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Environmental and economic analysis of the life cycle of Rooftop Greenhouses (RTGs)

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Environmental and economic analysis of the life cycle of Rooftop Greenhouses (RTGs)

Anàlisi ambiental i econòmic del cicle de vida dels hivernacles en coberta (RTGs)

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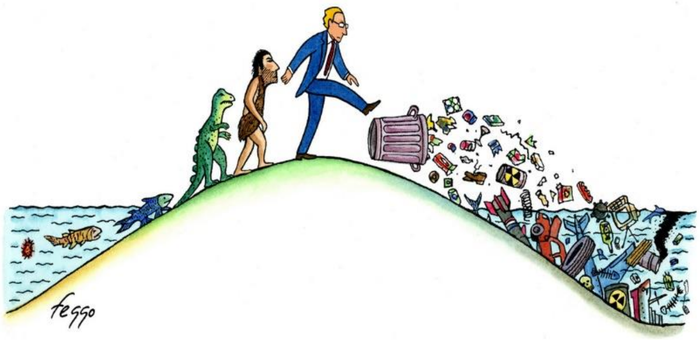

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RESUM

Els hivernacles en coberta (RTG) són una oportunitat que les ciutats no poden deixar passar. No només permeten el desenvolupament d'un nou model de producció agrícola de proximitat urbana, sinó que també contribueixen a una economia baixa en carboni, alhora que aprofiten els espais de la ciutat que fins ara estaven en desús: les cobertes dels edificis. L'objectiu d'aquest estudi és realitzar l'avaluació del cicle de vida ambiental i econòmic dels RTG en comparació amb els sistemes d'hivernacles convencionals mitjançant l'anàlisi de diferents materials de cobertura per a definir l'escenari òptim de RTG.

L'avaluació es divideix en: (1) un estudi comparatiu d'avaluació del cicle de vida (LCA) entre els dos hivernacles de referència: el RTG i l'hivernacle convencional (CG). (2) L'avaluació de diferents materials de cobertura: vidre per a horticultura (HG), policarbonat (PC), polietilè (PE), polietilè de doble capa i ETFE. (3) Una avaluació del cicle de vida amb el material de cobertura òptim per a analitzar les càrregues ambientals de l'escenari òptim per al RTG. Juntament amb l'avaluació del Cost del Cicle de Vida (LCC), que s'aplica per a analitzar l'acompliment econòmic de l'escenari actual i òptim i determinar la millor opció.

Seguint un enfocament del bressol a la tomba, s'inclouen en l'estudi les etapes de construcció, operació i final de la vida útil. La unitat funcional es defineix com 1 kg de tomàquets produïts durant 1 any. Els mètodes LCIA aplicats són el ReCiPe (jeràrquic, *midpoint*), que inclou les següents categories d'impacte: escalfament global (GW), eutrofització d'aigua dolça (FE), escassetat de recursos minerals (MRS) i consum d'aigua (WC), i el mètode únic de demanda d'energia acumulada (CED). Per a l'anàlisi econòmica es considera el Valor Actual Net (VAN).

Segons els resultats obtinguts en aquesta tesi, els resultats mostren que el RTG té un impacte ambiental entre 1.3 per a WC a 2.7 per a GW vegades major que el CG. Els valors obtinguts per als altres indicadors estan entre aquest interval. L'estructura de l'hivernacle (estructura, material de coberta i equip auxiliar) representa entre el 66% i el 98% de l'impacte total per al RTG i, entre el 60% i el 83% per al CG en tota la seva vida útil. A més, el polietilè és el material amb el menor impacte ambiental per cada hivernacle. S'ha valorat l'ETFE com a substitut del material de coberta actual del RTG, ja que el reemplaçament amb polietilè no compleix amb els requisits estructurals i de seguretat en els edificis.

Finalment, amb la nova coberta d'ETFE, hi ha una millora global per a totes les categories d'impacte. GW destaca per la seva reducció del 7% de les emissions de CO_2 eq, evitant 0.05 kg de CO_2 eq per kg de tomàquets produïts. També s'ha obtingut una reducció del 10% en la CED,

estalviant 0,84 MJ per kg de tomàquet. A nivell de costos, el reemplaçament de la cobertura total de RTG augmenta el preu en 6.8 € per m^2.

En conclusió, el polietilè pot considerar-se òptim, des d'un punt de vista ambiental i econòmic, per a hivernacles convencionals o RTG no integrats. No obstant això, per al RTG de referència en aquest treball, el material de coberta òptim és l'ETFE, que té resultats similars al polietilè mentre que "s'ajusta" millor en l'entorn urbà.

Paraules clau: RTG, hivernacle convencional, LCA, LCC, materials de cobertura, sostenibilitat.

RESUMEN

Los invernaderos en cubierta (RTG) son una oportunidad que las ciudades no pueden dejar pasar. No solo permiten el desarrollo de un nuevo modelo de producción agrícola de proximidad urbana, sino que también contribuyen a una economía baja en carbono, a la vez que aprovechan los espacios de la ciudad que hasta ahora estaban en desuso: las cubiertas de los edificios. El objetivo de este estudio es realizar la evaluación del ciclo de vida ambiental y económico de los RTG en comparación con los sistemas de invernaderos convencionales mediante el análisis de diferentes materiales de cobertura para definir el escenario óptimo de RTG.

La evaluación se divide en: (1) un estudio comparativo de evaluación del ciclo de vida (LCA) entre los dos invernaderos de referencia: el RTG y el invernadero convencional (CG). (2) La evaluación de diferentes materiales de cobertura: vidrio para horticultura (HG), policarbonato (PC), polietileno (PE), polietileno de doble capa y ETFE. (3) Una evaluación del ciclo de vida con el material de cobertura óptimo para analizar las cargas ambientales del escenario óptimo para el RTG. Junto con la evaluación del Costo del Ciclo de Vida (LCC), que se aplica para analizar el desempeño económico de los escenarios actual y óptimo y determinar la mejor opción.

Siguiendo un enfoque de la cuna a la tumba, se incluyen en el estudio las etapas de construcción, operación y final de la vida útil. La unidad funcional se define como 1 kg de tomates producidos durante 1 año. Los métodos LCIA aplicados son el ReCiPe (jerárquico, *midpoint*), que incluye las siguientes categorías de impacto: calentamiento global (GW), eutrofización del agua dulce (FE), escasez de recursos minerales (MRS) y consumo de agua (WC), y el método único de demanda de energía acumulada (CED). Para el análisis económico se considera el Valor Actual Neto (VAN).

Según los resultados obtenidos en esta tesis, los resultados muestran que el RTG tiene un impacto ambiental entre 1.3 para WC a 2.7 para GW veces mayor que un CG. Los valores obtenidos para los otros indicadores están entre este intervalo. La estructura del invernadero (estructura, material de cubierta y equipo auxiliar) representa entre el 66% y el 98% del impacto total para el RTG y, entre el 60% y el 83% para el CG en toda su vida útil. Además, el polietileno es el material con el menor impacto ambiental por cada invernadero. Se ha valorado el ETFE como sustituto del material de cubierta actual del RTG, ya que el reemplazo con polietileno no cumple con los requisitos estructurales y de seguridad en los edificios.

Finalmente, con la nueva cubierta de ETFE, hay una mejora global para todas las categorías de impacto. GW destaca por su reducción del 7% de las emisiones de CO_2 eq, evitando 0.05 kg de CO_2 eq por kg de tomates producidos. También se ha obtenido una reducción del 10% en la CED, ahorrando 0,84 MJ por kg de tomate. A nivel de costes, el reemplazo de la cobertura total de RTG aumenta el precio en 6.8 € por m^2.

En conclusión, el polietileno puede considerarse óptimo, desde un punto de vista ambiental y económico, para invernaderos convencionales o RTG no integrados. Sin embargo, para el RTG de referencia en este trabajo, el material de cubierta óptimo es el ETFE, que tiene resultados similares al polietileno mientras que "se ajusta" mejor en el entorno urbano.

Palabras clave: RTG, invernadero convencional, LCA, LCC, materiales de cobertura, sostenibilidad.

SUMMARY

Rooftop Greenhouses (RTG) are an opportunity that cities cannot miss. Not only do they allow the development of a new agricultural production model of urban proximity, but also contribute to a low carbon economy, all while taking advantage of the city's spaces that up until now were disused: the roofs of the buildings. The aim of this study is to perform the environmental and economic life cycle assessment of Rooftop Greenhouses (RTGs) in comparison with conventional greenhouses systems by analysing different covering materials to define the optimal RTG scenario.

The assessment is divided into: (1) a comparative Life Cycle Assessment (LCA) study between the two reference greenhouses: the RTG and the conventional greenhouse (CG). (2) The assessment of different covering materials– horticulture glass (HG), polycarbonate (PC), polyethylene (PE), polyethylene double-layer and ETFE. (3) A life cycle assessment with the optimal covering material to analyse the environmental burdens optimal scenario for the RTG. Along with the Life Cycle Costing (LCC) assessment, which is applied in order to analyse the economic performance of current and optimal scenario and determine the best option.

Following a cradle-to-grave approach, construction, operation and end-of-life stages are included in the study. The functional unit is defined as 1 kg of tomatoes produced over 1 year. The applied LCIA methods are the ReCiPe (hierarchical, midpoint), including the following impact categories: Global Warming (GW), Freshwater Eutrophication (FE), Mineral Resource Scarcity (MRS) and Water Consumption (WC), and the single method Cumulative Energy Demand (CED). For the economic analysis Net present value (NPV) are considered.

According to the results obtained in this thesis, results show that the RTG has an environmental impact between 1.3 for WC to 2.7 for GW times higher than a CG. The values obtained for the other indicators are between this interval. The structure of the greenhouse - structure, cover material and auxiliary equipment - represents between 66% and 98% of the total impact for the RTG and, between 60% and 83% for the CG in its whole useful life. Moreover, polyethylene is the material with the lowest environmental impact per greenhouse. The use of ETFE has been valued as a substitute for the current RTG covering, as the replacement with polyethylene does not meet the structural and safety requirements in buildings.

Finally, with the new ETFE cover, there is a global improvement for all impact categories. GW stands out for its reduction of 7% of CO_2 eq emissions, avoiding 0.05 kg of CO_2 eq by kg of tomatoes produced. An important reduction of 10% at CED was also identified, saving 0.84 MJ per kg of tomato. At a cost level, the replacement of the total RTG covering increases the price by 6.8€ per m2.

In conclusion, polyethylene can be considered optimal, from an environmental and economic point of view, for conventional greenhouses or non-integrated RTG. However, for the RTG of reference in this work, the optimal cover material is the ETFE, which has similar results than the polyethylene while it “fits” better in the urban environment.

Keywords: RTG, conventional greenhouse, LCA, LCC, covering materials, sustainability.

ABBREVIATIONS

Associations of Growing Producers of Fruit, Vegetables, Flowers and Live Plants	FEPEX
Building Integrated Photovoltaic Panel	BIPV
Cadmium telluride	CdTe
Conventional Greenhouse	CG
Copper indium gallium	CIG
Copper indium gallium diselenide	CGIS
Cumulative Energy Demand	CED
Current Retail Price Index	RPI
Efficient use of input in protected horticulture	EUPHOROS
Ethylene-tetrafluoroethylene	ETFE
Food and Agriculture Organization of the United Nations	FAO
Global Horizontal Irradiation	GHI
Horticulture Glass	HG
Institut de Ciència i Tecnologia Ambiental - Institut Català de Palentologia	ICTA-ICP
Institut de Recerca i Tecnologia Agroalimentàries	IRTA
Instituto Nacional de Estadística	INE
Instituto para la Diversificación y ahorro de la Energía	IDEA
Integrated-Rooftop Greenhouse	i-RTG
International Reference Life Cycle Data System Handbook	ILCD Handbook
International Standarization Organization	ISO
Japanese yen	JPY
Life Cycle Assessment	LCA
Life Cycle Costing	LCC
Life cycle inventory	LCI
Mercados Centrales De Abastecimientos Sa	MERCASA
Ministry of Economy and Competitiveness of Spain	MINECO
Net Present Value	NPV
Rooftop Greenhouse	RTG
Photosynthetically Active Radiation	PAR
Polycarbonate	PC
Polyethylene	PE
Polymethyl methacrylate	PMMA

Polyvinyl chloride	PVC
Semi-integrated Rooftop Greenhouse	si-RTG
Society of Environmental Toxicology and Chemistry	SETAC
Universitat Autònoma de Barcelona	UAB
Universitat Politècnica de Catalunya	UPC
Urban Agriculture	UA
United Nations Environment Programme	UNEP

1 INTRODUCTION

1.1 URBAN AGRICULTURE

Urban Agriculture can be defined as the growing, processing, and distribution of food and other products through plant cultivation and raising livestock in and around cities for feeding local populations or to sale in nearby markets. (FAO, 2019; Hendrickson & Porth, 2012).

Although cities only represent an occupation of 3% of the land surface, this portion of land concentrates more than 50% of the world population - 60% in 2030 according to the United Nations. Moreover, it consumes between 60 - 80% of the energy produced, 75% of global carbon emissions are emitted and concentrate between 70 - 90% of the economic activity (United Nations, 2019). As a result, cities have become the most vulnerable areas to climate change and natural disasters.

Furthermore, observing the trends that can be developed in the upcoming years, it is vital to be able to create policies and develop technologies in order to initiate a paradigm change in which the main objective is to make cities inclusive, safe, sustainable and resilient - Objective 11 of the Sustainable Development Goals (United Nations, 2019). With these data, the incorporation of sustainability criteria in this process of urban growth will be one of the main challenges of the twenty-first century (Alberti, 2008).

As the population in cities increases, food production is threatened as an effect of depopulation in rural areas which, aside from important environmental impacts, also affect social aspects such as: loss of biodiversity, erosion, degradation of the landscape, loss of cultural heritage, overpopulation of cities, loss of quality of life, etc. (Asociación Vidasana, 2018). The farming industry must assess food security challenges and involve strategic management practices to identify new possibilities, opportunities and risks (ElBialy et al., 2018).

In addition, current model of food and agriculture contributes to the fragmentation of habitats, extensive use of energy and increase in CO_2 emissions with the objective of meeting the requirements of large-scale marketing (Cerón-Palma, Sanyé-Mengual, Oliver-Solà, Montero, & Rieradevall, 2012). These challenges provide urban agriculture an opportunity to contribute to a low carbon economy due to the shorter supply chains and the amount of fossil fuels used in transportation, while increasing the yield of agriculture because costs are minimized (Ferreira, Guilherme, Ferreira, & Oliveira, 2018). This allows changing the current linear system of food production for a circular agricultural system that optimises urban cycles and contributes to the food security of vulnerable people with fewer resources, among others (Cerón-Palma et al., 2012).

Although urban agriculture can be classified according to different factors such as location, land ownership, use, or purpose (Nadal, 2015), for the present thesis it is distinguish between: greenhouse placed in the ground or Conventional Greenhouse (CG) and greenhouses on the roof of buildings, also called Rooftop Greenhouses (RTG).

1.2 GREENHOUSES

A greenhouse is a structure with a roof made of a transparent material that allows the sunlight transmission, facilitating the accumulation of heat during the day and releasing it slowly during the night. Its main objective is to provide a favourable microclimate environment for the crops which grow inside and to protect them from the outdoor climatic conditions, ensuring a good production. Moreover, when indoor conditions are not optimal, for instance due to high indoor temperatures, ventilation or artificial cooling is commonly applied to dissipate the heat surplus. A well-designed greenhouse must maintain the important climate factors as close as possible to specified optimum (Elsner et al., 2000a). Consequently, it favours off-season cultivation and also gives greater crop productivity (Bekkaoui et al., 2018).

Greenhouse plant production improves the yield and quality of crops through control of the growth environment in terms of light, water, temperature, relative humidity, CO_2 concentration, and ventilation. (Corcelli, Fiorentino, Petit-Boix, Rieradevall, & Gabarrell, 2019; ElBialy et al., 2018; Yano, Onoe, & Nakata, 2014).

Greenhouses can be classified in many ways according to construction characteristics - width, single or multispan, sidewall height, roof shape and slope -, covering materials - glass, rigid plastics, plastic-film or combinations of these - and construction materials - steel, aluminium, wood or combinations of these - (Elsner et al., 2000). In this thesis, the classification carried out consists in the covering material.

Before defining in detail each type of greenhouse, it is worth noting that the greenhouse design - conventional and RTG - depends on the climatic conditions of the area. This thesis will mainly focus on Mediterranean climate.

This distinction is mainly due to climate conditions and solar radiation that greenhouse might receive. In Northern/Central Europe, climate is characterised by cold Winters and moderate Summers, whereas in Southern Europe Winter is moderate, and Summer is hot. Consequently, the solar irradiance in Mediterranean countries is two to three times more intense than in Northern Europe (Elsner et al., 2000a).

Figure 1 shows the yearly sum of Global Horizontal Irradiation (GHI) in Europe and highlighting Spain; 10-years average of the period 1981-1990 [kWh/m^2]. Alternatively, the maps represent solar electricity [kWh] generated by a 1kWp[1] system per year with horizontal or inclined modules (Huld, Müller, & Gambardella, 2012). GHI is the amount of solar energy (integrated over a time) attenuated by all constituents of the atmosphere and falling on a horizontal surface on the Earth. GHI integrates direct, diffuse and reflected components of solar energy [Wh·m^{-2}] (INSPIRE - European Comission, 2019).

It is easily to see that in Northern/Central Europe there is a low intensity of natural light, particularly in Winter season. Instead, in Southern Europe - represented by Spain - the natural light intensity is notably higher (Tsoy, Prado, Wypkema, Quist, & Mourad, 2019).

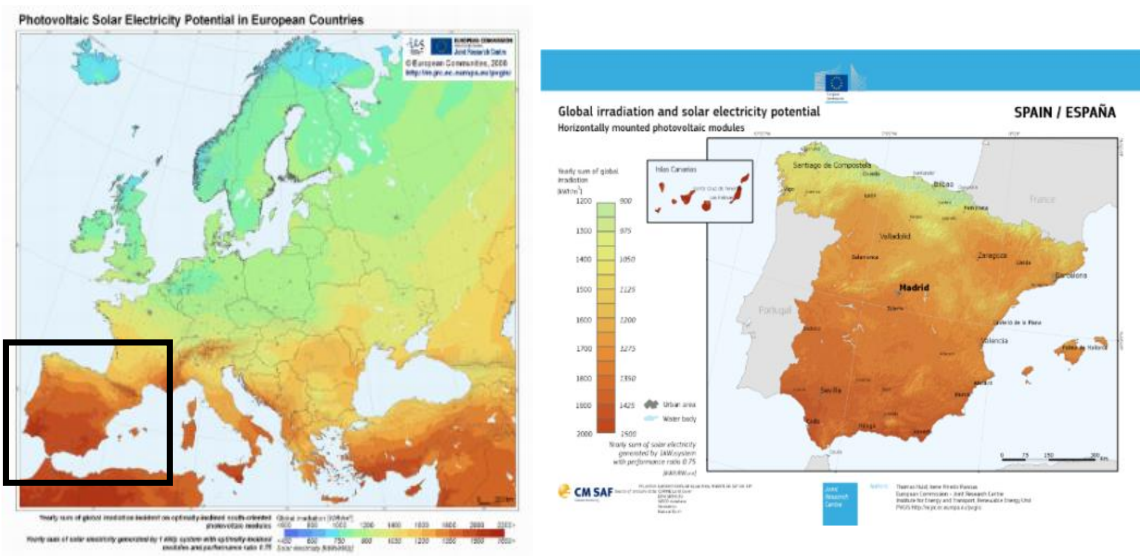

Figure 1. Yearly representation of the sum of global irradiation on a horizontal (inclined) surface in global Europe and Spain; 10-years average of the period 1981-1990 [kWh/m2]. Alternatively the maps represent solar electricity [kWh] generated by a 1kWp system per year with horizontal (or inclined) modules (Huld et al., 2012)

Light is one of the main factors related to the crop yield. A study of Marcelis, Broekhuijsen, Meinen, Nijs, & Raaphorst (2006) claims that 1% more of light results in a crop yield increase of 0.5% – 1%. However, there are other factors to take into account.

[1] Solar electricity systems are given a rating in kilowatts peak (kWp). This is essentially the rate at which it generates energy at peak performance for example at noon on a sunny day. http://www.solarae.co.uk/ask-rae/what-does-kwp-and-kwh-mean

Out of all features and focusing on climatic conditions, solar radiation influences the most. Its variability in the different latitude has a strong influence on the greenhouse design. For instance, Mediterranean climatic conditions, with mild winters and usually sunny days, allow the use of steel-framed, arched-roofed greenhouse with vertical sidewalls, usually covered with plastic film, with passive ventilation and without fixed installations for Winter heating called multi-tunnel. This kind of greenhouse, also called Mediterranean greenhouse is the most used in Mediterranean countries (Sanyé-Mengual, Oliver-Solà, Montero, & Rieradevall, 2015). These kind of greenhouses are completely different from northern ones which, in general, are made of more complex structures; covered with glass, with active ventilation and with fix heating installations that in Dutch greenhouses represent 75-90% of the energy consumed with the purpose to reach an optimum temperature for crop production (Hemming, Kempkes, & Janse, 2012). To sum up, in northern greenhouses advanced technology is needed for high productivity.

1.2.1 Characteristics of Mediterranean greenhouses

Von Elsner (2000) defined the general greenhouse design criteria claiming what Mediterranean greenhouses should have. These criteria are also considered applicable to RTG:

- High total light transparency
- Good heat insulation, especially for unheated greenhouses
- Heating equipment to increase the minimum temperature during night time
- Efficient ventilation by ventilators capable of being controlled
- High stability with respect to wind and in some regions to snow loads
- Gutters and tanks, which collect rain water for irrigation purposes
- Greenhouse volume as large as possible
- Availability to water saving irrigation systems
- Protection from insects by nets

Von Elsner (2000) also defined the main problems:

- Temperatures below the biological optimum in winter nights, making heating necessary for one to three months
- High temperatures during daytime in spring and summer
- High air humidity at night
- Low global radiation in winter
- Significant wind loads, and sometimes unexpected snow loads and hail
- Poor water availability and in certain areas poor water quality.

Greenhouse design is not trivial, it depends of many factors such as structural design, cooling technologies and, if possible, microclimate control (ElBialy et al., 2018). Greenhouse agriculture and cultivation has been described as 'protected' since it provides mechanical shields against outdoor climatic conditions, controlling temperature, relative humidity, carbon dioxide concentration and light to maximise crop yield and avoid plant injury. (Benli, 2013; Fatnassi, Boulard, & Bouirden, 2003; Li & Willits, 2008; Sethi, Dubey, & Dhath, 2009).

An effective greenhouse design should achieve high cooling efficiency - characterised by high coefficient of heat exchange - low cost of investment demonstrating commercial viability, low operating costs, low maintenance and water consumption (ElBialy et al., 2018).

RTGs also can be classified by their characteristics. One of the main classification system is based on the flows between the building and the greenhouse:

- (Non-integrated) Rooftop Greenhouse (RTG): installed as an addition to the building in which there is no connection between the building and the greenhouse. Although they are contained in the building they are treated separately.
- Integrated Rooftop Greenhouse (i-RTG): there is a connection of all the flows of the building with the greenhouse and vice versa, taking advantage of the development of the crop and maintaining optimum conditions in the building (exchange of temperature, ventilation, reuse of water, energy saving ...). An example of this type of greenhouse is the ICTA-IPC.
- Semi-integrated Rooftop Greenhouse (si-RTG): these are greenhouses that have a connection with the building through some of their flows. For example: reuse of water but not heat exchange.

Figure 2 shows examples of greenhouse types according to the flow between the building and the greenhouse.

