district or industrial, natural gas <GLO>| market for heat, district or industrial, natural gas | Alloc Def, U	6.650E-01	MJ
Heat, district or industrial, other than natural gas <GLO>| market for | Alloc Def, U	9.650E-01	MJ
Electricity, medium voltage <RFC>| market for | Alloc Def, U	1.122E-02	kWh
Output		
Emissions to air		
Particulates, < 2.5 um	2.500E-07	kg
Particulates, > 2.5 um, and < 10um	4.300E-07	kg
Particulates, > 10 um	3.200E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	9.000E-05	kg
Water/ m^3	2.513E-03	m^3
Emissions to water		
Suspended solids, unspecified	1.000E-06	kg
BOD5, Biological Oxygen Demand	1.600E-04	kg
TOC, Total Organic Carbon	2.620E-04	kg
Hydrocarbons, unspecified	4.990E-04	kg
COD, Chemical Oxygen Demand	1.020E-03	kg
DOC, Dissolved Organic Carbon	2.620E-04	kg
Water, RoW	4.050E-03	m^3

Table 4.2 shows the inputs and outputs for the PLA resin production in ALCA.

Flow values are for 1 kg of PLA resin production.

Table 4.2. Input/Output flows for 1 kg of PLA according to the Allocation Default method (Economic) Values for Consequential are the same

Input	**Amount**	**Unit**
Transport, freight, sea, transoceanic ship <GLO>| market for | Alloc Def, U	5.248E-01	tkm
Transport, freight, lorry, unspecified <GLO>| market for | Alloc Def, U	4.504E-01	tkm
Transport, freight, aircraft <GLO>| market for | Alloc Def, U	7.600E-03	tkm
Transport, freight train <US>| market for | Alloc Def, U	8.944E-02	tkm
Water, unspecified natural origin, GLO	3.200E-03	m^3
Maize grain <GLO>| market for | Alloc Def, U	1.507	kg
Chemical factory, organics <GLO>| market for | Alloc Def, U	4.000E-10	p

Table 4.2 (cont'd)

Waste plastic, mixture <GLO>| market for | Alloc Def, U	-0.001	kg
Hazardous waste, for incineration <GLO>| market for | Alloc Def, U	-0.0064	kg
Wastewater from maize starch production <GLO>| market for | Alloc Def, U	-0.0032	m^3
Natural gas, high pressure <GLO>| market for | Alloc Def, U	0.000606423	m^3
Naphtha <RoW>| market for | Alloc Def, U	0.005812402	kg
Electricity, low voltage <RFC>| market for | Alloc Def, U	0.086939382	kWh
Heat, district or industrial, natural gas <RoW>| market for heat, district or industrial, natural gas | Alloc Def, U	16.88373894	MJ
Heat, district or industrial, other than natural gas <RoW>| market for | Alloc Def, U	0.148994131	MJ
Output		
Emissions to air		
NMVOC, non-methane volatile organic compounds, unspecified origin	0.00252	kg

4.2. Intermediate processes

This stage consists of the extrusion process for manufacture of film or sheet, thermoforming process to produce clamshell containers, and refrigeration for strawberries kept under refrigerated conditions

Table 4.3 shows the inputs and outputs for the extrusion process. Flow values are for 1kg of extrusion process. One kg of this process amounted to 0.976 kg of extruded plastic film.

Table 4.3. Input/Output flows for 1kg of extrusion process according to the Allocation Default method (Economic)

Input	**Amount**	**Unit**
Water, cooling, unspecified natural origin, RoW	4.370E-02	m^3
Polyvinylchloride, suspension polymerised <GLO>| market for | Alloc Def, U	4.880E-05	kg
Polyethylene, low density, granulate <GLO>| market for | Alloc Def, U	2.150E-03	kg
Polypropylene, granulate <GLO>| market for | Alloc Def, U	6.830E-04	kg

Table 4.3 (cont'd)

Core board <GLO>| market for | Alloc Def, U	7.320E-03	kg
Solid bleached board <GLO>| market for | Alloc Def, U	9.760E-04	kg
Particle board, for outdoor use <GLO>| market for | Alloc Def, U	2.150E-05	m^3
Packaging box factory <GLO>| market for | Alloc Def, U	1.400E-09	p
Lubricating oil <GLO>| market for | Alloc Def, U	1.050E-04	kg
EUR-flat pallet <GLO>| market for | Alloc Def, U	1.440E-03	p
Steam, in chemical industry <GLO>| market for | Alloc Def, U	5.800E-02	kg
Waste plastic, mixture <GLO>| market for | Alloc Def, U	-2.410E-02	kg
Electricity, medium voltage <RFC>| market for | Alloc Def, U	3.818E-02	kWh
Output		
Emissions to air		
Water/m^3	1.693E-02	m^3
Emissions to water		
Water, RoW	2.677E-02	m^3

Table 4.4 shows the inputs and outputs for the extrusion process. Flow values are for 1kg of extrusion process. 1 kg of this process amounted to 0.977 kg of thermoformed, calendered plastic sheets.

Table 4.4. Input/Output flows for 1kg of thermoforming process according to the Allocation Default method (Economic)

Input	**Amount**	**Unit**
Water, cooling, unspecified natural origin, RoW	1.020E-01	m^3
Polyethylene, low density, granulate <GLO>| market for | Alloc Def, U	3.180E-02	kg
Core board <GLO>| market for | Alloc Def, U	7.970E-03	kg
Solid bleached board <GLO>| market for | Alloc Def, U	2.990E-03	kg
Kraft paper, bleached <GLO>| market for | Alloc Def, U	2.810E-02	kg
Packaging box factory <GLO>| market for | Alloc Def, U	1.430E-09	p
Lubricating oil <GLO>| market for | Alloc Def, U	6.180E-04	kg
EUR-flat pallet <GLO>| market for | Alloc Def, U	4.530E-04	p
Steam, in chemical industry <GLO>| market for | Alloc Def, U	8.510E-02	kg
Waste plastic, mixture <GLO>| market for | Alloc Def, U	-2.330E-02	kg

Table 4.4 (cont'd)

Heat, district or industrial, natural gas <RoW>| market for heat, district or industrial, natural gas | Alloc Def, U	1.690E-01	MJ
Heat, district or industrial, other than natural gas <RoW >| market for | Alloc Def, U	2.220E-01	MJ
Electricity, medium voltage <RFC>| market for | Alloc Def, U	5.756E-02	kWh
Output		
Emissions to air		
Water/m^3	3.953E-02	m^3
Emissions to water		
Water, RoW	6.248E-02	m^3

Data for the refrigeration process during distribution was obtained from the LCA DK Food library [49]. Table 4.5 shows the inputs and outputs for the extrusion process. Flow values are for 1kg of extrusion process.

Table 4.5. Input/Output flows for 1kg of refrigeration process

Input	**Amount**	**Unit**
Electricity (natural gas)	3.100E+00	Wh

The filling process when strawberries are introduced to the clamshell containers, and storage during the distribution of packed trays to the market through wholesale dealers and retailers, and the consumption stage were excluded from the study.

4.3. Transportation

The distance from the resin supplier by truck and train to container manufacturing was assumed for PET and PLA. PET resin was provided by Eastman Chemical Corporation, Columbia, South Carolina (29202) to Sambrailo Packaging, Watsonville, California

(95077). The distance between those locations was 4251 km [50]. For the PLA resin, NatureWorks LLC, Blair, Nebraska (68008) was selected as the supplier. The distance between NatureWorks LLC and Pinnacle Plastic Container, Oxnard, California (93033), the PLA container supplier, was 2592 km. Distances between the plastic converter and the strawberry sellers were estimated with reference to DSA, Watsonville, California (95077) and their local suppliers. DSA obtains PET containers from Sambrailo Packaging, also in Watsonville. The distance between DSA and Sambrailo Packaging is 1.92 km by truck, and the same distance was assumed by train [50]. Distance between DSA and Pinnacle Plastic Container was calculated to be 470 km by truck and 500 km by train.

Transportation was assumed to be by train and by trucks with 7.5~16 ton capacity. The data for trains were obtained from the US LCI database, and the data for trucks were from the Ecoinvent version 3 database. After the containers were packed at DSA, it was assumed that all the containers were shipped in equal portions to four retail distribution centers located in: Tacoma, Washington (train = 1100 km; truck = 1363 km); Loveland, Colorado (train = 1700 km; truck = 2071 km); Hooksett, New Hampshire (train = 4500 km; truck = 5166 km); and Lakeland, Florida (train = 4400 km; truck = 4504 km). The rail distances were calculated from public maps offered by National Atlas system [51].

4.4. Waste treatment

This stage represents the end-of-life scenario including the material recovery process, recycling (R), incineration (I) and landfill (L). Data for the material recovery process were obtained from a literature resource [42]. The end-of-life scenarios for PET and PLA clamshell containers were as follows:

- Scenario for PET – 13.8% R, 15.5% I, 70.7% L
- Scenario for PLA – 30% R, 70% L

According to the US Environmental Protection Agency (EPA), in 2012, plastic contributed 12.7% by weight of the municipal solid waste (MSW) in the United States, and 13.8% of plastics, which were disposed of in MSW, were recovered for recycling. Also, they reported MSW, which is not recovered for recycling or composting, is managed 82% by weight to landfill and 18% by weight to waste-to-energy incineration [52]. Therefore, for the PET clamshell container, as per the average municipal rate, in this end-of-life scenario 13.8% was regarded as recycling, 15.5% incineration and 70.7% landfill.

Data for recycling of PLA applied in this study was chemical recycling from literature, and the recycling rate of PLA was assumed based on literature [53-55]. Even though PLA is compostable, the predominant method of plastics disposal in the US is recycling or landfilling because only a few cities in the US have composting infrastructure [55]. For the PLA clamshell container, therefore, as per the average municipal rate, in this end-of-life scenario 30% was treated as recycling and 70% as landfill. The recycling rate for PLA in this case is higher than for PET. However, the main goal of this thesis is to compare ALCA and CLCA, so the detail of this assumption is not critical.

The databases for recycling, incineration and landfill of PET were taken from waste treatment categories in the SimaPro software, which contains detailed emissions for 100% PET. The data for recycling and landfill of PLA was derived from the data for recycling of PET and modified using literature resources. For example, 0.0238 kg of sodium hydroxide was needed for cleaning process, and 0.6 MJ and 1929 kJ of electricity were required for the recycling process of 1 kg of PLA, while 74 g of carbon dioxide was emitted.

Table 4.6. Input/Output flows for 1 kg of material recovery process

Input	**Amount**	**Unit**
Gas, natural, 35MJ per m3, in ground	0.036	Cuft
Diesel, at refinery/I/US	0.22	Gal
Propane <GLO>| market for | Alloc Def, U	0.579	kg
Electricity, medium voltage <NPCC, US only>| market for | Alloc Def, U	7.42	kWh
Output		
Final waste flows		
Plastic waste	87.1	lb

Table 4.7. Input/Output flows for 1 kg of recycling of PET

Input	**Amount**	**Unit**
Electricity, medium voltage <RoW>| market for | Alloc Def, U	0.6	kWh

Table 4.8. Input/Output flows for 1kg of recycling of PLA

Input	**Amount**	**Unit**
Sodium hydroxide	0.0238	Kg
Electricity, medium voltage <NPCC, US only>| market for | Alloc Def, U	0.6	MJ
Electricity, medium voltage <NPCC, US only>| market for | Alloc Def, U	1929	kJ
Output		
Emissions to air		
Carbon dioxide	74	g

4.5. Environmental benefit

This phase stands for environmental credit obtained from recycling and energy recovery from incineration. This study assumed that the scrap sheet after extrusion or thermoforming is recycled. For PET, 0.793 kg and 0.742 kg were recovered after sheet extrusion and thermoforming, respectively. For PLA, 0.745 kg and 0.697 kg were recovered after sheet extrusion and thermoforming, respectively. The data for energy

recovery from incineration was taken from literature sources. For example, the amount of energy recovery for PET was 21825.8 BTU/kg [42].

5. Life cycle impact assessment (LCIA)

The LCIA results of five different phases of PET and PLA clamshell containers were analyzed using the IMPACT 2002+ version 2.11 midpoint impact method. Fifteen impact categories were chosen to evaluate the EFP of PET and PLA containers. The selected impact categories were carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acidification / nitrification (TA), land occupation (LO), aquatic acidification (AC), aquatic eutrophication (AEU), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME).

Several studies have already explored the EFP of polymers used in packaging made from non-renewable polymers such as PET, polypropylene (PP), high-density polyethylene (HDPE) and polystyrene (PS) and renewable resources such as PLA [9-16]. Most of these studies concluded that bio-based polymers have lower environmental effect than petroleum-based polymers, and were conducted as ALCA. Although CLCA has emerged as a technology to evaluate EFP to provide the best reflection of the actual consequences of a decision, little research has been conducted on CLCA. This study concentrates on the comparison between PLA and PET using ALCA and CLCA methodology as calculated by SimaPro v8.2 and Ecoinvent 3. Before examining the clamshell system, the environmental footprints of 1 kg of PET and PLA resin is reported.

5.1. LCIA of PET and PLA

Table 5.1 shows the impact category values for ALCA and CLCA for 1 kg each of PLA and PET resin.

Table 5.1. Impact category values for ALCA and CLCA for 1 kg of PLA and PET resin

Impact Category	ALCA		CLCA	
	PLA	PET	PLA	PET
Carcinogens kg C_2H_3Cl eq	0.128	1.313	0.591	1.420
Non-carcinogens kg C_2H_3Cl eq	0.023	0.038	0.075	0.065
Respiratory inorganics kg PM2.5 eq	0.0037	0.0026	-0.0008	0.0015
Ionizing radiation Bq C-14 eq	45.34	27.75	-63.22	-5.16
Ozone layer depletion kg CFC-11 eq	1.47E-07	1.01E-07	1.61E-07	7.38E-08
Respiratory organics kg C_2H_4 eq	2.29E-03	2.03E-03	2.88E-03	2.22E-03
Aquatic ecotoxicity kg TEG water	366	159	490	257
Terrestrial ecotoxicity kg TEG soil	8.41	40.82	13.91	71.57
Terrestrial acidification / nitrification kg SO_2 eq	0.079	0.048	0.034	0.037
Land occupation m^2org.arable	1.126	0.032	1.170	0.130
Aquatic acidification kg SO_2 eq	2.14E-02	1.49E-02	8.89E-03	1.08E-02
Aquatic eutrophication kg PO_4 P-lim	1.47E-03	5.23E-04	1.01E-03	5.70E-04
Global warming kg CO_2 eq	2.996	2.867	1.928	2.475
Non-renewable energy MJ primary	44.59	78.93	39.38	75.59
Mineral extraction MJ surplus	0.131	0.165	0.274	0.360

In ALCA, PLA resin has a higher EFP than PET for 10 of the 15 impact categories: respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication and global warming. In CLCA, however, PET has a higher EFP than PLA for 9 impact categories: carcinogens, respiratory inorganics, ionizing radiation, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, global warming, non-renewable energy and mineral extraction. Further details of these differences will be discussed in the following sections.

Table 5.2 represents the impact category values for ALCA and CLCA for PLA and PET clamshell containers, and the cradle-to-grave contributions of each stage; resin production, intermediate process, transportation, waste treatment, and environmental benefit.

Table 5.2. Impact category values for ALCA and CLCA for PLA and PET clamshell containers

Impact Category	Stage	ALCA		CLCA	
		PLA	PET	PLA	PET
Carcinogens kg C_2H_3Cl eq	Resin production	3.977	43.368	18.343	46.900
	Intermediate process	1.800	1.915	1.765	1.878
	Transportation	0.671	0.363	-1.997	-1.074
	Waste treatment	0.643	0.147	-0.009	0.067
	Environmental benefit	0	0	-6.099	-8.375
	Total	**7.091**	**45.793**	**12.002**	**39.395**
Non-carcinogens kg C_2H_3Cl eq	Resin production	0.720	1.255	2.341	2.137
	Intermediate process	0.723	0.769	0.703	0.748
	Transportation	0.474	0.491	0.402	0.452
	Waste treatment	0.117	0.622	0.037	0.610
	Environmental benefit	0	0	-0.778	-0.460
	Total	**2.034**	**3.137**	**2.705**	**3.488**
Respiratory inorganics kg PM2.5 eq	Resin production	0.116	0.086	-0.024	0.051
	Intermediate process	0.072	0.077	0.073	0.077
	Transportation	0.078	0.053	0.072	0.050
	Waste treatment	0.003	0.004	0.002	0.005
	Environmental benefit	0	0	0.008	-0.015
	Total	**0.269**	**0.220**	**0.130**	**0.168**
Ionizing radiation Bq C-14 eq	Resin production	1407	917	-1962	-170
	Intermediate process	864	919	708	753
	Transportation	489	263	395	212
	Waste treatment	262	71	484	101
	Environmental benefit	0	0	653	-2158
	Total	3022	2170	277	-1261
Ozone layer depletion kg CFC-11 eq	Resin production	4.58E-06	3.35E-06	4.99E-06	2.44E-06
	Intermediate process	1.62E-06	1.72E-06	1.41E-06	1.50E-06
	Transportation	4.31E-06	2.32E-06	4.42E-06	2.38E-06
	Waste treatment	2.78E-07	1.71E-07	4.66E-07	1.39E-07
	Environmental benefit	0	0	-1.66E-06	-2.39E-06
	Total	**1.08E-05**	**7.57E-06**	**9.63E-06**	**4.07E-06**
Respiratory organics kg C_2H_4 eq	Resin production	0.0711	0.0672	0.0893	0.0735
	Intermediate process	0.0120	0.0128	0.0113	0.0120
	Transportation	0.0453	0.0276	0.0524	0.0314
	Waste treatment	0.0012	0.0009	0.0007	0.0008
	Environmental benefit	0	0	-0.0297	-0.0139
	Total	**0.1296**	**0.1085**	**0.1240**	**0.1038**
Aquatic ecotoxicity kg TEG water	Resin production	11362	5239	15204	8478
	Intermediate process	2812	2993	3467	3690
	Transportation	2524	2930	3082	3230
	Waste treatment	576	784	391	772
	Environmental benefit	0	0	-5055	-2673
	Total	**17274**	**11946**	**17088**	**13497**

Table 5.2 (cont'd)

Terrestrial ecotoxicity kg TEG soil	Resin production	261	1348	432	2364
	Intermediate process	665	708	938	998
	Transportation	1660	894	2182	1175
	Waste treatment	62	23	52	24
	Environmental benefit	0	0	-144	-621
	Total	**2649**	**2973**	**3460**	**3940**
Terrestrial acidification / nitrification kg SO_2 eq	Resin production	2.463	1.576	1.055	1.219
	Intermediate process	0.939	1.000	0.866	0.921
	Transportation	2.506	1.823	2.447	1.791
	Waste treatment	0.051	0.064	0.038	0.066
	Environmental benefit	0	0	-0.351	-0.334
	Total	**5.959**	**4.462**	**4.055**	**3.664**
Land occupation m^2 org.arable	Resin production	34.945	1.058	36.323	4.281
	Intermediate process	2.362	2.513	3.436	3.657
	Transportation	2.750	1.480	4.265	2.296
	Waste treatment	0.092	0.088	0.099	0.102
	Environmental benefit	0	0	-12.078	-0.844
	Total	**40.148**	**5.140**	**32.045**	**9.492**
Aquatic acidification kg SO_2 eq	Resin production	0.666	0.494	0.276	0.356
	Intermediate process	0.340	0.361	0.306	0.325
	Transportation	0.387	0.274	0.323	0.239
	Waste treatment	0.029	0.018	0.018	0.019
	Environmental benefit	0	0	-0.092	-0.114
	Total	**1.422**	**1.147**	**0.830**	**0.825**
Aquatic eutrophication kg PO_4 P-lim	Resin production	0.0457	0.0173	0.0312	0.0188
	Intermediate process	0.0078	0.0083	0.0083	0.0089
	Transportation	0.0040	0.0022	0.0047	0.0026
	Waste treatment	0.0004	0.0004	0.0005	0.0006
	Environmental benefit	0	0	-0.0104	-0.0051
	Total	**0.0579**	**0.0282**	**0.0344**	**0.0258**
Global warming kg CO_2 eq	Resin production	93.01	94.71	59.85	81.76
	Intermediate process	51.61	54.92	47.30	50.34
	Transportation	61.82	36.87	57.28	34.43
	Waste treatment	4.57	13.05	3.52	12.91
	Environmental benefit	0	0	-19.90	-22.15
	Total	**211.01**	**199.55**	**148.05**	**157.28**
Non-renewable energy MJ primary	Resin production	1384	2607	1222	2497
	Intermediate process	734	781	664	707
	Transportation	1014	596	981	578
	Waste treatment	80	44	79	42
	Environmental benefit	0	0	-406	-748
	Total	**3212**	**4029**	**2540**	**3076**

Table 5.2 (cont'd)

Mineral extraction MJ surplus	Resin production	4.057	5.463	8.512	11.884
	Intermediate process	0.765	0.814	1.758	1.871
	Transportation	1.531	0.824	2.755	1.483
	Waste treatment	0.048	0.037	0.111	0.066
	Environmental benefit	0	0	-2.830	-2.521
	Total	**6.400**	**7.138**	**10.305**	**12.783**

Figure 5.3 to 5.4 show the comparisons for PET and PLA using ALCA and CLCA. As shown in Figure 5.1, for PET, ALCA has a higher EFP than CLCA for 10 of the 15 impact categories: carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, global warming and non-renewable energy. For PLA, ALCA has a higher EFP than CLCA for 11 impact categories: respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming and non-renewable energy, as shown in Figure 5.2

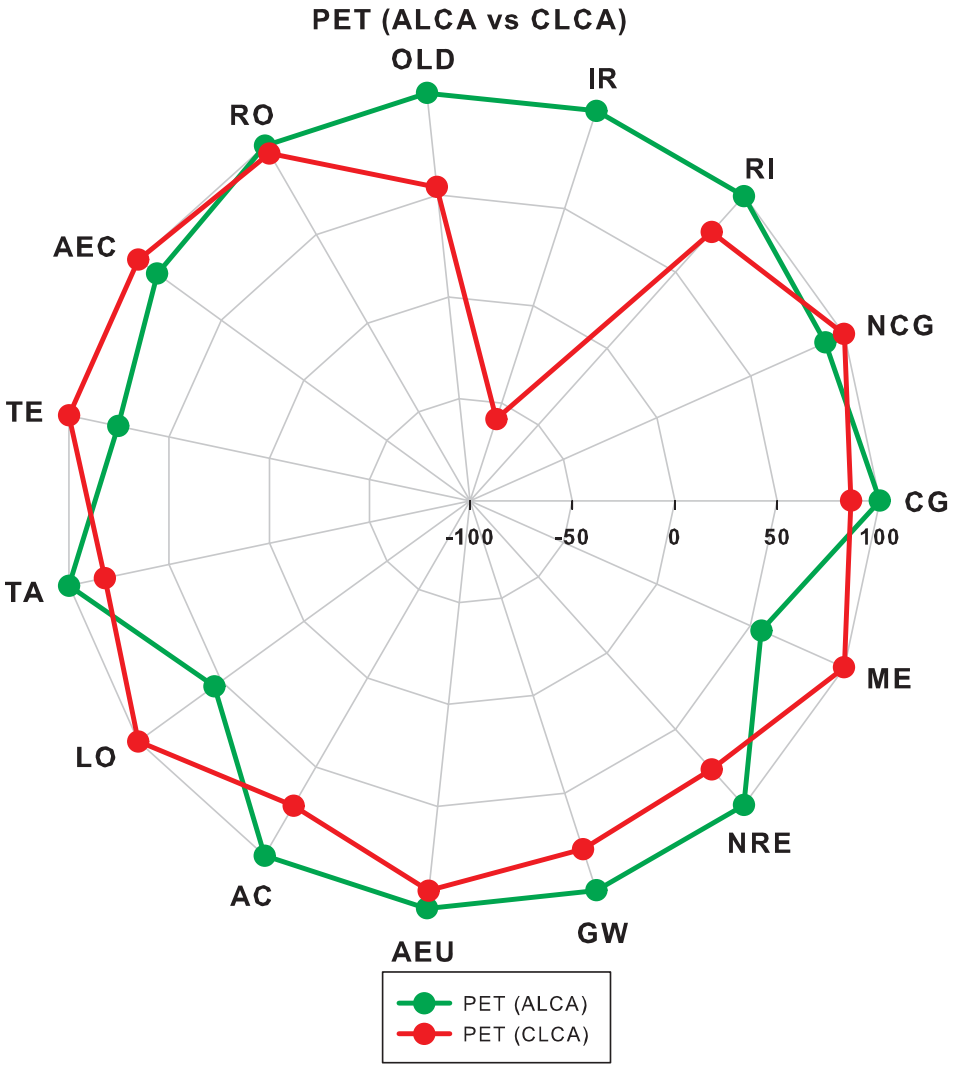

Figure 5.1. Impact assessment of PET compared between ALCA and CLCA (Characterization)

Note: carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acidification / nitrification (TA), land occupation (LO), aquatic acidification (AC), aquatic eutrophication (AEU), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME).