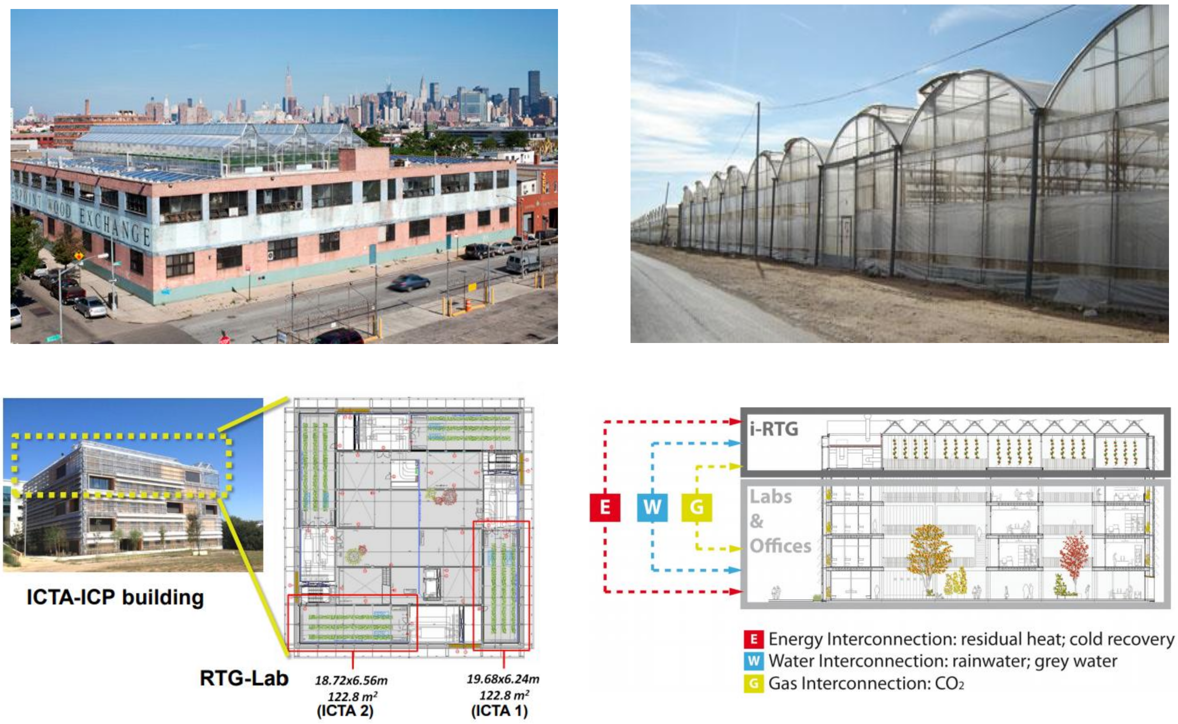

Figure 2. Not integrated Rooftop Greenhouse - Gotham Greens (Brooklyn, NYC) – top left; Multitunnel as an exemple of Conventional Greenhouse – IRTA (Cabrils) – top – right; ICTA-ICP Building. RTG-Lab location and dimensions. Flow exchange between ICTA-ICP building and its RTG-Lab (FertileCity I) - bottom

There are many structural design features that have an incidence in the effectiveness of the greenhouse such as: dimensions, shapes, orientations, and covering materials. Although all features are important, **this study focuses on the covering materials.**

1.3 COVERING MATERIALS

Covering materials are directly related to light, temperature and humidity, which are some of the main variables that affect the crops. As a consequence, the selection of covering material needs to be done thoroughly.

For years, many authors have studied different options of materials and configurations to the envelopes of greenhouses. Bibliography related to covering materials is extensive, for it allows us to know its properties and characteristics. In the end, the knowledge and exploitation of the physical properties of the covering materials end up being very important because it allows for all those related with greenhouse industry deciding what is best suited to the needs of crops (G. Papadakis et al., 2000).

The properties of mechanical materials such as density, stiffness, strength or durability among others, have a direct relationship to the greenhouse design, its maintenance and the greenhouse covering lifetime in relationship with the lifespan of the material (Dayan et al., 1993; ElBialy et al., 2018; Mongkon, Thepa, Namprakai, & Pratinthong, 2013, 2014; Papadopoulos & Hao, 1997; Sacilik, Keskin, & Elicin, 2006; Wei et al., 2016). However, in scope definition of this work, it was decided to focus on the radiometric and thermal properties of the covering materials, since apart from being those that are almost exclusively responsible for the determination of the microclimate in the greenhouse, and therefore have a more direct relationship with the productivity of the crops and with energy consumption, they are also the most studied (G. Papadakis et al., 2000).

The greenhouse covering material constitutes the barrier between the crop and the outside weather. The cover not only should provide a refuge during bad weather conditions, but also should facilitate the modification of the microclimate to ensure optimal crop growth. A cover material should have good insulating properties, but the fact that they are generally thin covers results in low thermal capacity and poor insulating performance (G. Papadakis et al., 2000). The basic premise of a greenhouse cover material is to **provide maximum solar radiation transmittance in such a way that enough light reaches the plants combined with minimum heating requirements** during the cold season so that the heat lost through the covering materials should be as low as possible (Elsner et al., 2000a; IDAE, 2008). In fact, a small fraction of all the light energy that reaches the plant is absorbed by the crop and directly used in the process of photosynthesis. This small fraction of light - wavelights 400-700 nm - is Photosynthetically Active Radiation (PAR) (Ting & Giacomelli, 1987)(Ting & Giacomelli, 1987). The rest of radiation is transformed into heat and contributes to the heating of the plant (sensible heat) and transpiration (latent heat). The low light intensity is the most limiting environmental factor for photosynthesis and maximum crop development, especially in certain latitudes and in Winter conditions. In sum, the roofing material should always be chosen to provide greater transmission in this radiation zone (Enrique Espi, 2012).

1.3.1. Physical properties

Although there are many types of materials that could meet the main functional requirements, these can be distinguished between glass and rigid plastics and films (Elsner et al., 2000b):

1.3.1.1. Glass and rigid plastics

According to Papadakis et al., (2000) glass is the most common material used in greenhouses in Northern Europe, used both in small and large greenhouses. Although glass is a material that matches the functional requirements which greenhouse cover materials have to meet (low thermal radiation transmittance and high visible radiation transmittance), it is much heavier

(2400 kg/m^3) than plastic films (920 kg/m^3 for polyethylene), it requires a support frame and is generally much more expensive than plastic films, 15.83 €/m^2 of horticulture glass vs. 3.19 €/m^2 of polyethylene (ITeC, 2019).

There are also covers formed by a double-wall glass. This type of roof is associated with an energy saving of between 40-50%, at the expense of a loss of transmissivity, which in a double-wall [glass] can be reduced up to 10% and a greater load for the structure (Elsner et al., 2000b).

In recent years, rigid plastic covers have been introduced into the greenhouse industry with the aim of replacing the glass. The most used materials being polymethyl methacrylate (PMMA), polycarbonate (PC), and polyvinyl chloride (PVC). Although these materials have shown higher yields of insulation, some of them compromise the transmissivity of light and are too expensive (Elsner et al., 2000a, 2000b).

1.3.1.2. Film plastics

Unlike glass, plastic films have been used in an intense way in warm climates. Historically, glass has always had advantage to plastic. However, since there are more plastic-film greenhouses in Europe than glass greenhouses, the plastic industry offers a full variety of different plastics with the aim to substitute glass covers. Besides, although glass has a superior thermal performance, there are plastics which have close performance to glass (Hanson, 1963).

The difference between the types of plastics is found in the physical, chemical and mechanical properties of each (Al-Mahdouri, Baneshi, Gonome, Okajima, & Maruyama, 2013).

There are extra design criteria specifically for plastic-film greenhouses (Elsner et al., 2000b):

- Tensioning of films to avoid damage due to fluttering.
- Film installation to allow easy replacement.
- Insulation of those parts of the structure heated by solar radiation and in contact with the film.
- Prevention of condensed water falling from the cover onto the crops.

1.3.2. Optical properties

The main optical properties which define the material response to the incident radiation are (Kailas, 2016; New Technologies Research Centre. University of West Bohemia, 2019; George Papadakis et al., 2000).

- **Transmissivity:** optical property of a material, which describes how much light is transmitted through material in relation to an amount of light incident on the material. The light that was not transmitted was either reflected or absorbed.
- **Reflectivity**: optical property of material, which describes how much light is reflected from the material in relation to an amount of light incident on the material. The reflection occurs always on the surface of the material, for the light-diffusing (translucent) materials also in the volume of the material. On a smooth surface the reflection is specular (direct). On a rough surface the reflection is diffuse (scattered).
- **Absorptivity:** is an optical property of a material, which describes how much light was absorbed in material in relation to an amount of light incident on the material. The light absorption occurs for optically opaque materials on their surface and for semi-transparent materials on the surface and in the bulk of the material.

In any case, the total intensity of the incident light striking a surface is equal to the sum of the absorbed, reflected, and transmitted intensity (Figure 3).

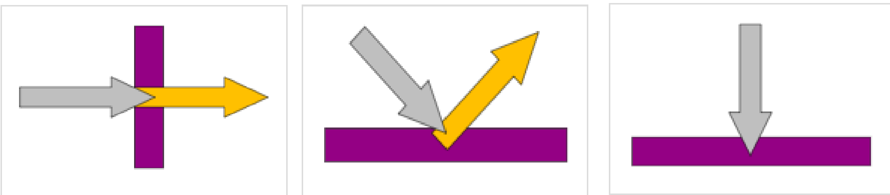

Figure 3. From right to left: transmissivity, reflectivity, absorptivity.

Furthermore, materials can be classified due to their interaction with visible light into three categories:

- **Transparent:** material which permits a large portion of radiation to pass through.
- **Opaque:** material which blocks radiation. These are the materials that do not allow the passage of light, and you cannot see through them.
- **Translucent or semi-transparent:** These are materials that allow the passage of light, but they do not allow seeing clearly through them. These materials break up radiation rays; this causes radiation to go in all directions, giving isotropic radiation distribution and weak shadows on the side of the material opposite to the radiation source.

It is important to mention that an unclear appearance of a material does not mean that the material possesses high or low transmittance (G. Papadakis et al., 2000).

Consequently, it can be concluded that radiation may pass through a transparent material according to the following:

- **Direct Solar Radiation on a horizontal surface [W·h/m^2]:** the radiation is direct beam comes in a direct line from the sun and passes directly through the material maintaining the same direction with some distortion. The direct part of the global solar radiation is of mayor importance at southern latitudes. (Elsner et al., 2000a; Swinkels, Sonneveld, & Bot, 2002)
- **Diffuse Solar Radiation on a horizontal surface [W·h/m^2]:** the diffuse radiation is scattered out and it is breaking up in rays that cause the radiation to go in all directions. At northern latitudes, diffuse light dominates the global radiation (Elsner et al., 2000a; Swinkels et al., 2002)

The sum of Direct Solar Radiation and Diffuse Solar Radiation results in Horizontal Global Solar Radiation [W·h/m^2].

The radiometric properties of the covering material in short wavelengths directly influence the microclimate inside the greenhouse. As a consequence, the transmissivity of the cover materials are the most studied elements both at the theoretical and practical levels (G. Papadakis et al., 2000).

Solar radiation is emitted by the Sun and forms the major source of energy reaching the Earth's surface. Solar irradiance has its peak at a wavelength of about 500 nm. About 40% of the solar energy is emitted at wavelengths of between 400 and 700 nm, while about 39% is emitted at wavelengths of between 700 and 1500 nm (near infrared) (Monteith & Unsworth, 2013). Light corresponds to the spectral region from 380 to 760 nm (visible radiation-practically same range as PAR).

The intensity of the incoming solar radiation is an important parameter influencing the indoor climate, as well as the photosynthetic activity of the plants.

The greenhouse structure and the covering material are responsible for solar radiation losses. Specifically, the transmitted global radiation is reduced by:

- Absorption and reflection at the covering material.
- Shading by greenhouse structural components.
- Dirt on the covering material.
- Condensation on the covering material.

The radiation spectra of interest for greenhouse covering materials are listed in

Table 1.

Table 1. Classification of radiation spectra of interest greenhouse covering materials adapted from (G. Papadakis et al., 2000).

Radiation	Wavelength, nm
Solar (short wave)	$\approx 200 - 380$
Photosynthetically active (PAR)	$380\ to\ 760$
Thermal (long wave)	> 760

When crop photosynthesis is examined, the determination of the radiometric properties of the cover should take into account the spectral sensitivity of the crop (IDAE, 2008). Table 2 shows the different physiological effects that plants have on the basis of the wavelength which they receive. In addition, a figure of the electromagnetic spectrum has also been joined to easily identify the different wavelength bands defined in Table 2 (Figure 4)

Table 2. Physiological effects on plants of different radiation wavelengths (Tesi, 1989)

Color	Wavelength, nm	Plants effect
Medium and short ultraviolet	< 280	Lethal effect for vegetables and germicidal action
Long ultraviolet	$280 - 380$	Damages and possibly undesirable formative effects (smaller plants and very narrow leaves)
Blue violet	$380 - 490$	Photosynthetic and photoperiodic effects.
Green yellow	$490 - 595$	Limited photosynthetic effect
Red-orange	$595 - 760$	Maximum photosynthetic and photoperiodic effect.
Medium and short infrared (MIR and SIR)	$760 - 2500$	Excessive stem extension. Heating of the environment
Far infrared (FIR)	< 2500	Thermal effect on the environment (radiation absorbed by plants and converted into heat)

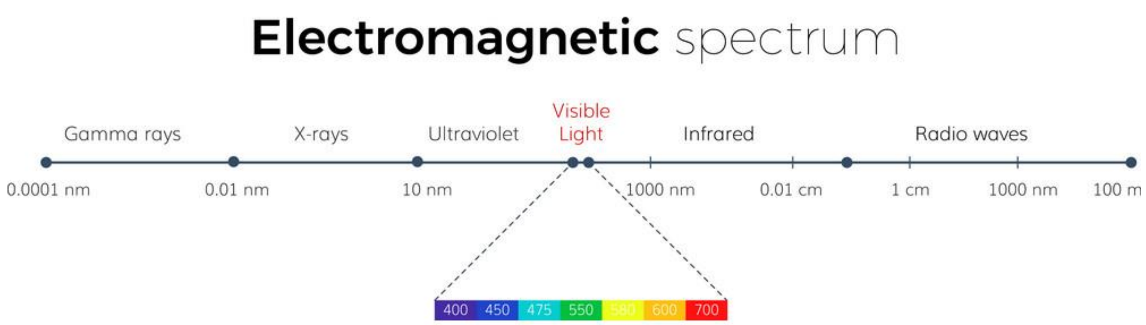

Figure 4. Electromagnetic spectrum. VectorStock.

1.3.3. Thermal properties

Thermal radiation is defined as the electromagnetic radiation emitted by a body because of its temperature. When it concerns covering material, understanding its thermal characteristics is important to understand its behaviour in front of the temperature conservation inside the greenhouse.

Two types of materials can be distinguished: those which allow thermal radiation to pass through and those which block this change. The last ones tend to conserve energy better and to keep a greenhouse warmer than other materials. Accordingly, the less thermal radiation transmissivity the better. For instance, thermal radiation transfer is a very important mechanism responsible for heat losses of polyethylene-covered greenhouses, due to the fact that polyethylene, unlike glass, has high transmissivity to thermal radiation (Nijskens, J; Deltour, J; Nisen, A; Coutisse, 1989; George Papadakis et al., 2000)

The global greenhouse thermal behaviour is defined by U value. U value is a measure of heat loss in a building element or in this case, in a greenhouse. This means that the higher the U value, the worse the thermal performance of the building envelope. Consequently, low U value indicates high levels of insulation(Brennan, n.d.).

The greenhouse U value depends on (George Papadakis et al., 2000):

- The type and condition of material (e.g. wet or dry).
- The convection heat exchange mechanism at the inside and the outside of the cover.
- The thermal radiation exchange.
- The air leakage.
- The area of the covering material.
- The type of the greenhouse (structure, geometry).
- Its ground area
- The presence of a thermal screen.

As a conclusion of the last two sections, it can stated that ideal cover has to accomplish two basic characteristics (George Papadakis et al., 2000):

- **To allow 100% PAR transmissivity while restricting the transmissivity of solar radiation outside the PAR in accordance with the requirements of the greenhouse.**
- **To have good insulation characteristics associated with a low U.**

There are other characteristics that a greenhouse cover has to satisfy. For instance, radiation diffusion characteristics for better radiation penetration into the plant foliage and a better distribution within the greenhouse or the K value of the covering material, which is only one component of the U value and only takes into account the overall heat transfers through the covering material due to the combined action of conduction and convection.

1.4 GREENHOUSE PRODUCTION

Spain is an agricultural country with more than 17 million hectares of arable land, which represents a third of its entire geographical area. Within this area, 13,239,403 ha (77.8%) are destined for dryland farming, in which cereals are mainly grown. With an occupation of 3,703,741 ha (21.8%), irrigated farming is mainly used for the cultivation of fruit trees, olive trees and vineyards. Finally, only 70,545 ha (0.4%) are used for greenhouse cultivation. (Gobierno de España, 2018).

At a Catalan level, the distribution of crops is similar; of all the present cultivation area (822,681 ha) greenhouse cultivation only represents 0.1%, with 839 ha of the total arable land compared to 68.2%, which represents the dryland farming cultivation and 31.7% occupied by irrigated farming (Generalitat de Catalunya. Direcció General de Planificació i Relacions Agràries, 2018). It can be concluded that, in this territory, greenhouse cultivation is relatively low.

Nowadays, the main horticultural crops produced in greenhouses in the Mediterranean area are tomato, pepper, zucchini, melon, strawberry, cucumber and beans. Although it can also be found in a smaller amount lettuce, cabbage, cauliflower, peas, among others (Novagric, 2015).Out of all these crops, the one used as a reference in different studies, as well as in this thesis, is the tomato crop (*Solanum lycopersicum*).

Nowadays, tomato is one of the most consumed and appreciated vegetables in the world with a total production of 170,750 million kilos in 2017. Spain is the eighth largest producer in the world and the second largest tomato producer country in Europe after Italy, with a total destined area of 56,120 ha (23.41%) and a production of 4,768,800 t (27.95%) (Eurostat, 2018). In Catalonia, at the same time period, 26,000 tn of tomato were produced, of which 15,150 tn were produced in greenhouses.

Tomato is the second most consumed fresh vegetable in Spain after potatoes with a total of 13.2 kg per capita and year -according to 2018 data, which represents 23.1% of the total consumption of fresh vegetables according to Spanish Federation of Associations of Growing Producers of Fruit, Vegetables, Flowers and Live Plants (FEPEX) and MERCASA (FEPEX, 2019; MERCASA, 2018). In addition, tomato crops cultivation is carried out in the RTG in the ICTA-ICP building, so first-hand data is available for the realisation of this study. The same crop was used for conventional greenhouse.

2 SCOPE AND OBJECTIVES

2.1. Scope

In the framework of this thesis, an environmental and economic analysis of the life cycle Rooftop Greenhouses (RTGs) is attained by analysing the different materials used for the construction and operation. These include the structural elements and covering of these greenhouses as well as the results of the production process in comparison with conventional greenhouse systems.

A comparative Life Cycle Assessment (LCA) study is carried out for two types of greenhouse: the RTG and the Conventional Greenhouse (CG). The purpose of this comparison is to determine which of the structures has a better environmental performance. However, one of the central parts of the work is the selection and study of different covering materials. Structural design features are numerous: dimensions, shapes, orientations, and covering materials. Although all features are important, this study focuses on the covering materials due to its direct relationship to the main energy source for plants: solar radiation. Finally, after determining the different scenarios for the study, Life Cycle Costing assessment is applied in order to understand their economic performance.

This thesis operates within the framework of the FertileCity II project (CTM2016-75772-C3-1-R). FertileCity II is a research carried out by the Sostenipra research group (Universitat Autònoma de Barcelona (UAB) and Universitat Politècnica de Catalunya (UPC)) funded by the Research Agency, AI / EU-Feder, and Ministry of Economy and Competitiveness of Spain (MINECO), aiming to provide deeper research and promotion on urban agriculture through integrated rooftop greenhouses, giving information and tools that allow a path to urban food security within circular economy.

2.1 Aim

The aim of this thesis is to conduct an environmental and economic analysis of the RTG life cycle in comparison to the conventional GH while analysing the different covering materials in order to define the optimal RTG scenario.

2.2 Objectives

Specific objectives are defined below:

- Carry out a review of the existing background on structural materials and covering used in greenhouses, more specifically on roofs of buildings.

- Define the needs (functional, structural, etc.) of a greenhouse, identifying the specific needs for each type (conventional vs. RTG)
- Review the existing background on the works oriented to the analysis of environmental life cycle and costs related to the selected materials, and their application in conventional greenhouses (ground installation) and on building roofs.
- Define and apply the most appropriate life cycle and cost analysis methodology (based on the background) for the evaluation of the environmental and economic impact associated with the selected materials. An inventory analysis, evaluation of the life cycle and cost impact and its interpretation will be carried out.
- Compare the alternatives of materials considered, both economically (material cost, assembly / disassembly cost, maintenance cost, etc.) and environmental.
- Carry out a comparison (economic and environmental) of a greenhouse type design on roofs of buildings with a greenhouse of the same functional characteristics, but of conventional type (with ground installation).
- Carry out a comparative environmental study between production in RTG systems and the conventional system.

3 METHODOLOGY

3.1 Environmental Analysis

Concerning environmental analysis and to compare the environmental burdens of the systems contemplated in the objectives of this work, the chosen method was the Life Cycle Assessment (LCA) (ISO, 2006a). This method is defined as:

"LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product System throughout its life cycle (i.e., consecutive and interlinked stages of a product System, from raw materials acquisition or generation from natural resource to final disposal)" (ISO, 2006a).

Life Cycle Assessment (LCA) (ISO, 2006a, 2006b) is a structured, comprehensive and internationally standardised method. It quantifies all relevant emissions and resource consumption as well as, related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of any goods or services. However, the Life Cycle Assessment (LCA) is only the environmental part of the sustainability measures; it is important to introduce the Life Cycle Sustainability Assessment (LCSA) concept. LCSA allows the evaluation of all environmental, social and economic impacts and benefits in the decision-making processes for the development of sustainable products and services throughout their entire LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) (UNEP & SETAC, 2011).

ISO 14040 (ISO, 2006a) presents a four-stage method for the development of and LCA. Figure 7 depicts a schema of the LCA process:

- Goal and scope definition.
- Inventory.
- Life Cycle Impact Assessment (LCIA) (in the environmental analysis).
- Interpretation.

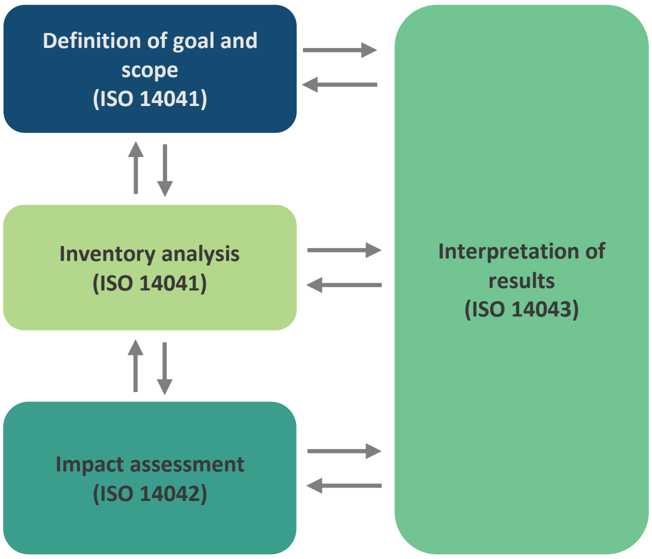

Figure 5. LCA stages ((ISO, 2006a).

LCA study is an iterative process, based on the repetition of the previous scheme process to arrive to the decision or the desired result by the repetition of the 4 steps.

3.1.1 Goal and scope

The goal and scope definition is the first phase of any life cycle assessment. During the definition of the goal, the decision context, the planned applications of the study and the target audience are identified.

During the scope definition phase, the object of the LCI is identified and defined in detail. This shall be done in line with the goal definition. The scope definition focuses on describing and detailing the following aspects:

- The system or process under assessment, in terms of function, functional unit and reference flows.
- The LCI modelling framework.
- The system boundaries. Defining the life cycle phases that are included in the study, extraction of materials, manufacturing, use, re-processing and end-of-life (cradle-to grave), or any of the many options available (gate-to-gate, cradle-to-gate, cradle-to-site, etc.). These boundaries will be subject to data availability and their accuracy and should also define what aspects were excluded and a justification for these decisions (lack of data, negligible inputs/outputs). Figure 6 shows summarised as a scheme the different system boundaries that exist.

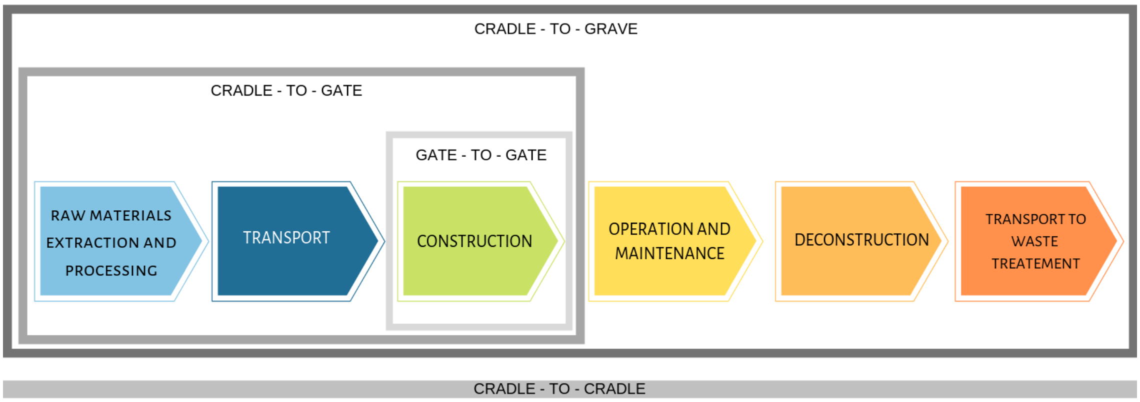

Figure 6. Example of the different system boundaries that can exist in a life cycle assessment of a given system. Source: own elaboration

- The LCI data quality requirements.
- The LCIA impact categories and methods to be used.

During the goal and scope definition, the definition of the functional unit is a key aspect, since it quantifies the qualitative and quantitative aspects of the functions of the system under assessment.

3.1.2 Life cycle inventory

The life cycle inventory consists in the compilation of all the environmental inputs and outputs associated with a product or service, such as all the resources consumed and all the emissions released into the environment throughout the entire life cycle of a system, process or product. Inputs can be categorised as resources from nature (e.g., mineral extraction, water) or resources from the technosphere (e.g., plastics, electricity), the use of raw materials and energy, the emission of pollutants and the waste streams. Outputs are differentiated among emissions to the environment (air, water, soil) and to the technosphere (wastes to treatment) (European Commission - Joint Research Centre, 2010a).

Typically, the LCI phase requires the highest efforts and resources of an LCA. It is necessary to perform an iterative procedure to develop a good LCI. The main steps are described below (European Commission - Joint Research Centre, 2010a):

- Identifying the processes that are required for the system: attributional or consequential modelling. System boundaries vary depending on the type of LCA performed: attributional, which describes the environmentally relevant physical flows to and from subsystems within the overall system analysed, and consequential, an evaluation of consequences of system actions (Ekvall & Weidema, 2004).

- Planning of the collection of the raw data and information, and of data sets from secondary sources.
- Collecting for the foreground system unit process inventory data for these process ensuring the quality and how to deal with missing inventory data.
- Developing generic LCI data, especially when average or specific data are not available and cannot be developed.
- Obtaining complementary background data as a unit process or LCI result data sets from data providers.
- Averaging LCI data across process or products, including for developing production, supply and consumption mixes.
- Modelling the system by connecting and scaling the data sets correctly, so that the system is providing its functional unit.
- Calculating LCI results, e.g. summing up all inputs and outputs of all processes within the system boundaries.

3.1.3 Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in an LCA when the inputs and outputs of elementary flows, that were collected and reported in the inventory, are transformed into impact indicators. This is achieved by applying an impact assessment method, such as ReCiPe (Goedkoop et al., 2008), CML-IA method (Guinee, 2002), or ILCD 2011 Midpoint + (European Commission; Joint Research Centre; Instirute for Environment and Sustainability, 2012), with the aim to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system.

According to ISO 14044, Life Cycle Impact Assessment consists of two mandatory steps and two optional steps (ISO, 2006b)

- Mandatory Steps:
    - **Classification**: the environmental impacts relevant to the study are defined. The elementary flows from the life cycle inventory (e.g. resource consumption, emissions into air, etc.) are then assigned to impact categories according to the substances ability to contribute to different environmental problems.
    - **Characterisation**: the impact of each emission or resource consumption is modelled quantitatively, according to the environmental mechanism. The result is expressed as an impact score in a unit common to all contributions within the impact category by applying the so-called characterisation factors. For example,

kg of CO_2 eq. for greenhouse gases contributing to the impact category Global Warming.

- Optional Steps
    - **Normalisation**: in this step the characterised impact scores are associated to a common reference.
    - **Weighting**: the different environmental impact categories and/or Areas of Protection are ranked according to their relative importance.

Impacts can be assess at the midpoint or endpoint level (UNEP & SETAC, 2011). Midpoint impact categories are links in the cause-effect environmental chain, and while these are easier to quantify, they are more difficult to understand. Contrastingly, endpoint categories represent the end of the chain, the final effect, which is easier to understand, but more difficult to quantify. Figure 7 represents, in a schematic way, the general classifications of midpoint impact categories linking damage categories or endpoint.

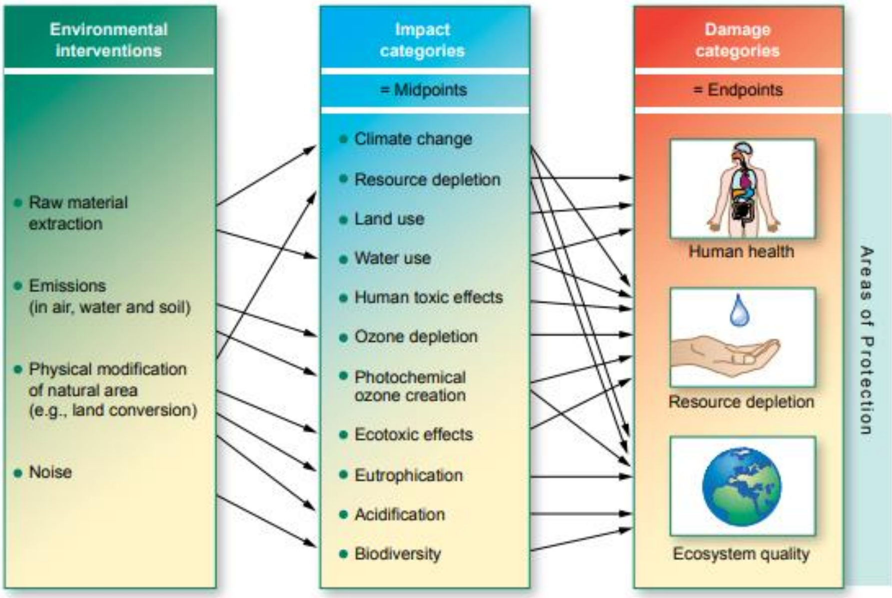

Figure 7. Overall UNEP/SETAC scheme of the environmental LCIA framework, linking LCI results via the midpoint categories to damage categories (adapted from Jolliet et al., (2003))

In this study, midpoint categories will be depicted because these focus on specific environmental impacts, unlike the endpoint categories, which integrates the midpoint categories into three general indicators. The endpoint categories, as a result of the aggregation of midpoint results, provide uncertainty in the results, so they were intentionally avoided (National Institute for Public Health and the Environment, 2018).

ReCiPe and Cumulative Energy Demand (CED) are chosen as an impact evaluation method because they are the most referenced methods in the bibliography and they facilitates the comparison of results and their discussion. The ReCiPe impact categories (Goedkoop et al., 2008) and CED (Frischknecht, Wyss, Knöpfel, Lützkendorf, & Balouktsi, 2015) as an energy flow indicator are described in Table 3.

Table 3. List of the ReCiPe impact categories and CED as an energy flow indicator.

ReCiPe IMPACT CATEGORIES			
Impact Category	**Abbreviation**	**Unit**	**Description**
Global warming	**GW**	kg $CO_{2\ eq}$	Impact of some anthropogenic emissions (CO_2, CH_4, etc.) to the atmosphere that contribute to global warming.
Stratospheric ozone depletion	**SOD**	kg CFC11 $_{eq}$	The stratospheric ozone layer blocks a large part of the harmful UV radiation before it reaches the surface. Certain (mostly bromine and chlorine containing) substances however have the potential to destroy stratospheric ozone and thereby increase the amount of radiation that reaches the surface which causes damage to human health.
Ionizing radiation	**IR**	kBq Co-60 $_{eq}$	Radiation emitted in the form of particles, X-rays or gamma rays with sufficient energy to cause ionization in the medium through which it travels.
Ozone formation, Human health	**OF, HH**	kg $NO_{x\ eq}$	It refers to the formation of ozone that affects human health.
Fine particulate matter formation	**FP**	kg $PM_{2.5\ eq}$	Particulate matter formation starts with an emission of NO_x, NH_3, SO_2, or primary $PM_{2.5}$ to the atmosphere, followed by atmospheric fate and chemistry in the air; NO_x, NH_3, and SO_2 are transformed in air to secondary aerosols.
Ozone formation, Terrestrial ecosystems	**OF, TE**	kg $NO_{x\ eq}$	It corresponds to the formation of ozone that affects terrestrial ecosystems.
Terrestrial acidification	**TA**	kg $SO_{2\ eq}$	Soil acidification as a result of the deposition of acidifying inorganic substances such as sulphates, nitrates and phosphates.
Freshwater eutrophication	**FE**	kg P_{eq}	Eutrophication of fresh water as a result of a high concentration of nutrients, usually P and N. It results in a decay of the oxygen concentration in the water.
Marine eutrophication	**ME**	kg N_{eq}	The same concept as in eutrophication in fresh water, but in marine waters.
Terrestrial ecotoxicity	**TEcotox**	kg 1,4-DCB	Ecotoxicity refers to the impact of chemicals that affect ecosystems. Is calculated considering the persistence and effect of these chemicals.
Freshwater ecotoxicity	**FEcotox**	kg 1,4-DCB	Ecotoxicity affecting freshwater.
Marine ecotoxicity	**MEcotox**	kg 1,4-DCB	Ecotoxicity that affects seawater.
Human carcinogenic toxicity	**HCT**	kg 1,4-DCB	Human carcinogenic toxicity from materials and used resources.
Human non-carcinogenic toxicity	**HnCT**	kg 1,4-DCB	Toxicity that affects humans but not in a carcinogenic way.
Land use	**LU**	m^2a crop $_{eq}$	Represents the occupation of land as a main driver of global biodiversity loss. Within a

			product's life cycle, the land use impacts can represent a significant portion of their total environmental burden.
Mineral resource scarcity	**MRS**	kg Cu $_{eq}$	Corresponds to the scarcity of mineral resources.
Fossil resource scarcity	**FRS**	kg oil $_{eq}$	Corresponds to the scarcity of fossil resources.
Water consumption	**WC**	m^3	Water consumption used throughout the analysis
ENERGY FLOW INDICATOR			
Cumulative Energy Demand	**CED**	MJ	CED quantifies the energy content of all the different energy resources (renewable and non-renewable). The method is based on higher heating values (HHV).

ReCiPe offers different cultural perspectives. These are based on different temporal perspectives and the more or less proven effects of them. Three great models of behaviour are defined:

- **Egalitarian:** long-term perspective. A minimum of scientific evidence justifies the inclusion of a certain category of damage.
- **Individualist:** short-term temporary perspective, only the fully tested effects are included.
- **Hierarchist:** a balanced, short-term and long-term perspective, the consensus among scientists determines the inclusion of certain effects.

3.1.4 Interpretation

The interpretation stage is the last in an LCA study. This is necessary for identifying, quantifying, checking and evaluating information from the results of the LCI and/or the LCIA. During the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the Life Cycle Inventory model and to meet the needs derived from the study goal. Finally, when the study is finalised, this interpretation phase should achieve the main conclusions and recommendations of the study.

3.1.5 Limitations of LCA studies

LCA is a methodology in constant development. This is basically due to the fact that there are still no generally accepted methodologies defined to associate inventory data with the potential environmental impacts, in a consistent and accurate manner. The same happens with the impact categories that define each methodology, since over the years, they are evolving by incorporating or eliminating parameters or even by creating new ones. Another handicap is the subjectivity associated both with the choice and evaluation of impact categories, and in the phase of environmental impact assessment.

Finally, it is considered that the traceability of any data is vital to ensure the transparency of the study at all times. It is crucial to define the origin of the data used (geographic origin and time), as well as the hypotheses, assumptions and limitations that are taken into account in order to keep in mind the uncertainties associated with the study (Antón Vallejo, 2004; LCA notes from Análisi de Ciclo de Vida (subject), 2018).

3.2 Material selection

For the selection of materials, different criteria were defined based on the bibliography consulted and specific interests of this study. Among these criteria one can distinguish those that must compulsorily meet all materials: (1) functional requirements and (2) availability. Last, specific criteria, which are those that only some materials have, though considered to be interesting to study due to current usage, promising innovative materials and functional advantages.

- **Functional requirements** can be summarised in two main ones: provision of maximum solar radiation transmittance in a way that enough light reaches the plants combined with minimum heating requirements during the cold season so that heat losses through the covering materials should be as low as possible (Elsner et al., 2000a; IDAE, 2008).
- **Availability:** material is available in the market and accessible at the specific location.
- **Current usage:** Polycarbonate, Polyethylene and Glass are probably the top three most widely applied materials. Case studies for this dissertation are already using two of these materials: ICTA-ICP building's RTG employs polycarbonate and IRTA, polyethylene.
- **Innovation:** ETFE plastic is widely used in the construction industry as a substitute for glass. Therefore, it has been considered that this material could also be a good substitute for horticultural glass since it is highly transparent in light of the entire spectrum of visible light and it has a high level of heat retention, retaining the thermal radiation of long wave.
- **Other:** the 2 layers of polyethylene is considered as a cover because this is the cheapest material and according to studies, the use of two layers has functional advantages(Kim, Kang, Moon, Lee, & Oh, 2018; Sirelkhatim K Abbouda, Emad A Almuhanna, & Ali M Al-Amri, 2012).

3.3 Cost analysis

Life-cycle costing (LCC) (ISO, 2017) is a consolidated methodology which provides a framework for calculating the overall cost of a product or a service over its lifespan or life cycle. It is defined in the ISO standard, Buildings and Constructed Assets, Service-life Planning, Part 5: Life-cycle Costing (ISO 15686-5) as an:

"Economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability."

LCC was developed originally from a strict financial cost accounting perspective, but in recent years LCC has gained importance and it is applied in the framework of decisions over products or investments requiring high initial capital such as: buildings, energy systems, transport, and durable goods in general, since it provides robust level of comparative analysis and cost benchmarking between alternatives.

Hunkeler et al. (2008) were the first to specify an LCC methodology with the aim to provide an assessment of the costs of a product across its entire life cycle consistent to an (environmental) LCA (UNEP & SETAC, 2011).

Life cycle costing is extremely useful for monitoring costs under different scenarios, making it attractive to the product's clients and the financial sector. Basically, LCC consists in an aggregation of all costs that are directly related to a product over its entire life cycle – from resource extraction, processes, construction, maintenance and disposal. It is usually carried out following ISO 15686-5:2017 and the same life cycle approach as LCA.

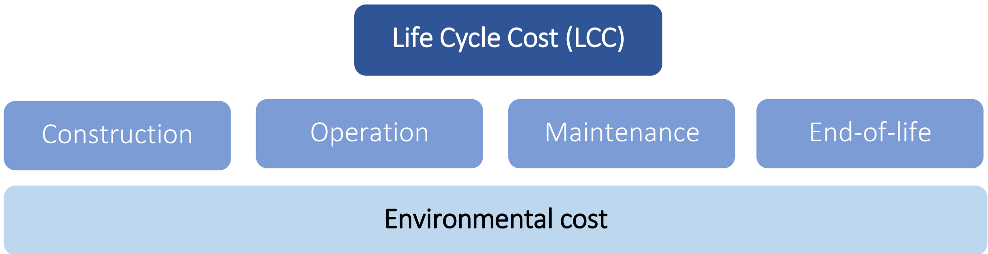

Figure 8.Costs that should be included in life-cycle costing (adapted from (ISO, 2008))

For an LCC study, the goal of the study, a functional unit, system boundaries, allocation procedures and discount rates must be defined. At this stage, a cost breakdown structure (CBS) should also be developed in order to facilitate the consistent collection of data along the full life cycle and which can too be aggregated along the life cycle.

Although converting future costs into a present value for current decision-making, applying a discount rate is generally accepted, there is no consensus on criteria about which discount rate should be applied for an LCC.

An LCC is always conducted for a certain function that must be fulfilled by the analysed system. This function is quantified by the functional unit, which provides a reference to which all costs and benefits are then related.

LCC can be studied through different cost evaluations like: cost-benefit analysis, cost-effective analysis, risk-benefit analysis, and others. In this study, only the calculation of Net Present Value (NPV) is assumed. Internal Rate of Return (IRR) and the Payback period cannot be calculated for there is no economic benefit - it is not possible to recover the initial investment.

Net present value (NPV) (Eq 1) is considered a standard criterion to decide if an option can be justified on economic principles. NPV (euros) is the sum of the discounted future cash flows, defined as the difference between the present value of inflows and outflows, and determines the current value of the initial investment and all future incomes/outcomes over the 50 years of lifespan of the system.

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{F_t}{(1+k)^t} = -I_0 + \frac{F_1}{(1+k)^1} + \frac{F_2}{(1+k)^2} + \cdots + \frac{F_n}{(1+k)^n} \quad (Eq. 1)$$

Where:

F_t : are the cash flows in each period t.

I_0 : is the investment made at the initial moment $(t = 0)$.

n: number of time periods.

k: is the discount rate or interest rate required for the investment

The NPV is mainly used for: (1) to determine if the investments are effective and (2) see which investment is better in absolute terms compared to others.

The decision criteria is the following:

- $NPV > 0$: The updated value of future payments and payments of the investment, at the chosen discount rate will generate benefits.
- $NPV = 0$The investment project will not generate benefits or losses, being in principle, indifferent.
- $NPV < 0$: The investment project will generate losses, so it must be rejected.

4 CASE STUDIES

In order to study the direct relation between the covering materials and the yield in production, two greenhouses were used as a reference in this study: i-RTG Lab located in the ICTA-ICP building as example of RTG and a multitunnel greenhouse of IRTA (Cabrils) as example of CGs. The use of these greenhouses is mainly chosen for the data availability and the commonly applied characteristics in Mediterranean climates.

4.1 Rooftop Greenhouse - ICTA-ICP building

The Institute of Environmental Science and Technology - Catalan Institute of Palaeontology Miquel Crusafont (ICTA-ICP) building was built in 2014 and includes, as the name implies, the Institute of Environmental Science and Technology and the Catalan Institute of Palaeontology. The building has an area of 7500 m^2 distributed over six floors and is located at Universitat Autònoma de Barcelona (UAB) on the Bellaterra Campus. The ICTA-ICP has an external “double skin” that surrounds the rooftop (including i-RTG). This structure is made up of a metal frame with corrugated polycarbonate sheets, with a lifespan of 10 years, which opens and closes depending on internal and external temperature, allowing passive acclimatisation and ventilation in the building and the greenhouse.

The RTG which is been assumed as a reference is one of the i-RTG Lab located in the ICTA-ICP building. As mentioned before, the choice of reference greenhouses has been mainly based on data availability. Therefore, although the RTG used is really an i-RTG, for the realisation of this thesis, this distinction has not proceeded, for the flows present in the building have not been included in detail.

The RTG is located on the south-eastern corner of the ICTA-ICP building roof. It has an area of 122.8 m^2 and a cultivation area of 84.34 m^2. Its structure consists mainly of galvanised steel. The 280.85m^2 of roof is also a "double skin" of corrugated polycarbonate.

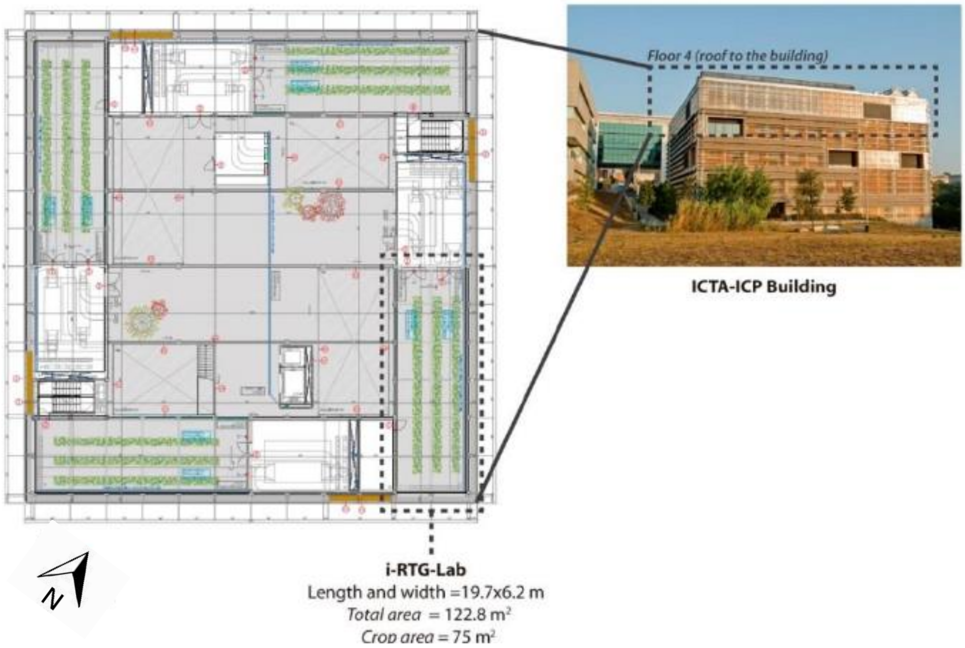

Figure 9. Layout of the rooftop of the ICTA-ICP building and the i-RTG (Sanyé-Mengual et al., 2015).

The tomato crop conducted in i-Lab of ICTA-ICP is taken as a reference crop for RTG. Considering data from 2015-2016, the density of tomato plants was 2 plants per square meter. In the 15.5 months (from February 2015 to July 2016, with the exception of August 2015, as there was no activity in the building) in which different studies on RTG production were done, three different crops were conducted.

Table 4. Characteristics and periods of tomatoes cultivation in ICTA-ICP 2015-2016 (Sanjuan Delmás, 2017)

Cultivation	Season	Starts	Finishes	Days (n)
S1	Spring – Summer	10/02/2015	23/07/2015	164
W	Fall – winter	15/09/2015	04/03/2016	169
S2	Spring - Summer	08/03/2016	20/07/2016)	133

A hydroponic system was used for irrigation to supply a nutrient solution (water plus fertilisers, also called fertigation) to plants located on an inert substrate: perlite. The perlite was supplied in bags of 40 L. These bags were placed on a row and each provided a substrate for three plants. The same bags were used for all three crops (S1, W and S2) (Sanjuan Delmás, 2017).

4.2 Conventional Greenhouse - IRTA

A steel-framed, arched-roofed greenhouse with vertical sidewalls called multi-tunnel is the most used in Mediterranean countries (Antón Vallejo, 2004). However, in this thesis, the conventional greenhouse of reference is a Venlo type greenhouse located at IRTA in Cabrils (Maresme). It consists of a greenhouse of 240 m^2 (20 meters long and 12 meters wide) formed by four chapels. It has a maximum height of 6 meters and 3.5 meters to the gutters. The structure is basically formed by galvanized steel and the cover (514 m^2) is low density polyethylene .