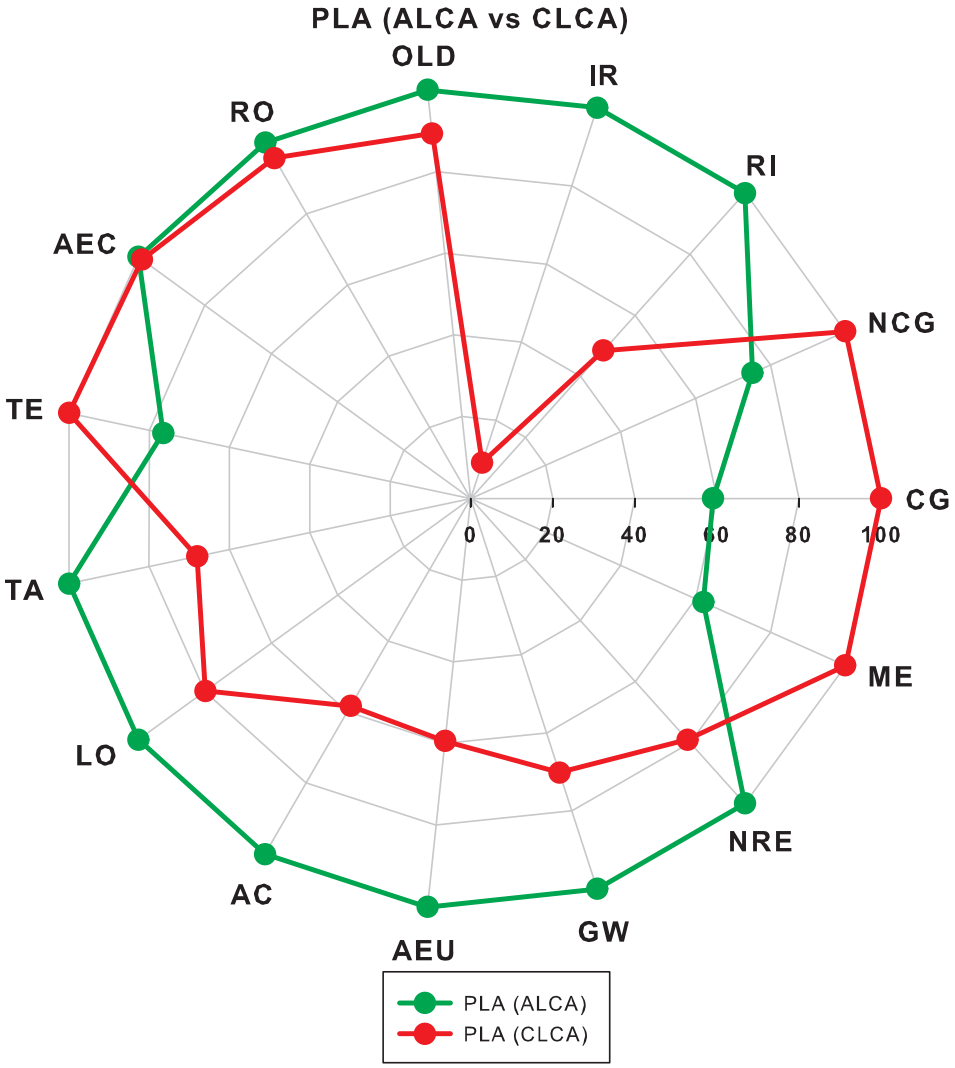

Figure 5.2. Impact assessment of PLA compared between ALCA and CLCA (Characterization)

Note: carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acidification / nitrification (TA), land occupation (LO), aquatic acidification (AC), aquatic eutrophication (AEU), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME).

As shown in Figure 5.3, using ALCA. PLA has a higher EFP than PET for 10 of the 15 impact categories: respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication and global warming. In CLCA, however, the EFP of PLA is only higher than PET for 8 categories: ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic ecotoxicity and aquatic eutrophication, as shown in Figure 5.4.

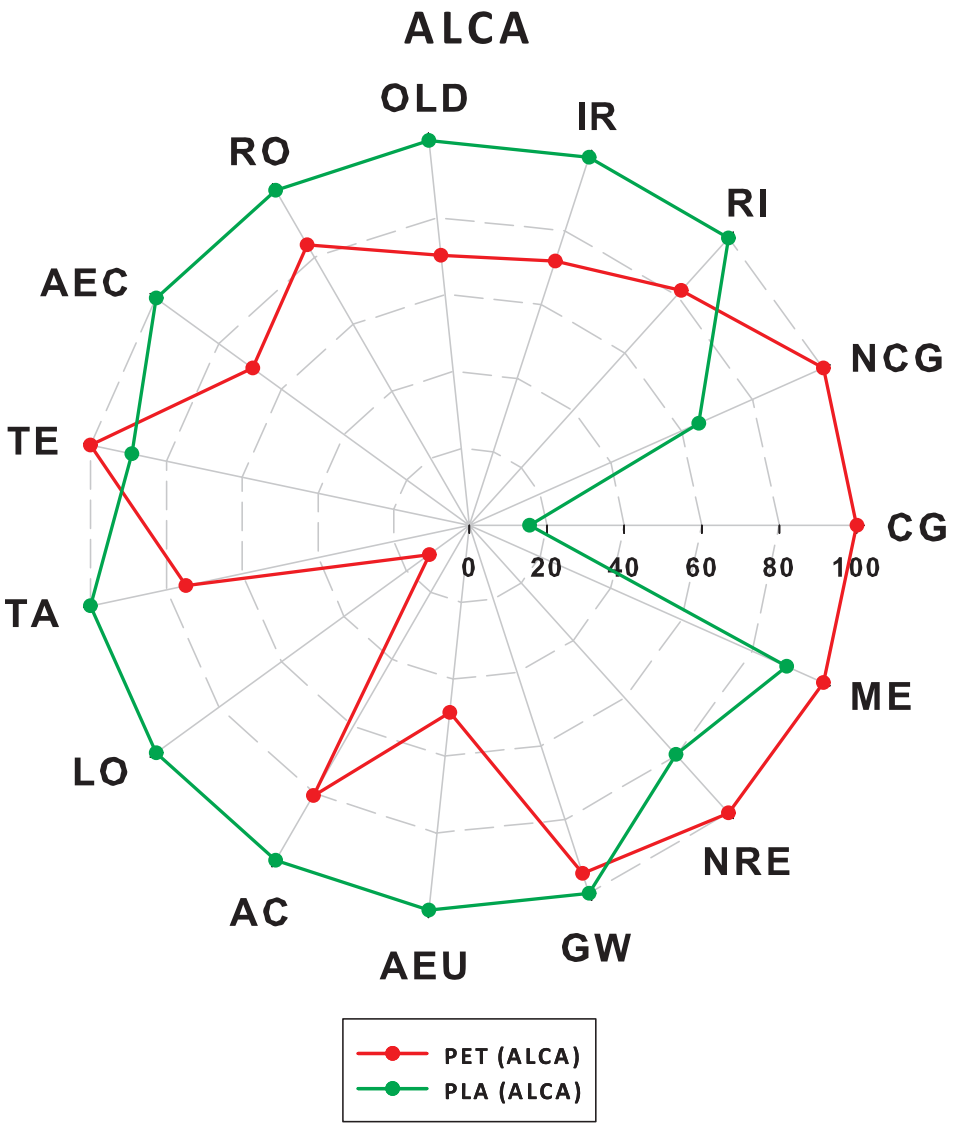

Figure 5.3. Impact assessment of ALCA (Characterization)

Note: carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acidification / nitrification (TA), land occupation (LO), aquatic acidification (AC), aquatic eutrophication (AEU), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME).

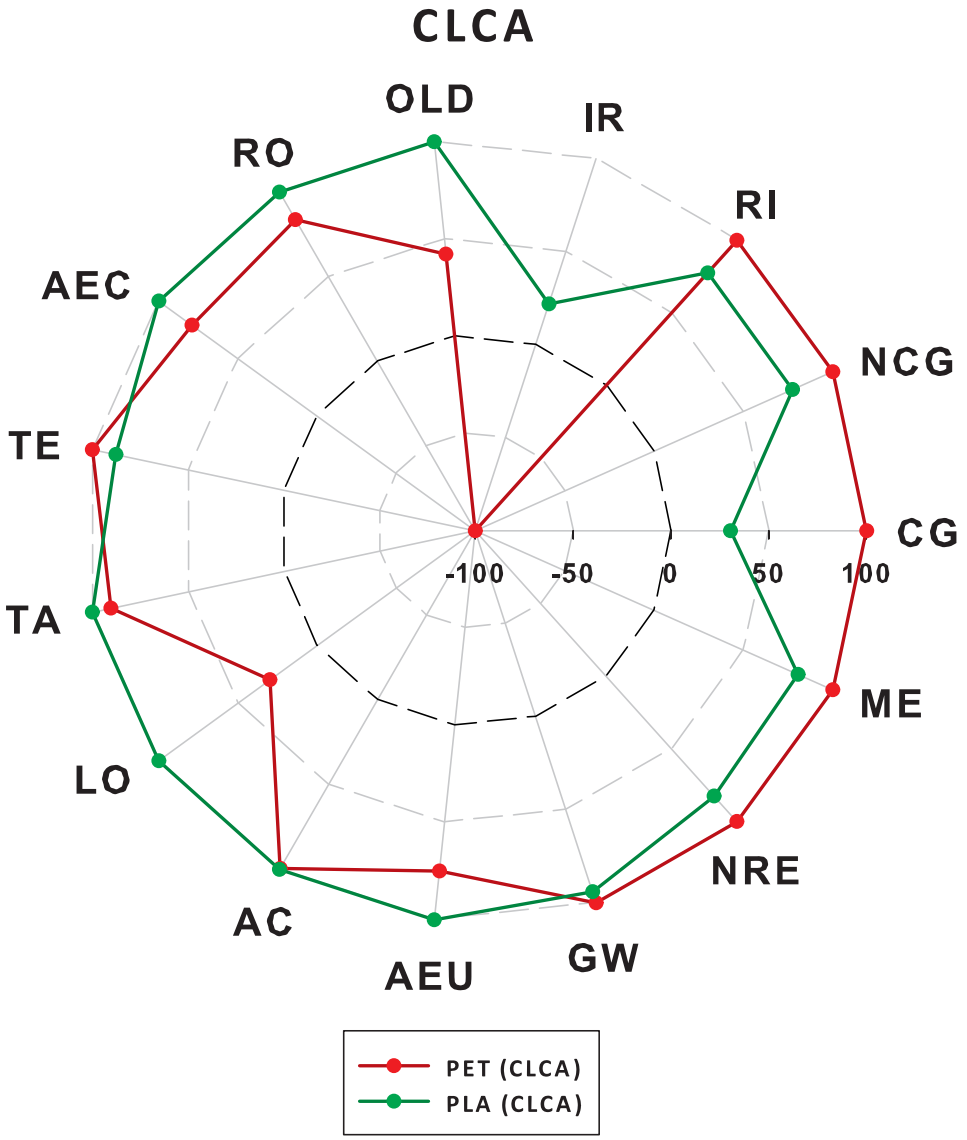

Figure 5.4. Impact assessment of CLCA (Characterization)

Note: carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acidification / nitrification (TA), land occupation (LO), aquatic acidification (AC), aquatic eutrophication (AEU), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME).

After conducting normalization according to IMPACT 2002 V2.1+ with SimaPro software, only four impact categories; carcinogens, respiratory inorganic, global warming and non-renewable energy, were shown to be significantly different between ALCA and CLCA. Figure 5.5 shows that the EFP of PLA, according to CLCA, had the lowest impact in respiratory inorganics, global warming and non-renewable energy when compared with CLCA and ALCA for PET. The negative values in CLCA were attributed to the avoided burden of the recycled PLA and PET resin and energy recovery from incineration for PET waste treatment. For the contribution analysis, the resin production contributed the most to carcinogens, global warming and non-renewable energy.

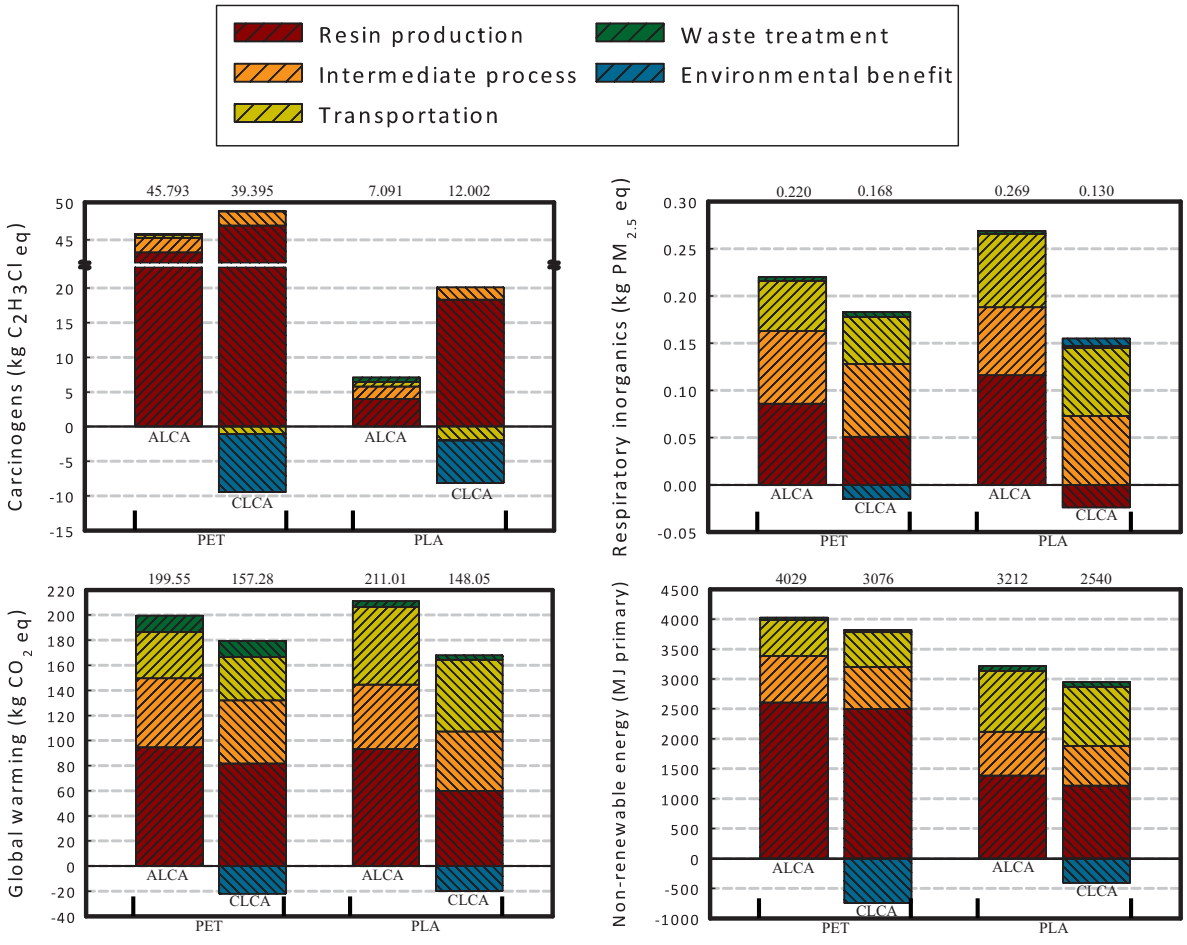

Figure 5.5. Normalized impact value comparing PET and PLA using ALCA and CLCA

5.2. Carcinogens

For the carcinogens impact category, the EFP of PLA was significantly lower than the EFP PET in both ALCA and CLCA. The total amount of kg C_2H_3Cl for PET was more than six times as high as for PLA in ALCA. This difference between PET and PLA in ALCA came mainly from the resin production. In CLCA, the carcinogens impact category of PET was triple the amount for PLA due to resin production, similarly to ALCA. In both ALCA and CLCA, the EFP of purified terephthalic acid production for producing the PET resin caused the dissimilarity between PET and PLA.

The resin production stages for PET contributed 43.368 kg and 46.900 kg of C_2H_3Cl that were about 95 % and 120 % of the total kg chloroethylene equivalents into air in ALCA and CLCA, respectively. For PLA, the resin production stages also contributed the highest C_2H_3Cl, 3.977 kg and 18.343 kg of C_2H_3Cl in ALCA and CLCA respectively.

Figure 5.6 through Figure 5.9 show the networks of PET and PLA in ALCA and CLCA, respectively. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1 lb capacity each for the packaging of strawberries.

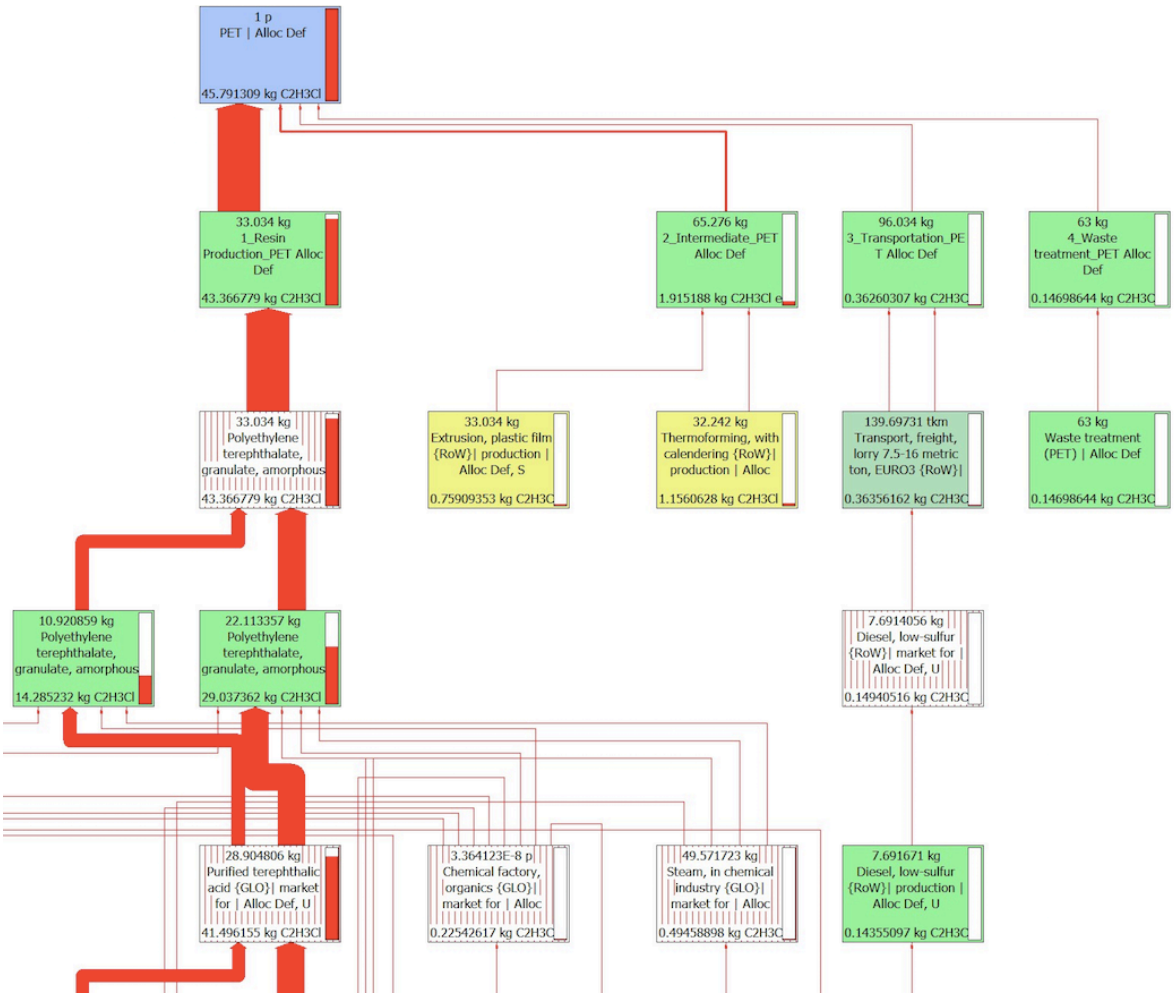

Figure 5.6. Network of PET in ALCA for carcinogens

Note: A 0.32% cut-off rule was applied in this figure due to the abundance of nodes, and the figure shown is only a part of the full network since the figure was so large.

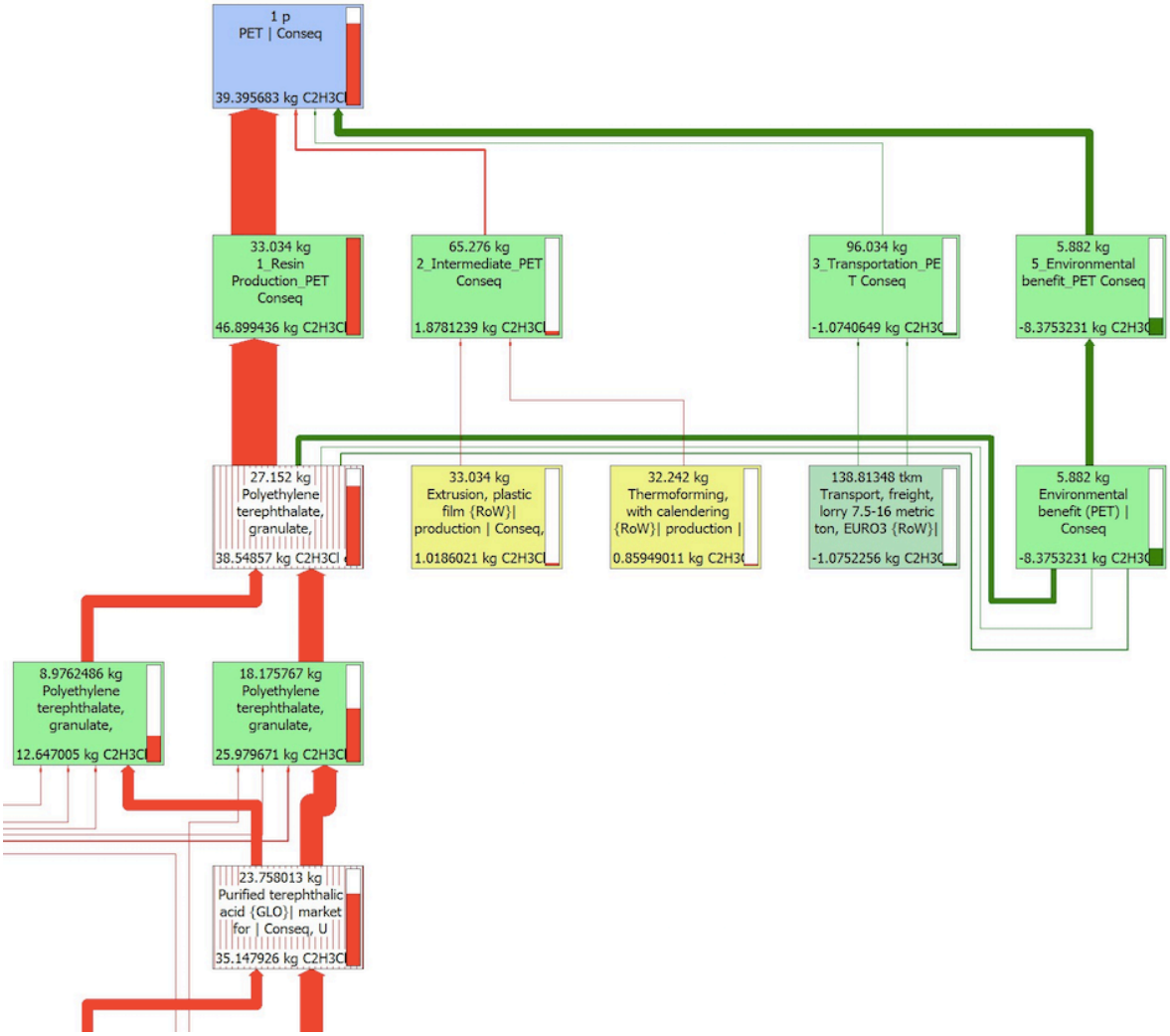

Figure 5.7. Network of PET in CLCA for carcinogens

Note: A 1% cut-off rule was applied in this figure due to the abundance of nodes, and the figure shown is only a part of the full network since the figure was so large.

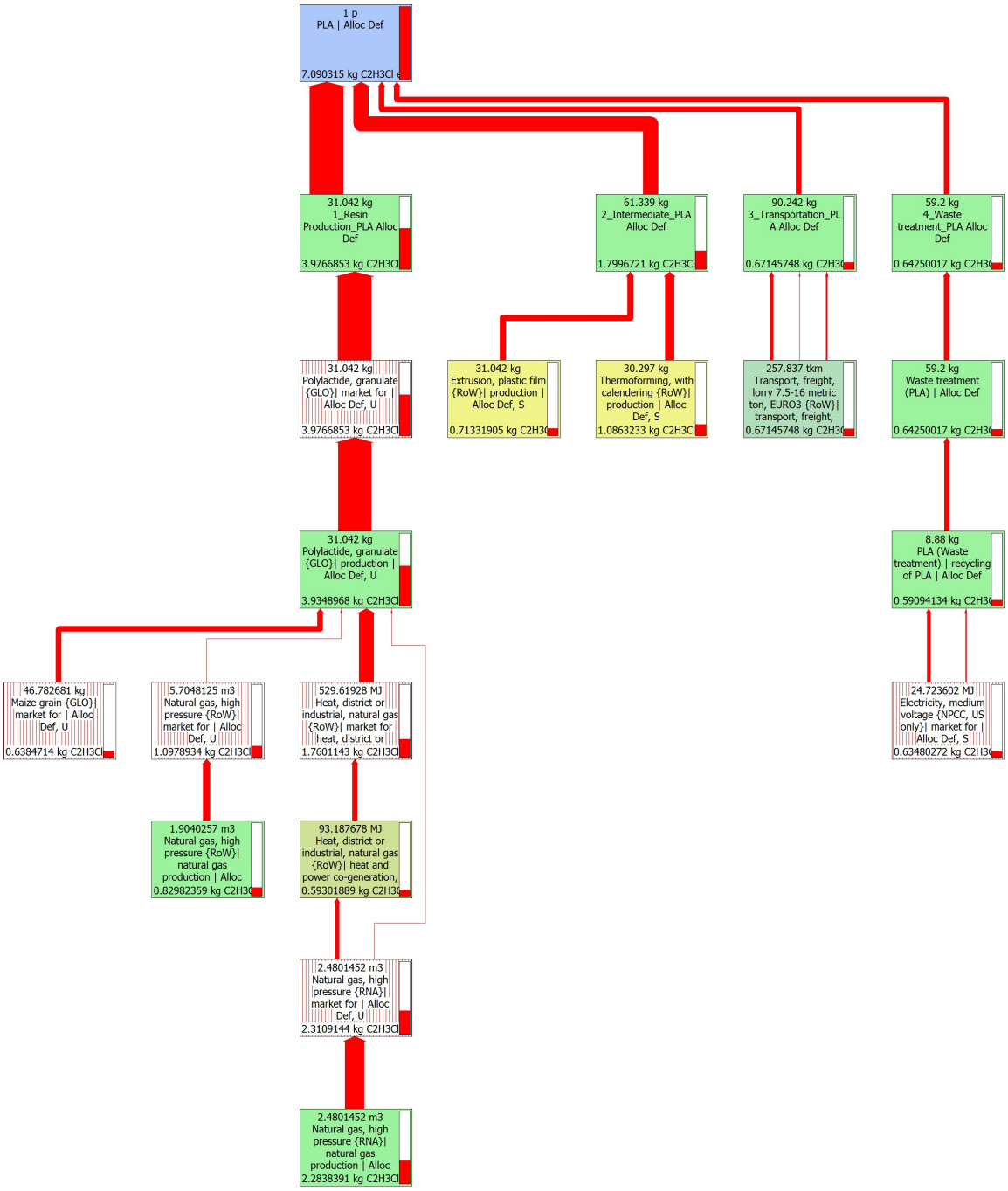

Figure 5.8. Network of PLA in ALCA for carcinogens

Note: A 8.33% cut-off rule was applied in this figure due to the abundance of nodes.