Figure 10. Greenhouses in IRTA – Cabrils and the interior of greenhouse studied. (Ribas, 2019)

Regarding the crop chosen for the conventional greenhouse, the one established in the EUPHOROS project was used and adapted to the conventional reference greenhouse defined for the present study.

The cultivation of the EUPHOROS project was carried out on a crop area of 10,000 m2 between September 15, 2007 and June 4, 2008. It is clear that the crop period is much shorter than the one that took place at the ICTA-ICP. In this scenario, the yield obtained was 16.5 kg of tomatoes per square meter. A fertirrigation and perlite system was also used as a substrate, but for one crop only. (Montero, Antón, Torrellas, Ruijs, & Vermeulen, 2011).

4.3 Materials selected

4.3.1 Horticulture Glass (HG)

Horticultural glass was the most widely used material in greenhouses in Northern Europe. It is the material with the best thermal properties for it does not allow the transmission of infrared or thermal radiation from outside (0%) and a light transmissivity in the visible wavelength of 91 % (Table 5). In addition, horticultural glass is a material that provides good thermal insulation, it is resistant to adverse weather conditions and agrochemicals and it has a long lifespan (in this work it has been considered a useful life of 50 years) (Nijskens, J; Deltour, J; Nisen, A; Coutisse, 1989; George Papadakis et al., 2000).

However, it is also a very heavy material (5.31 kg/m^3), which results in the need for a reinforced structure that supports the roof. It is a fragile material and therefore its impact resistance is also low.

Figure 11. Agròpolis UPC - Horticulture glass covered greenhouse (Interempresas, 2010; Ribas, 2019)

4.3.2 Polyethylene (PE)

Polyethylene is the most used plastic film in the Mediterranean regions. Unlike glass, it is characterised by allowing both visible radiation (88 - 0.91 %) and infrared radiation (70 – 84 %) to pass with a U value of 9.1 W/m^{2}ºC. In addition, it has a reduced lifespan (between 3 and 4 years). At a structural level, it is susceptible to mechanical failure due to harsh conditions of high temperature, solar radiation, and wind (Abbouda, Almuhanna, & Al-amri, 2014).

The main advantage is that it is a very cheap and easily accessible material and does not require a complex structure to install.

Figure 12. Polyethylene covered multitunnel greenhous in Almeria (left) and IRTA Cabrils - Polyethylene covered greenhouse (right) (Montero et al., 2011; Ribas, 2019)

4.3.3 Polyethylene double-layer

As stated earlier, polyethylene is one of the cheapest materials. Therefore, it has been considered to study the effects of using a double layer without air space since authors such as (George Papadakis et al., 2000) or (Nijskens, J; Deltour, J; Nisen, A; Coutisse, 1989) have reported U values of 4.2-6.0 W/m^2 °C and 4.8-6.4 W/m^2 °C, respectively for double polyethylene covers vs. the value of 9.1 W/m^2 °C of a single layer.

Multiple layers of materials alter the incoming radiation and compromise the light transmissivity almost up to a 10% lower than single layer transmissivity and consequently the energy balance in the greenhouse resulting into high operational costs (Sanford, 2011).

Figure 13. Double layer polyethylene cover greenhouse (Tunnel Vision Hoops, 2019)

4.3.4 Polycarbonate (PC)

Polycarbonate is a material that combines good optical and thermal properties with very good mechanical resistance. It is a thermoplastic that lets the visible radiation pass easily enough (transmissivity around 80%) and prevents, to a large extent, the passage of infrared rays (it allows about 2-3% the passage of this type of ray). It is not entirely transparent. Just like glass, it is quite a good thermal insulation. It has a low density that makes it ideal for this type of structure. It is not an expensive material and has a very high useful life time compared to other cover materials (Brett Martin, 2019; George Papadakis et al., 2000).

Figure 14. ICTA-ICP - Polycarbonate cover greenhouse (Sanjuan Delmás, 2017).

4.3.5 ETFE

ETFE (ethylene-tetrafluoroethylene) consists of modified copolymers of ethylene and tetrafluoroethylene. In recent years, it has been widely used in the construction industry as a substitute for glass. Therefore, it has been considered that this material could also be a good substitute for horticultural glass since it is highly transparent in light of the entire spectrum of visible light and it has a high level of heat retention, retaining the thermal radiation of long wave. In addition, ETFE can maintain this transparency and this force for more than 30 years.

It is a very light material. A ETFE sheet (0.25 mm thickness) weighs only 0.70 kg/m^2, while a single layer of glass (4 mm thick) weighs 10 kg/m^2. ETFE is 14 times lighter than glass. ETFE is a very ductile material, in fact, it can stretch up to three times its length without breaking. When broken, its strong intermolecular links prevent the material from breaking like glass.

Finally, fluorocarbon polymers are relatively inert and are especially not active against chemical and weather attack (Designing Buildings Wiki, 2011; SpecialChem, 2019).

Figure 15. ETFE covered greenhouse (AGC Chemicals, 2019).

4.3.6 Solar panels

During the process of selecting materials, the option to study a solar cover was considered. This option can be presented as a cover that further accomplishes the previous requirements, while officially the add value of energy production in order to improve the overall sustainability of the covering material.

There are different studies and practical cases in which the use of conventional and semi-transparent photovoltaic technologies is studied. For example, Ureña-Sánchez et.al. (2012) studied the effect produced by the installation of flexible solar panels mounted on greenhouse roof with a crop of tomatoes and thus see what effects there was on the yield and the quality of the fruit. This study concluded that the Mediterranean basin, with a cover ratio of 9.8%, the production of tomatoes was not compromised, but that the shape, size and colour of the fruits were affected.

Other authors such as Fatnassi et al. (2018) wanted to identify with their studies design features such as the ideal height of the greenhouses, the best orientation or the best distribution of conventional solar panels to the covers of the greenhouses to define the design criteria for the new generation of greenhouses. As a result, conclusions such as the checkerboard pattern and the N-S orientation allow to improve the uniformity of the light have been obtained.

Although there are several solutions for photovoltaic panels: organic photovoltaic cells, semiconductors such as CdTe (Cadmium telluride), CIG (Copper indium gallium) and CGIS (Copper indium gallium diselenide) or panel types (flexible, thin films), semi-transparent photovoltaic technology is considered strategic.

Figure 16. On the left, inside of a greenhouse with a solar cover of conventional panels. On the right, a semi-transparents panels with Sphelar® Technology (Cossu et al., 2016)

After an extensive bibliographic review, the option posed by this thesis and characterised by its innovative nature was a semi-transparent photovoltaic cover with *Sphelar®* technology.

Sphelar® technology, developed by Kyosemi Corporation, is based on single-crystalline silicon spheres, with a diameter of between 1-2 mm. Each sphere works like an individual solar cell, allowing countless combinations. However, the main feature is that it is the only photovoltaic technology capable of capturing solar radiation from all directions.

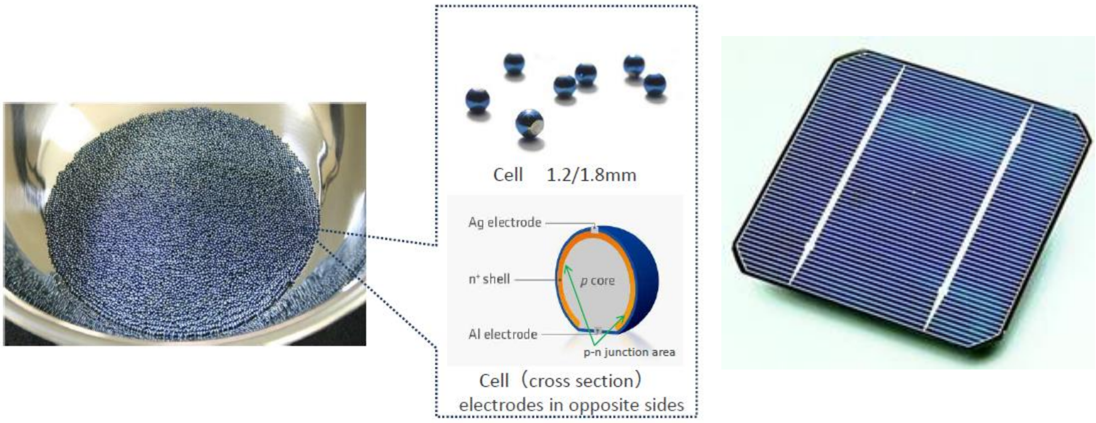

Figure 17. Sphelar® cells with 1-2 mm diameter (Sphelar Power Corporation, 2019b) *vs. Conventional solar cell 156 x 156 mm (Wikipedia, 2019).*

Another advantage is that it allows maximising the effective use of silicon in its production in addition to being able to use 'kerf loss', that is, the excess silicon of the production of conventional photovoltaic panels thanks to its size. Therefore, the generation of raw material waste can be considered minimal.

Figure 18. Detail of Sphelar panel (left). Example of two Building Integrated Photovoltaic Panels (BIPV) one in its straight version and another showing the flexibility capacity (right).

Generally, its creators analysed the different advantages that this technology presents. They are the following:

- *Sphelar®* module can easily make Series/Parallel.
- Bigger of power generation per nominal maximum output.
- Smaller in directivity of sunlight.
- Fewer influence of partial shade
- Higher mechanical strength for the shape of spherical
- More excellent earthquake resistance, strong winds
- Resistance such as typhoons, and impact resistance
- Recycling possible
- Resistant to light damage
- Friendly to the landscape
- Rich in design, such as see-through, flexibility.

Despite all the specified advantages, this is not extensively implemented technology. There is only one study (Cossu et al., 2016) in which a first integration of a photovoltaic panel with *Sphelar®* is carried out.

A greenhouse prototype was built and a semi-transparent photovoltaic module, composed by 4800 spherical silicon micro-cells (1.2 mm diameter) put together between 3-mm- thick glass plates after they were embedded in 2-mm-thick transparent resin and integrated in a greenhouse roof with a 26.5° slope. The percentage of the semi-transparent photovoltaic module area covered with micro-cells was 2.3%, reaching 9.7% considering the metallic conductors. The cell density was 2 cells cm^{-2} and the measured perpendicular light transmissivity of the semi-transparent area was 73%.

Although this study concluded that the energy produced by the semi-transparent photovoltaic module is still insufficient to fulfil the greenhouse electrical demands which are consumed in Mediterranean greenhouses equipped with basic climate control appliance. Hence, technology improvements to increase the conversion efficiency and the light transmissivity of the module are necessary.

However, in *Silicon cells: Catching rays* (Taira & Nakata, 2010) it is verified that the energy accumulated for each panel with *Sphelar®* technology for 1 Wp was 2.7 times higher than the energy accumulated by a conventional panel. Consequently, with the same cover ratio of 9.7% (considering spheres and metal conductors), the performance of a conventional panel is obtained by almost 3 times.

So far, the solar cover with *Sphelar*® technology meets the common criteria of functional requirements, as despite almost 10% of the covering surface is covered by the spheres and the conductor filaments, the measured perpendicular light transmissivity of the semi-transparent area is 73% and depending on the material (glass or plastic) the adequate thermal properties would have been achieved.

Regarding the availability criteria, no bibliographic data were available, so contact was made via email with *Sphelar*® Power Corporation, a spin-off from Kyosemi Corporation.

From there, information was obtained on the commercialisation of this technology, the feasibility of producing massively, the production process and the price.

Regarding the commercialisation and viability of mass production, a positive response was obtained. A mass production was viable, making the price of the Building Integrated Photovoltaic Panel (BIPV) down and making it accessible. However, in this response, it was also said that this is not the case at the moment.

In relation to the production process, the information is not very extensive. It is comprehensible as to avoid plagiarism. This was one of the main reasons why this cover was not taken into account as an option in this work. To carry out the LCIA, one needs information such as raw materials, processes, consumption of electricity, transport, etc. As follows, not having these data was considered the option to make an estimate from the data of production of conventional solar panels. However, in the end, the idea was rejected, since it was considered that the results obtained would not be entirely reliable.

Finally, the price of a BIPV is, approximately 300,000 JPY/m^2 (about 2,500 EUR/m^2).

Therefore, despite being a very interesting option, for everything mentioned above, this was discarded. Although the aim was to address it in this thesis in order to take it into account for the future.

Table 5. Characteristics of the selected materials. Adapted from (IDAE, 2008).

Material	Lifespan	Thickness (mm)	Transmissivity		U ($W/m^{2o}C$)	Density (kg/m^3)	Kg/m^2 (according to thickness)	Availability	Cost (€/m^2)
			Visible radiation (380 - 760 nm)	Thermic radiation (2500 - 40000 nm)					
Horticulture glass [3, 4]	30	4	0.91	0	6.7	2400	10	Yes	50
Polyethylene [1, 2, 3]	4	0.1	0.88-0.91	0.79-0.84	9.1	920	0.88–0.96	Yes	3.2
Polyethylene) x 2 layers [1, 2, 3,7]	4	4 + 4	0.78	0.50	4.8-6.45	1840	0.88–0.96	Yes	6
Polycarbonate [1, 2, 5]	10	4	0.75-0.79	0.02-0.03	3.5	170 - 200	4,8	Yes	7.5
Ethylene Tetrafluoroethylene (ETFE) [6]	50	0.25	0.92-095	0.11	5.6	175	1,7	Yes	280
Semi-transparent Photovoltaic panels (glass + silicon sphere cells) [8]	-	-	0.91	0	-	-	-	Yes. Non-large scale	2500

1. (Nisen, A.; Coutisse, 1981)
2. (Nijskens, J.; Deltour, J.; Coutisse, 1984)
3. (Nijskens, J; Deltour, J; Nisen, A; Coutisse, 1989)
4. (Feuilloley, P.; Issanchou, G.; Jaques, J.C.; Guillaume, S.; Mekikdjian, CH.; Mirabella, J.F.; Merlot, 1994)
5. (Brett Martin, 2019)
6. (AGC Chemicals, 2019)
7. (Sanford, 2011)
8. (Sphelar Power Corporation, 2019a; Taira & Nakata, 2010)

5 LCA

5.1 Goal and scope

Assessment is divided in three parts. The first one allows to evaluate the reference greenhouses – RTG and CG – in its current scenario. The second one evaluates the different covering materials that have been selected to determine the optimal RTG. Finally, with the optimal material selected, an environmental assessment of the scenario defined as optimal is conducted.

5.1.1 Functional unit

The functional unit is defined as **1 kg of tomatoes produced over 1 year**.

5.1.2 System boundaries

A **cradle-to-grave** analysis is conducted. The assessment includes the following stages: **construction**, **operation** and **end of life** for each greenhouse. Moreover, a covering material assessment is carried out too. Figure 19 (see below) depicted the system boundaries of this study.

In the construction phase, the structure - formed mainly by steel and concrete, the rainwater collection system (RTG only), the auxiliary equipment that includes all the necessary materials to carry out the tomato production - pipes, tanks, etc. – and cover are considered. In this part, the maintenance of the structure is considered too.

In the operation stage, the production carried out in the greenhouse is considering taking into account the consumption of expanded perlite, fertilizers, water, etc.

Finally, the end of life stage takes into account the deconstruction of greenhouses and the transport of waste to the treatment, without valuing the waste management. Recycling or final disposal of materials is not considered part of the system under study because it was considered that it lacked accurate information related to the treatment of each material. In all stages, materials (extraction and processing), energy consumption and transport are taken into account.

At the same time, an LCA **cradle-to-grave** is also achieved for each of the selected materials. This analysis takes into account the phase of **installation, maintenance and end of life**

The lifespan of RTG is 50 years according to other studies. In order to compare the RTG with the conventional greenhouse, a 50-year lifespan for the conventional greenhouse has also been considered.

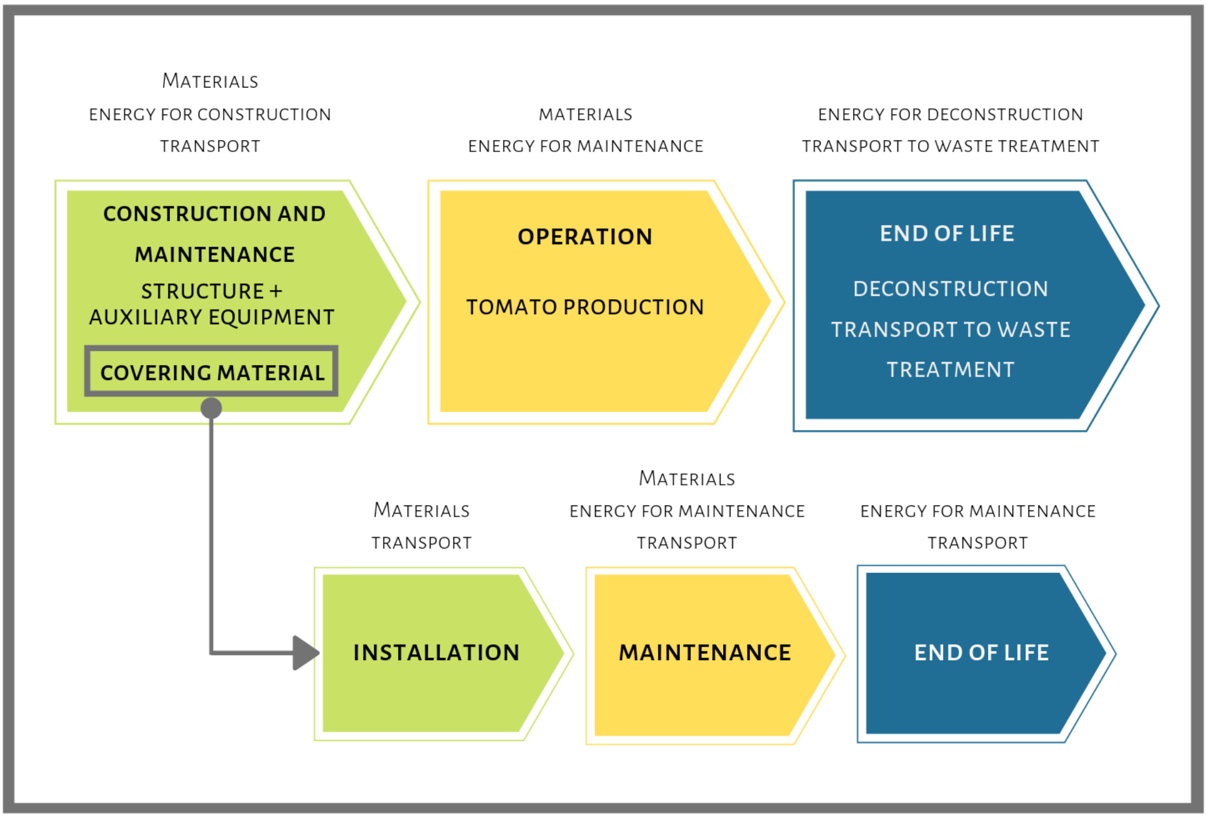

Figure 19. System boundaries of the LCA.

Greenhouses are constituted, basically by three components: 1) the greenhouse structure, 2) the covering materials and 3) the production

5.1.3 Greenhouse structure

The RTG and the conventional greenhouse structures are made up of two parts: the first one is the own greenhouse structure - made mainly of galvanised steel and concrete. This part stays constant during the whole life of the greenhouse (with the corresponding maintenance, if applicable). Only in the case of the RTG has the rainwater harvesting system been considered as part of the structure. Secondly, the auxiliary equipment is the part that is characterised by being subject to changes according to the crop, considering the necessary auxiliary equipment that is needed to grow the plants (banks, leaks, pipes, etc.). The material associated with the pump and distribution network of water for irrigation has been considered for the conventional greenhouse, which is extracted from a nearby well and is boosted to the greenhouse.

In this part, the following limitations were considered:

- ICTA-ICP is a building that due to its uniqueness, it is not reproducible. However, it is considered interesting to study due to its data accessibility.
- The structure of the ICTA-ICP takes into account the rainwater harvesting system as a structure. This is a specific installation of the ICTA-ICP which is not considered in the conventional greenhouse.
- It is assumed that the conventional greenhouse is located in the same place as the ICTA-ICP, consequently, all distances have been assumed. This is applicable in the analysis of the covering materials.
- On the one hand, the inventory of RTG materials (structure, rainwater harvesting, covering material, auxiliary equipment) are from published articles. On the other hand, conventional greenhouse inventory, based on IRTA, has been attained from a recent study in which only the structure and cover is taken into account. Based on this, it is been assumed that the auxiliary equipment for this last greenhouse will be the same as for the RTG adapted to its dimensions. Both the conventional greenhouse inventory and the auxiliary equipment inventory have been contrasted with other studies (Antón Vallejo, 2004; Torrellas et al., 2012).
- With the available data, the construction and maintenance of the entire structure has been taken into account in the construction stage. From the literature, it is determined in which phase most of the impact is concentrated: construction, maintenance or end of life.

5.1.4 Covering materials

Five materials were previously selected, based on common and specific criteria. Once the selection was made, the weight of covering material for each of the two greenhouses were calculated.

Weight is determined by the area and consulted bibliography and technical data sheets of materials that provide the density ($kg \cdot m^{-2}$) and requirements. Table 5 (see below) shows specific quantification for each material and greenhouse. The evaluation of the cover materials include the following stages: installation, maintenance and end of life.

For each stage it was considered the materials (extraction and processing), maintenance and transport to the waste treatment centre. Therefore, the mentioned is also a cradle-to-grave analysis as the greenhouse structure.

In this part, the following limitations were considered:

- Auxiliary material for the installation of each cover was not considered due to data availability.
- Energy associated with the maintenance, understanding maintenance as the action of changing the cover so that the material reach the end of their lifespan. The use of a lifting platform was also considered with the help of a ladder. The energy for the realisation of a single change was estimated from the available data of the replacement of the polycarbonate panels of the ICTA-ICP.

5.1.5 Production

In the production part, all those elements associated with the production of tomatoes are taken into account (Table 6).

Table 6. Data production of RTG and Conventional Greenhouse

	RTG (ICTA-ICP) *Adapted from* (Sanjuan Delmás, 2017)	CONVENTIONAL GREENHOUSE *Adapted from* (Montero et al., 2011)
Crop period (days)	333 *(Summer: 10/02/2015 – 23/07/2015 Winter: 15/09/2015 – 04/03/2016*	263 *(15/09/2007 – 04/06/2008)*
Crop surface (m^2)	84.34	166
Yield tomato production (kg · m^2)	25	16.5
Substrate	Perlite	Perlite
n. substrate bag (40L)	57	111
Plants (plants · m^{-2})	2	1,2
Water use (L · kg tomato)	214,9	28,81
Water use (L · m^{-2})	6,471.97	474.8
N (kg · m^{-2})	0.28	0.08
P_2O_5 (kg · m^{-2})	0.06	0.05
K_2O (kg · m^{-2})	0.51	0.16
Phytosanitary treatment (fungicide and insecticide) ((kg · m^{-2})	0.09	$3.23 \cdot 10^{-3}$

It is imperative to consider the following limitations:

- Regarding productivity, production data is taken from two different sources; (1) for RTG data comes from the study about the environmental assessment of food production in a i-RTG considering rainwater residual heat (energy) , residual air (CO_2) and food from an industrial ecology perspective (Sanjuan Delmás, 2017), (2) for conventional greenhouse data comes from the European project EUPHOROS (2011). The data used in this section is presented in Table 4. It should be taken into account that the availability of data regarding production in greenhouses, either conventional or RTG, are limited. For this reason, at this point some simplifications and estimations were used.

- The years and periods of production are factors to consider. Both the production years and the periods are different and therefore, the external environmental conditions are too. In other words, the solar radiation the crops receive, as well as the temperature outside will be different from one crop to another. This is also linked to the physical location of the two crops. The EUPHOROS data was collected in Almeria in the year 2008, whereas the data from the ICTA-ICP building was collected from 2015 to 2016 in Barcelona. There is no preceding data since the ICTA-ICP building was built in 2014.
- The available production data corresponds to an industrial greenhouse (19,440 m^2) and the reference conventional greenhouse thesis is 240 m^2; 80 times smaller. At this point, it is necessary to adapt all available data from the industrial greenhouse to the reference greenhouse. Therefore, the values that have changed are those of cultivation area and bags of perlite. This reduction in a surface area also entails a clear decrease in the consumption of water, fertilizers, etc.
- Another simplified factor is the use of nutrients and phytosanitary treatments. For instance, in the Sanjuan-Delmás's thesis shows the values of macronutrients and micronutrients used and required for each of the crops. However, it was considered that for the present study, this level of detail was not necessary, so only phosphorus, nitrogen and potassium data were taken into account.