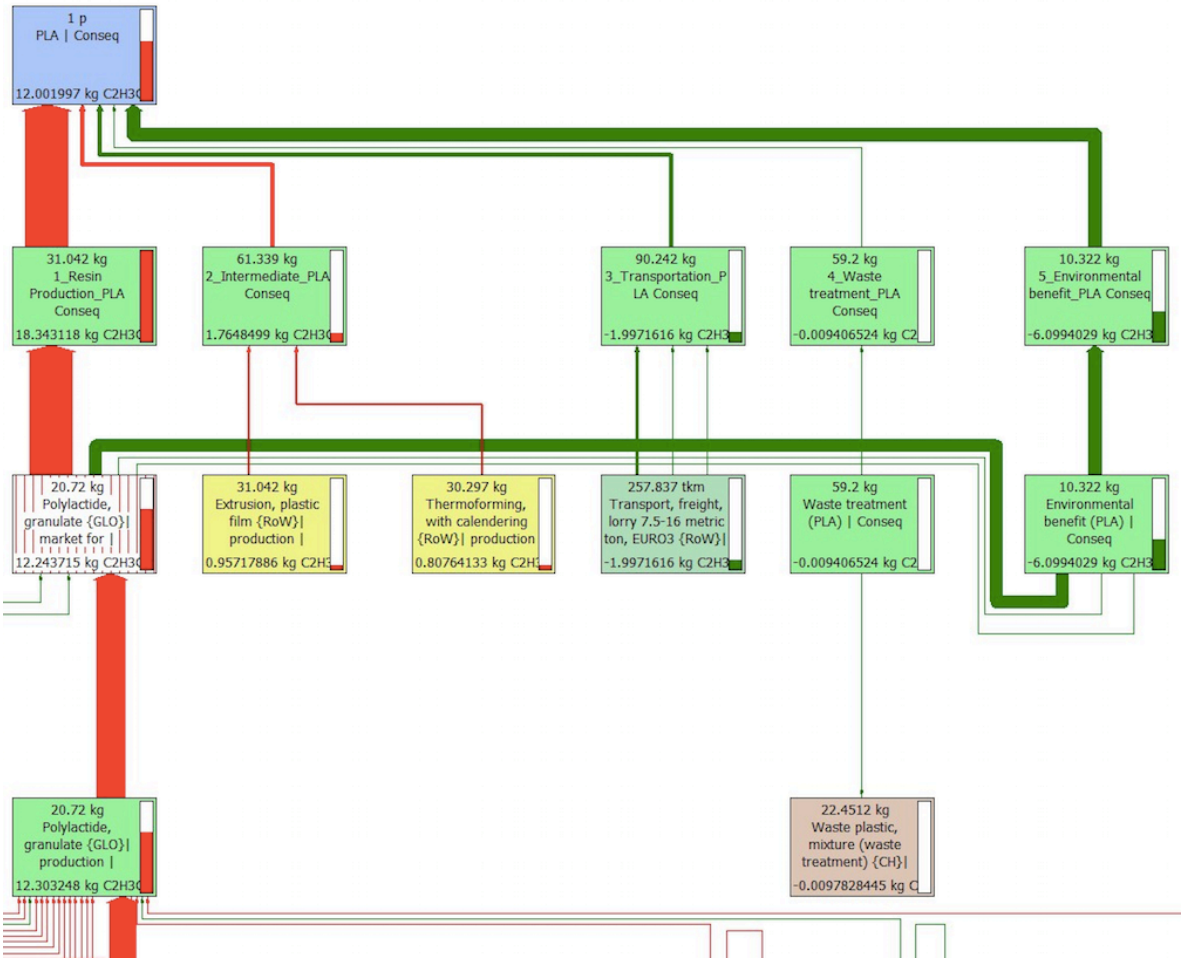

Figure 5.9. Network of PLA in CLCA for carcinogens

Note: A 0.0533% cut-off rule was applied in this figure due to the abundance of nodes, and the figure shown is only a part of the full network since the figure was so large.

The EFP due to carcinogens of PET in ALCA was higher than that in CLCA. The difference came mainly from the resin production, transportation and environmental benefit stages including recycling and energy recovery from incineration. For the carcinogens, the EFP of carcinogens during the transportation stage in CLCA was negative due to petroleum production. As described in chapter 3, natural gas in CLCA was added as a negative value in the crude oil production. For the carcinogen indicator, however, the EFP of natural gas is much higher than the EFP of crude oil (diesel in this process). Therefore, the EFP of

transportation had a negative value in CLCA for both PET and PLA. The networks of the transportation process in ALCA and CLCA for PET are shown in Figure 5.10 and Figure 5.11. The networks of transportation process in ALCA and CLCA for PLA are omitted since they are very similar to those for PET. For the transportation processes in the figures, the functional unit was 138.8 tkm, which is equivalent to the functional unit in this study, in both ALCA and CLCA.

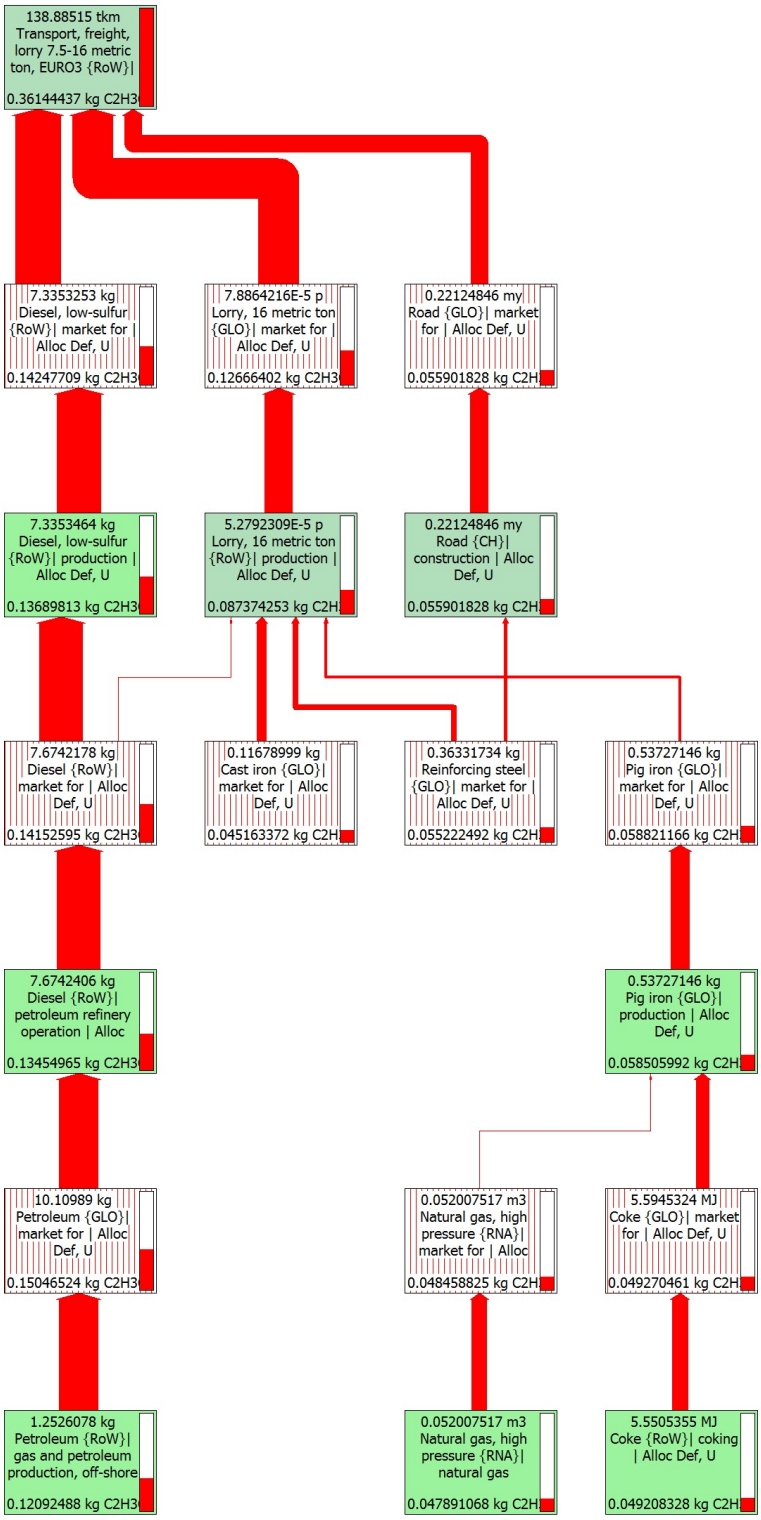

Figure 5.10. Network of transportation process of PET in ALCA for carcinogens

Note: A 11% cut-off rule was applied in this figure due to the abundance of nodes.

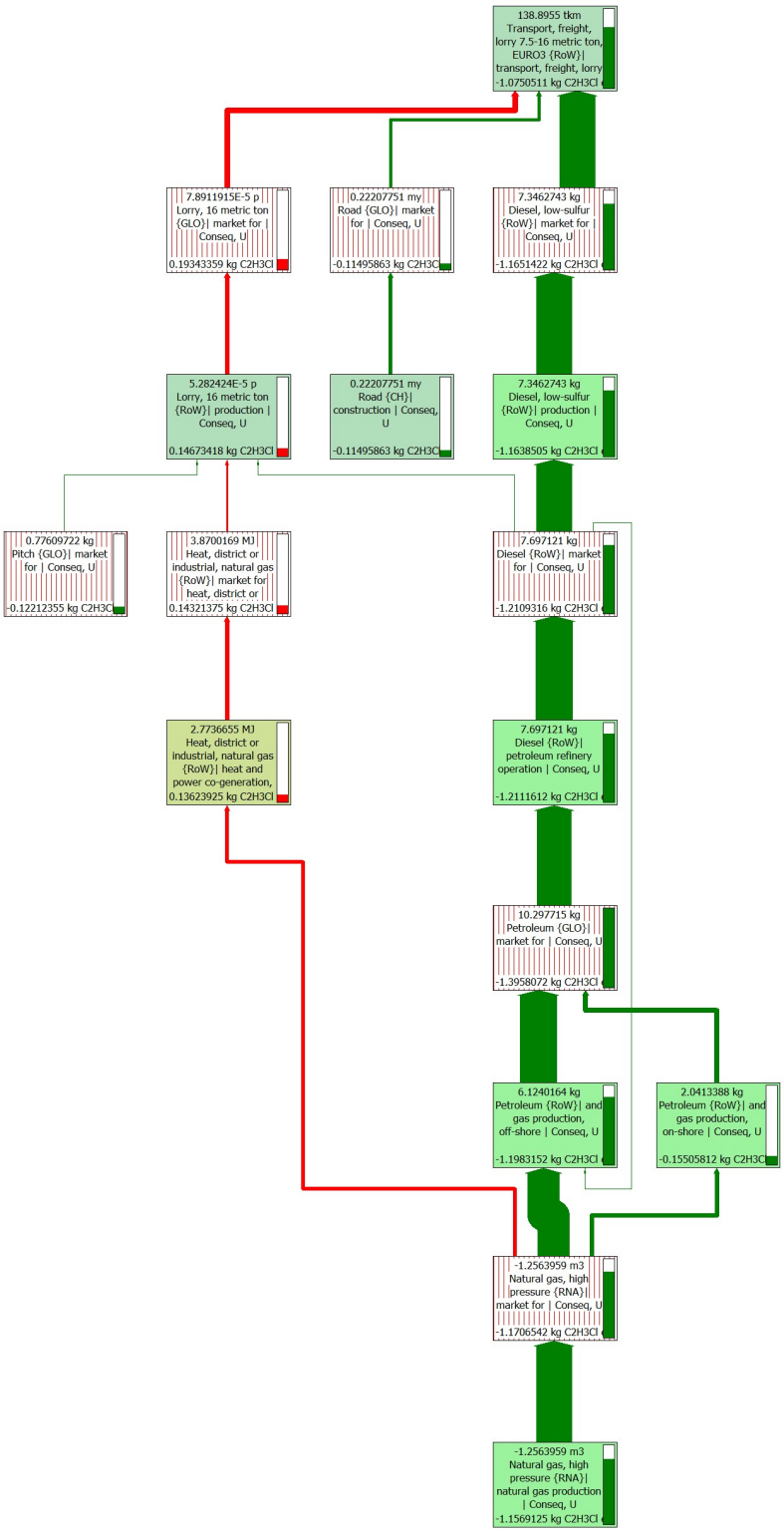

Figure 5.11. Network of transportation process of PET in CLCA for carcinogens

Note: A 7.5% cut-off rule was applied in this figure due to the abundance of nodes.

The EFP due to carcinogens of PLA in CLCA was higher than that of PLA in ALCA. This dissimilarity arose mainly from PLA resin production due to heat production using natural gas, and from the environmental benefit phase including recycling and landfill. Since the EFP of heat production using natural gas in CLCA was more than 10 times higher than in ALCA, the EFP of PLA in CLCA was higher than in ALCA. The resin production stage (31.042 kg) including heat production in ALCA and CLCA, for carcinogens is shown in Figure 5.12 and Figure 5.13.

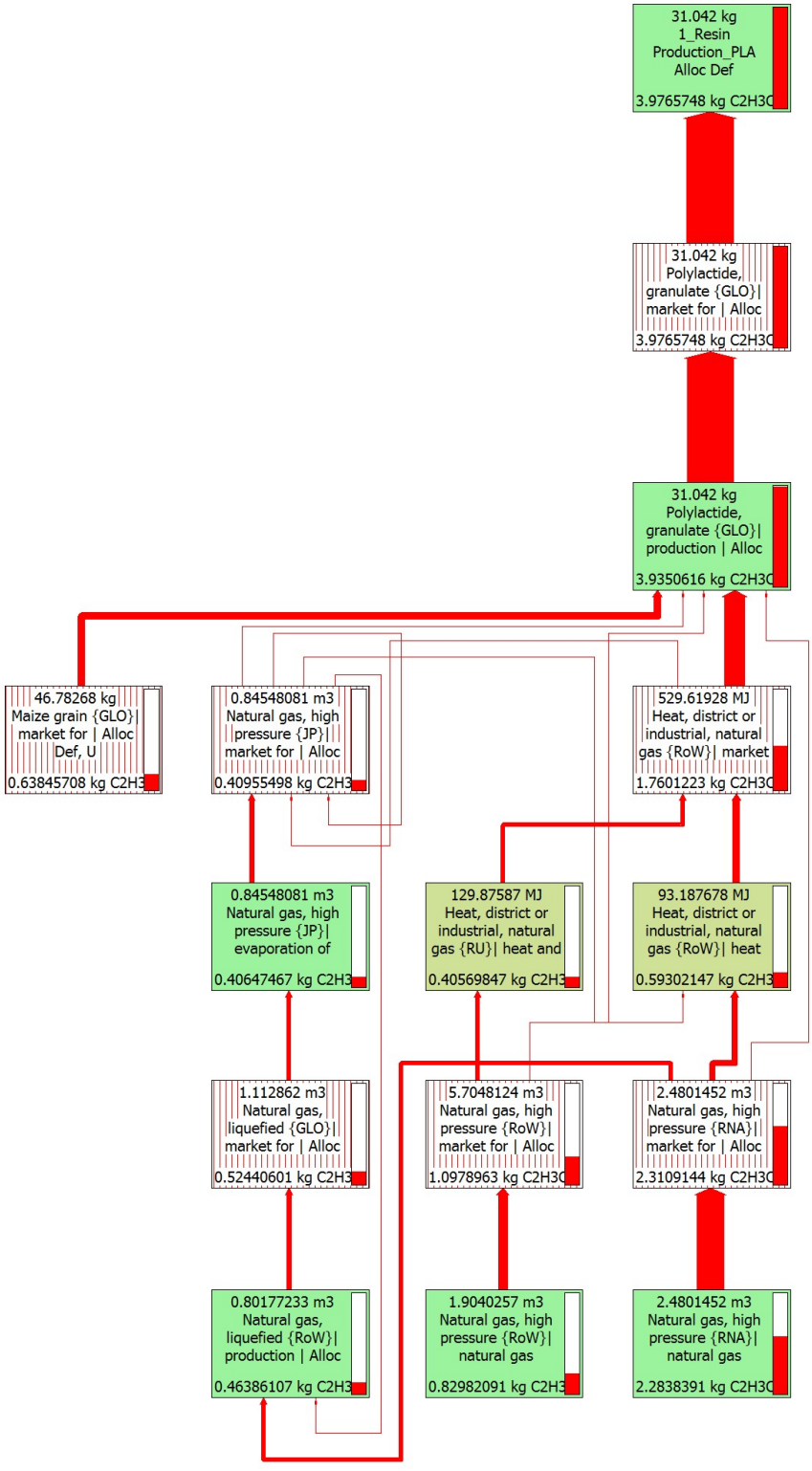

Figure 5.12. Network of the resin production of PLA in ALCA for carcinogens

Note: An 8.3% cut-off rule was applied in this figure due to the abundance of nodes.

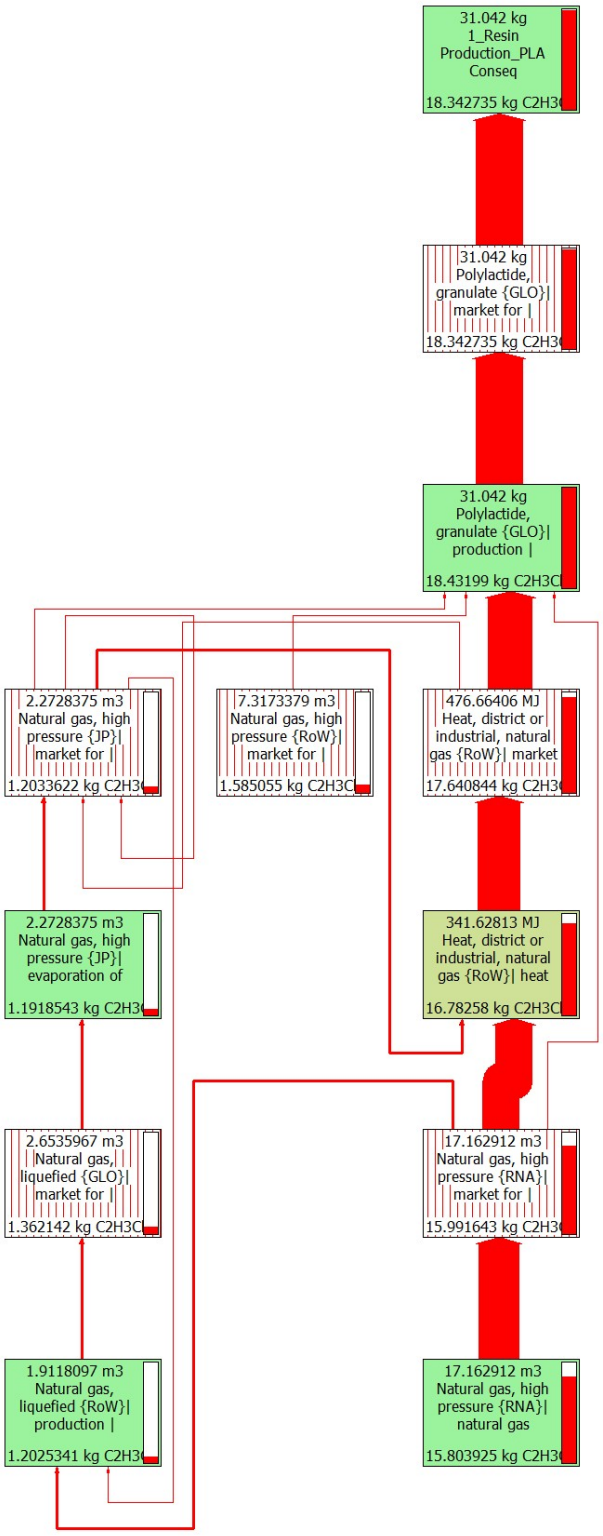

Figure 5.13. Network of resin production of PLA in CLCA for carcinogens

Note: A 6.47% cut-off rule was applied in this figure due to the abundance of nodes.

5.3. Non-carcinogens

For the non-carcinogens impact category, the EFP of PLA was significantly lower than the EFP of PET in both ALCA and CLCA. This difference between PET and PLA in ALCA and CLCA came mainly from resin production. Especially, the EFP of purified terephthalic acid production in PET resin production caused the difference between PET and PLA in both ALCA and CLCA.

The highest value in the non-carcinogens impact category was PET using CLCA with 3.488 kg C_2H_3Cl. The most contributing stage for the non-carcinogens category was resin production with 0.72 kg, 1.255 kg, 2.341 kg and 2.137 kg of C_2H_3Cl of PLA in ALCA, PET in ALCA, PLA in CLCA and PET in CLCA, respectively.

Figure 5.14 through Figure 5.17 show the networks of PET and PLA in ALCA and CLCA for non-carcinogens. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1 lb capacity each for the packaging of strawberries.

Figure 5.14. Network of PET in ALCA for non-carcinogens

Note: A 13% cut-off rule was applied in this figure due to the abundance of nodes.

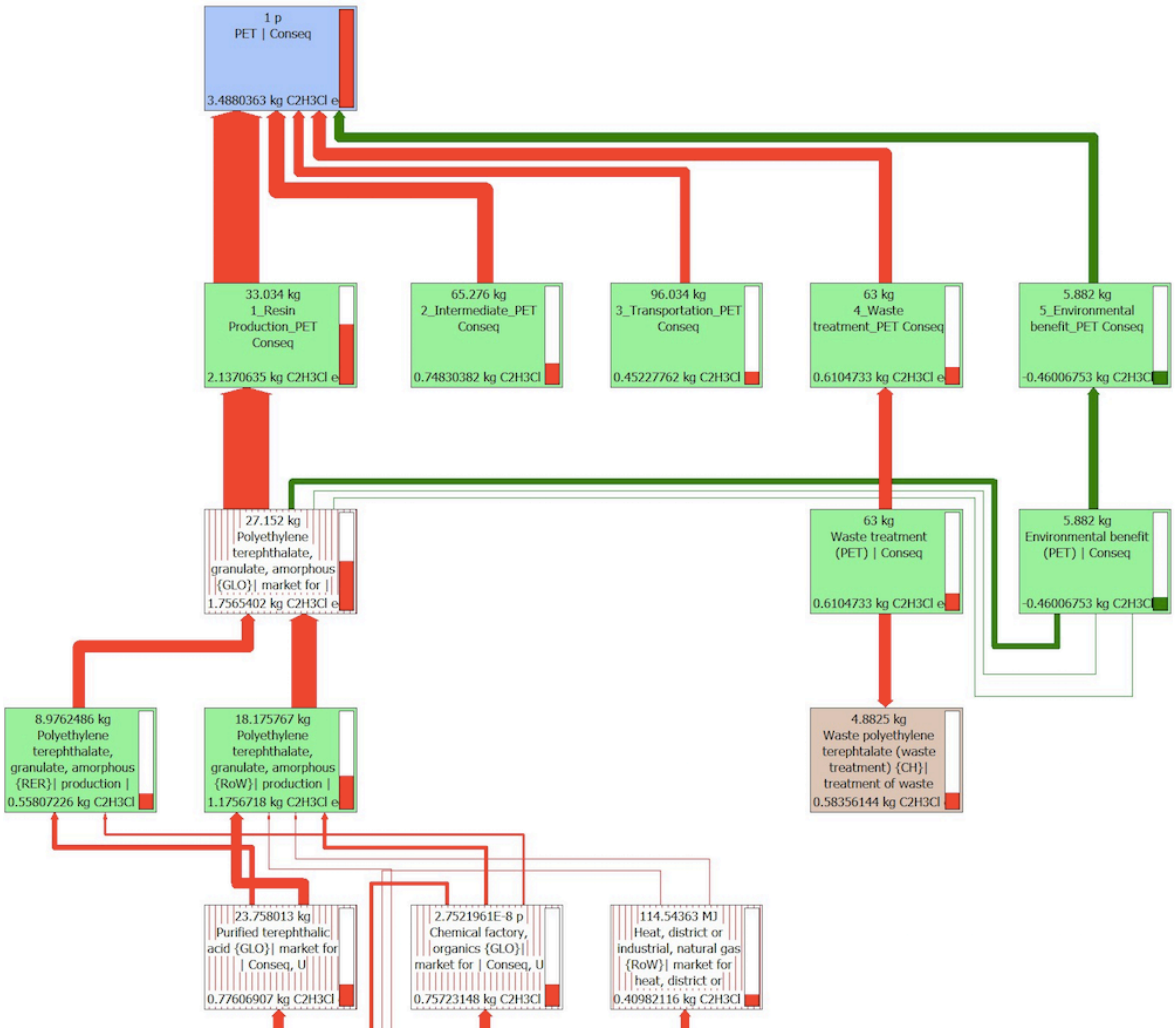

Figure 5.15. Network of PET in CLCA for non-carcinogens

Note: A 12 % cut-off rule was applied in this figure due to the abundance of nodes, and the figure shown is only a part of the full network since the figure was so large.