5.2 Life cycle inventory

Material and energy data was mainly obtained from bibliographic sources and the Ecoinvent v3 database (Swiss Center for Life Cycle Inventories, 2013). Production data for RTG was obtained from experimental data of ICTA-ICP researchers. When lacking of bibliographic data, approximations were considered, along with its reliability and accuracy.

Table 7 contains all the sources of information used for the inventory of greenhouse structures. More details are available in Table 15 and Table 16 the Annex

Table 7. LCI of greenhouse structures

LIFE CYCLE INVENTORY OF GREENHOUSES WITHOUT COVERING MATERIAL		
	RTG	CONVENTIONAL
STRUCTURE		
Construction		
Materials	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)
Processes materials	(Sanyé-Mengual et al., 2015)	Calculated
Transport materials	(Sanyé-Mengual et al., 2015)	Calculated
Construction	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)
Maintenance		

Materials	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)
Processes materials	(Sanyé-Mengual et al., 2015)	Calculated
Transport materials	(Sanyé-Mengual et al., 2015)	Calculated
Maintenance	(Antón Vallejo, 2004)	(Antón Vallejo, 2004)
End of life		
Deconstruction	(Ribas, 2019)	(Ribas, 2019)
Waste transport	(Sanyé-Mengual et al., 2015)	Calculated
WATER		
	Rainwater Harvesting	The conventional greenhouse have not got rainwater harvesting
Installation and Maintenance		
Materials	(Sanjuan Delmás, 2017)	
Processes materials	(Sanjuan Delmás, 2017)	
Transport materials	(Sanjuan Delmás, 2017)	
Installation	(Sanjuan Delmás, 2017)	
End of life		
Deconstruction	(Sanjuan Delmás, 2017)	
Waste transport	(Sanjuan Delmás, 2017)	
AUXILIARY EQUIPMENT		
Installation		
Materials	(Sanjuan Delmás, 2017)	(Sanjuan Delmás, 2017)
Processes materials	(Sanjuan Delmás, 2017)	(Sanjuan Delmás, 2017)
Transport materials	(Sanjuan Delmás, 2017)	(Sanjuan Delmás, 2017)
End of life		
Waste transport	(Sanjuan Delmás, 2017)	(Sanjuan Delmás, 2017)
PRODUCTION		
Installation		
Materials	EUPHOROS (Montero et al., 2011) + (Llorach-Massana et al., 2017)	EUPHOROS (Montero et al., 2011) + (Llorach-Massana et al., 2017)
Processes materials	EUPHOROS	EUPHOROS
Transport materials	EUPHOROS (Montero et al., 2011) + (Llorach-Massana et al., 2017)	EUPHOROS (Montero et al., 2011) + (Sanjuan Delmás, 2017)
Operation		
Operation	(Ribas, 2019)	(Ribas, 2019)
End of life		
Waste transport	Calculated	Calculated

Table 8 contains all the sources of information used for the inventory of covering materials.

Table 8. LCI of covering materials

LIFE CYCLE INVENTORY OF COVERING MATERIAL					
	POLYCARBONATE	POLYETHYLENE	POLYETHYLENE (2 LAYERS)	HORTICULTURE GLASS	ETFE
INSTALLATION					
Materials	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated
Processes	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated
MAINTENANCE					
Materials	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated
Processes	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)					
Materials	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated
Processes	(Sanyé-Mengual et al., 2015)	(Ribas, 2019)	Calculated from (Ribas, 2019)	Calculated	Calculated

5.3 Life cycle impact

Environmental impact at midpoint level was calculated using ReCiPe 2016 v1.1 (Goedkoop et al., 2008) through a hierarchic perspective, as recommended in the ILCD Handbook (European Commission - Joint Research Centre, 2010b) and SimaPro 9.0 (Pré Consultants, 2019) software. The selection of impact categories were made based on the existing bibliography. Moreover, Cumulative Energy Demand (CED) was calculated too.

- **Global Warming (GW):** It is considered a popular indicator both at the level of scientific community and at a general level, since it is a widely known global problem. It was calculated for all the LCAs.
- **Freshwater Eutrophication (FE):** This category is directly linked to the production phase of the greenhouses. It allows to determine the impact of the nutrients used in the production of tomatoes.
- **Mineral Resource Scarcity (MRS):** This indicator allows to see the effect caused to mineral resources (mainly metals) as a consequence of the structure and covering materials.
- **Water Depletion (WD):** In a similar way to GW, water consumption is also an understandable indicator for all audiences and applied in various studies. It has been calculated for all the LCAs.
- **Cumulative Energy Demand (CED)**: is an energy flow indicator that quantifies the energy content of all the different energy resources (renewable and non-renewable). It is extensively used.

First, a comparative analysis is carried out between RTG and CG with their current covering. This analysis allows to obtain the current environmental burdens for each greenhouse on its current scenario. It is wanted to determine which of the two greenhouses has a higher environmental impact.

Subsequently, a comparative analysis is performed between the 5 covering materials selected using the impact categories selected above. The purpose of this point is to determine the material with the least associated impact.

The last analysis is to evaluate the optimum scenario. The new environmental burdens of the greenhouses along with the optimal covering are analysed, compared to the current scenarios. Finally, the environmental improvement with the covering replacement is calculated.

6 LCC

A Life Cycle Costing (LCC) analysis was performed for each of the structures studied. In order to carry out this evaluation, the inventory defined in the Life Cycle Assessment part was used. The prices corresponding to the different elements were assigned. It should be taken into account that in some cases the price of an item was assumed and not its material, such as pumps or tanks.

The majority of prices have been taken from the iTeC database of the year's price bank. Those prices which were not contemplated in this database, were obtained from external reliable sources.

In order to conduct this analysis, the construction materials (both the initials and those used for maintenance), labour and machinery associated to construction, maintenance, transport, electrical consumption and deconstruction were considered. Finally, all these costs were grouped into: construction, maintenance, production and end of life. Table 9 shows the global results for each stage. However, all the details of the prices are found in the Annex Table 27.

The economic evaluation was carried out assuming a lifespan of 50 years for all the greenhouses by 1 m^2. Current Retail Price Index (RPI) - 0.3 positive in August 2019 (Instituto Nacional de Estadística (INE), 2019)- was taken into account in order to calculate the costs for the following years acknowledging the reference prices.

From here, the NPV was calculated with the mainly purpose of determining if the current investment is better than the optimal or vice versa. It was calculated with an interest rate of 0.55% (Satista, 2019).

Table 9. Global economic data for current RTG with polycarbonate and optimal RTG with ETFE.

	RTG POLYCARBONATE	RTG ETFE
	€/m2	€/m2
Materials	48.15	147.75
Production	36.3	36.3
Construction	67.8	76.6
Maintenance	7.8	1.6
Deconstruction	32.9	32.95

7. RESULTS

7.1. Current scenario assessment: RTG with polycarbonate and CG with polyethylene

This section deals with the global analysis which was performed comparing the RTG and the CG in their current scenario for all impact categories. It is important to bear in mind that the greenhouses are divided into different parts - structure, auxiliary equipment, production and covering. However there are some difference between each greenhouse, mainly in the structure. RTG has a complex structure made with galvanised steel and concrete and with a rainwater harvesting system included. On contrary, CG has a much more simple structure with less material associated and has not got any rainwater harvesting system. Regarding production and end of life, both greenhouses have similar composition.Figure 20Figure 20 compares the RTG and the CG according to the impact category of global warming. For the RTG, the highest impact is associated to the structure, which represents 54% of the total CO_2 eq emissions per kg of tomatoes. Furthermore, production raises to a 27% and becomes second when considering the highest impact, followed by covering which represents a 14% of the total of emissions. Finally, the auxiliary equipment represents the part with the lowest impact with only a 5%. In sum, for each kilo of tomatoes, the RTG emissions reach 0.80 kg of CO_2 eq.

Focusing on the CG, the part with the highest impact falls on production with 43% of total CO_2 eq emissions per kg of tomatoes. The structure, with 35%, is the second part with the highest impact. Finally, the auxiliary equipment and cover are the parts with the least impact with 16% and 6% of the total respectively. For every kg of tomatoes, the CG emits 0.30 kg CO_2 eq. It can be concluded that the complete life cycle of **the RTG emits 2.7 times more kg of CO_2 eq/kg of tomato than the CG.**

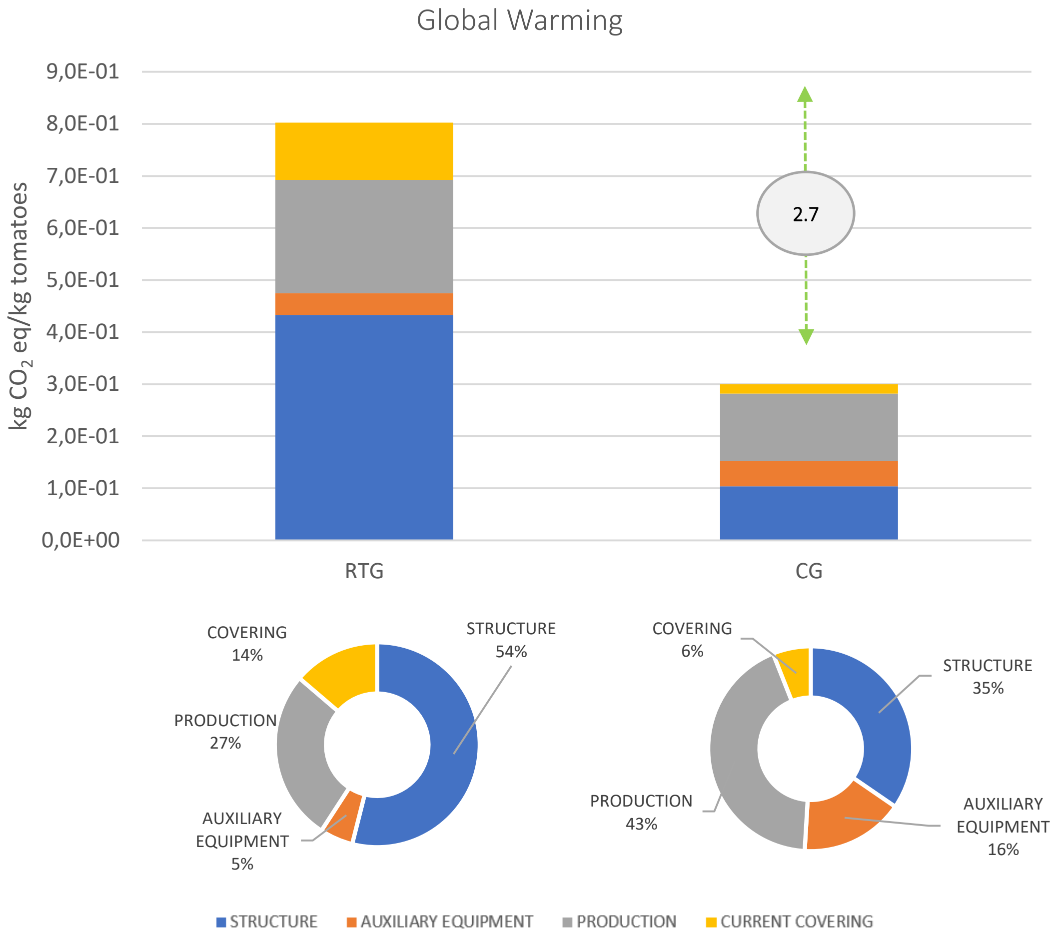

Figure 20. Comparison between the current RTG and current CG for the Global Warming impact category.

Figure 21 shows the results of comparing RTG and CG based on the Freshwater Eutrophication impact category. It can be seen that both the auxiliary equipment and the cover lose importance when it comes to the structure and the production. For RTG, the structure represents 84% of the total emissions of P eq., a 13% increase in comparison to the CG. Regarding production, RTG represents 14% of the total and 21% for the CG. Finally, the auxiliary equipment and the cover material have an insignificant weight in both greenhouses, for both the RTG auxiliary equipment and the cover material represent 1%. For CG, the auxiliary equipment shows a 7%, while the cover 1%. For each kilo of tomatoes produced, the RTG emits $3.5 \cdot 10^{-4}$ kg P eq and CG $1.54 \cdot 10^{-4}$ kg P eq. Globally, every life cycle of **the RTG emits 2.3 times more P eq/kg tomatoes than the CG.**

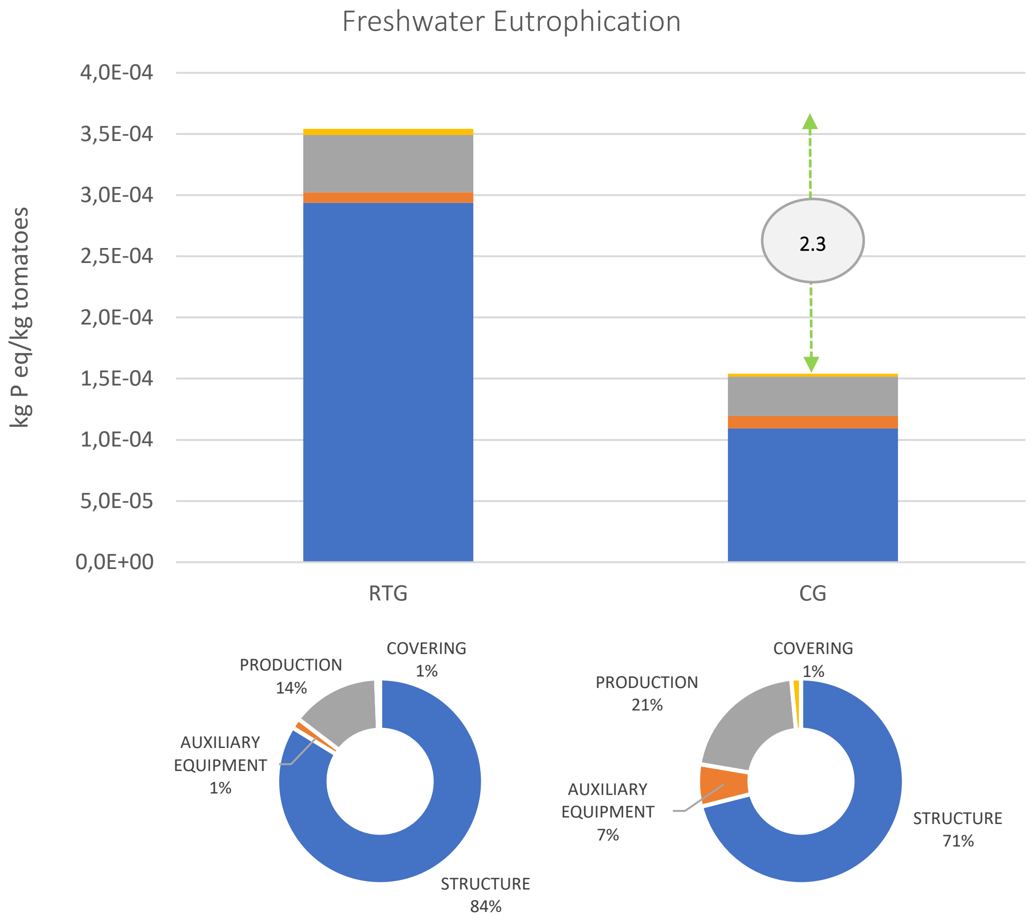

Figure 21. Comparison between the current RTG and current CG for the Freshwater Eutrophication impact category.

The Mineral Resource Scarcity impact category on both analysed structures is shown in Figure 22. The results obtained for this impact category are similar to those obtained by Freshwater Eutrophication. In this impact category and for the two reference greenhouses, the structure is the part that consumes most mineral resources: 90% for the RTG and 80% for the CG. The parts of the greenhouses not mentioned above, have a less important relative weight than the structure itself. Production for RTG represents 9% of the consumption of Cu eq/kg tomatoes and 17% for CG. The rest of the parts altogether add up to less than 3% of the total as a whole for each greenhouse. In general, RTG consumes $6.47 \cdot 10^{-3}$ kg Cu eq per kg of tomatoes and CG $3.20 \cdot 10^{-3}$ kg Cu eq throughout its life cycle. Finally, **the RTG has a consumption of mineral resources 2 times higher than CG.**

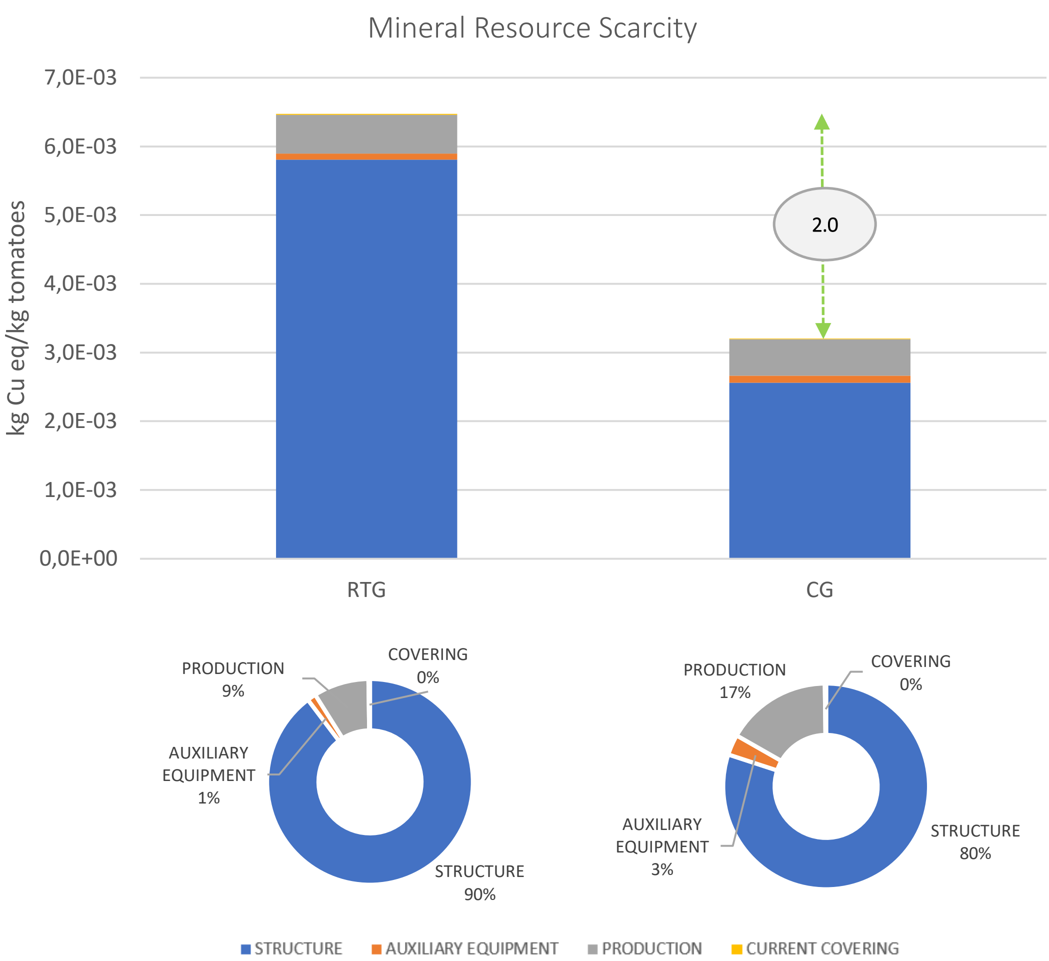

Figure 22. Comparison between the current RTG and current CG for the Mineral Resource Scarcity impact category.

The results obtained by Water Consumption (Figure 23) are clearly different from those obtained so far. At this point, it can be seen that for the two greenhouses, the production represents the highest water consumption - 73% of the total for RTG and 94% of the total for CG. Regarding the rest of the parties, only the structure of the RTG stands out with a 24% of water consumption. For the rest -auxiliary equipment and production of the RTG and structure, auxiliary equipment and production of the CG - represent little more than a 3% for both greenhouses. For the RTG, the global water consumption is 0.04 m3 per kg of tomatoes and for CG of 0.03 m3 per kg of tomatoes. **The RTG represents a water consumption 1.3 times higher than CG.**

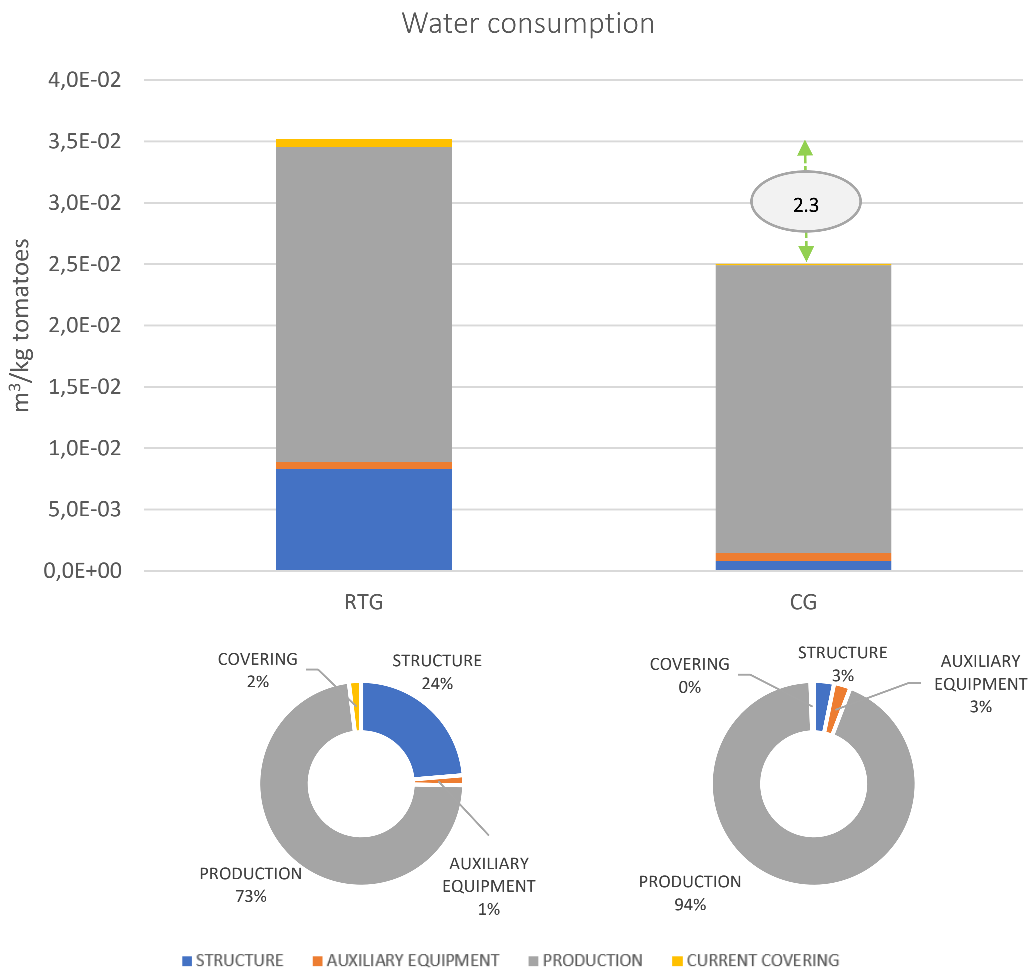

Figure 23. Comparison between the current RTG and current CG for the Water Consumption impact category

Finally, for the Cumulative Energy Demand (Figure 24) we find that the proportion of energy demand for each of the parts is different between the two greenhouses. For RTG, the part with the most accumulated primary energy is the structure, which represents 58% of the total MJ/kg tomatoes, followed by production, with 23% of MJ per kg of tomato. On the contrary, for CG the most weighted part is the production with 48% of the total MJ/kg tomatoes followed by the structure by 27%. This same behaviour occurs between the auxiliary equipment and the covering material. For the RTG, the polycarbonate cover represents 11% of the total energy followed by the auxiliary equipment with 8%. Oppositely, for CG, the polyethylene cover is the part with the least accumulated energy, only 2% compared to the 23% that represents the auxiliary equipment. According to the mentioned data, the primary energy accumulated in RTG throughout its life cycle is 8.6 MJ per kg of tomatoes and for CG is 3.6 MJ per kg of tomato. So that the accumulated energy of the RTG is 2.4 higher than that of the CG.

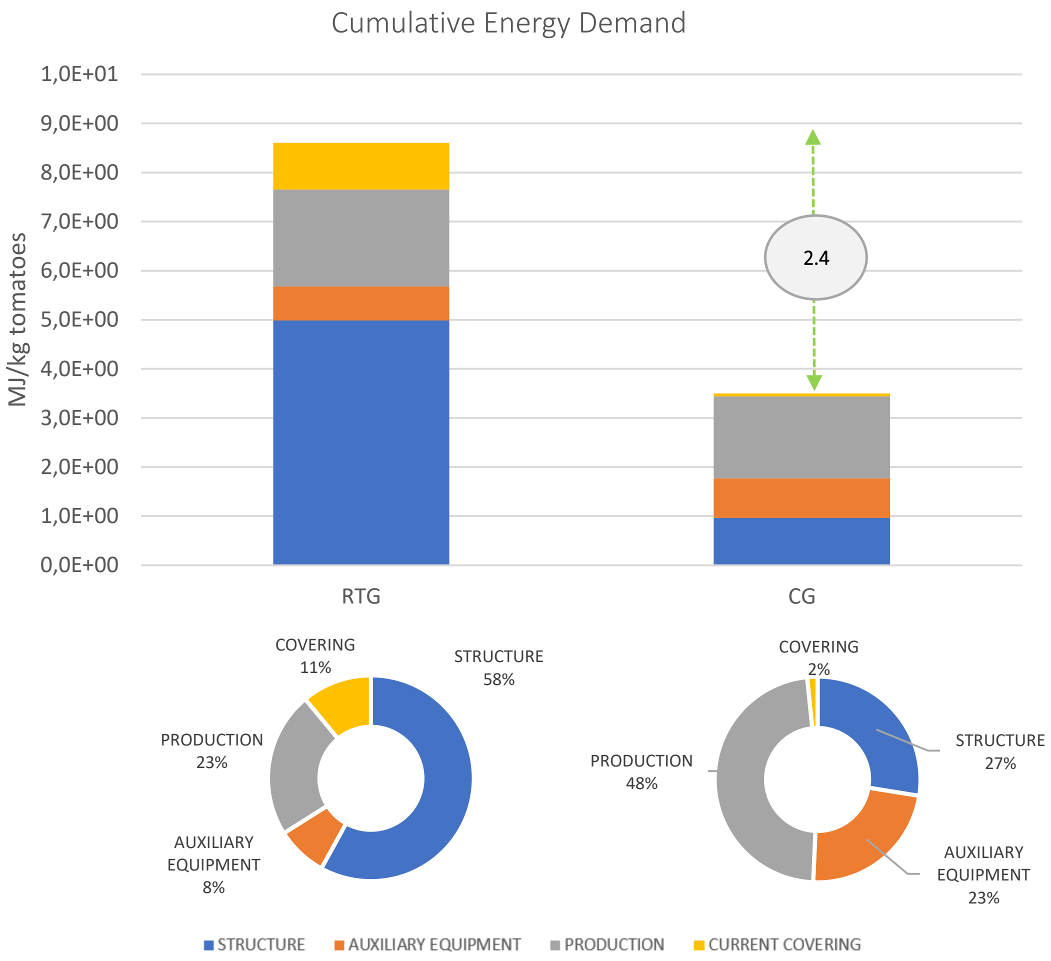

Figure 24. Comparison between the current RTG and current CG for Cumulative Energy Demand

7.2. Covering materials assessment

The total values – including installation, maintenance and end of life - relative to each impact category are shown in Table 10. The purpose of this table is to represent, in a visual way, the relative impact value of each material and for each category of impact by taking the highest value as the reference value. Following this, the comparison between materials is simplified and allows an easy selection of the most optimal cover material at the environmental level.

Table 10. Relative value of the impact of each material for each type of greenhouse and indicator, taking as the reference value the highest value.

	GW (kg CO_2 eq)		FE (kg P eq)		MRS (kg Cu eq)		WC (m^3)		CED (MJ)	
	%		%		%		%		%	
	RTG	CG	RTG	CG	RTG	CG	RTG	CG	RTG	CG
Polycarbonate	8.7	19.0	1.4	3.1	0.4	0.8	5.0	10.9	6.6	14.5
Polyethylene	1.3	1.3	0.5	0.5	0.2	0.2	1.4	1.4	2.4	2.4
Polyethylene double-layer	2.5	2.5	1.0	1.0	0.3	0.3	2.7	2.7	4.8	4.8
Horticulture glass	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
ETFE	4.4	4.4	0.5	0.5	0.3	0.3	0.6	0.6	0.4	0.4

The horticultural glass followed by the polycarbonate are the two covering materials with the highest relative impact both for the RTG and the CG (Table 10). It should be taken into account that the polycarbonate, despite being the second material with the most associated environmental impact, is far from the values obtained by horticultural glass.

Although polyethylene, double layer polyethylene and ETFE have lower values in contrast to glass or polyethylene, polyethylene double-layer is the material which takes third position.

Regarding polyethylene and ETFE, polyethylene has the lowest impact value for the GW and MRS categories. Instead, ETFE has the lowest values for WC and CED. For FE, the relative value is equal to polyethylene and ETFE.

Therefore, it can be determined that **polyethylene is the material with a lower environmental impact** compared to all the materials evaluated.

However, **ETFE is also selected as an optimal material**. Consequently, polyethylene film is not feasible to use it in construction, whereas ETFE is. In addition, the values obtained for the ETFE are very similar to those of the polyethylene, except for those obtained by GW.

For both materials, a graphic was produced showing the impact associated to each type of greenhouse based on the different impact categories, and for each phase of its life cycle (installation, maintenance and end of life). Percentage impact values were normalized to facilitate graphic representation. In the Annex, the same pictures for polycarbonate can be found (Figure 32), for polyethylene double-layer (Figure 34) and for horticulture glass (Figure 35).

In Figure 25, the maintenance of polyethylene can be observed. This is the phase of its life cycle with the most associated impact: 92% of the total. The installation only represents 8% and the end of life is considered despicable. The results obtained in this section are clearly conditioned by the useful life of polyethylene, approximately 4 years. Taking into account that a 50-year lifespan of each greenhouse was assumed, this created the need to change covers every 4 years, with a total of approximately 12 changes. Regarding the end of life, the fact of considering only the transport to the gate of the management, without taking into account any treatment, causes that only the impact associated with the own transport is taken into account which is minimum regarding the phases of construction and maintenance.

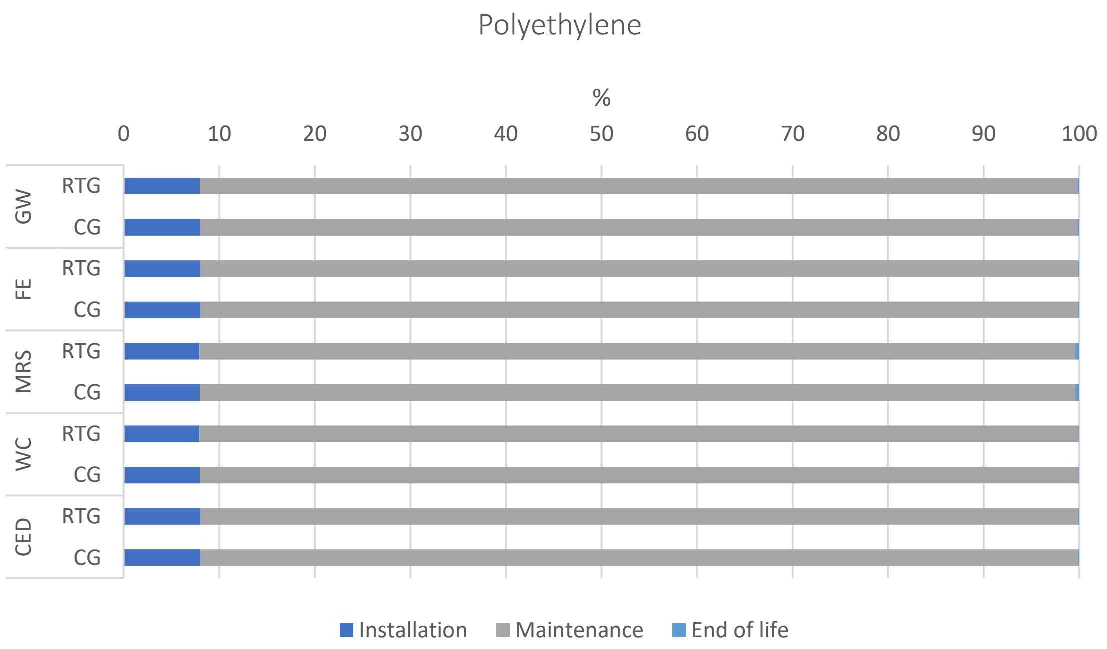

Figure 25. Representation of the impact of the polyethylene life cycle for each stage of the life cycle, distinguishing between greenhouses and for all impact categories.

The results for ETFE for each life cycle stage (Figure 26). Almost 100% of the impact is associated to the installation phase - a proportion less than 1% is associated to the end of life. Unlike polyethylene, this material does not require maintenance since its lifespan is equal to the greenhouses lifespan (50 years) and therefore, it should not be replaced at any time. That is why the entire impact is concentrated in the installation phase. The despicable value of the end of life has the same explanation given by plastic polyethylene.

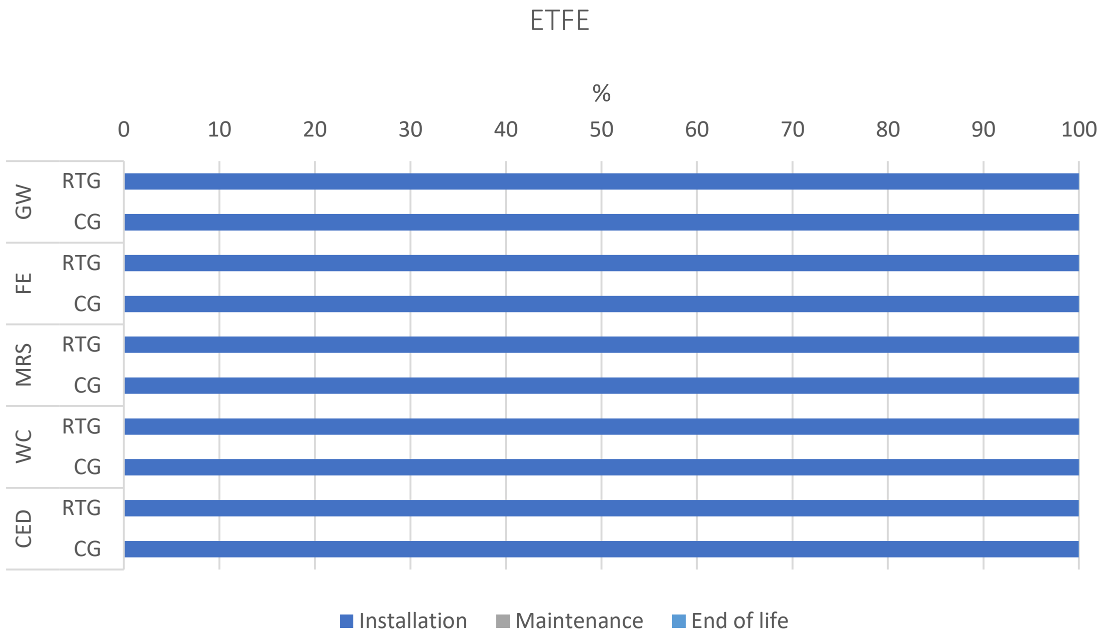

Figure 26. Representation of the impact of the ETFE life cycle for each stage of the life cycle, distinguishing between greenhouses and for all impact categories.

The relative improvement that could be achieved with the change of polycarbonate to polyethylene cover for RTG (Table 11). It is clear that, for all impact categories, this change of polycarbonate to polyethylene would be an improvement since the impact would be between 2.3 and 6.9 times lower, according to the indicator evaluated. Whereas for the change of polycarbonate to ETFE, it is observed that due to the impact categories of GW and MRS, the reduction of the impact is not so attractive for what is achieved with polyethylene. However, for WC and CED categories, a remarkable reduction is obtained - 7.8 times the impact of the WC and 15.8 times the impact of the CED. For FE, the same decrease is obtained.

Table 11. Relation between the current RTG material covering - polycarbonate and the materials defined as optimal - polyethylene and ETFE

RTG	GW (kg CO_2 eq)	FE (kg P eq)	MRS (kg Cu eq)	WC (m^3)	CED (MJ)
	%	%	%	%	%
Polycarbonate	8.7	1.4	0.4	5.0	6.6
Polyethylene	1.3	0.5	0.2	1.4	2.4
ETFE	4.4	0.5	0.3	0.6	0.4
Polycarbonate/Polyethylene	6.9	3.0	2.3	3.6	2.8
Polycarbonate/ETFE	2.0	3.0	1.4	7.8	15.7

In Table 12, the same exercise was done for CG. It is worth mentioning that this greenhouse has polyethylene as a current cover material, therefore only the change to ETFE was evaluated. Even though the environmental impact increases due to GW and MRS, when WC and CED are evaluated, the impact is 2.2 and 5.7 lower respectively. No changes can be noticed concerning

FE. Despite some improvement over the current cover material, the change of coverage with ETFE does not imply a global improvement for the CG.

Table 12. Relation between the current CG material covering - polycarbonate and the materials defined as optimal - polyethylene and ETFE

CG	GW (kg CO_2 eq)	FE (kg P eq)	MRS (kg Cu eq)	WC (m^3)	CED (MJ)
	%	%	%	%	%
Polyethylene	1.3	0.5	0.2	1.4	2.4
ETFE	4.4	0.5	0.5	0.6	0.4
Polyethylene/ETFE	0.3	1.0	0.6	2.2	5.7

7.3. Optimal scenario assessment

Based on the selection of the optimal material, each impact category and CED is represented by the current RTG and the optimum scenario of each, obtained from the change of cover material. In the optimum scenarios, the structure, auxiliary equipment and production were preserved and only the cover material was modified. Therefore, any optimisation of the greenhouses will be given by the change of this last element.

In Figure 27, it is seen that in RTG, along with the ETFE cover, the CO_2 eq emitted by kg of tomatoes decreases in contrast to the current RTG cover of polycarbonate

As for the current greenhouse, the cover represents 14% (0.11 kg of CO_2 eq/kg tomatoes) of the total. Contrary to this, with ETFE it represents 7% (0.05 kg of CO_2 eq/kg tomatoes). It has been obtained that with change of cover to ETFE, **the emissions of CO_2 eq would be approximately 7% inferior avoiding the emission of 0.06 kg CO_2 eq/kg tomatoes.**

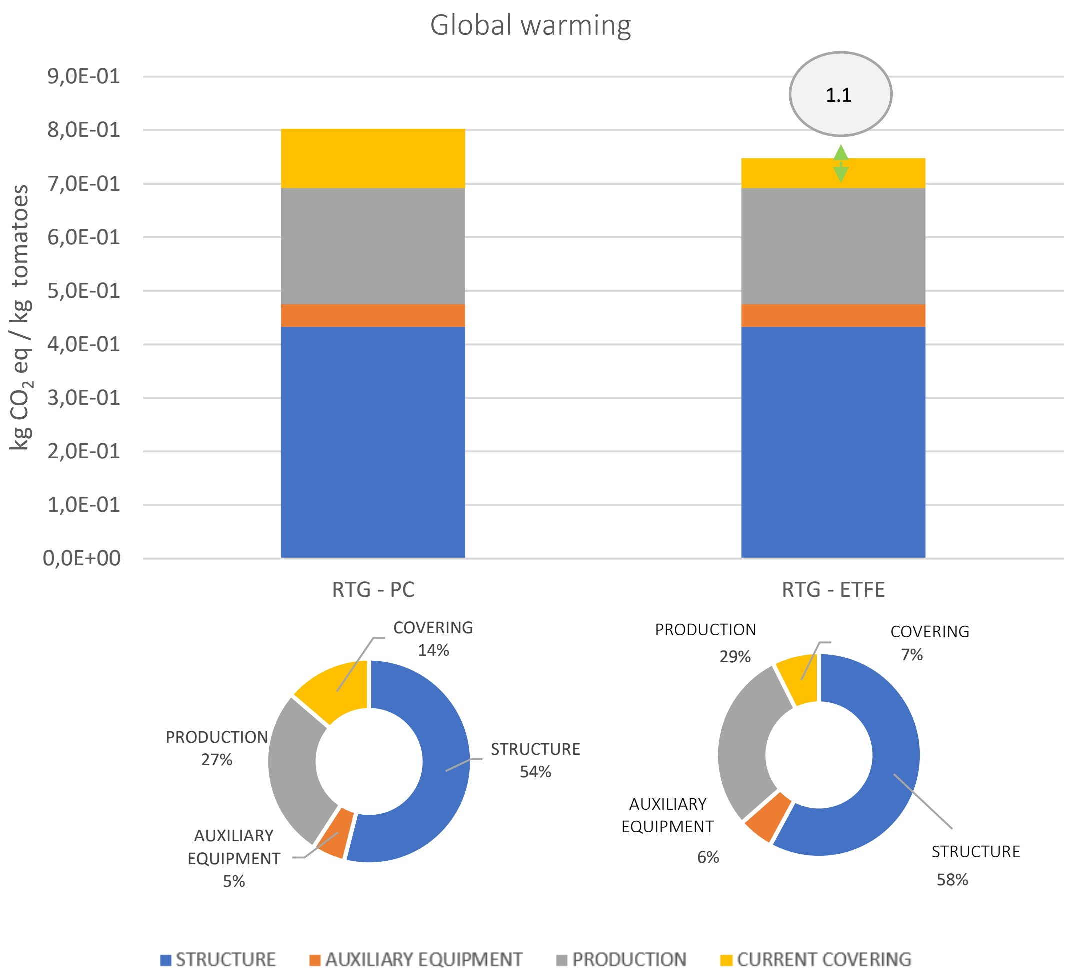

Figure 27. Comparison, based on Global warming, between the current RTG with polycarbonate covering and the optimised version: RTG with ETFE cover.

Figure 28 presents the same results as the previous figure, but dealing with Freshwater eutrophication. In this impact category it can be observed that the cover has a very discreet representation in contrast to the rest of parts of the greenhouses for RTG on its current version – 1.4% ($4.82 \cdot 10^{-6}$ kg of P eq/kg tomatoes). Considering the low weight the covering has in the global greenhouse, it can be expected that the reduction of kg of P eq emitted by kilo of tomato will be very low. **For the ETFE the kg of P eq decreases to 1% ($3.51 \cdot 10^{-4}$ kg of P eq/kg tomatoes).**

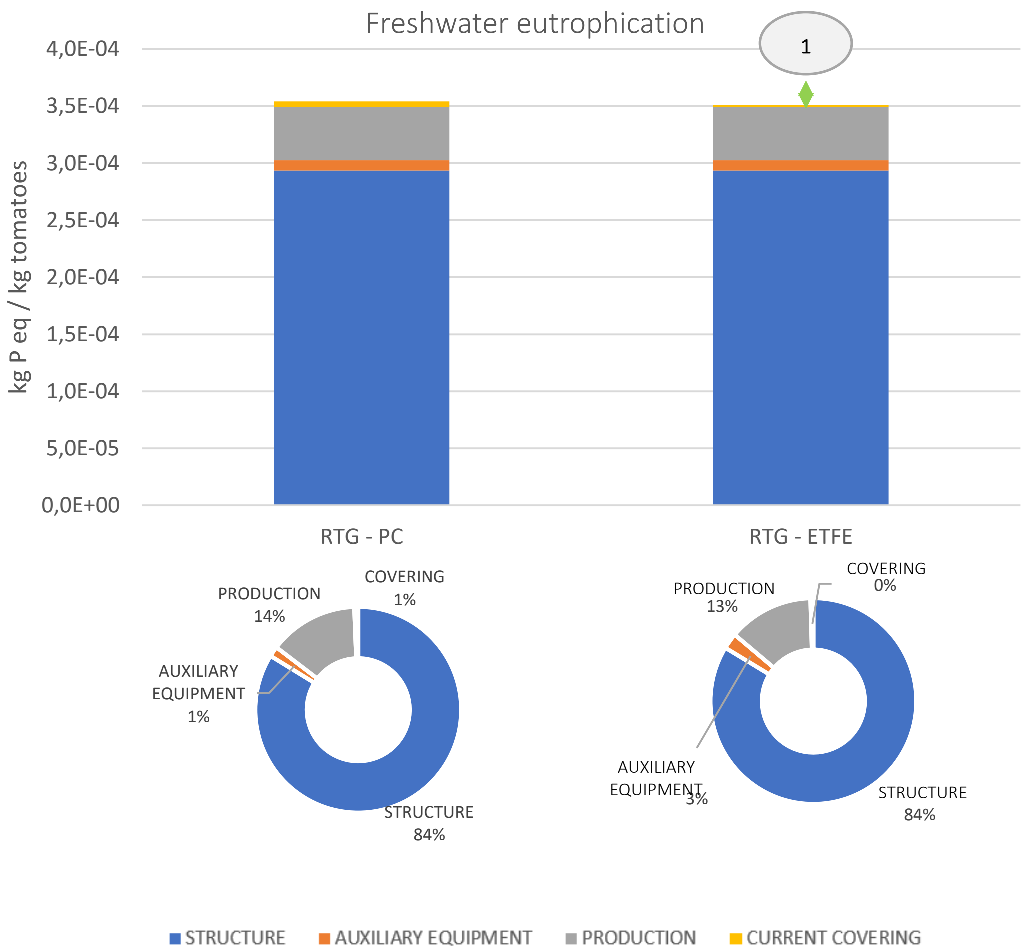

Figure 28. Comparison, based on Freshwater eutrophication, between the current RTG with polycarbonate covering and the optimised version: RTG with ETFE cover.

For Mineral resource scarcity (Figure 29), the depiction of the cover material is almost negligible. For RTG, the covering only represents 0.2% ($1.53 \cdot 10^{-5}$ kg of Cu eq/kg tomatoes).By changing the covering, the percentage loses importance. It represents the ETFE 0.2% ($1.16 \cdot 10^{-5}$ kg of Cu eq/kg tomatoes).