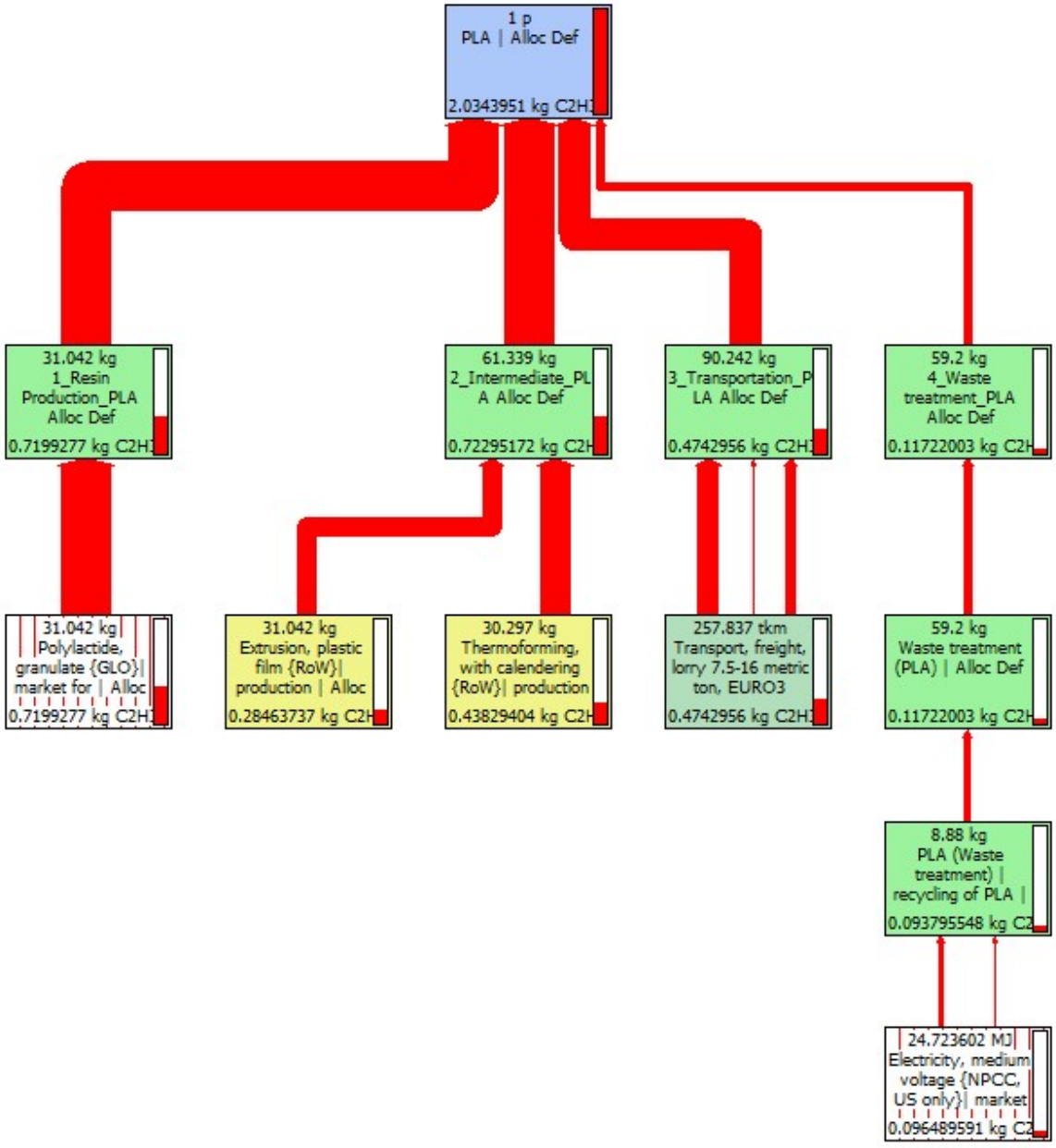

Figure 5.16. Network of PLA in ALCA for non-carcinogens

Note: A 1.5 % cut-off rule was applied in this figure due to the abundance of nodes.

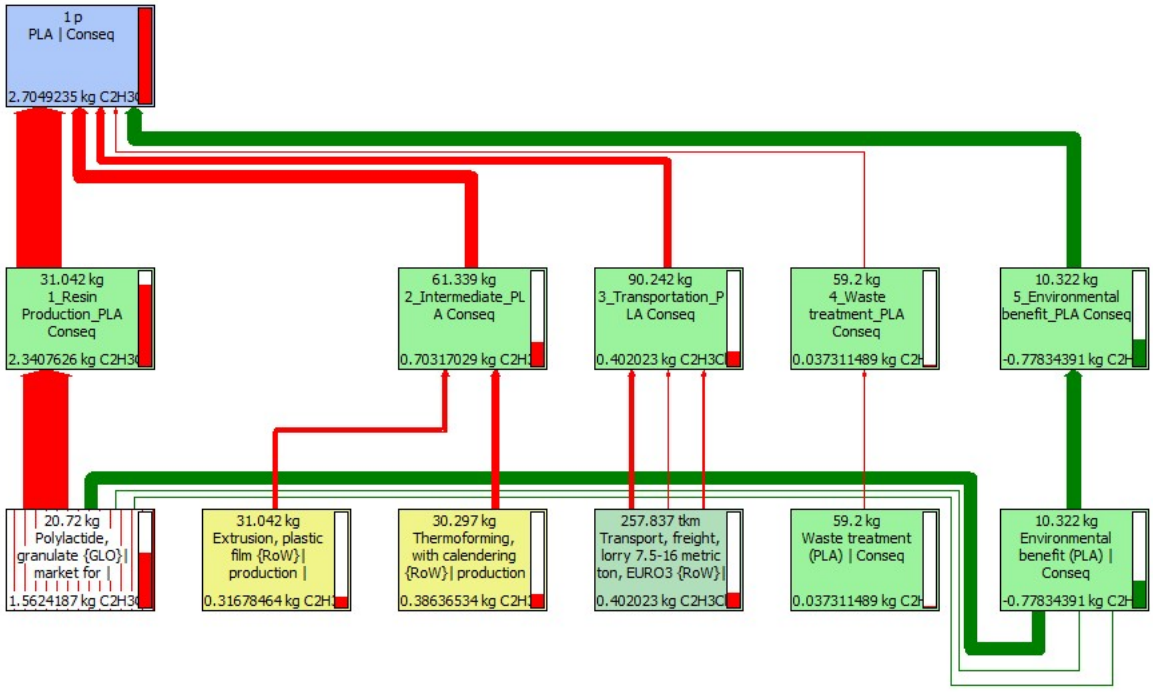

Figure 5.17. Network of PLA in CLCA for non-carcinogens

Note: A 1 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP due to non-carcinogens of PET in CLCA was higher than that of ALCA. This dissimilarity came mainly from the resin production and environmental benefit stages. Even though the environmental benefit stage in CLCA provides a negative value, the difference between resin production in ALCA and CLCA was much higher than the negative value from environmental benefit.

The EFP due to non-carcinogens of PLA in CLCA was higher than the EFP of PLA in ALCA. This dissimilarity arose mainly from PLA resin production due to heat production using natural gas, and from the environmental benefit phase including recycling. As for the PET, even though the environmental benefit in CLCA was a negative value (-0.778 kg of C_2H_3Cl), the resin production in CLCA was much higher than this negative

value. Moreover, as with PLA for carcinogens, the EFP from heat production using natural gas in CLCA was more than 10 times higher than that in ALCA. so the EFP of PLA in CLCA was higher than in ALCA.

5.4. Respiratory inorganics

The respiratory inorganics value for PLA using ALCA was more than twice as high as for PLA using CLCA. The resin production stage for PLA and PET in ALCA provided the highest contribution with 0.116 kg and 0.086 kg of PM2.5 equivalents, about 43 % and 39 % of the total EFP potential, respectively. However, in CLCA, the intermediate processes for PLA and PET had the highest contribution, were 56 % and 46 %, respectively.

Figure 5.18 through Figure 5.21 show the networks of PET and PLA in ALCA and CLCA, respectively. As before, ‘1p’ indicates the functional unit of the study, 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

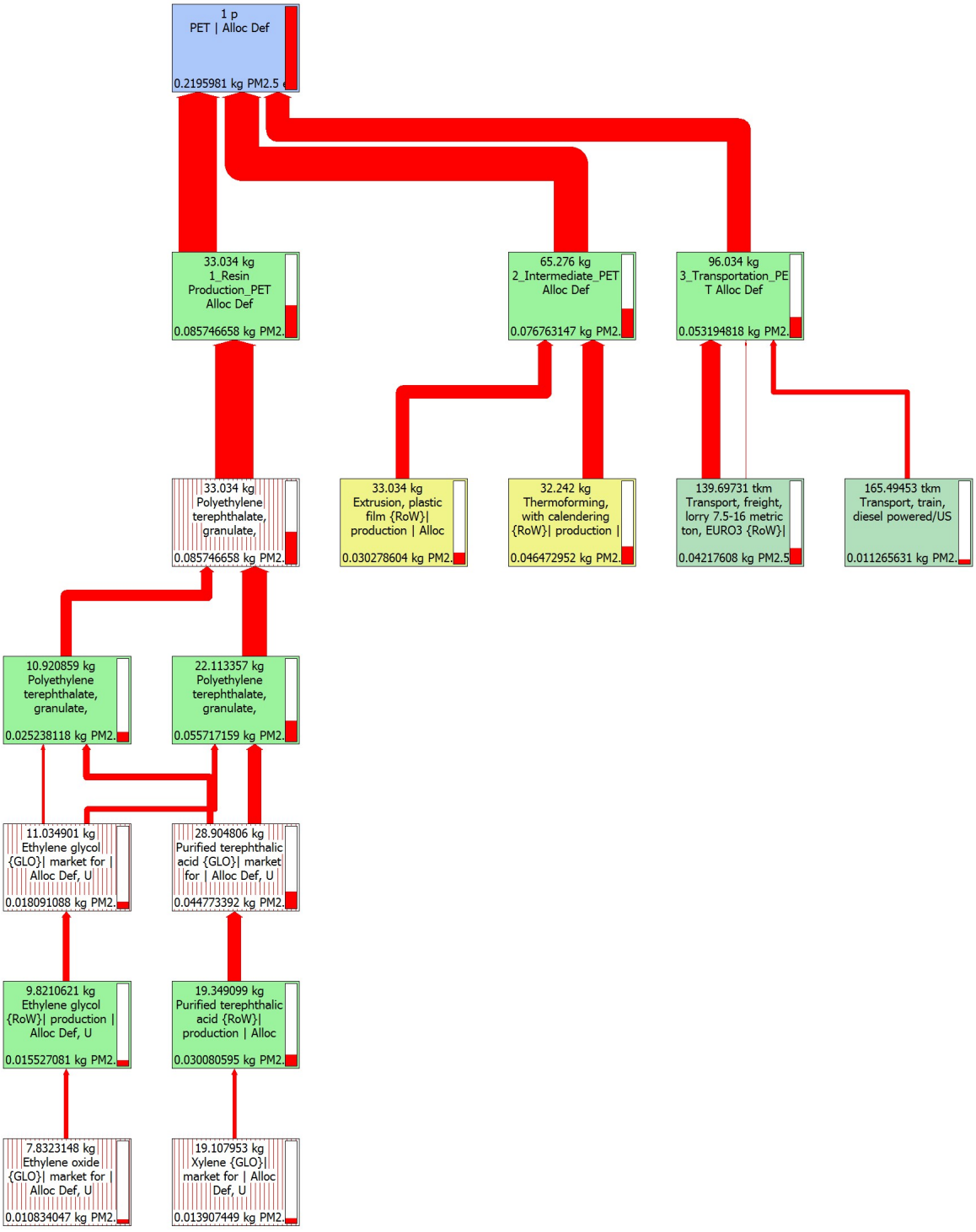

Figure 5.18. Network of PET in ALCA for respiratory inorganics

Note: A 4.9 % cut-off rule was applied in this figure due to the abundance of nodes.

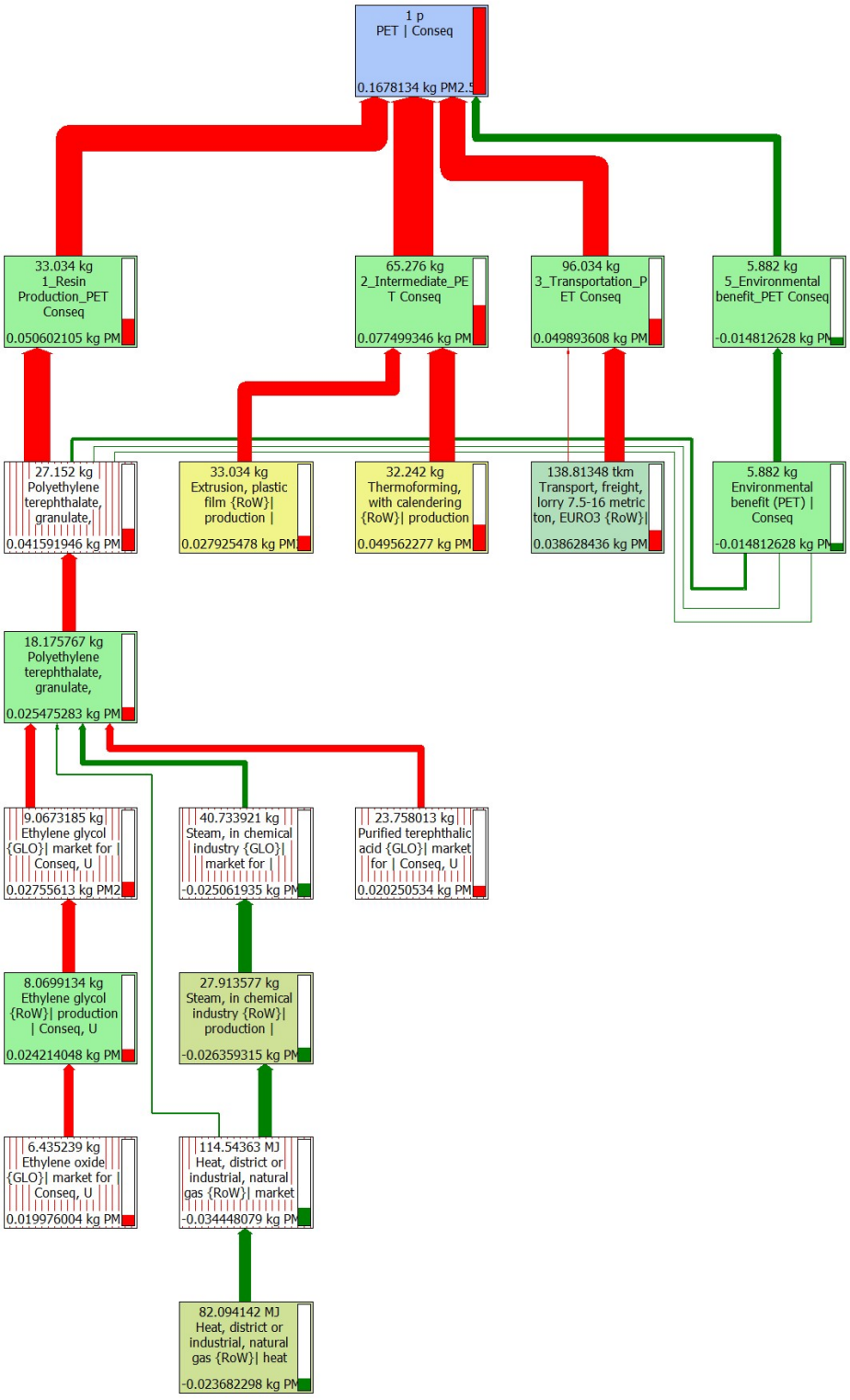

Figure 5.19. Network of PET in CLCA for respiratory inorganics

Note: A 8.8 % cut-off rule was applied in this figure due to the abundance of nodes.

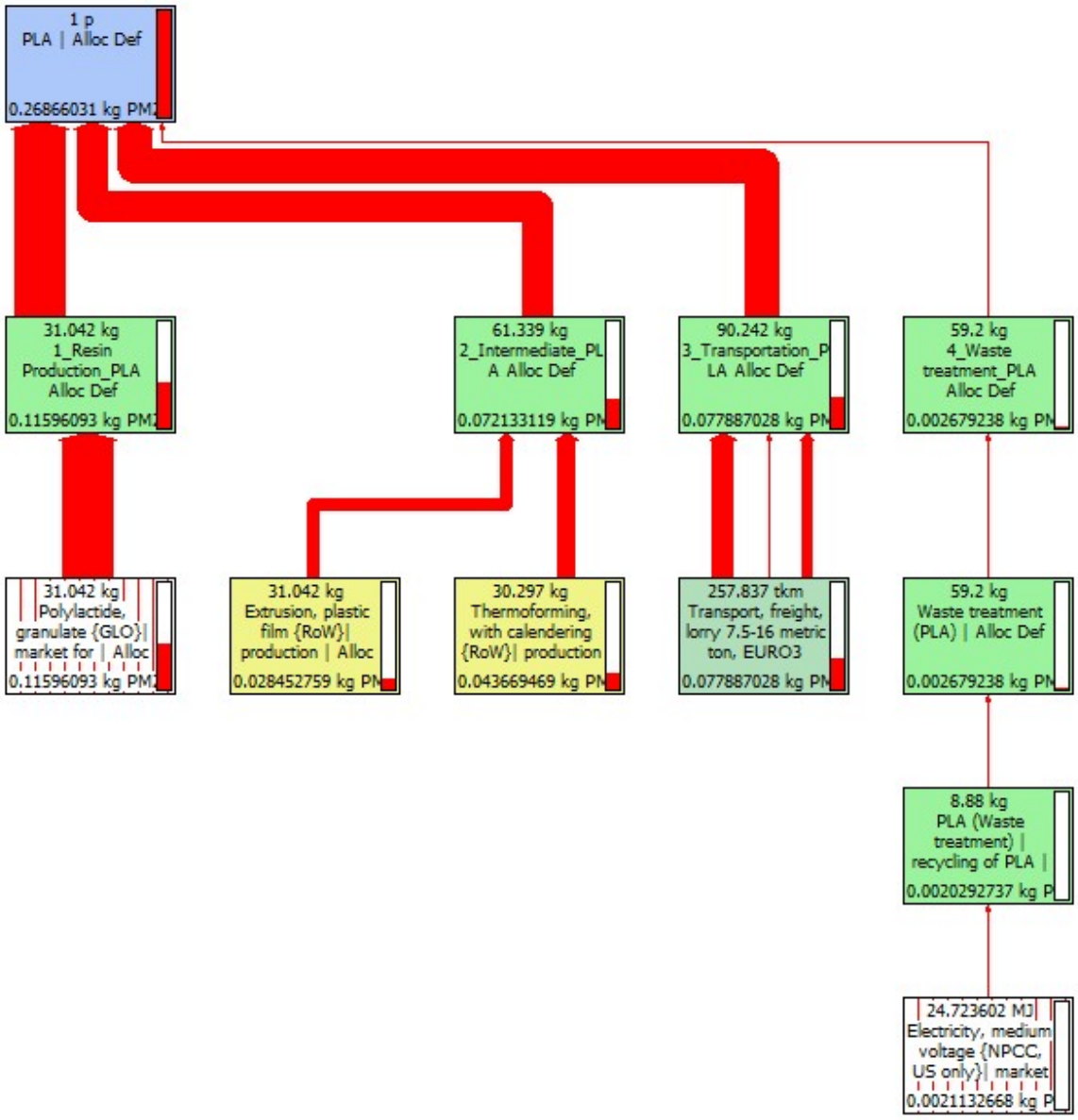

Figure 5.20. Network of PLA in ALCA for respiratory inorganics

Note: A 0.77 % cut-off rule was applied in this figure due to the abundance of nodes.

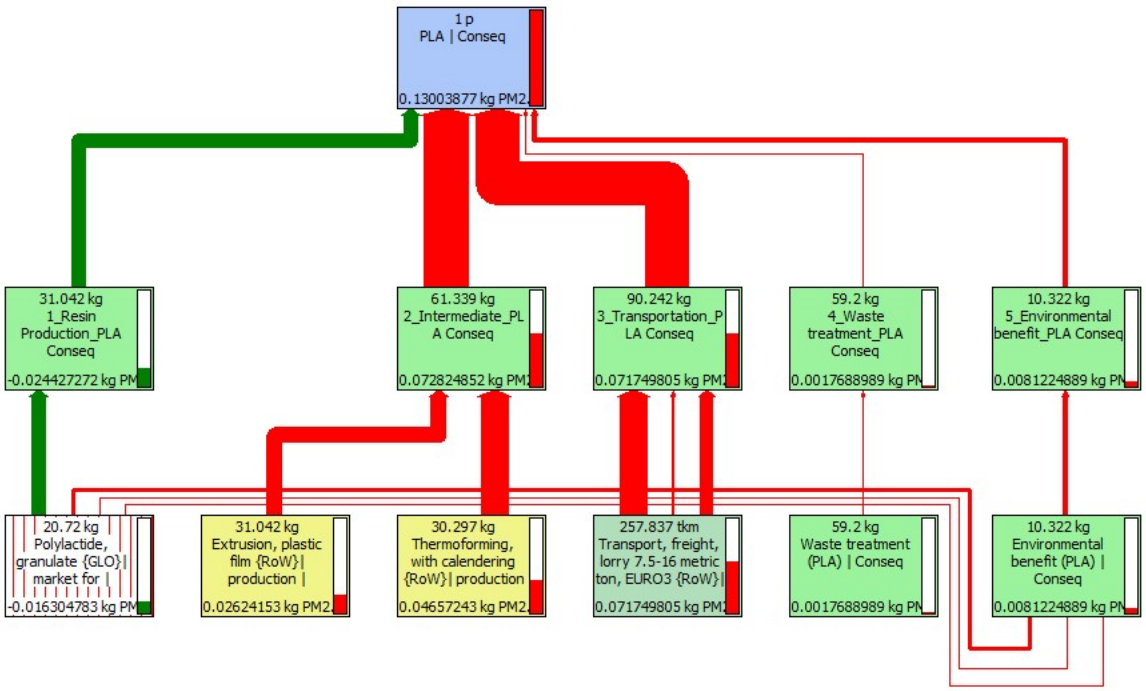

Figure 5.21. Network of PLA in CLCA for respiratory inorganics

Note: A 17 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP due to respiratory inorganics of PET in ALCA was higher than in CLCA. The difference came from the resin production phase and the environmental benefit phase. For the respiratory inorganics, the the EFP of steam production in the PET resin production process was negative due to a number of electricity processes in CLCA. Therefore, the EFP of PET in CLCA was lower than in ALCA. The networks for 40.7 kg of steam production for respiratory inorganics in ALCA and CLCA are shown in Figure 5.22 and Figure 5.23.

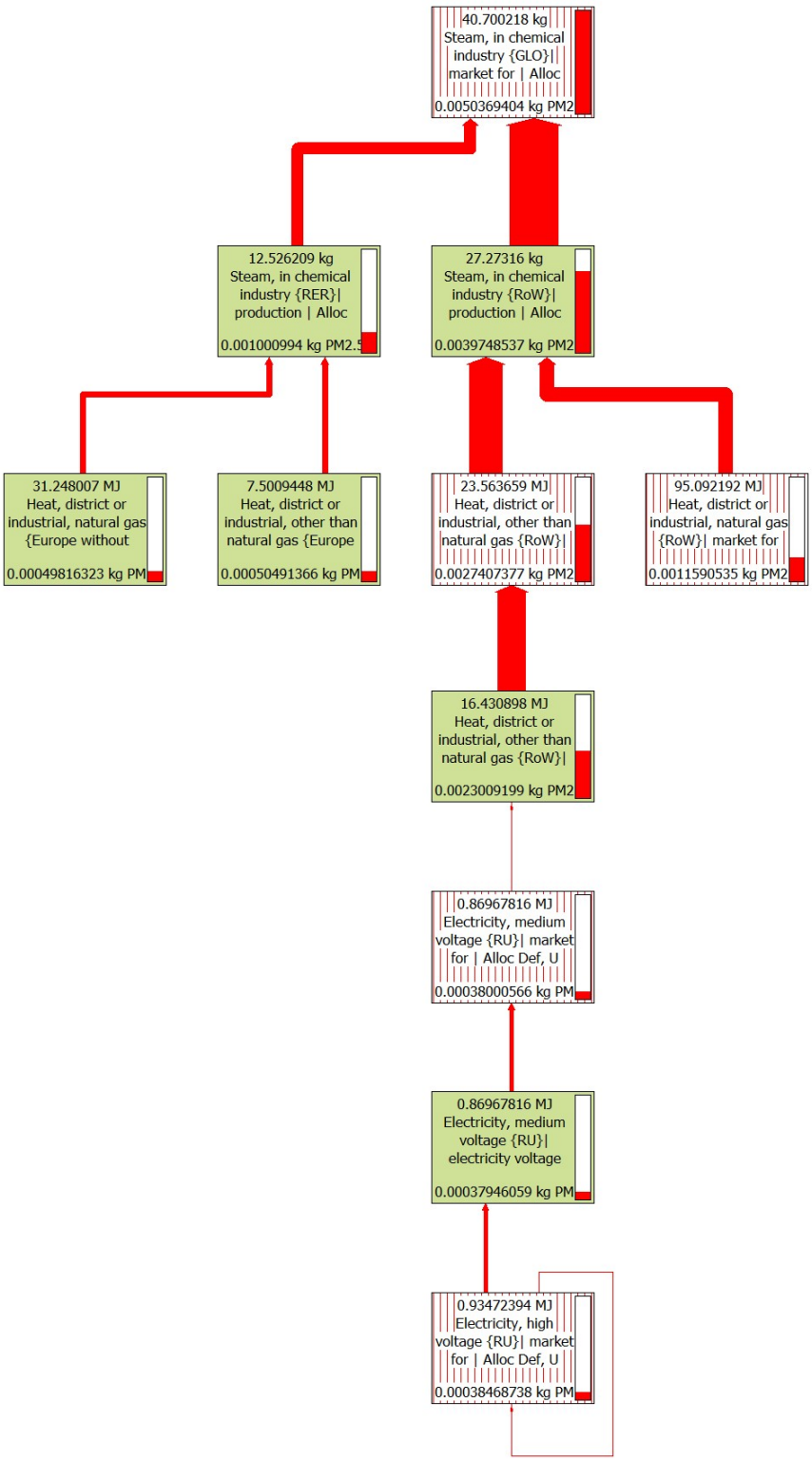

Figure 5.22. Network of steam production of PET in ALCA for respiratory inorganics

Note: A 7.6 % cut-off rule was applied in this figure due to the abundance of nodes.