As for the previous category, given the low weight that covers have in the global greenhouse, it is expected that the reduction of kg of Cu eq issued by tomato kg will be very low. **For the new ETFE cover, the decrease in kg of Cu eq is 0.0% ($3.7 \cdot 10^{-6}$ kg of Cu eq/kg tomatoes).**

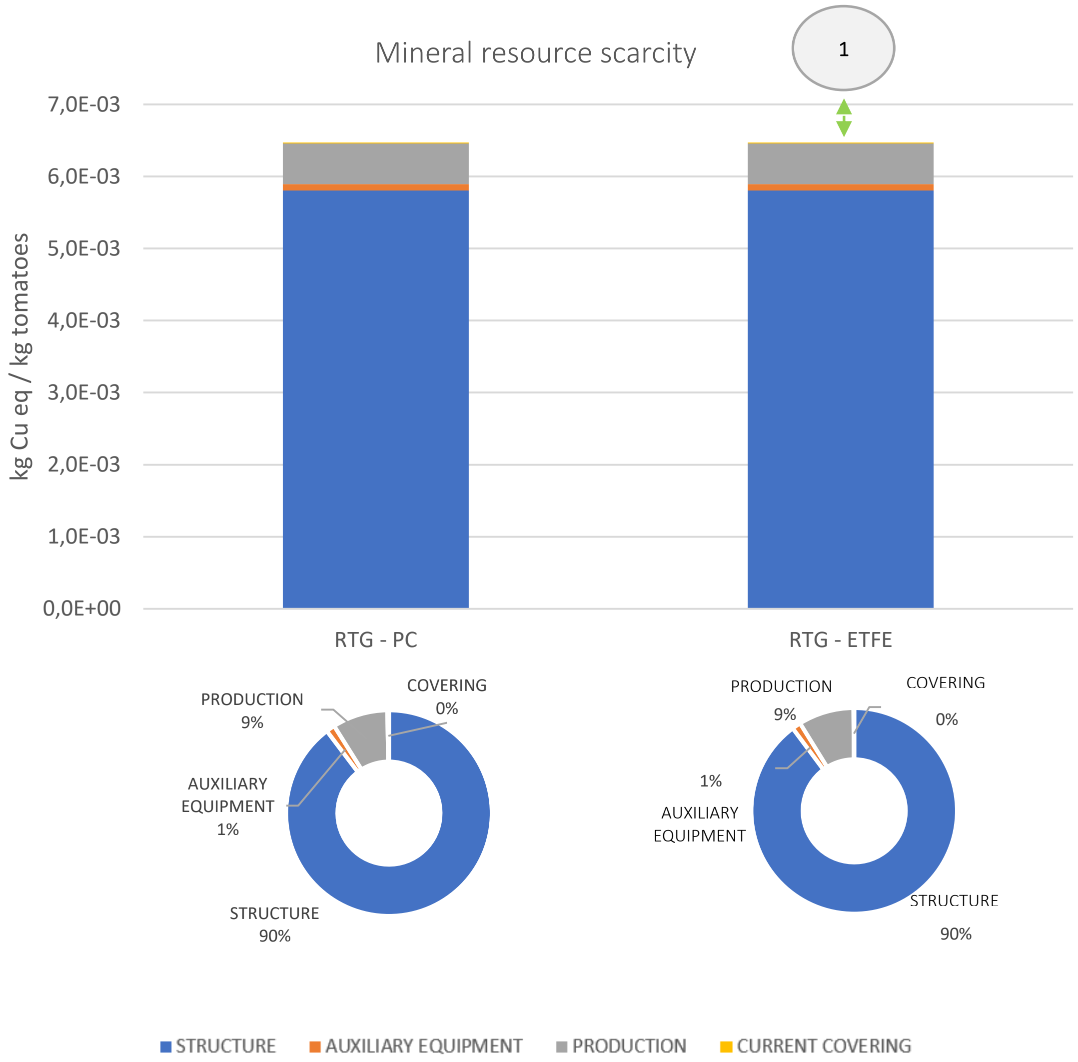

Figure 29. Comparison, based on Mineral resource scarcity, between the current RTG with polycarbonate covering and the optimised version: RTG with ETFE cover.

For water consumption, the cover has no significant representation (Figure 30). For RTG, the cover only represents 2% ($6.8 \cdot 10^{-4}$ m^3/kg tomatoes). With the respective cover change, this percentage loses even more importance. In the case of RTG with ETFE, it represents 0 % ($8.7 \cdot 10^{-5}$ m^3/kg tomatoes).

As for the previous category, seeing the little weight the covering has in the global greenhouse, it is expected that the reduction of the consumption of m^3 of water per kg of tomato will also be very low. **For the new ETFE cover, the decrease of m^3 is 2% ($5.9 \cdot 10^{-4}$ m^3/kg tomatoes).**

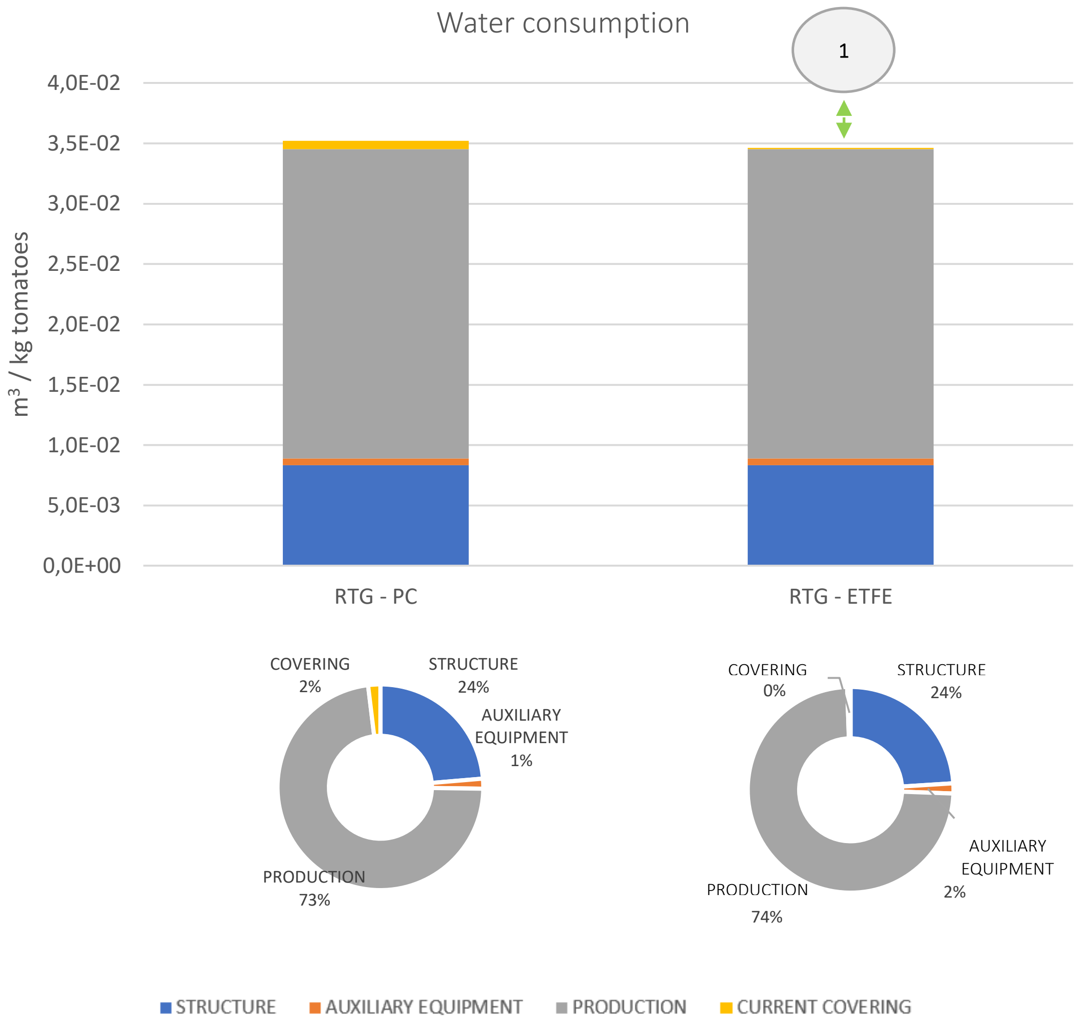

Figure 30. Comparison, based on Water consumption, between the current RTG with polycarbonate covering and the optimised version: RTG with ETFE cover

In Figure 31, the Cumulative Energy Demand for each of the RTG with different covering materials is evaluated. Based on this indicator, it can be observed that the cover has a relative higher importance than previously evaluated categories - FE, MRS and WC. Therefore, for the present RTG, the covering represents 11% (0.9 MJ/kg tomatoes).

With the replacement of a new cover, it is observed for the RTG, that with the new ETFE cover, the primary energy (MJ) associated to one kg of tomato would be 1% ($6.0 \cdot 10^{-2}$ MJ/kg tomatoes) lower. **This value is also reflected on the fact that the relative weight of the ETFE cover also decreases to 10%.**

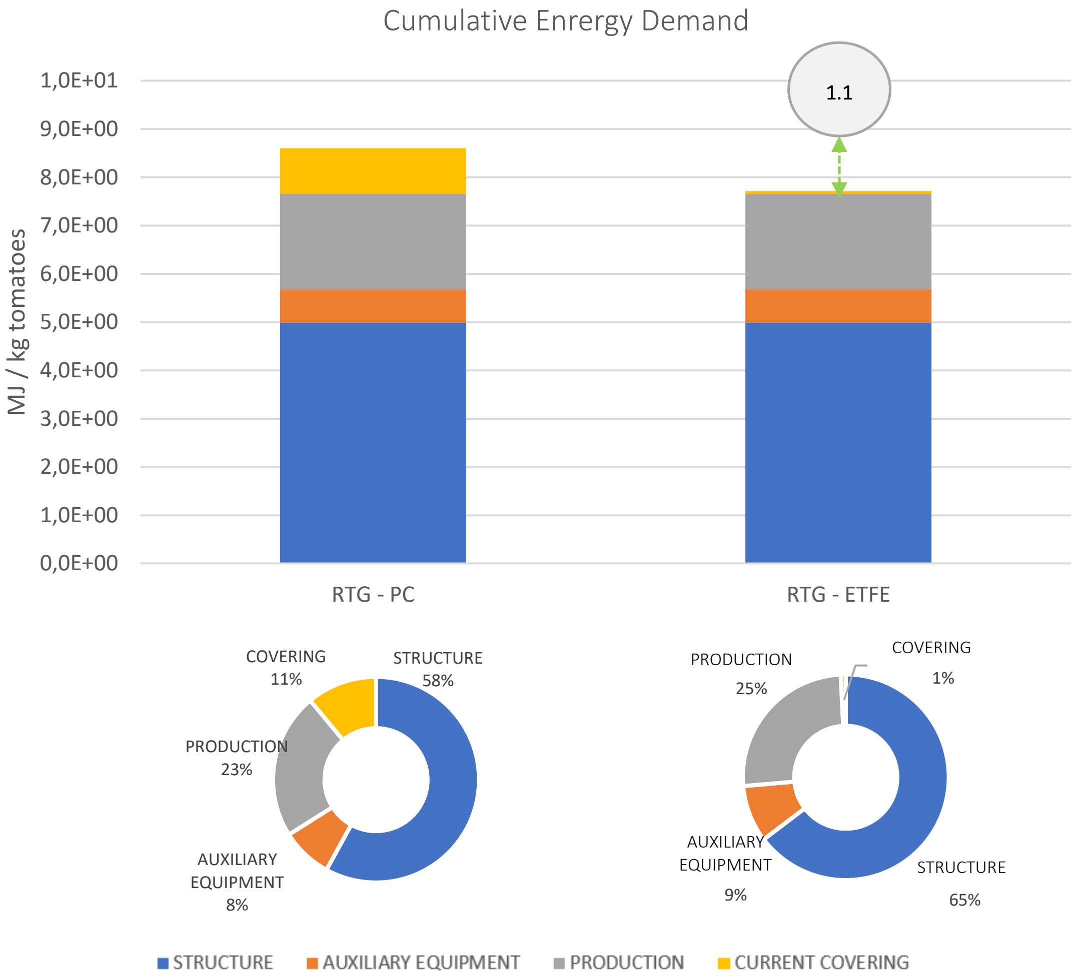

Figure 31. Comparison, based on Cumulative Energy Demand, between the current RTG with polycarbonate covering and the optimised version: RTG with ETFE cover.

7.4. Economic assessment

Within this section, only the RTG was evaluated in its current scenario, along with the scenario considered optimal at an environmental level. It was decided to obviate the economic evaluation of the CG. The results obtained in the environmental analysis as a result of the change of polyethylene cover to ETFE do not imply a significant environmental improvement. Moreover, the price per m^2 of the ETFE covering (280€/m^2) is the highest, so it allows us to determine that it is the worst option in reference to the current CG scenario with polyethylene (the cheapest plastic).

Table 27 of the Annex shows the price per m^2 per 1 year for the elements of the RTG. We assume some elements negligible and we simplify others. It should be noted that the only part that varies is that related to the cover and its maintenance, since it is determined by the type of material.

Table 13 shows the total investment per m^2 and per 50 years for the greenhouse in its current scenario and in the optimal scenario, differentiating construction, maintenance, production and end of life for each type of RTG. In addition, the percentages of the relative weight are included.

Table 13. Total investment for m^2 of RTG in 50 years.

Price (€/m2)	RTG – PC	RTG - ETFE
Construction	125.5 (11%)	224.4 (19%)
Maintenance	202.4 (17%)	112.9 (10%)
Production	812.95 (69%)	812,95 (69%)
End of life	38.6 (3%)	36,0 (3%)
TOTAL	**1179.5**	**1186.3**

It can be determined that the investment for the RTG with ETFE is higher than the investment for RTG with polycarbonate. The difference between the both investment is 6.8 €.

Table 14 shows the NPV obtained for RTG with polycarbonate and RTG with ETFE.

Table 14. Net Present Value (NPV) for RTG with polycarbonate and RTG with ETFE

	RTG – PC	RTG - ETFE
NPV	- 117.5	- 182.1

As expected, both results are negative, since the generation of any kind of benefit has not been taken into account and therefore the cash flow is always negative. However, RTG-PC has a less negative NPV, which means that recovering this investment so that the NPV is equal to 0 or higher, would be easier than for the RTG –ETFE.

Figure 32 shows how the costs are shared. It can be seen that the majority are associated to the production phase, and the lowest at the end of life represented by the transport of waste to the point of treatment. The parts that present more variation are the construction and the maintenance. It can be seen that RTG - PC cost of maintenance – 202.4 €/m^2 – is higher than the cost of construction – 125.5 €/m^2. On the one hand, the RTG - ETFE is inverse - 118.9 €/m^2. On the other hand, the cost of building the first greenhouse is lower than the RTG with an ETFE cover: 224.4 €/m^2 for construction and 112.9 €/m^2 for maintenance (see Table 13). This is mainly associated with the useful life of these materials and the need to replace them.

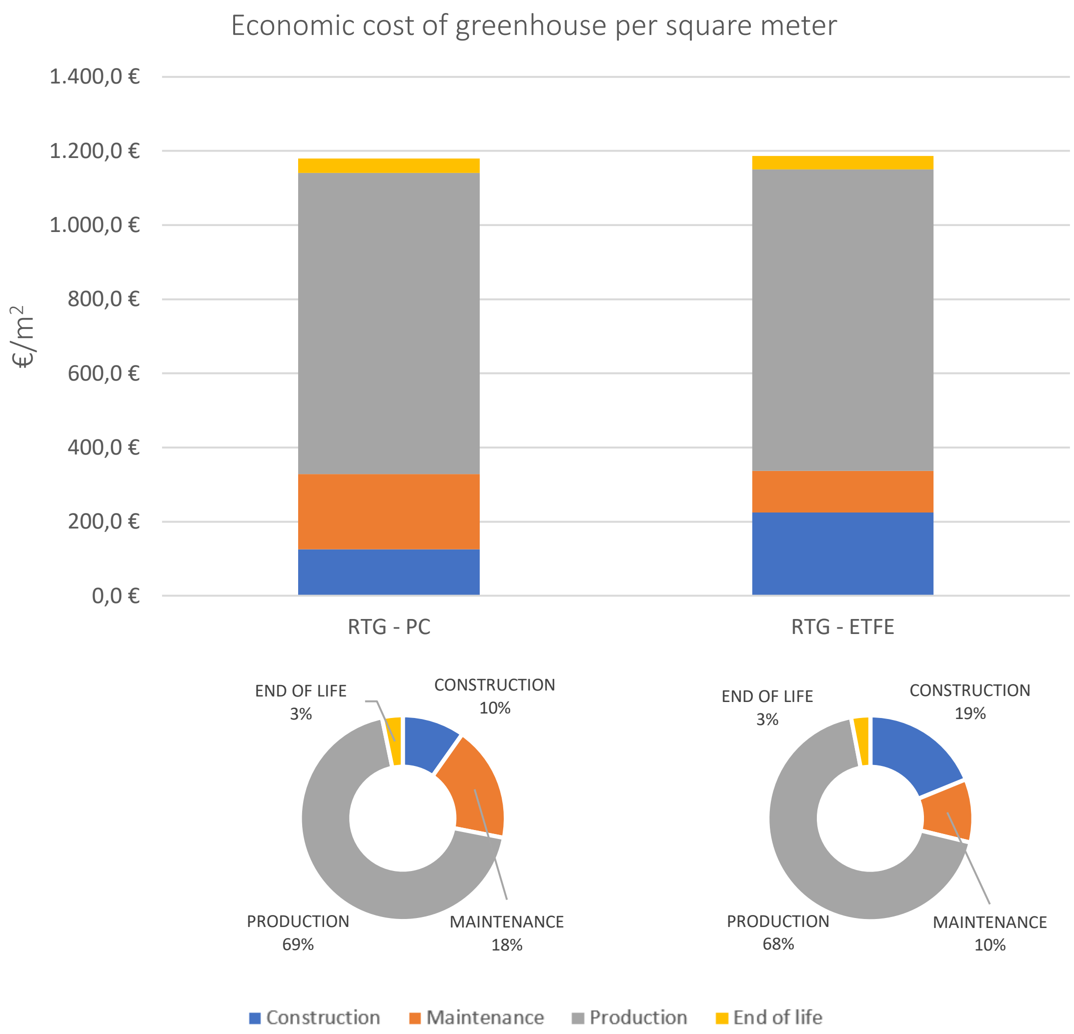

Figure 32. Economic cost per square meter of greenhouse. Representation for RTG with polycarbonate (current scenario), RTG with polyethylene and RTG with ETFE.

8. DISCUSSION

The aim of this thesis was to analyse the environmental and economic performance of Greenhouses. As well as to analyse the different materials used for the construction of the structural elements and covering of these greenhouses and the results of the production process in comparison with conventional greenhouse systems.

Based on the results obtained, it is determined that RTG is less environmentally friendly than CG in its current scenarios. Depending on the impact category evaluated, it is determined that the impact of the RTG, in its entire useful life, is between 1.3 to 2.7 times higher than that associated with the CG.

These results are close to those obtained by Sanyé-Mengual et al.,(2015) with some nuances. Sanyé-Mengual et al. concludes in its work that the production of 1 kg of tomatoes produces 0.216 kg of CO_2 eq and a CED of 3.25 MJ. However, in this work, it has been obtained that for each kg of tomatoes, 0.43 kg of CO_2 eq and a 5 MJ CED are produced.

At this point, the results obtained are justified by the rainwater harvesting system, which has been contemplated as part of the structure of the RTG in this work and has not been taken into account in Sanyé-Mengual et al. study. Rainwater harvesting is made up of a fiberglass reinforced polyester tank. The high impact can be associated to the process of manufacture of silicon-based fiberglass and requires a very high energy demand to reach high temperatures (1500 - 2000°C) for its processing (Loewenstein, 1975).

In this work, the evaluation of the stages of the life cycle of greenhouses was analysed, to determine in which stage most of the impact is concentrated. This analysis has only been carried out for cover materials. However, the results of Sanyé-Mengual et al. (2015) are assumed in this piece of work. In their study, it is reported that the materials represent most of the impact caused by the RTG. In particular, steel is the material with the largest environmental impact (69.5-96.4%), followed by polycarbonate (2.2-26.8%). With these results, it can be concluded that the impact of the conventional greenhouses is lower due to: (1) at structural level is formed by a very simple structure, with less amount of material and (2) the impact associated to polycarbonate is completely avoided.

It should be taken into account that this impact is distributed throughout the life cycle of the greenhouses, depending on the lifespan of the materials used. For instance, the impact of the structure is concentrated in the construction phase, since the materials that form it - the steel or concrete - have a lifespan of 50 years, coinciding with the lifespan established by the greenhouses. On the contrary, the impact of the auxiliary equipment or the cover material is reflected in the maintenance phase as a result of the lifespan of the materials that make them up. For example, most auxiliary equipment elements have a lifespan of 10 years, which means that in over 50 years, it would be necessary to renew all the equipment at least 5 times.

Considering the different stages of the life cycle of greenhouses, it can be determined that the construction of the RTG has an important weight in terms of the overall impact of the RTG, as it represents an important investment in terms of resources - materials, energy and transportation. This weight is reflected on the majority of impact categories, in which structure and auxiliary equipment represent very high percentages. However, the MRS category stands out, which has values of up to 90% for RTG and 80% for CG as a result of the steel that forms the structure.

At this point, it is interesting to see that the RTG, unlike the CG, has a complex structure with high consumption of materials, mainly steel. Sanjuan (2017) collects in his work the need to consider the optimisation of this structure, which would reduce the associated environmental impacts notably. In addition, a very recent master thesis by Esteban Garballo (UPC) in the frame of the Fertilecity II project, in which the optimisation of the structure of the ICTA-ICP was studied, has allowed to determine the possibility of obtaining a structure approximately with 65% of the current steel. This optimisation would have a direct positive impact on RTG.

Sanyé-Mengual also reported that maintenance stage is more impacting in those categories related to fossil resources, such as GWP, mainly due to the production of polycarbonate and consequent emissions of carbon dioxide and methane. With the change in covering that has been evaluated, this impact would drastically reduce for two reasons: (1) ETFE has a lower environmental impact in all phases of its life cycle, (2) the ETFE has a life of 50 years, which implies that it does not need maintenance. Therefore, the global impact of the maintenance phase would also be reduced. The results obtained from the evaluation of cover materials are discussed further in this study.

The operation stage of greenhouses has also been evaluated. At this point, the impact of the RTG and the CG are the same since the CG only carried out an adaptation of the system used in the RTG. Based on this work, the only category in which production has been the higher impact, is in WC, since it is in the phase where more water is consumed for the crops. However, in categories such as GW or CED it also has an important weight. This impact is mainly associated with the use of fertilisers (Sanjuan Delmás, 2017).

Regarding the analysis of the selected cover materials, the environmental impact of each material, and for each of the reference greenhouses, has been evaluated. Horticultural glass, polycarbonate and polyethylene double-layer were discarded as optimal for RTG and CG. Horticultural glass is the material with the highest values in all impact categories. These values are associated to the process of producing glass, which requires a lot of energy to reach the right temperatures to be processed. It can be determined that the values of the rest of the covering materials are much lower than those obtained by the horticultural glass. For cover materials adapted to the RTG and, for all impact categories, the values are between 91.3% and 99.8% lower than the horticulture glass values. For CG, the values are between 81% and 99.8% lower than the horticulture glass values.

Finally, it has been determined that polyethylene would be the material with which the environmental burdens of each greenhouse followed by ETFE would be further reduced. Polyethylene is the best material in terms of GW, FE and MRS and has the second best values of WC and CED. On the opposite, the ETFE represents the best material at the WC and CED level and has worse results compared to GW, FE and MRS.

Despite the positive results of polyethylene, the use of ETFE has been valued as a substitute for polycarbonate. Although polyethylene is an extensively employed plastic in conventional greenhouses, the replacement of the current polycarbonate cover of the ICTA-ICP could not be made by a polyethylene cover, as this material does not meet the structural and safety requirements in buildings, for it is a simple film. At this point, the interest for the ETFE increases exponentially, since it is a material with environmental impact values very similar to polyethylene and, moreover, it can be used in construction. On a different scale, ETFE has been used as cover material in: the Media-TIC building in Barcelona, the Allianz Riviera stadium in Nice, or the restaurant Les Cols in Olot (Girona).

According to the results, it is clear to see that there is the possibility of improving the environmental impact caused by the RTG by changing the current cover material for ETFE. The conventional greenhouse, in its current version, has the most optimal configuration. Consequently, the only change in coverage that could be made - from polyethylene to ETFE - would only mean an increase in environmental burdens and the cost of CG.

Through the analysis of the results obtained for each of the selected materials, it was also worth analysing the materials according to their useful life. On the one hand, polycarbonate or polyethylene have been identified with relatively short lifespans, and therefore, they need to be renewed often. On the other hand, horticultural glass or ETFE with a much longer lifespan, do not require to be changed often.

Polycarbonate and polyethylene, which are plastics with a relatively short useful life (10 and 4 years), need changing 5 times for polycarbonate, and 12.5 times for polyethylene within 50 years, which is the useful lifespan of greenhouses. Contrarily, both glass and ETFE, with useful lives of 30 years and 50 years, mean a drastic reduction in the need to renew them.