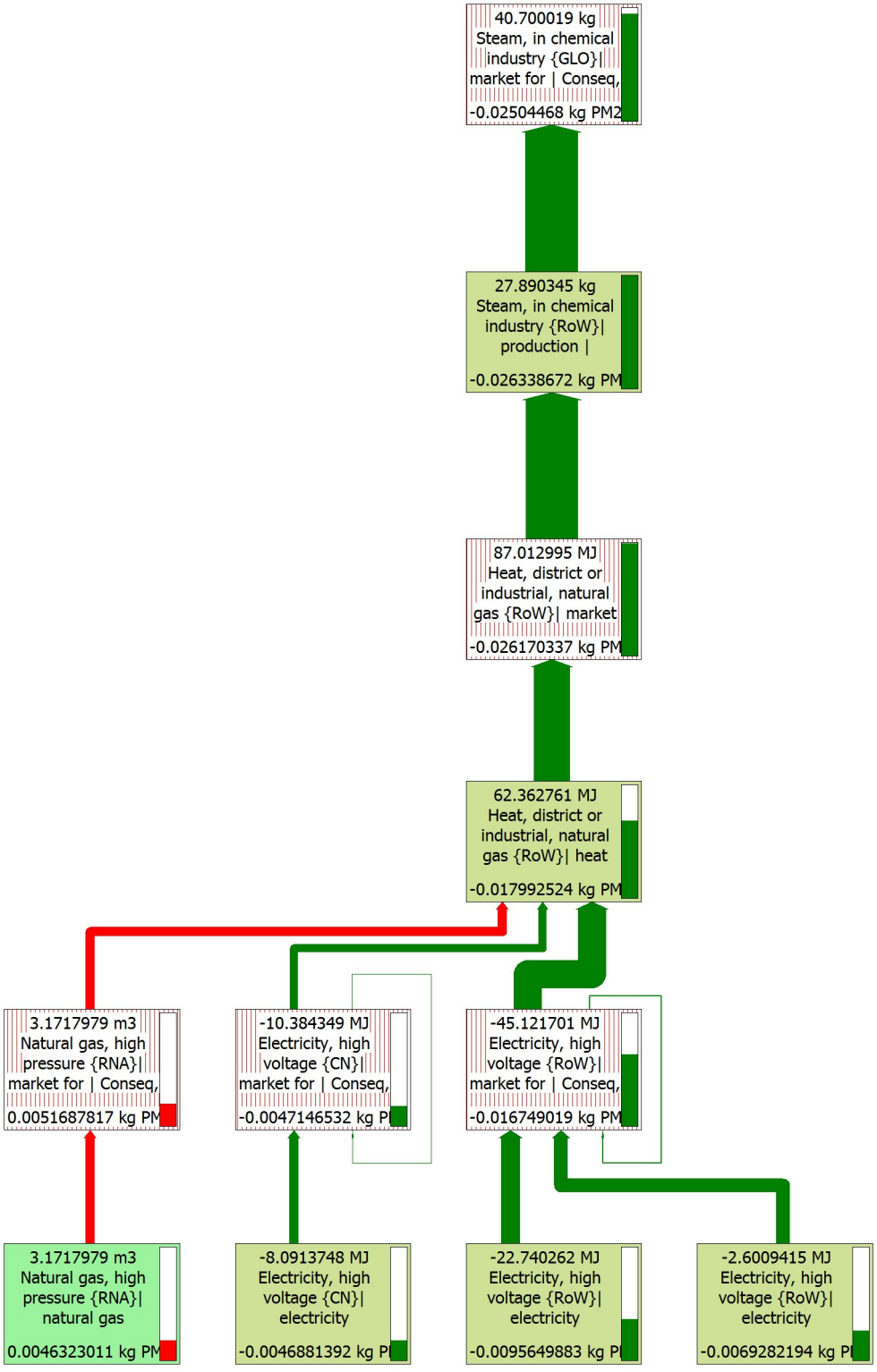

Figure 5.23. Network of steam production of PET in CLCA for respiratory inorganics

Note: A 16.6 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP due to respiratory inorganics of PLA in CLCA was lower than the EFP of PLA in ALCA. This difference arose mainly from PLA resin production due to heat production using electricity and from the environmental benefit stage including recycling. As shown in Figure 5.21, the EFP due to resin production in CLCA is negative because of the heat process . The networks of 318 MJ of heat, which was used for PLA resin production, for respiratory inorganics in ALCA and CLCA are shown in Figure 5.24 and Figure 5.25.

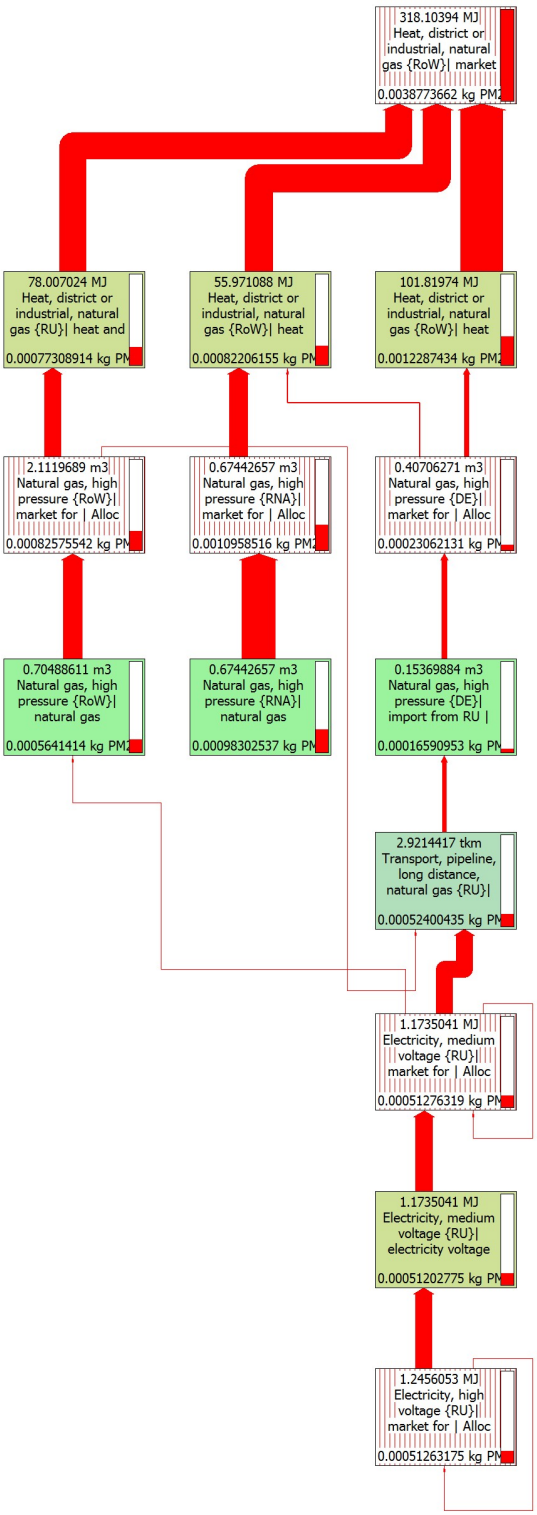

Figure 5.24. Network of heat process of PLA in ALCA for respiratory inorganics

Note: A 13.2 % cut-off rule was applied in this figure due to the abundance of nodes.

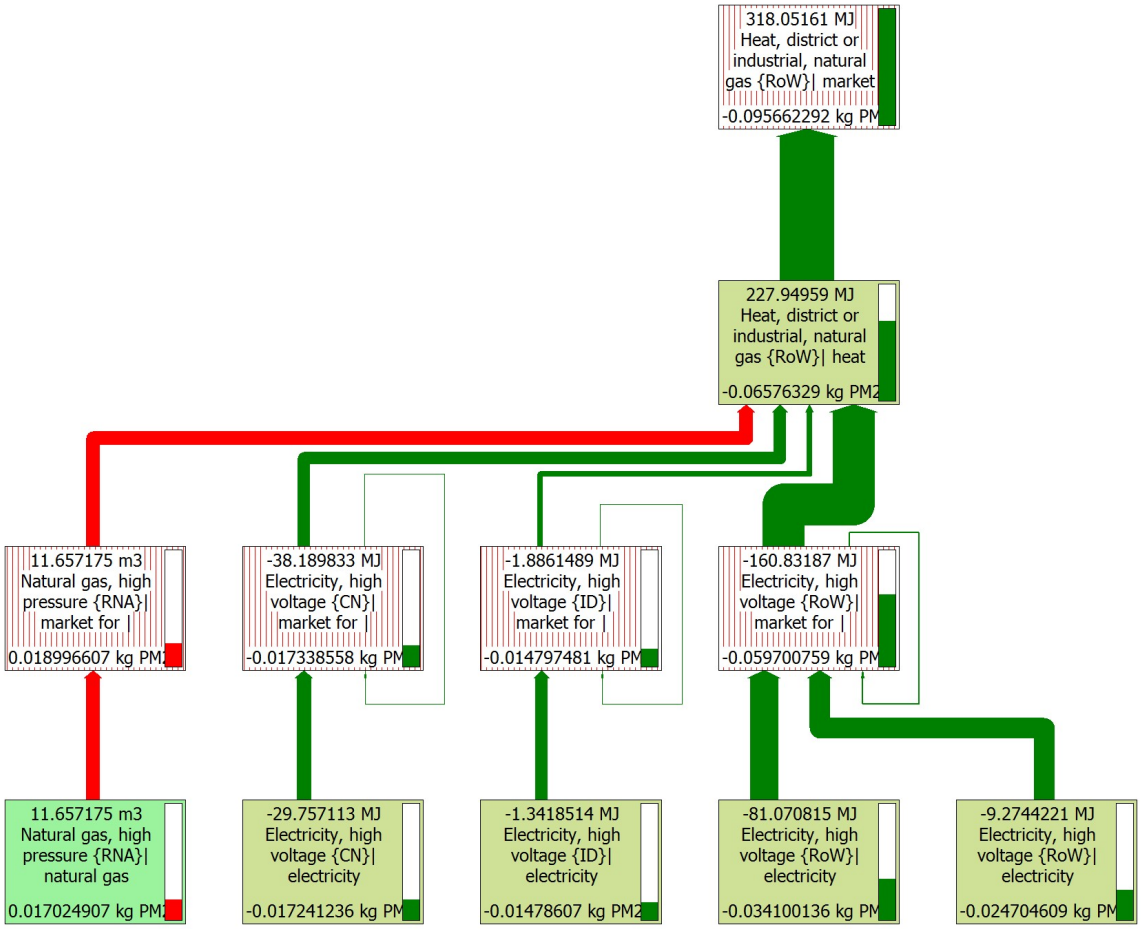

Figure 5.25. Network of heat process of PLA in CLCA for respiratory inorganics

Note: A 15.4 % cut-off rule was applied in this figure due to the abundance of nodes.

5.5. Ionizing radiation

Ionizing radiation for PLA in ALCA was the highest with 3022 Bq C-14 equivalents, and for PET in CLCA was the lowest with -1261 Bq C-14 equivalents. The resin production phase in ALCA for PLA and PET contributed about 47 % and 42 % of the total indicator. For PLA and PET in CLCA, however, intermediate processes had the highest contribution with 708 Bq and 753 Bq C-14 equivalents. The total EFP for PET in CLCA was – 1261 Bq C-14 equivalents.

Figure 5.26 through Figure 5.29 show networks of PET and PLA in ALCA and CLCA, respectively. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

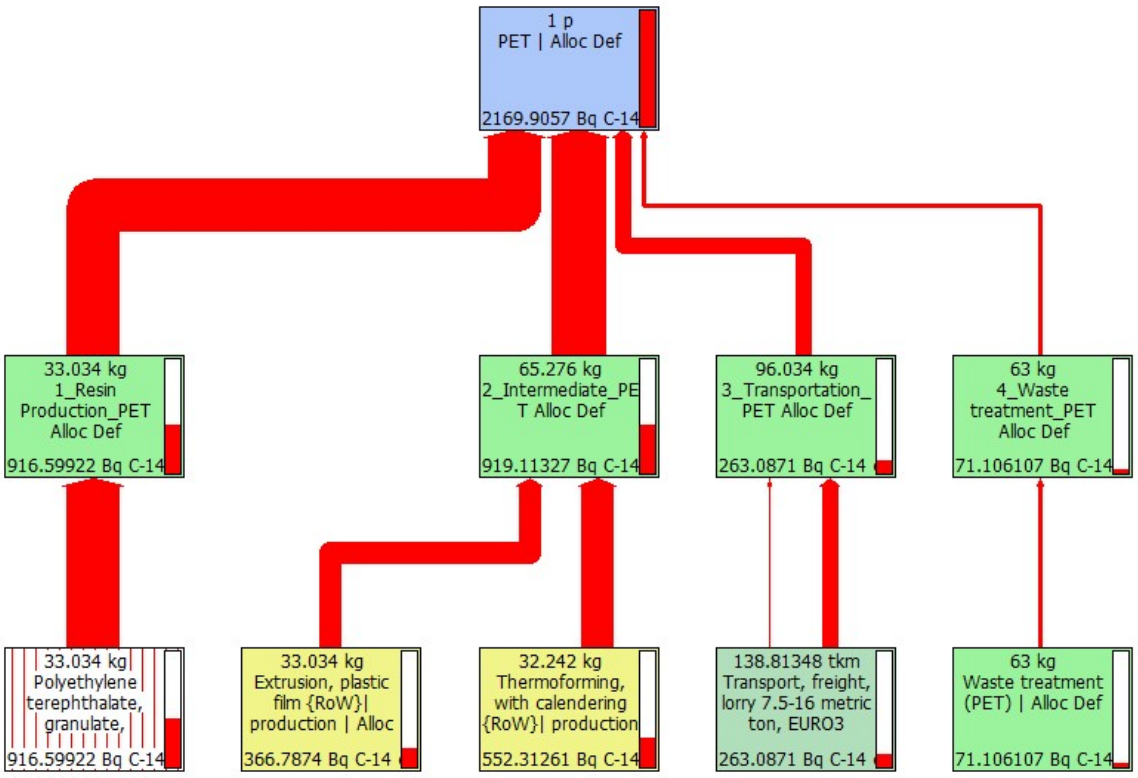

Figure 5.26. Network of PET in ALCA for ionizing radiation

Note: A 2.2 % cut-off rule was applied in this figure due to the abundance of nodes.

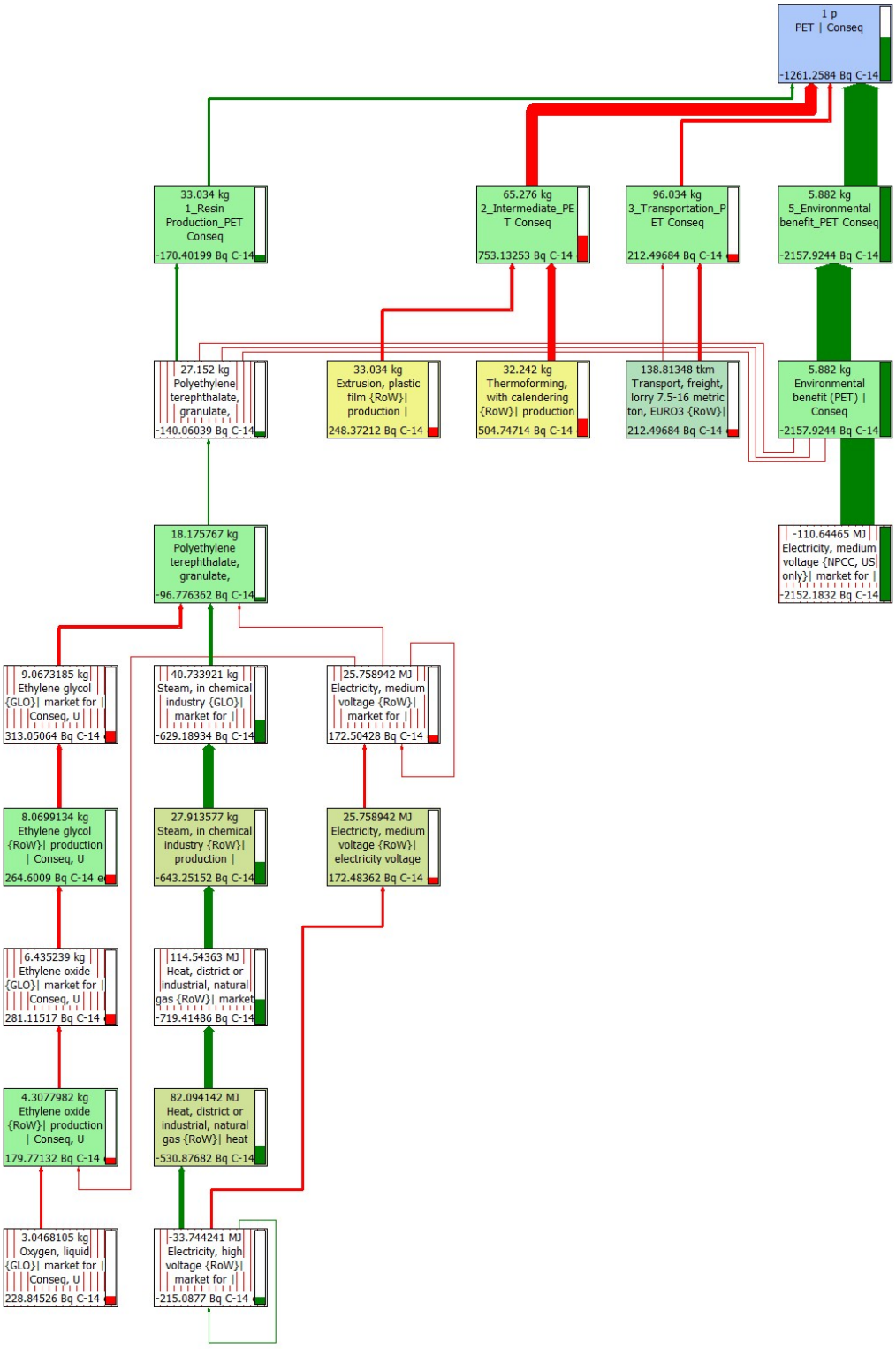

Figure 5.27. Network of PET in CLCA for ionizing radiation

Note: A 7.8 % cut-off rule was applied in this figure due to the abundance of nodes.

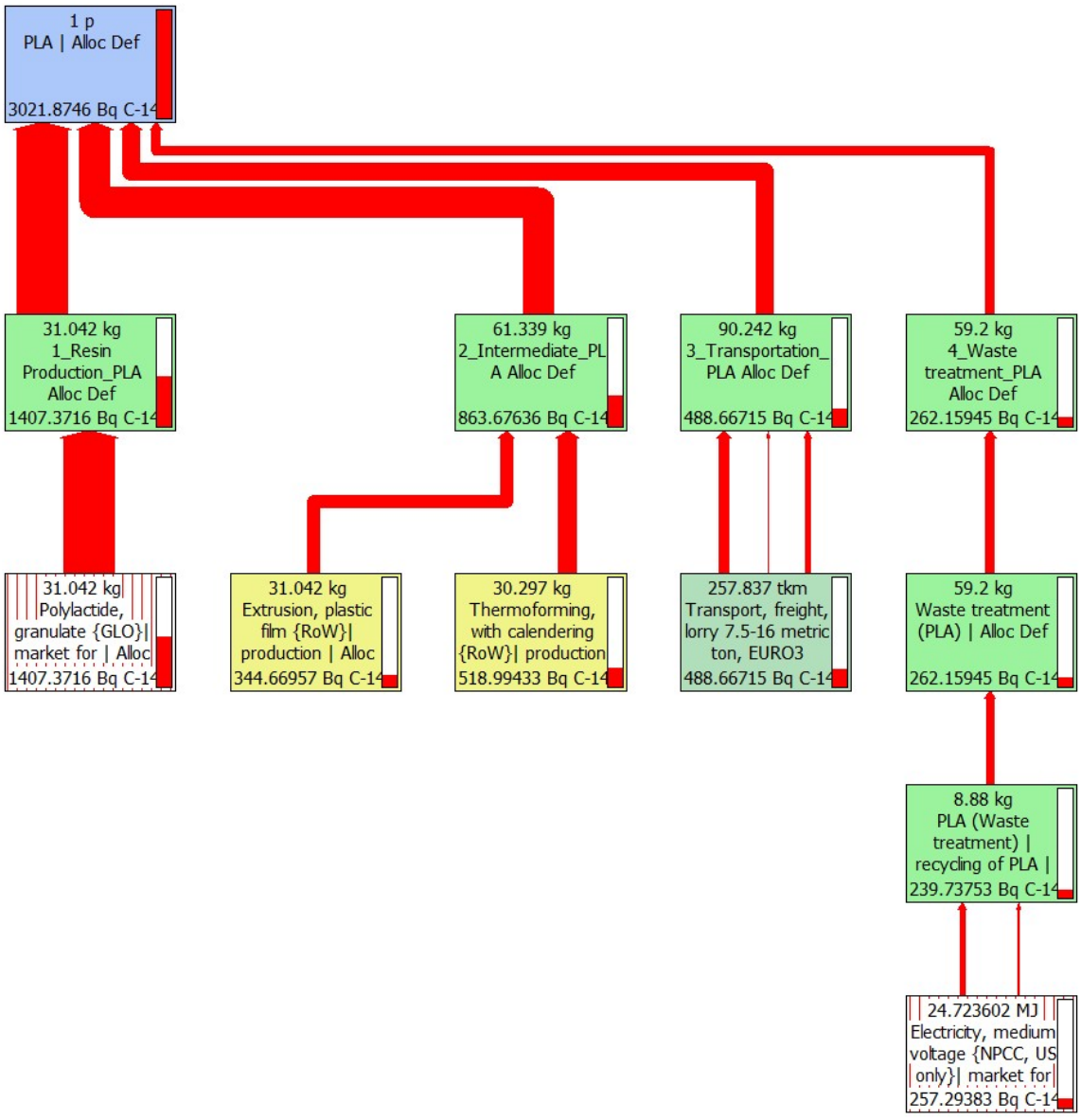

Figure 5.28. Network of PLA in ALCA for ionizing radiation

Note: A 2 % cut-off rule was applied in this figure due to the abundance of nodes.

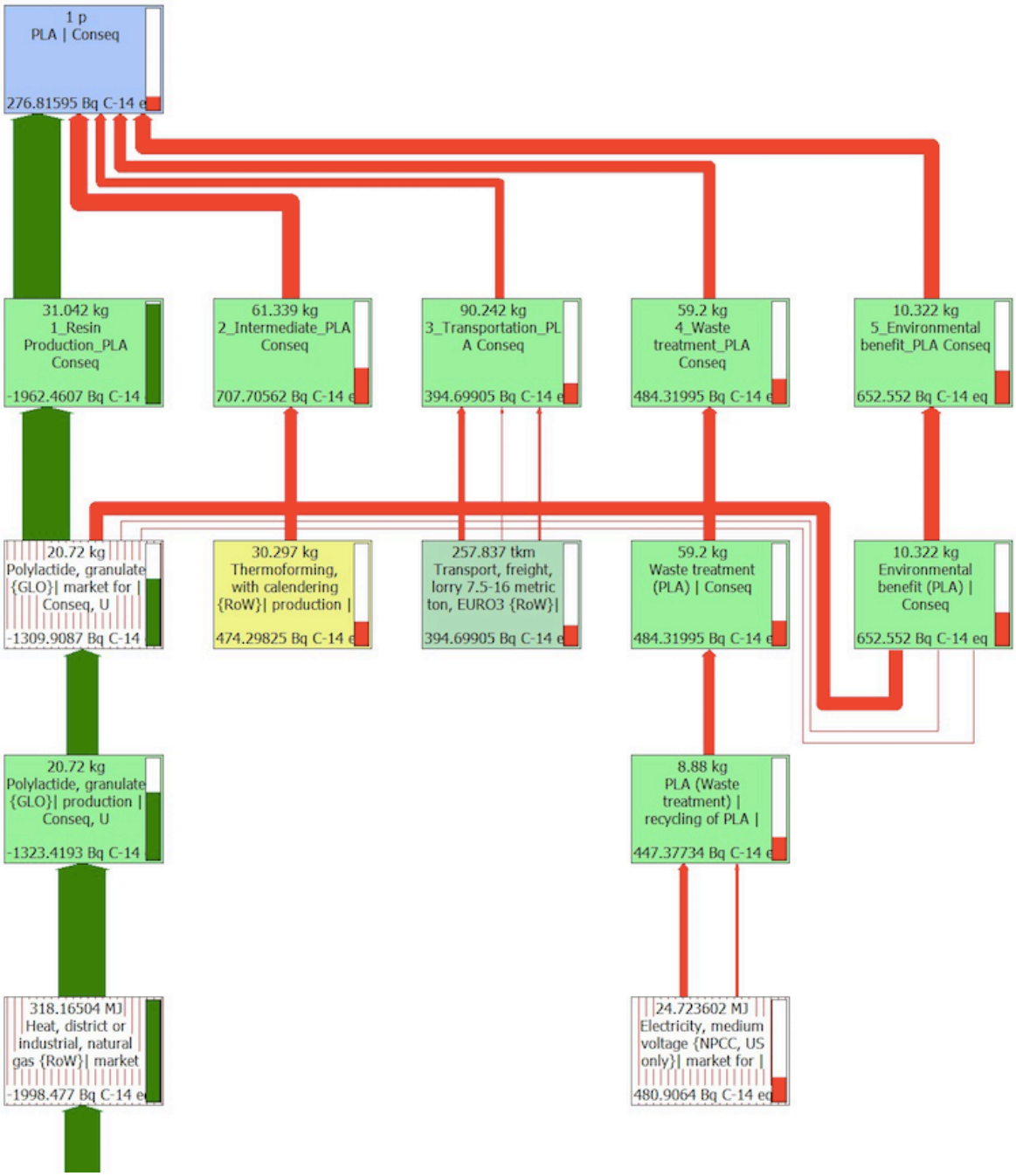

Figure 5.29. Network of PLA in CLCA for ionizing radiation

Note: A 19 % cut-off rule was applied in this figure due to the abundance of nodes, and the figure shown is only a part of the full network since the figure was so large.

The EFP due to ionizing radiation of PET in ALCA was much higher than in CLCA.

The difference arose mostly from the resin production and the environmental benefit phases.

Especially, the EFP of the environmental benefit stage was -2158 Bq C-14 equivalent. The EFP of resin production in CLCA was -170 Bq C-14 due to the steam process, similarly to respiratory inorganics.

The EFP of PLA in CLCA was lower than in ALCA. The dissimilarity came mainly from the resin production stage due to the heat process, which was from electricity made using uranium and nuclear fuel elements, similarly to respiratory inorganics.

5.6. Ozone layer depletion

For ozone layer depletion, PLA using ALCA was the highest and PET using CLCA was the lowest. For PLA and PET in ALCA and CLCA, the major contributor was resin production, around 42 % and 44 % for PLA in ALCA and CLCA and 52 % and 60 % of the total EFP for PET in ALCA and CLCA, respectively.

Figure 5.30 through Figure 5.33 show the networks of PET and PLA in ALCA and CLCA. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

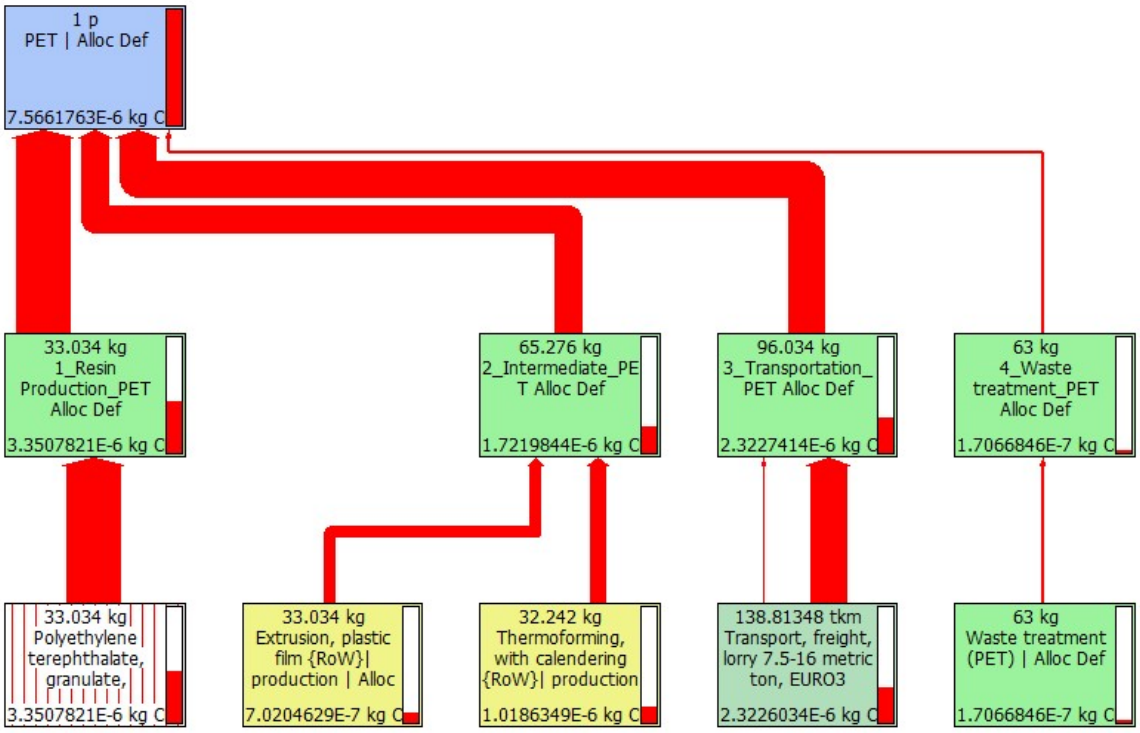

Figure 5.30. Network of PET in ALCA for ozone layer depletion

Note: A 1.5 % cut-off rule was applied in this figure due to the abundance of nodes.

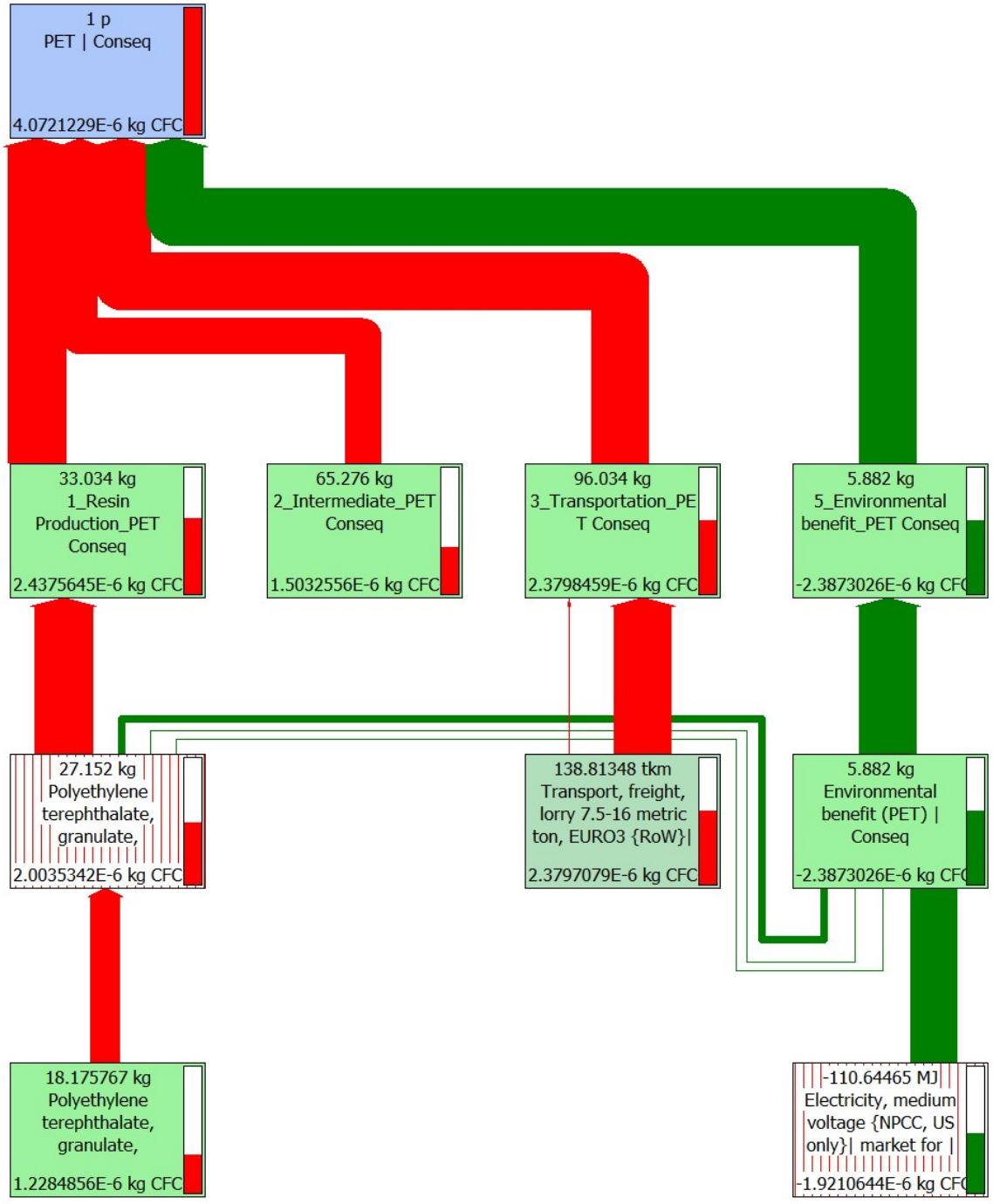

Figure 5.31. Network of PET in CLCA for ozone layer depletion

Note: A 28 % cut-off rule was applied in this figure due to the abundance of nodes.

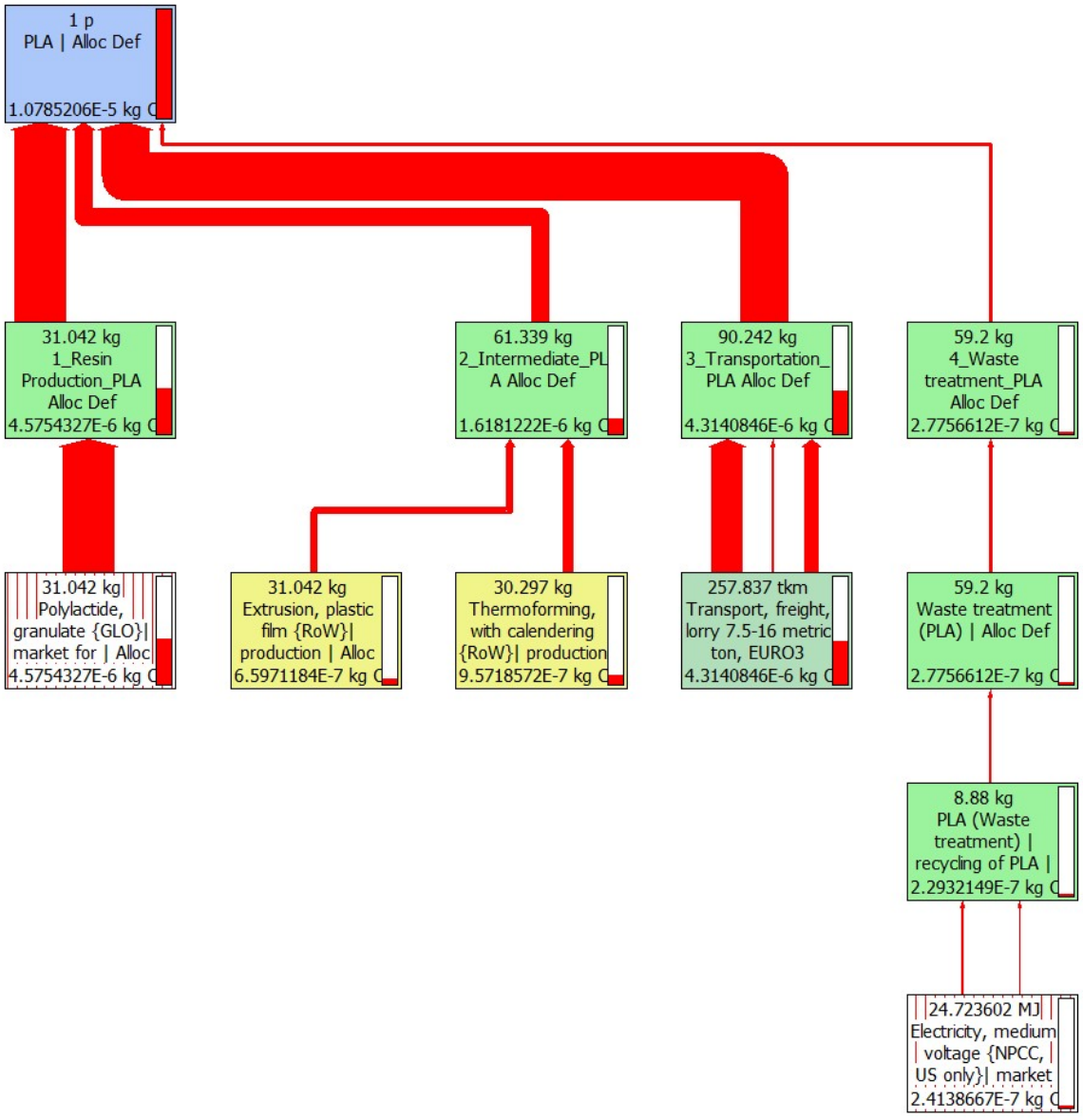

Figure 5.32. Network of PLA in ALCA for ozone layer depletion

Note: A 2 % cut-off rule was applied in this figure due to the abundance of nodes.

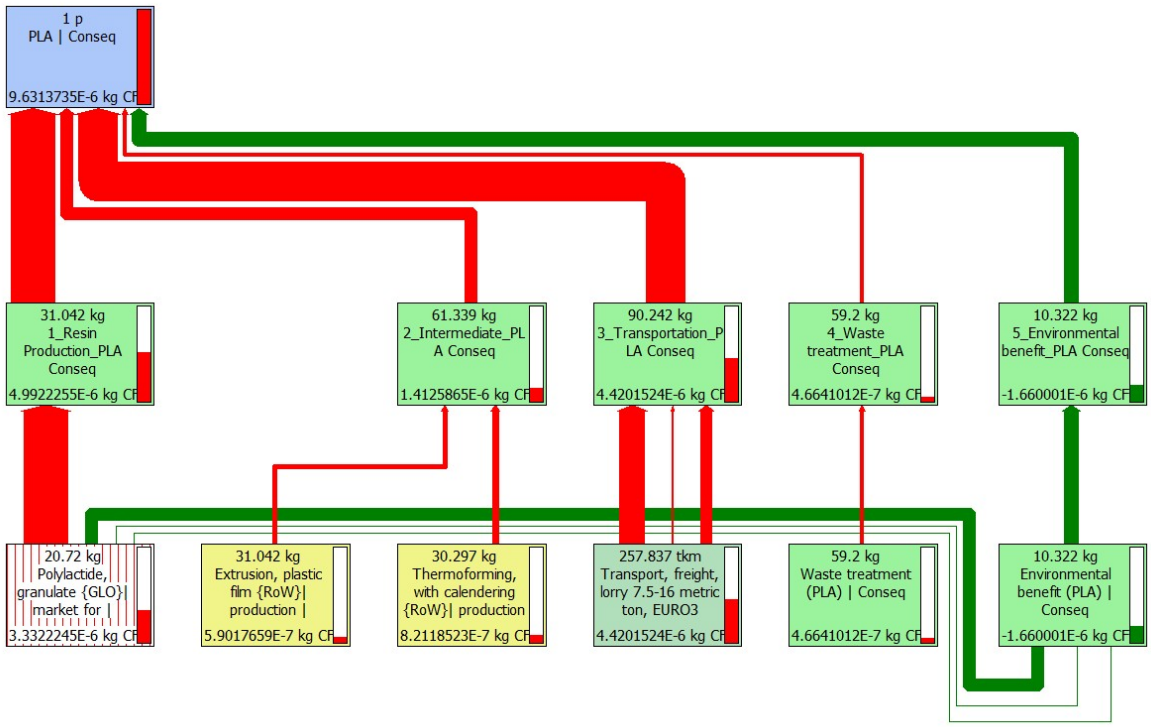

Figure 5.33. Network of PLA in CLCA for ozone layer depletion

Note: A 4.5 % cut-off rule was applied in this figure due to the abundance of nodes.

For the EFP of ozone layer depletion of PET and PLA in ALCA and CLCA, PET in ALCA were higher than in CLCA. The difference came mainly from the environmental benefit phase including recycling, landfill and energy recovery from incineration.

5.7. Respiratory organics

For the respiratory organics impact category, there were only small differences between ALCA and CLCA for both PLA and PET For PLA, the values were 0.1296 kg C_2H_4 and 0.1240 kg C_2H_4, in ALCA and CLCA, respectively. For PET in ACLA and CLCA, the amounts were 0.1085 kg C_2H_4 and 0.1038 kg C_2H_4. The resin production

stages for PLA contributed 0.0711 kg of C_2H_4 and 0.0893 kg of C_2H_4, about 55 % and 72 % of the total kg of ethylene equivalents into air in ALCA and CLCA, respectively. For PET, the resin production stages also had the highest environmental impact, 0.0672 kg and 0.0735 kg of C_2H_4 in ALCA and CLCA, respectively.

Figure 5.34 through Figure 5.37 show networks of PET and PLA in ALCA and CLCA. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

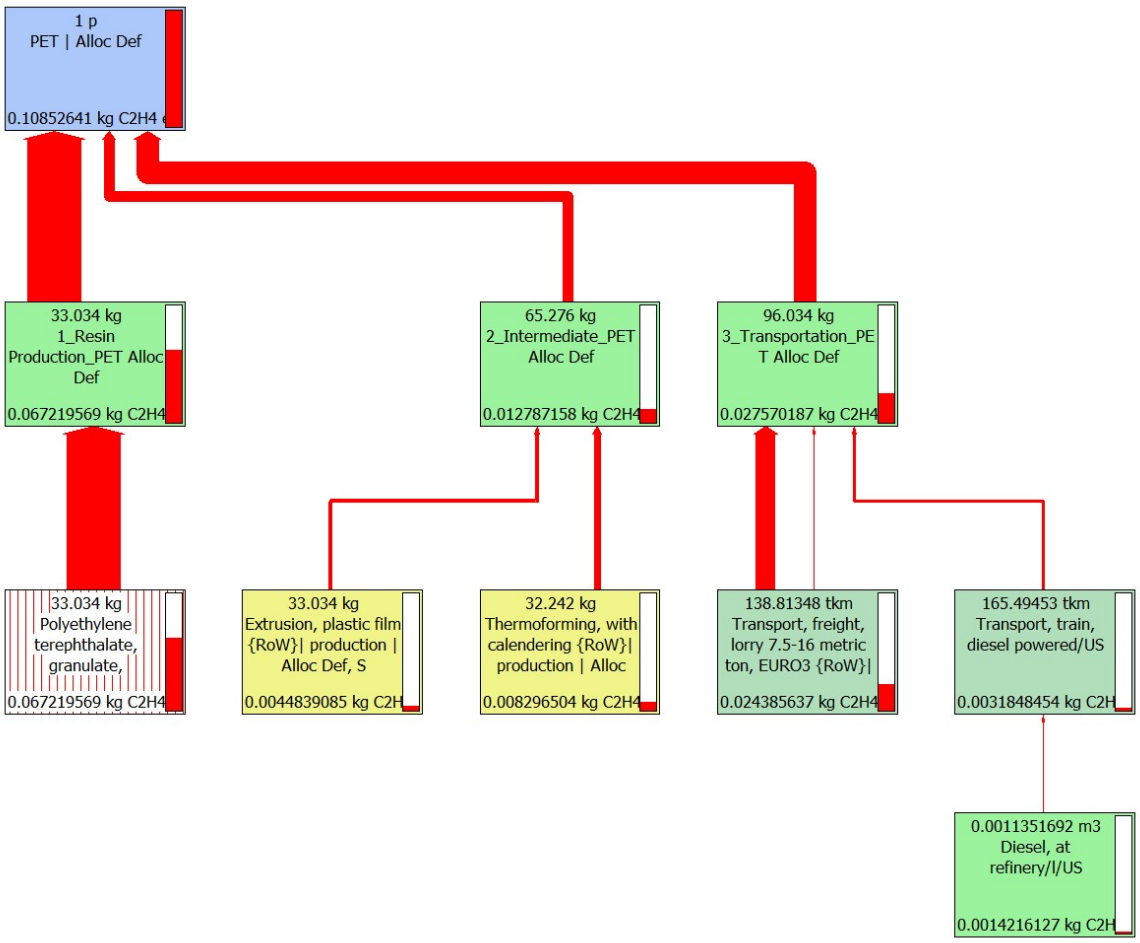

Figure 5.34. Network of PET in ALCA for respiratory organics

Note: A 1.2 % cut-off rule was applied in this figure due to the abundance of nodes.

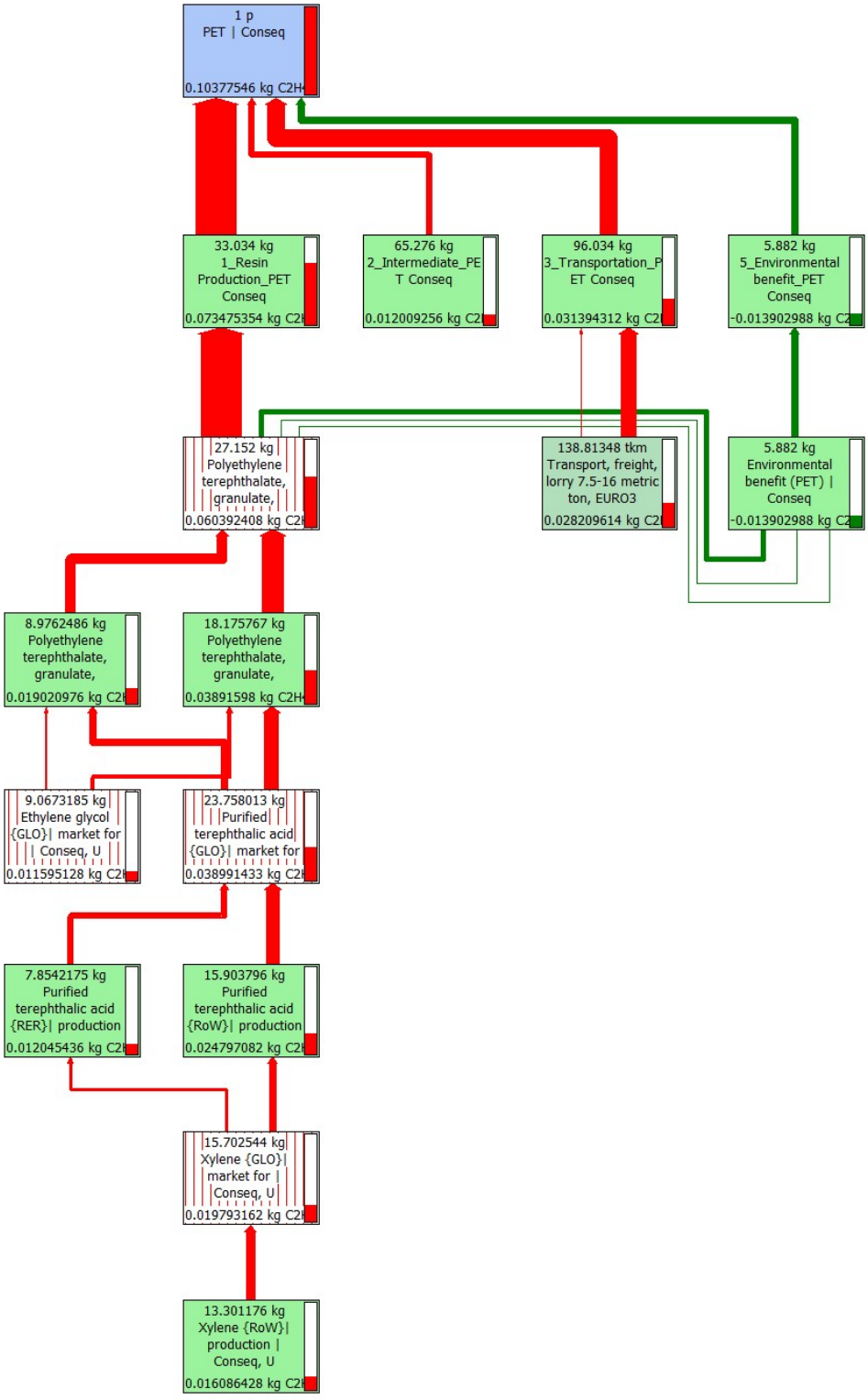

Figure 5.35. Network of PET in CLCA for respiratory organics

Note: A 11 % cut-off rule was applied in this figure due to the abundance of nodes.

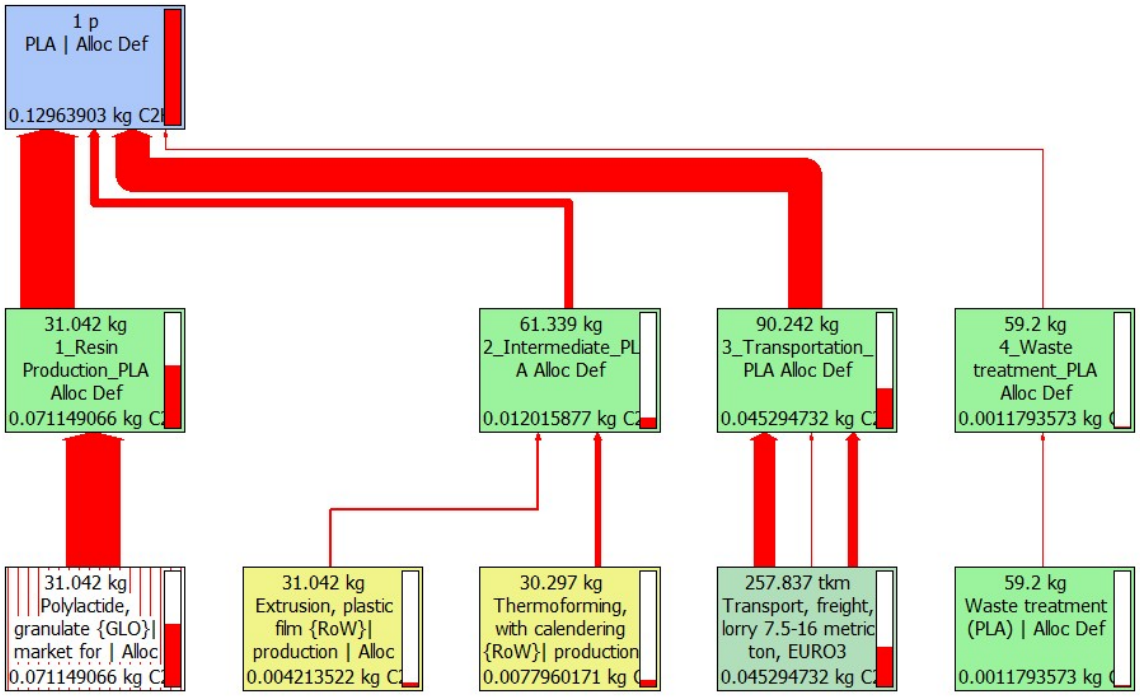

Figure 5.36. Network of PLA in ALCA for respiratory organics

Note: A 0.6 % cut-off rule was applied in this figure due to the abundance of nodes.

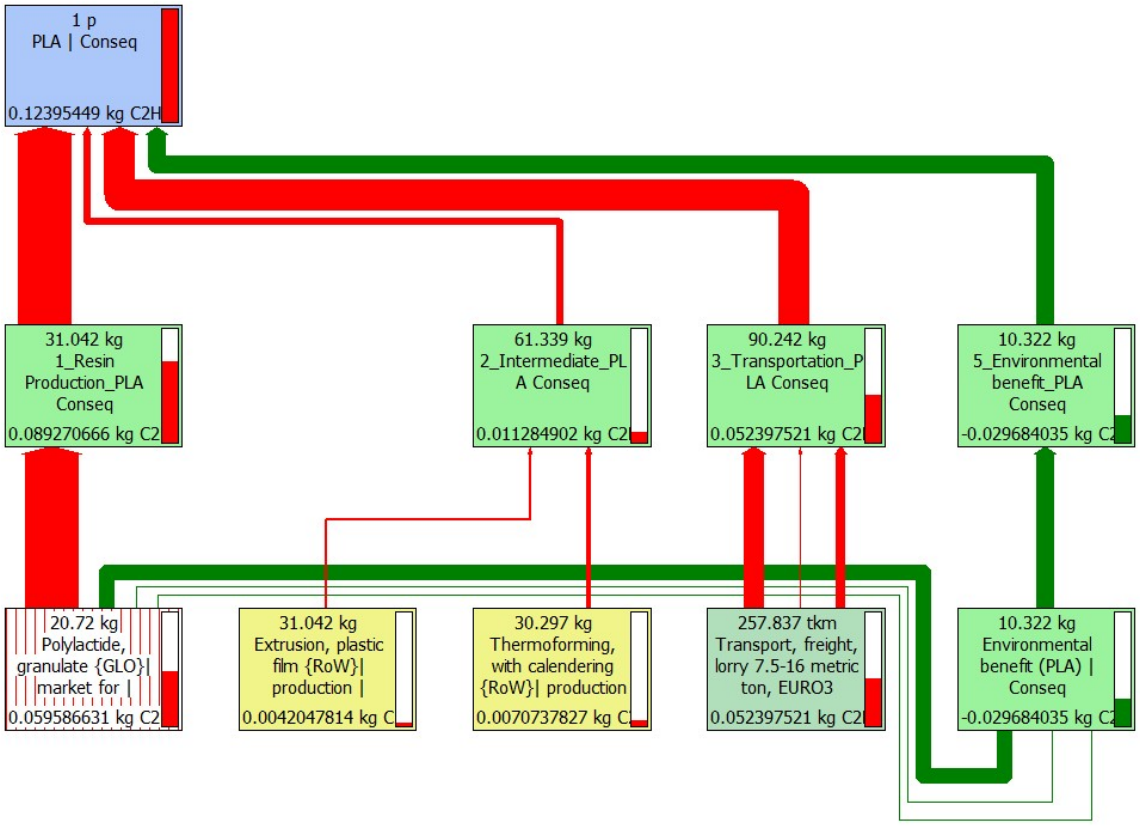

Figure 5.37. Network of PLA in CLCA for respiratory organics

Note: A 0.7 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP due to respiratory organics of PET and PLA in ALCA were a higher than in CLCA.. The major difference came from the environmental benefit phase including recycling, and energy recovery from incineration.

5.8. Aquatic ecotoxicity

The aquatic ecotoxicity of PET using ALCA was the lowest, followed by PET using CLCA. The highest value was for PLA using ALCA followed by PLA in CLCA. Similarly with other impact categories, the resin production stages for PLA and PET in ALCA and

CLCA were the highest contributors with 66 %, 44 %, 89 % and 62 % of the total indicator for PLA in ALCA and CLCA and for PET in ALCA and CLCA, respectively.

Figure 5.38 through Figure 5.41 show networks of PET and PLA in ALCA and CLCA. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

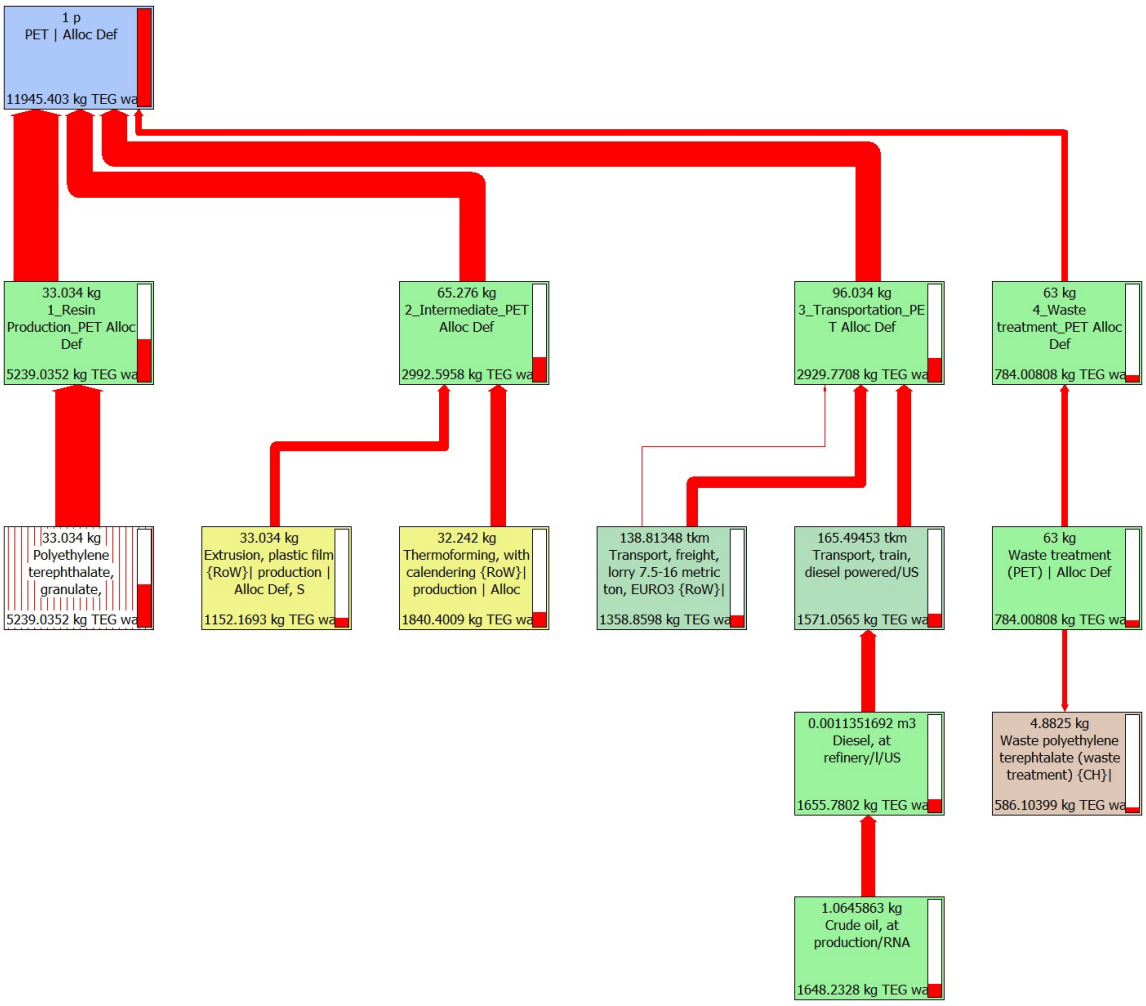

Figure 5.38. Network of PET in ALCA for aquatic ecotoxicity

Note: A 1.2 % cut-off rule was applied in this figure due to the abundance of nodes.

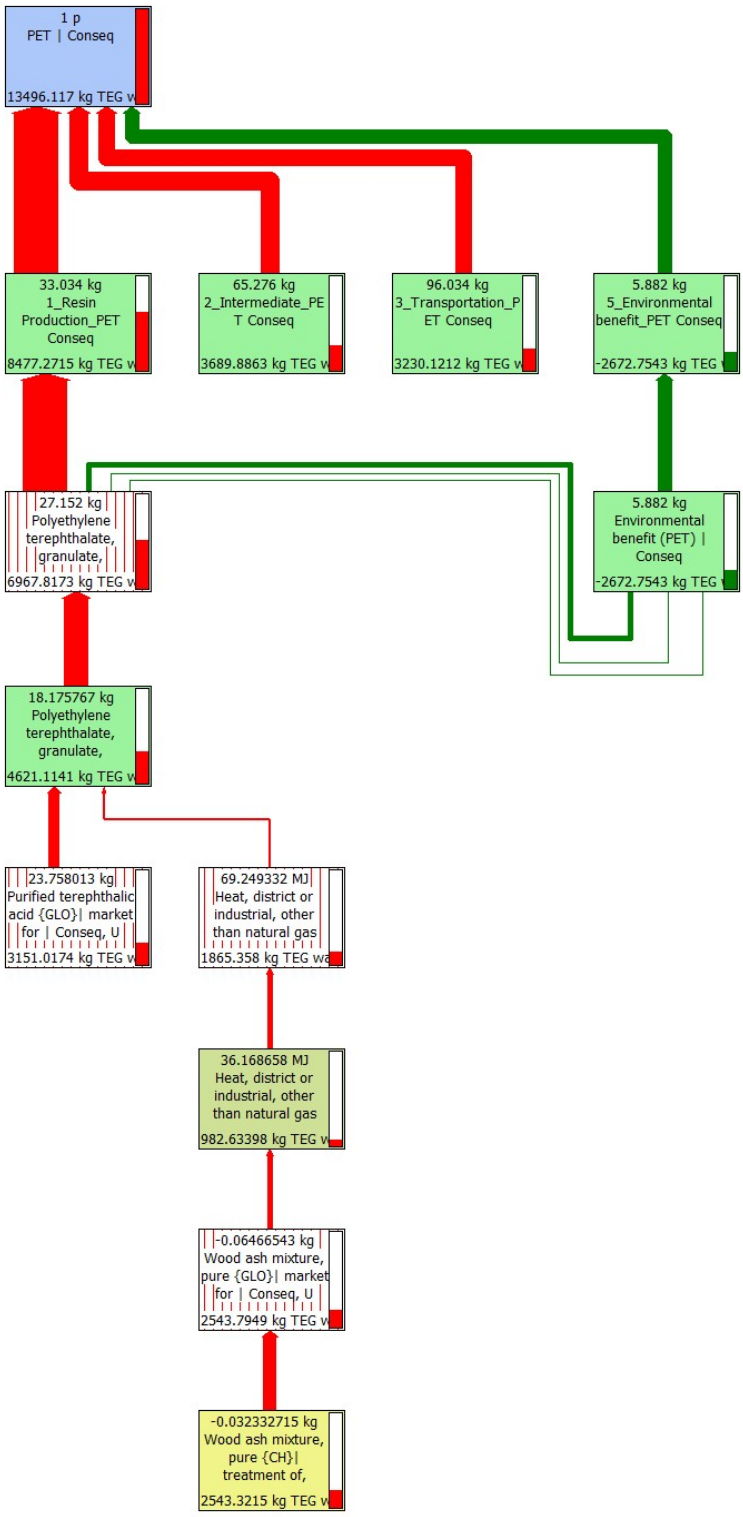

Figure 5.39. Network of PET in CLCA for aquatic ecotoxicity

Note: A 17 % cut-off rule was applied in this figure due to the abundance of nodes.

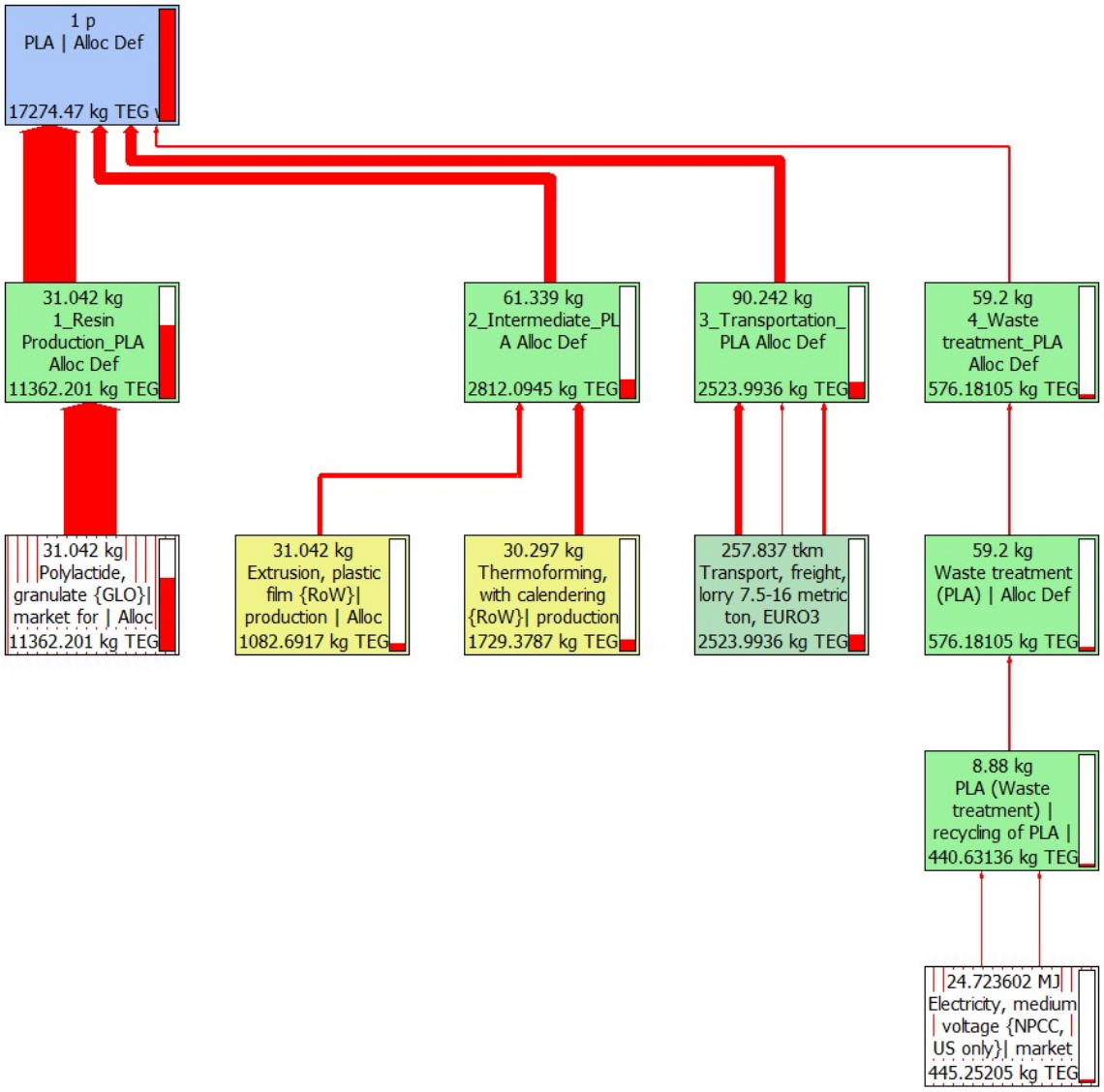

Figure 5.40. Network of PLA in ALCA for aquatic ecotoxicity

Note: A 0.9 % cut-off rule was applied in this figure due to the abundance of nodes.

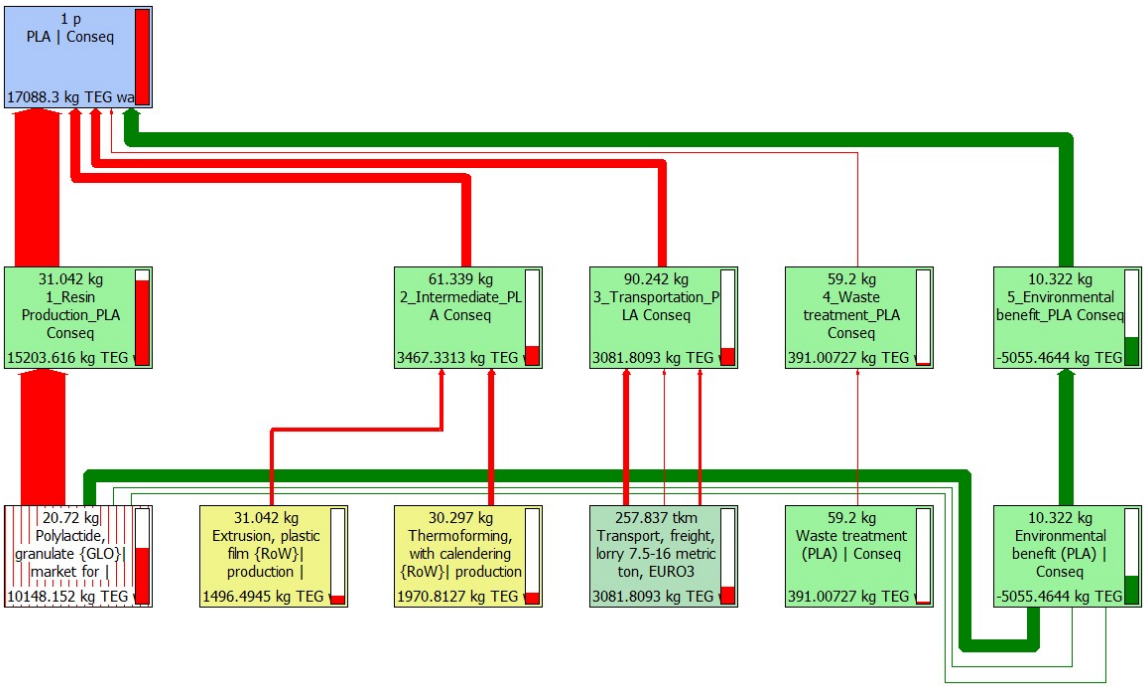

Figure 5.41. Network of PLA in CLCA for aquatic ecotoxicity

Note: A 1.9 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP of PET due to aquatic ecotoxicity in ALCA was lower than that in CLCA. The difference was mainly from the resin production and the environmental benefit stages. For aquatic ecotoxicity, the EFP of the heat process (a wood ash mixture process) was a large portion of resin production in CLCA. In contrast, this process in ALCA was a small amount of resin production.

The EFP of PLA due to aquatic ecotoxicity in ALCA was higher than the EFP of PLA in CLCA. This dissimilarity arose mainly from the PLA resin production and environmental benefit stages. The EFP of resin production in CLCA was higher than one in ALCA because heat process made from natural gas in CLCA was much higher than one in ALCA. The networks for 318 MJ of heat used for PLA resin production, for aquatic ecotoxicity in ALCA and CLCA are shown in Figure 5.42 and Figure 5.43.

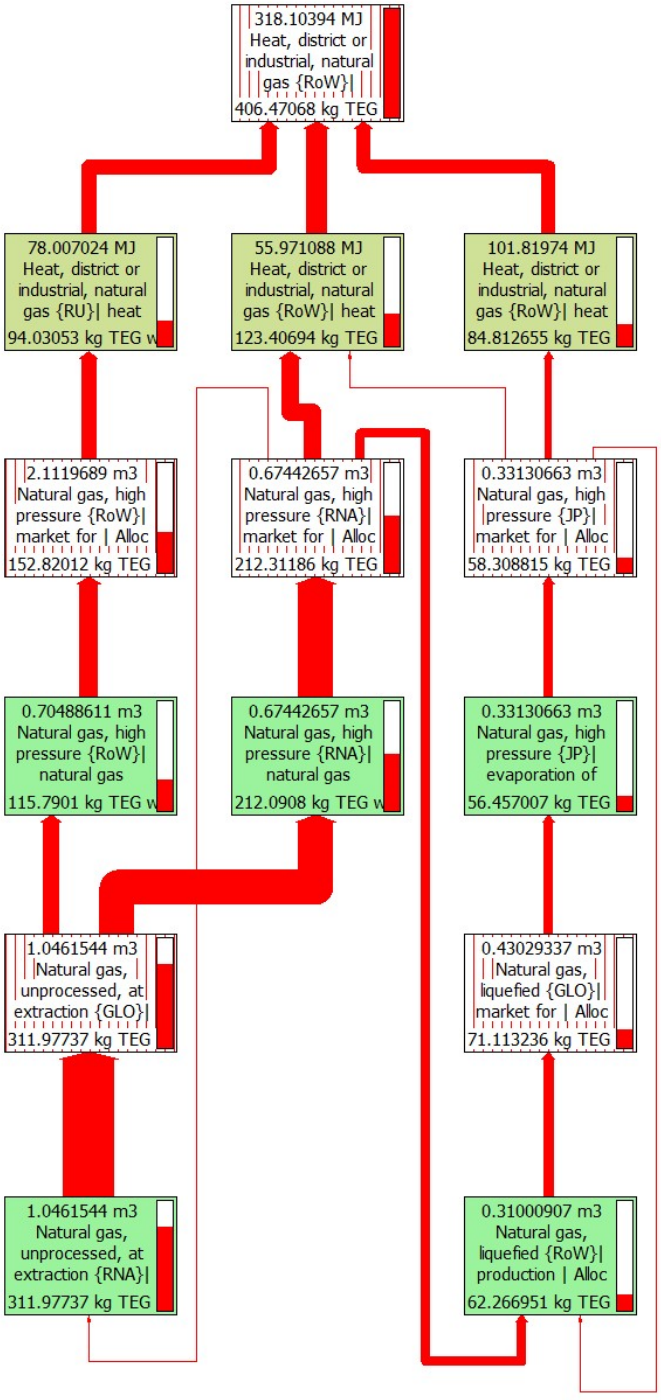

Figure 5.42. Network of heat process of PLA in ALCA for aquatic ecotoxicity

Note: A 15.3 % cut-off rule was applied in this figure due to the abundance of nodes.

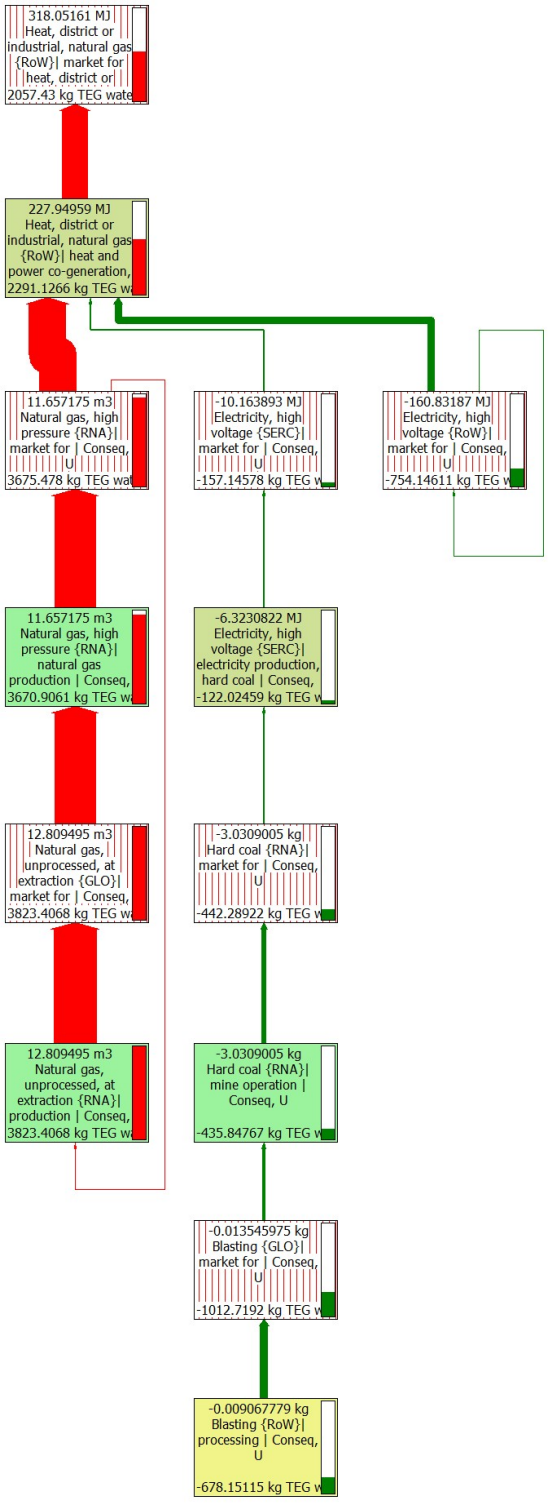

Figure 5.43. Network of heat process of PLA in CLCA for aquatic ecotoxicity

Note: A 17.5 % cut-off rule was applied in this figure due to the abundance of nodes.

5.9. Terrestrial ecotoxicity

PET in CLCA showed the highest terrestrial ecotoxicity indicator with 3940 kg TEG soil followed by PLA in CLCA. For this category, PLA and PET using ALCA were lower than those using CLCA. For PLA in ALCA and CLCA, the transportation stage provided the highest contribution with 1660 kg and 2182 kg TEG soil, which was about 62 % and 63 %, respectively, of the total indicator. For PET in ALCA and CLCA, the major contribution was the resin production that contributed around 45 % and 60 %, respectively.

Figure 5.44 through Figure 5.47 show networks of PET and PLA in ALCA and CLCA, respectively. In the networks, '1p' indicates the functional unit of the study, which means 1000 clamshell containers of 1lb capacity each for the packaging of strawberries.

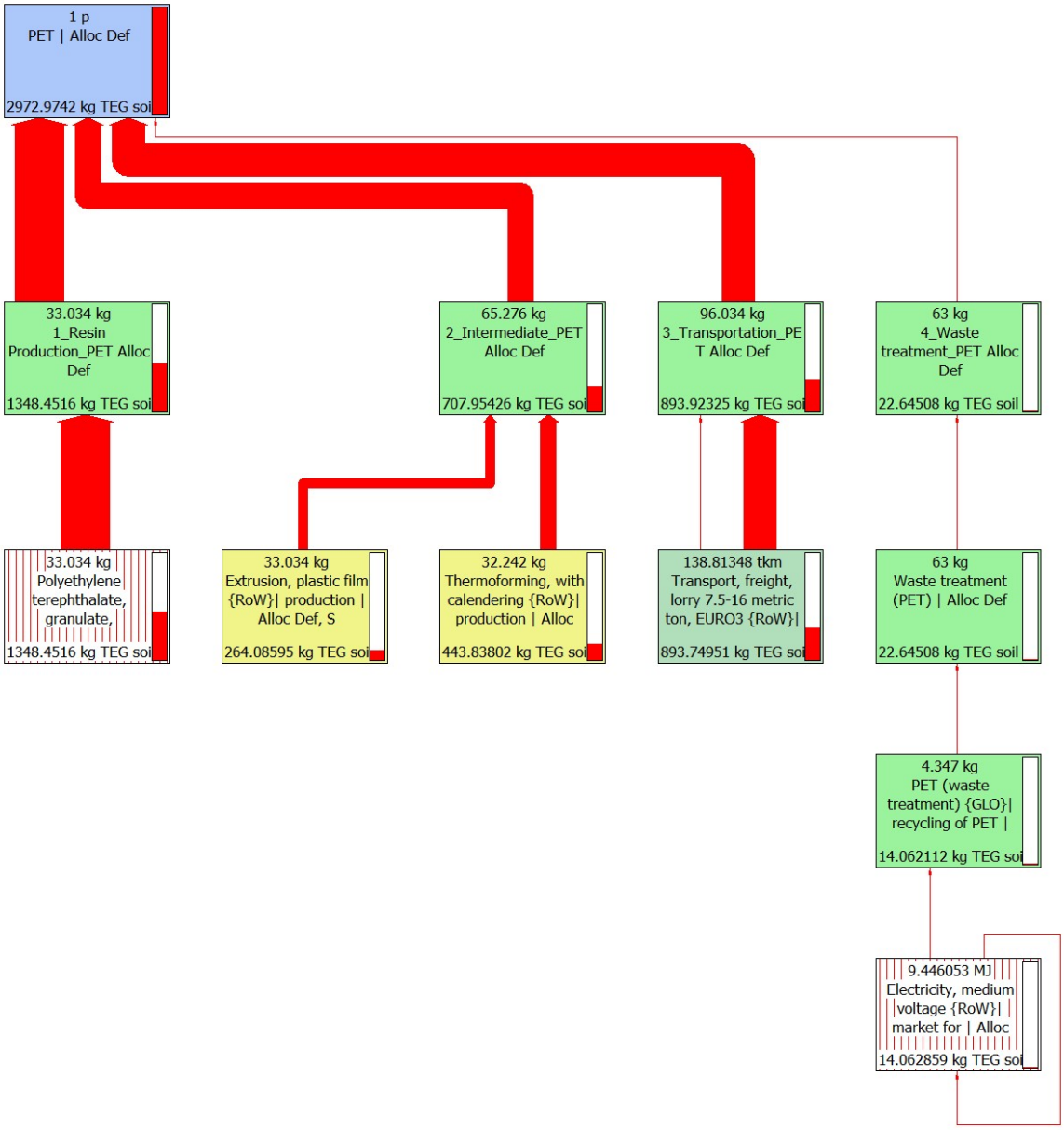

Figure 5.44. Network of PET in ALCA for terrestrial ecotoxicity

Note: A 0.43 % cut-off rule was applied in this figure due to the abundance of nodes.

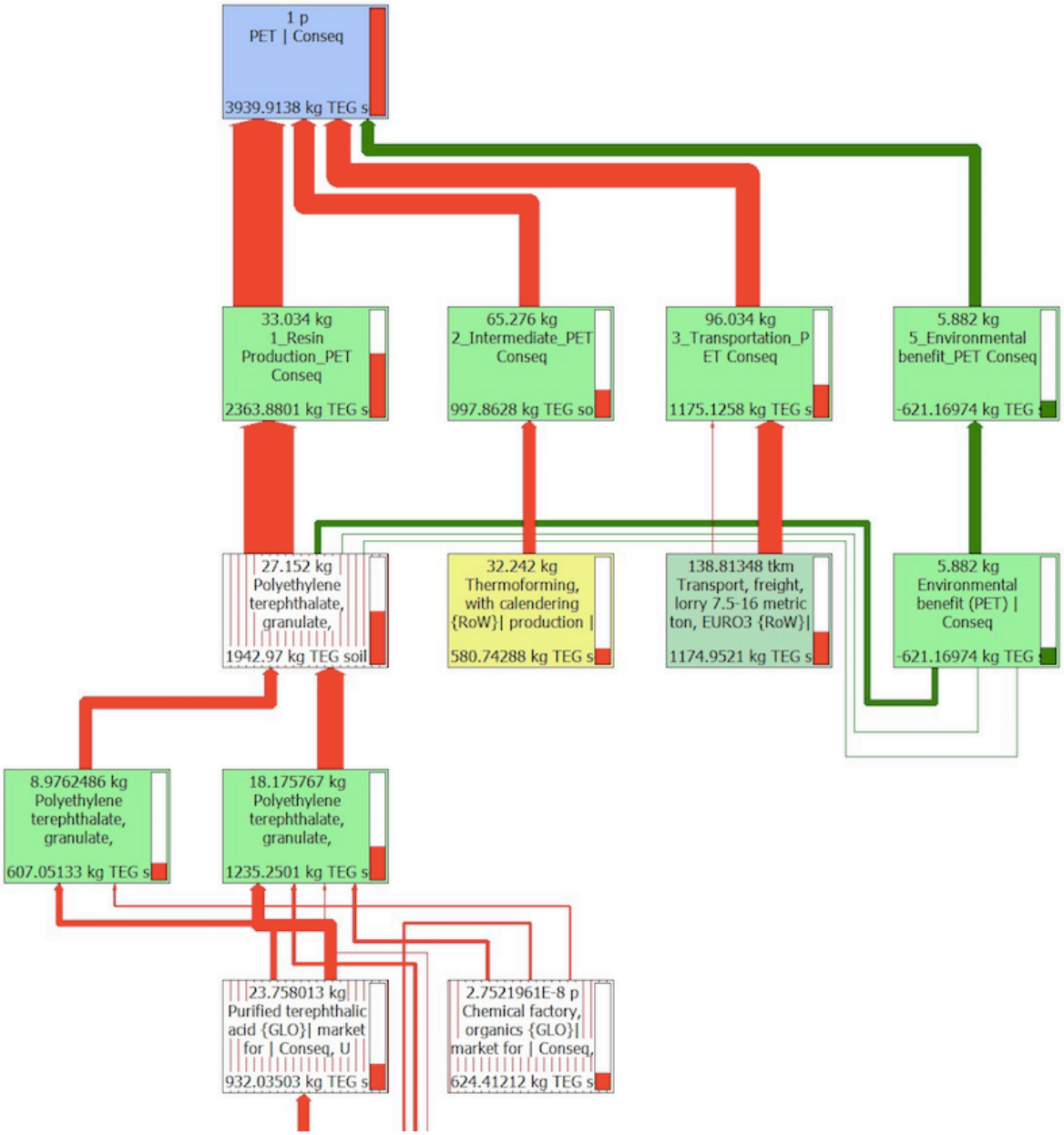

Figure 5.45. Network of PET in CLCA for terrestrial ecotoxicity

Note: A 11 % cut-off rule was applied in this figure due to the abundance of nodes.

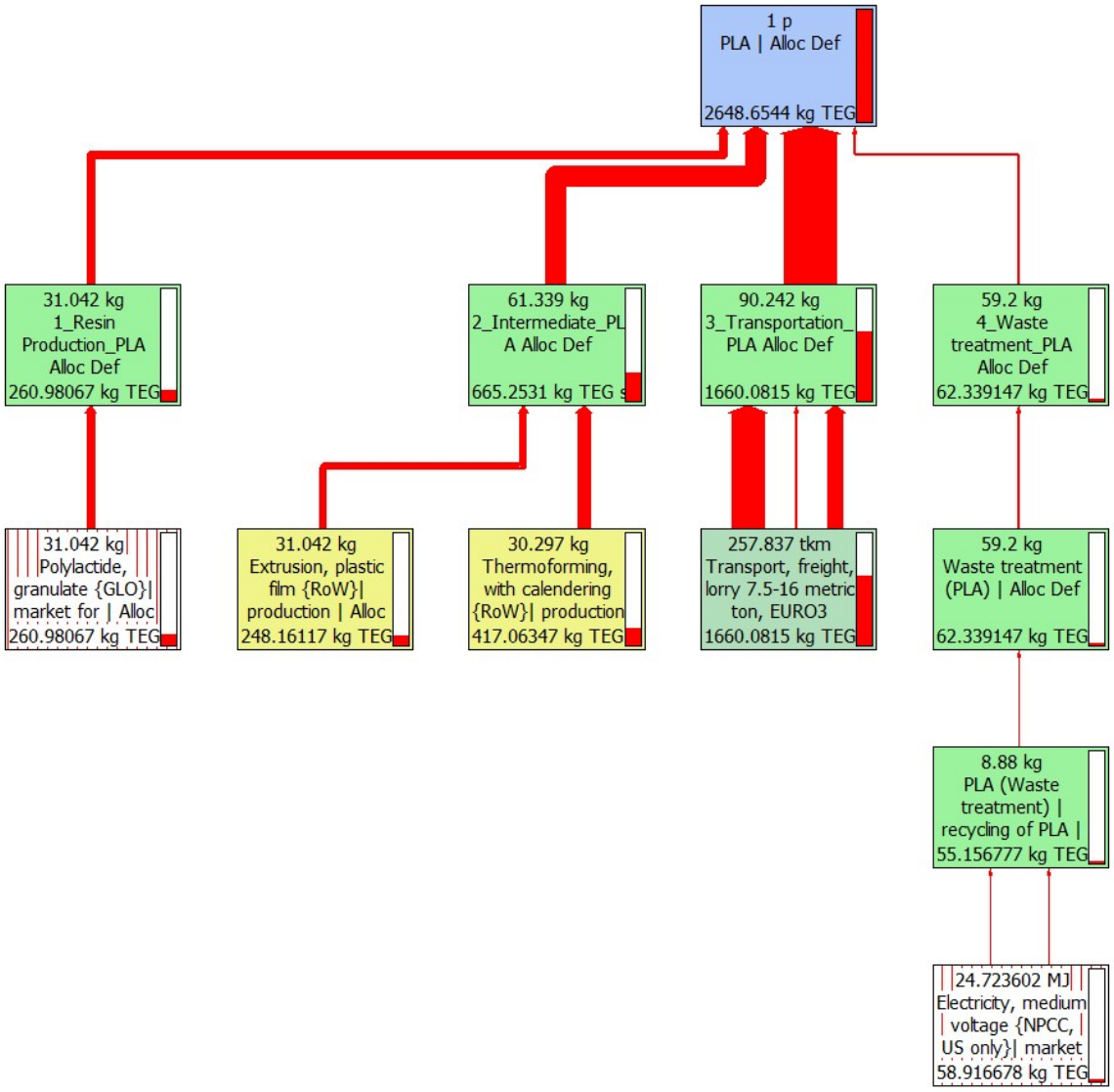

Figure 5.46. Network of PLA in ALCA for terrestrial ecotoxicity

Note: A 0.89 % cut-off rule was applied in this figure due to the abundance of nodes.

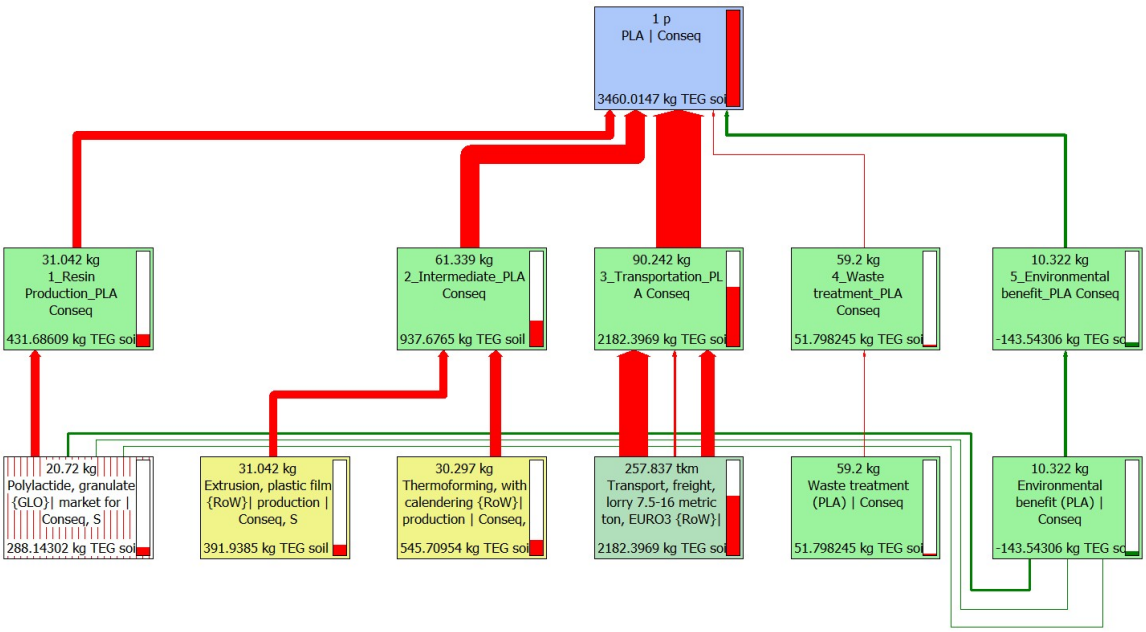

Figure 5.47. Network of PLA in CLCA for terrestrial ecotoxicity

Note: A 1.4 % cut-off rule was applied in this figure due to the abundance of nodes.

The EFP of PET due to terrestrial ecotoxicity in ALCA was lower than in CLCA. The difference came mainly from the resin production and environmental benefit stages. For terrestrial ecotoxicity, the EFP of heat from the wood ash mixture process was a large portion of the indicator for resin production in CLCA. On the contrary, this process in ALCA was a small amount of the resin production, as it was for aquatic ecotoxicity.

The EFP of PLA due to terrestrial ecotoxicity in ALCA was lower than that in CLCA. This dissimilarity arose mainly from the transportation stage. The EFP of the heat process, which is used for diesel production, made from wood ash mixture process was a large portion of the transportation stage in CLCA. On the contrary, this process in ALCA was a small amount of the transportation.

5.10. Terrestrial acidification / nitrification

The EFP of PLA due to terrestrial acidification and nitrification using ALCA was significantly higher than other scenarios. The major contribution for this category was transportation, which contributed around 42 %, 40 %, 60 % and 49 % of the total kg SO_2 equivalents for PLA in ALCA and CLCA and for PET in ALCA and CLCA, respectively.

For the EFP of terrestrial acidification and nitrification of PET in ALCA and CLCA, the EFP was higher in ALCA than in CLCA. The differences came mainly from the resin production and environmental benefit phases including recycling, and energy recovery from incineration. For terrestrial acidification and nitrification, similarly to the respiratory inorganics, the EFP of steam production in the PET resin production process was negative due to a number of electricity processes in CLCA. Therefore, the amount of EFP of PET in CLCA was lower than that in ALCA.

The EFP for terrestrial acidification and nitrification of PLA in ALCA was higher than that in CLCA. The difference came mainly from the resin production and environmental benefit phases including recycling. For terrestrial acidification and nitrification, the amount of the EFP of the resin production stage in CLCA was much lower than in ALCA due to the heat process using electricity corresponding to PET in CLCA regarded as benefit in CLCA.

5.11. Land occupation

For land occupation, PLA in ALCA was significantly higher than the other evaluations, and PET in ALCA was the lowest. The EFP of PLA using ACLA was more than eight times as high as PET using ALCA. The resin production phase for PLA

contributed 34.945 m^2 and 36.323 m^2 organic arable land, about 87 % and 113 % of the total m^2 org.arable in ALCA and CLCA, respectively. For PET, the resin production stages contributed also the highest C_2H_3Cl as well, which were 3.977 kg and 18.343 kg of C_2H_3Cl in ALCA and CLCA respectively.

The EFP of PET in ALCA was lower than in CLCA. The difference came mainly from the resin production and environmental benefit stages. For land occupation, the EFP of the heat process from wood chips process was a large portion of resin production in CLCA similarly to PET in CLCA for aquatic ecotoxicity.

The EFP of PLA in ALCA was also higher than in CLCA. The difference came mainly from the environmental benefit phase including recycling.

5.12. Aquatic acidification

The lowest EFP for aquatic acidification was PET using CLCA. PLA in ALCA was the highest with 1.422 kg SO_2 equivalents. The resin production for PLA contributed 0.666 kg SO_2, about 47 % of the total in ALCA. In CLCA, however, transportation for PLA was the highest contribution with 0.323 kg SO_2, about 29 % of the total kg SO_2 equivalents. For PET, the largest contribution for aquatic acidification was resin production with 0.494 kg and 0.356 kg SO_2 equivalents, about 43 % for ALCA and CLCA.

The EFP of aquatic acidification of PET and of PLA was higher in ALCA than in CLCA. The differences came mainly from the environmental benefit phase including recycling and energy recovery from incineration.

5.13. Aquatic eutrophication

For PLA in ALCA and CLCA, the resin production stage had the highest contribution to aquatic eutrophication, with 0.0457 kg and 0.0312 kg PO_4 equivalents into P-limited water, about 79 % and 91 %, respectively. For PET, the major contribution was also the resin production with 0.0173 kg and 0.0188 kg PO_4 P-lim that contributed around 61 % and 73 % in ALCA and CLCA, respectively.

For the EFP of aquatic eutrophication of PET in ALCA and CLCA, the EFP of PET in ALCA was also higher than one in CLCA. The difference came mainly from the environmental benefit phase including recycling and energy recovery from incineration for both PET and PLA.

5.14. Global warming

In the comparison between ALCA and CLCA, PLA and PET with CLCA had lower environmental effect than with ALCA. PLA had higher environmental impact than PET in ALCA. However, in CLCA, PLA had lower global warming impact than PET. The resin production stages were the highest contributors in all four of those scenarios, with 93 kg, 94.71 kg, 59.85 kg and 81.76 kg CO_2 equivalents into air, about 44 %, 47 %, 40 % and 52 % for PLA in ALCA and CLCA and for PET in ALCA and CLCA, respectively, of the total indicator.

The differences between ALCA and CLCA arose mainly from the resin production phase due to electricity for heat and the environmental benefit phase including recycling and energy recovery from incineration.

5.15. Non-renewable energy

The environmental impact for PLA in ALCA and CLCA is lower than for PET in ALCA and CLCA. The total energy for this category for PLA and PET in ALCA and CLCA was 3212 MJ, 4029 MJ, 2540 MJ and 3076 MJ primary non-renewable, respectively. In CLCA, the environmental benefit has negative values, -406 MJ for PLA and -748 MJ for PET. These environmental credits came from recycling and energy recovery from incineration. The largest contributors were resin production for PLA and PET in ALCA and CLCA, about 43 %, 65 %, 48 % and 81 % of the total, respectively.

The EFP of non-renewable energy of PET and of PLA in ALCA was higher than in CLCA. The differences were mainly from the resin production phase due to heat using a number of electricity processes, which used uranium and nuclear energy treated as an environmental credit.

5.16. Mineral extraction

Mineral extraction for PLA and PET in CLCA were significantly higher than in ALCA. PLA had lower EFP for mineral extraction than PET in both ALCA and CLCA. For PLA in ALCA and CLCA, the resin production stages were the highest contributors with 4.057 MJ and 8.512 MJ surplus energy, about 63 % and 83 %, respectively. For PET, the major contribution was also the resin production stage with 5.463 MJ and 11.884 MJ surplus energy, around 77 % and 93 % of the total, in ALCA and CLCA, respectively.

The EFP of mineral extraction of PET and PLA in ALCA was higher than in CLCA. The difference came mainly from the environmental benefit stage including recycling and energy recovery from incineration.

6. Interpretation

6.1. Evaluation of the results

This chapter represents the interpretation of this LCA study. A completeness check, consistency check and contribution analysis were performed to follow the ISO 14044 guideline.

6.1.1. Completeness check

According to ISO 14044, the goal of the completeness check is to confirm that all related information and data required for the interpretation are available and complete for fulfilling the goal and scope of the LCA [4]. The completeness check helps to substantiate that the data containing the unit process datasets are compatible with the system boundaries and representative of the defined product or technology. Table 6.1 provides the results of the completeness check of the data. This table also indicates that the life cycle inventories of the study were completed. Data for some processes were assumed based on literature resources, and some processes were not included in this study.

Table 6.1. Completeness check

Stage	Unit process	PET
Resin production	PET resin	Complete
Intermediate process	Extrusion	Complete
	Thermoforming	Complete
	Refrigeration	Complete
Transportation	Truck	Complete
	Train	Complete

Table 6.1 (cont'd)

Waste treatment	Recycling	Complete
	Incineration	Complete
	Landfill	Complete

Stage	**Unit process**	**PLA**
Resin production	PLA resin	Complete
Intermediate process	Extrusion	Complete
	Thermoforming	Complete
	Refrigeration	Complete
Transportation	Truck	Complete
	Train	Complete
Waste treatment	Recycling	#
	Incineration	-
	Landfill	#

-: Incineration for PLA was excluded in this study

#: Recycling and landfill were assumed based on literature

6.1.2. Consistency check

A consistency check was performed to determine whether the assumptions, methods, models and data were compatible with either along a products life cycle or between several options. Table 6.2 shows the results of the consistency check. Some unit processes were not consistent. In the data accuracy category, "caution" indicates that the LCI database was assumed from literature or another source. In the technology coverage entry, "commercial

level" indicates that the unit process is already in industrial use. "Pilot" denotes that the technology for the unit process is being developed, so that it is not fully available.

Table 6.2. Consistency check

Stage	Unit process	Data source	Data accuracy	Data age	Technology coverage	Geographical coverage
Resin production	PET resin	Database	Good	within 6 yrs	Commercial level	US
Intermediate process	Extrusion	Database	Good	within 6 yrs	Commercial level	US
	Thermoforming	Database	Good	within 6 yrs	Commercial level	US
	Refrigeration	Database	Good	within 6 yrs	Commercial level	DK
Transportation	Truck	Database	Good	within 6 yrs	Commercial level	US
	Train	Database	Good	within 6 yrs	Commercial level	US
Waste treatment	Recycling	Database	Good	within 6 yrs	Commercial level	US
	Incineration	Database	Good	within 6 yrs	Commercial level	US
	Landfill	Database	Good	within 6 yrs	Commercial level	US
Environmental benefit	Recycling	Database	Good	within 6 yrs	Commercial level	US
	Energy recovery	Literature	Good	within 6 yrs	Commercial level	US

Stage	Unit process	Data source	Data accuracy	Data age	Technology coverage	Geographical coverage
Resin production	PLA resin	Database	Good	within 6 yrs	Commercial level	US
Intermediate process	Extrusion	Database	Good	within 6 yrs	Commercial level	US
	Thermoforming	Database	Good	within 6 yrs	Commercial level	US
	Refrigeration	Database	Good	within 6 yrs	Commercial level	DK
Transportation	Truck	Database	Good	within 6 yrs	Commercial level	US
	Train	Database	Good	within 6 yrs	Commercial level	US

Table 6.2 (cont'd)

Waste treatment	Recycling	Literature	caution	within 6 yrs	Pilot (estimation)	US
	Incineration	-	-	-	-	-
	Landfill	Literature	caution	within 6 yrs	Pilot (estimation)	US
Environmental benefit	Recycling	Literature	caution	within 6 yrs	Pilot (estimation)	US
	Energy recovery	Literature	caution	within 6 yrs	Pilot (estimation)	US

7. Conclusions and future work

Attributional and consequential life cycle assessment (ALCA and CLCA) studies have been gaining momentum to evaluate the environmental footprint (EFP) of products and systems. In this work, the EFP of PET and PLA polymers were compared to better identify EFP tradeoffs between the different alternatives. The main purpose of this work was to explore the environmental footprint of a bio-based polymer, PLA, and a petroleum-based polymer, PET, used for strawberry clamshell packaging applications, using ALCA and CLCA.

Among the fifteen impact categories in the IMPACT 2002+ midpoint indicator, PLA clamshells had the highest impact values for ten impact categories in ALCA, which were respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification / nitrification, land occupation, aquatic acidification, aquatic eutrophication and global warming. In CLCA, PLA clamshells had the highest impact values for eight impact categories, which were ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial acidification / nitrification, land occupation, aquatic acidification and aquatic eutrophication. For most of those impact categories, resin production was the stage with the highest contribution, followed by transportation.

After normalization, only four impact categories: carcinogens, respiratory inorganics, global warming and non-renewable energy, were significantly different between ALCA and CLCA. When normalized values were applied, PET in CLCA was significantly higher than PLA in CLCA. PLA using CLCA had the lowest impact in respiratory inorganics, global warming and non-renewable energy. The negative values for CLCA are

attributed to the avoided burden of the recycled PLA and PET resins and energy recovery from incineration of PET. Resin production contributed the most to carcinogens, global warming and non-renewable energy. For the respiratory inorganic impact category, resin production contributed the most in ALCA. In CLCA, however, the intermediate process for PLA and PET provided the highest contribution, 56 % and 46 %, respectively.

Most categories of the EFP of PET and PLA in CLCA were significantly lower than those in ALCA except for carcinogens, non-carcinogens, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation and mineral extraction. The major differences in the EFP between ALCA and CLCA were in the environmental benefit and resin production stages. In some impact categories, such as respiratory inorganics for PLA in CLCA and ionizing radiation for PLA in CLCA, the environmental benefit was positive, not negative, which was because the EFP of the heat process using electricity made from nuclear or uranium was calculated as an environmental credit for the resin production.

For global warming and non-renewable energy, which were significant after normalization, the major differences between ALCA and CLCA were from resin production and environmental benefit.

8. Recommendation for future work

This study presented a preliminary study about CLCA. This thesis focused on determining some of the differences between ALCA and CLCA, but further analyses are needed to properly model the marginal processes for PET and PLA, and to better understand how to allocate the multifunction of the maize process in CLCA for PLA. Also, specific data regarding recycling and landfilling of PLA is needed, so that data need to be developed. In this study, chemical recycling was used for the recycling of PLA. Other recovery methods for PLA can be used in future studies, such as mechanical recycling, industrial composting, anaerobic digestion, direct fuel substitution in industrial facilities or incineration with heat recovery in municipal solid waste incinerators.

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