It is easy to see that the environmental impact associated with short life materials will be shared over time and concentrated in the maintenance phase. This is the case of polyethylene, with 92% of its environmental impact occuring in the maintenance phase, and only 8% in the construction phase. On the other hand, long-life materials will concentrate their impact on the construction phase, as in the case of the ETFE, with practically 100% of the environmental impact concentrated in it.

It has been determined that, although it is not referenced in this work as an optimum material, polyethylene, with a short useful life, is the material with the least associated environmental impact. Whereas the ETFE, with a long useful life, has very similar results to the polyethylene, this last being slightly worse.

At an economic level, the behaviour is identical. For short-term life materials, the economic investment is spread over time, unlike the long-life materials, in which the investment is concentrated in the construction phase.

The initial cost of polyethylene - 1.1 €/m^2 is lower than its maintenance price - 5.1 €/m^2. In contrast, ETFE's behaviour is the opposite with an initial investment of 122.1 €/m^2 and a maintenance of 0 €. With these values, it is easy to determine that at the environmental and economic level the most optimal material is polyethylene. However, taking into account the impossibility of replacing the current polycarbonate cover with a new polyethylene cover, the same comparative exercise between polycarbonate and ETFE was performed. Continuing with the same dynamics as polyethylene, the initial cost of installing polycarbonate is 12.5 €/m^2, much lower than the cost of installing ETFE. On contrary, the cost of maintenance of ETFE is 0€, while the maintenance cost of the polycarbonate is 72.6 €/m^2. The cost of polycarbonate maintenance is clearly higher than that of ETFE.

The sum of the material used in the installation and maintenance of polycarbonate is approximately 85.0 €/m^2, 37.0 € less than the total cost of the ETFE. Therefore, although the option with ETFE is more expensive at a cost level, it can be considered that its substitution could be generally valued as positive, since it has an impact on the environment, less than the polycarbonate.

End of life stage was deemed negligible for all materials, in comparison with the other stages. This stage considers only energy for deconstruction and transport from site to the point of waste management disregarding waste treatment.

Finally, the aim was to quantify the environmental improvement achieved globally throughout the RTG by substituting the polycarbonate cover for ETFE. In GW, the CO_2 eq emissions resulted in a reduction of 7%, this implies a reduction of 0.05 kg of CO_2 eq less, per kg of tomatoes produced. An important reduction is also detected in CED, which results in a 10% decrease, saving 0.84 MJ per kg of tomato. For the rest of impact categories, the representation of the cover is almost insignificant.

Regarding the functional requirements, it should be taken into account that the change of polycarbonate cover to ETFE coverage means an improvement in the transmissivity. The ETFE has values of 92-95% of the transmission unlike the polycarbonate that has values of 75-79% of the transmissivity. As for the U-value, the replacement of the cover implies a worsening of the isolation. It goes from a value of 3.5 (W/m^{2}ºC) to a value 5.6 (W/m^{2}ºC).

At a cost level, the change of cover means a modification of the percentages in relative cost of the construction and the maintenance phase. With the polycarbonate cover, the construction phase was 11% of the total cost of the RTG life cycle - 125.5 €/m^2. With the change of cover, the relative weight of the construction becomes 19% with a price of 224.4 € per square meter. The opposite effect occurs in the maintenance phase; it loses importance with the ETFE being 112.9 €/m^2 - 10% of the total price associated with the maintenance of the RTG without taking into account the cover, since it does not require maintenance. Polycarbonate's cost, on the other hand, is 202.4 €/m^2 - 17% - from which approximately 89.5€, are associated to the maintenance cost of the cover. Globally, the RTG price using polycarbonate is 1179.5 €/m^2 and, the RTG price using ETFE per m2 is 1186.3 €. This means an approximate increase in the total RTG price per m^2 of 6.8 €.

9. CONCLUSIONS AND FUTURE RESEARCH

The conclusions were structured in relation to the approach of the initial objectives:

The original aims of this thesis have been met.

- RTG is less environmentally friendly than CG in its current scenarios. Depending on the impact category evaluated, it is determined that the impact of the RTG, in its entire useful life, is between 1.3 to 2.7 times higher than that associated with the CG.
- The greenhouse structure, cover material and auxiliary equipment represents between 66% and 98% of the total impact for the RTG and for the CG between 60% and 83%.
- Of all studied materials, polyethylene is the material with less environmental burdens followed by ETFE. Although polyethylene is a plastic used extensively in conventional greenhouses, the replacement of the current polycarbonate cover of the RTG could not be made by a polyethylene cover, since this material does not meet the structural and safety requirements in buildings polyethylene can be considered as optimal for conventional greenhouses or non-integrated RTG.
- For the RTG the optimal cover material is the ETFE.
- The environmental impact of a material is not associated to how extensive its lifespan is: polyethylene has a short useful life - 4 years, whereas ETFE has a long lifespan - 50 years. It is shown that both these materials have the least environmental impact.
- The lifespan of a material is directly related to the distribution of environmental impact produced over time. The environmental impact associated with short lifespan materials is shared over time and concentrated in the maintenance phase. On the other hand, long-lifespan materials concentrate their impact on the construction phase, as ETFE does, which practically concentrates 100% of the environmental impact.
- The cover replacement causes a reduction in the overall impact of the greenhouse in contrast to RTG with polycarbonate. This can be seen in categories such as GW or CED. The first shows that the change of covering produces a 7% reduction of CO_2 emissions, avoiding therefore the emission by a 0.05 kg of CO_2 eq less per kg of tomatoes produced. An important reduction is also detected at a CED level, in which the change in coverage results in a 10% decrease, saving 0.84 MJ per kg of tomato.
- The RTG price with polycarbonate is 1179.5 €/m^2 and the RTG price with ETFE per m^2 is 1186.3 €. This means an approximate increase in the total RTG price per m^2 of 6.8 €.

For further research, it would be interesting to continue with the guidelines provided as follows:

Most recent studies focus on analysing the environmental and economic impact of greenhouses in their life cycle. For the sake of the research in the field, further studies could include the analysis of the logistics associated to each type of greenhouses: the impact caused by the recollection of production, logistics within greenhouses, transport, etc.

Also, it would be interesting to conduct a study of other cover materials such as solar coverings. In this thesis, the possibility of using a solar cover with *Sphelar®* technology was taken into consideration. However, it was ruled out due to lack of information.

Finally, I would suggest a similar work to the present, in which the RTG in the current scenario and the RTG in the optimised scenario at a structure level and coverage, are compared.

REFERENCES

AGC Chemicals. (2019). *F-CLEAN (R) Clear*.

Al-Mahdouri, A., Baneshi, M., Gonome, H., Okajima, J., & Maruyama, S. (2013). Evaluation of optical properties and thermal performances of different greenhouse covering materials. *Solar Energy*, *96*, 21–32. https://doi.org/10.1016/j.solener.2013.06.029

Alberti, M. (2008). *Advances in urban ecology: Integrating humans and ecological processes in urban ecosystems*.

Antón Vallejo, M. A. (2004). Utilización del Análisis del ciclo de vida en la evaluación del impacto ambiental del cultivo bajo invernadero mediterráneo. *TDX (Tesis Doctorals En Xarxa)*. Retrieved from http://www.tesisenred.net/handle/10803/6827

Bekkaoui, A., Bouharroud, R., Gourdo, L., Demrati, H., Ezzaeri, K., Bazgaou, A., … Aharoune, A. (2018). The effect of photovoltaic panels on the microclimate and on the tomato production under photovoltaic canarian greenhouses. *Solar Energy*, *173*(September), 1126–1134. https://doi.org/10.1016/j.solener.2018.08.043

Benli, H. (2013). A performance comparison between a horizontal source and a vertical source heat pump systems for a greenhouse heating in the mild climate Elaziğ, Turkey. *Applied Thermal Engineering*, *50*(1), 197–206. https://doi.org/10.1016/j.applthermaleng.2012.06.005

Brennan, J. (n.d.). *U-VALUES : DEFINITION AND CALCULATION*.

Brett Martin. (2019). *Plastic sheets: Marlon CS hortisheet*.

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J. I., & Rieradevall, J. (2012). Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. *Journal of Urban Technology*, *19*(4), 87–103. https://doi.org/10.1080/10630732.2012.717685

Corcelli, F., Fiorentino, G., Petit-Boix, A., Rieradevall, J., & Gabarrell, X. (2019). Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. *Resources, Conservation and Recycling*, *144*(February), 321–336. https://doi.org/10.1016/j.resconrec.2019.01.040

Cossu, M., Yano, A., Li, Z., Onoe, M., Nakamura, H., & Matsumoto, T. (2016). Advances on the semi-transparent modules based on micro solar cells : First integration in a greenhouse system Advances on the semi-transparent modules based on micro solar cells : First integration in a greenhouse system. *APPLIED ENERGY*, *162*(November 2017), 1042–1051. https://doi.org/10.1016/j.apenergy.2015.11.002

David Hunkeler; Kersin Lichtenvort; Gerals Rabitzer. (2008). *Environmental Life Cycle Costing*. SETAC.

Dayan, E., van Keulen, H., Jones, J. W., Zipori, I., Shmuel, D., & Challa, H. (1993). Development, calibration and validation of a greenhouse tomato growth model: I. Description of the model. *Agricultural Systems*, *43*(2), 145–163. https://doi.org/10.1016/0308-521X(93)90024-V

Designing Buildings Wiki. (2011). *The Modern Construction Material ETFE*.

Ekvall, T., & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment*, *9*(3), 161–171. https://doi.org/10.1007/BF02994190

ElBialy, E. M. A. A., Abdelhalim, A. M., Gamaledin, S. M. A., Ismail, S. M., Ghani, S., Rashwan, M. M., & Bakochristou, F. (2018). Design challenges of agricultural greenhouses in hot and arid environments – A review. *Engineering in Agriculture, Environment and Food*, *12*(1), 48–70. https://doi.org/10.1016/j.eaef.2018.09.004

Elsner, B. Von, Briassoulis, D., Waaijenberg, D., Mistriotis, A., Zabeltitz, C. Von, & Gratraud, J. (2000a). *Review of Structural and Functional Characteristics of Greenhouses in European Union Countries : Part I , Design Requirements*. 1–16.

Elsner, B. Von, Briassoulis, D., Waaijenberg, D., Mistriotis, A., Zabeltitz, C. Von, & Gratraud, J. (2000b). *Review of Structural and Functional Characteristics of Greenhouses in European Union Countries , Part II : Typical Designs*. 111–126. https://doi.org/10.1006/jaer.1999.0512

Enrique Espi. (2012). Materiales de cubierta para invernaderos. *Cuadernos de Estudios Agroalimentarios (CEA03)*, 211–226. https://doi.org/ISSN 2173-7568

European Commission; Joint Research Centre; Instirute for Environment and Sustainability. (2012). *Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods.* Luxembourg: Office of the European Union.

European Commission - Joint Research Centre. (2010a). *ILCD Handbook: General guide for Life Cycle Assessment - Provisions and action steps* (First edit). https://doi.org/10.2788/94987

European Commission - Joint Research Centre. (2010b). International Reference Life Cycle Data System (ILCD) handbook: Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. In *European Commission - Joint Research Centre - Institute for Environment and Sustainability*. https://doi.org/10.2788/38719

Eurostat. (2018). Crop production - Tomato. Retrieved from https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

FAO. (2019). *Urban agriculture*.

Fatnassi, H., Boulard, T., & Bouirden, L. (2003). Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens. *Agricultural and Forest Meteorology*, *118*(1–2), 97–111. https://doi.org/10.1016/S0168-1923(03)00071-6

Fatnassi, H., Li, Z., Poncet, C., Cossu, M., Cossu, A., Deligios, P. A., … Ledda, L. (2018). Assessment and comparison of the solar radiation distribution inside the main commercial photovoltaic greenhouse types in Europe. *Renewable and Sustainable Energy Reviews*, *94*(July), 822–834. https://doi.org/10.1016/j.rser.2018.06.001

FEPEX. (2019). *Consumo frutas y hortalizas*. Retrieved from https://www.fepex.es/datos-del-sector/consumo-frutas-hortalizas

Ferreira, A. J. D., Guilherme, R. I. M. M., Ferreira, C. S. S., & Oliveira, M. de F. M. L. de. (2018). Urban agriculture, a tool towards more resilient urban communities? *Current Opinion in Environmental Science & Health*, *5*, 93–97. https://doi.org/10.1016/j.coesh.2018.06.004

Feuilloley, P.; Issanchou, G.; Jaques, J.C.; Guillaume, S.; Mekikdjian, CH.; Mirabella, J.F.; Merlot, A. (1994). Films plastique de couverture de serre: condensations et propriétés thermiques. *Résultats de Mesure. Plasticulture*, *103*, 2–10.

Frischknecht, R., Wyss, F., Knöpfel, S. B., Lützkendorf, T., & Balouktsi, M. (2015). *Cumulative energy demand in LCA : the energy harvested approach*. 957–969. https://doi.org/10.1007/s11367-015-0897-4

Generalitat de Catalunya. Direcció General de Planificació i Relacions Agràries. (2018). *Superfícies i produccions dels conreus agrícoles. Any 2018* (Vol. 2018).

Gobierno de España. (2018). *Encuesta sobre Superficies y Rendimientos de Cultivos Aviso Legal : los contenidos de esta publicación podrán ser reutilizados , citando la fuente y la fecha , en su caso , de la última actualización Publicación elaborada por la*.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2008). Report I: Characterisation. *ReCiPe : A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*, 132.

Guinee, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment*, *7*(5), 311–313. https://doi.org/10.1007/BF02978897

Hanson, K. J. (1963). The Radiative Effectiveness of Plastic Films for Greenhouses. *Journal of Applied Meteorology*, *2*(6), 793–797. https://doi.org/10.1175/1520-0450(1963)002<0793:TREOPF>2.0.CO;2

Hemming, S., Kempkes, F. L. K., & Janse, J. (2012). New greenhouse concept with high insulating double glass and new climate control strategies - Modelling and first results from a cucumber experiment. *Acta Horticulturae*, *952*, 231–240.

Hendrickson, M. K., & Porth, M. (2012). Urban Agriculture — Best Practices and Possibilities. *University of Missouri Extension*, (June), 1–52.

Huld, T., Müller, R., & Gambardella, A. (2012). A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy*, *86*(6), 1803–1815. https://doi.org/10.1016/j.solener.2012.03.006

IDAE. (2008). *Ahorro y Eficiencia Energética en Invernaderos*. Retrieved from http://www.idae.es/uploads/documentos/documentos_10995_Agr07_AyEE_en_invernaderos_A2008_9e4c63f5.pdf

INSPIRE - European Comission. (2019). Global Horizontal Irradiation. Retrieved from http://inspire.ec.europa.eu/codelist/SolarPotentialValue/globalHorizontalIrradiation

Instituto Nacional de Estadística (INE). (2019). Índice de Precios de Consumo (IPC). Retrieved from https://www.ine.es/prensa/ipc_tabla.htm

Interempresas. (2010). Interempresas.net - Horticulture. Retrieved from https://www.interempresas.net/Horticola/Articulos/44958-Se-inaugura-el-polo-cientifico-tecnico-Agropolis-en-Viladecans-(Barcelona).html

ISO. (2006a). *ISO 14040: Environmental management — Life cycle assessment — Principles and framework*.

ISO. (2006b). *ISO 14044: Environmental management – Life cycle assessment – Requirements and* *guidelines.*

ISO. (2008). *ISO 15686-5: Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing*.

ISO. (2017). *ISO 15686-5:2017(en), Buildings and constructed assets*.

ITeC. (2019). *BEDEC - Banc de dades iTeC*.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324–330. https://doi.org/10.1007/BF02978505

Kailas, S. V. (2016). *Material Science: Optical Properties*.

Kim, H. K., Kang, G. C., Moon, J. P., Lee, T. S., & Oh, S. S. (2018). Estimation of thermal performance and heat loss in plastic greenhouses with and without thermal curtains. *Energies*, *11*(3), 14–18. https://doi.org/10.3390/en11030578

LCA notes from Análisi de Ciclo de Vida (subject). (2018). *LCA - Análisi de Ciclo de Vida (ACV o LCA)*.

Li, S., & Willits, D. H. (2008). Comparing low-pressure and high-pressure fogging systems in naturally ventilated greenhouses. *Biosystems Engineering*, *101*(1), 69–77. https://doi.org/10.1016/j.biosystemseng.2008.06.004

Loewenstein, K. L. (1975). Manufacture of Continuous Glass Fibres. *Platinum Metals Review*, *19*(3), 82–87.

Marcelis, L. F. M., Broekhuijsen, A. G. M., Meinen, E., Nijs, E. M. F. M., & Raaphorst, M. G. M. (2006). QUANTIFICATION OF THE GROWTH RESPONSE TO LIGHT QUANTITY OF GREENHOUSE GROWN CROPS. *Acta Horticulturae*, (711), 97–104. https://doi.org/10.17660/ActaHortic.2006.711.9

MERCASA. (2018). *Alimentación en España 2018*. Retrieved from http://www.mercasa-ediciones.es/alimentacion_2018/pdfs/Alimentacion_en_Espana_2018_web.pdf

Mongkon, S., Thepa, S., Namprakai, P., & Pratinthong, N. (2013). Cooling performance and condensation evaluation of horizontal earth tube system for the tropical greenhouse. *Energy and Buildings*, *66*, 104–111. https://doi.org/10.1016/j.enbuild.2013.07.009

Mongkon, S., Thepa, S., Namprakai, P., & Pratinthong, N. (2014). Cooling performance assessment of horizontal earth tube system and effect on planting in tropical greenhouse. *Energy Conversion and Management*, *78*, 225–236. https://doi.org/10.1016/j.enconman.2013.10.076

Monteith, J. L., & Unsworth, M. H. (2013). The Scope of Environmental Physics. In *Principles of Environmental Physics* (pp. 1–3). https://doi.org/10.1016/B978-0-12-386910-4.00001-9

Montero, J., Antón, A., Torrellas, M., Ruijs, M., & Vermeulen, P. (2011). Environmental and economic profile of present greenhouse production systems in Europe. Deliverable n. 5. *Wageningen, UR*, (September), 1–101.

Nadal, A. (2015). Urban Agriculture in the Framework of Sustainable Urbanism. *Temes de Disseny*, *0*(31), 92–103.

National Institute for Public Health and the Environment. (2018). LCIA: the ReCiPe model. Retrieved from Ministry of Health, Welfare and Sport - Netherlands website: https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

New Technologies Research Centre. University of West Bohemia. (2019). Optical properties of materials and products. Retrieved from University of West Bohemia website: https://ttp.zcu.cz/en/laboratories/optical-properties/optical-properties

Nijskens, J; Deltour, J; Nisen, A; Coutisse, S. (1989). Radiometric and thermal properties of the new plastic films for greenhouse covering. *Acta Horticulturae*, *245*, 71–77.

Nijskens, J.; Deltour, J.; Coutisse, S. (1984). Proprietes radiometriques des materiaux plastiques. *Acta Horticulturae*, *154*, 33–42.

Nisen, A.; Coutisse, S. (1981). Photometric poperties of double wall plastics used as covering for greenhouses. *Acta Horticulturae*, *115*, 85–97.

Novagric. (2015). Cultivos en Invernadero: INVERNADERO PARA HORTALIZAS. Retrieved from https://www.novagric.com/es/blog/articulos/cultivos-invernadero-hortalizas

Papadakis, G., Briassoulis, D., Scarascia Mugnozza, G., Vox, G., Feuilloley, P., & Stoffers, J. A. (2000). Review Paper (SE—Structures and Environment). *Journal of Agricultural Engineering Research*, *77*(1), 7–38. https://doi.org/10.1006/jaer.2000.0525

Papadakis, George, Briassoulis, D., & Vox, G. (2000). *Radiometric and thermal properties of , and testing methods for , greenhouse covering materials Radiometric and Thermal Properties of , and Testing Methods for , Greenhouse Covering Materials*. (January).

https://doi.org/10.1006/jaer.2000.0525

Papadopoulos, A. P., & Hao, X. (1997). Effects of three greenhouse cover materials on tomato growth, productivity, and energy use. *Scientia Horticulturae*, *70*(2–3), 165–178. https://doi.org/10.1016/S0304-4238(97)00054-X

Pré Consultants. (2019). *SimaPro*.

Ribas, A. (2019). *Avaluació ambiental de materials constructius per hivernacles integrats en cobertes d'edificis . Anàlisi comparativa del potencial de millora de l'ecoeficiència.* Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

Sacilik, K., Keskin, R., & Elicin, A. K. (2006). Mathematical modelling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering*, *73*(3), 231–238. https://doi.org/10.1016/j.jfoodeng.2005.01.025

Sanford, S. (2011). Reducing greenhouse energy consumption—An overview. *Energy*, 1–16. Retrieved from http://low.sare.org/content/download/61997/845719/file/ENC07-098 Reducing Greenhouse Energy Consumption.pdf

Sanjuan Delmás, D. (2017). *Environmental assessment of water supply : cities and vertical farming buildings*. Retrieved from https://ddd.uab.cat/record/187311

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J. I., & Rieradevall, J. (2015). An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *International Journal of Life Cycle Assessment*, *20*(3), 350–366. https://doi.org/10.1007/s11367-014-0836-9

Satista. (2019). Evolución anual del tipo de interés oficial en España desde 2011 hasta 2021. Retrieved from https://es.statista.com/estadisticas/639398/tipo-de-interes-oficial-espana/

Sethi, V. P., Dubey, R. K., & Dhath, A. S. (2009). Design and evaluation of modified screen net house for off-season vegetable raising in composite climate. *Energy Conversion and Management*, *50*(12), 3112–3128. https://doi.org/10.1016/j.enconman.2009.08.001

Sirelkhatim K Abbouda, Emad A Almuhanna, & Ali M Al-Amri. (2012). EFFECT OF USING DOUBLE LAYERS OF POLYETHYLENE COVER WITH AIR GAP ON CONTROL ENVIRONMENT INSIDE GREENHOUSES. *2012 Dallas, Texas, July 29 - August 1, 2012*, (November). https://doi.org/10.13031/2013.42044

SpecialChem. (2019). A Complete Guide on Ethylene Tetrafluoroethylene (ETFE). Retrieved April 21, 2019, from Omnexus. The material selection platform. website: https://omnexus.specialchem.com/selection-guides/c-thermoplastics-fluoropolymer-etfe-ectfe

Sphelar Power Corporation. (2019a). *Sphelar® BIPV module*.

Sphelar Power Corporation. (2019b). *Spherical Solar Cell (Sphelar®*. 1–24. Retrieved from http://www.sphelarpower.com/technology/

Swinkels, G. L. A. M., Sonneveld, P. J., & Bot, G. P. A. (2002). SE—Structures and Environment. *Journal of Agricultural Engineering Research*, *79*(1), 91–97. https://doi.org/10.1006/jaer.2000.0676

Swiss Center for Life Cycle Inventories. (2013). *Ecoinvent database v3.0.*

Taira, K., & Nakata, J. (2010). Silicon cells: Catching rays. *Nature Photonics*, *4*(9), 602–603. https://doi.org/10.1038/nphoton.2010.193

Ting, K. C., & Giacomelli, G. A. (1987). Solar photosynthetically active radiation transmission through greenhouse glazings. *Energy in Agriculture*, *6*(2), 121–132. https://doi.org/10.1016/0167-5826(87)90010-6

Torrellas, M., Antón, A., Ruijs, M., García Victoria, N., Stanghellini, C., & Montero, J. I. (2012). Environmental and economic assessment of protected crops in four European scenarios. *Journal of Cleaner Production*, *28*, 45–55. https://doi.org/10.1016/j.jclepro.2011.11.012

Tsoy, N., Prado, V., Wypkema, A., Quist, J., & Mourad, M. (2019). Anticipatory Life Cycle Assessment of sol-gel derived anti-reflective coating for greenhouse glass. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2019.02.246

Tunnel Vision Hoops. (2019). TUNNEL VISION HOOPS. Retrieved from https://www.tunnelvisionhoops.com/

UNEP, & SETAC. (2011). *Towards a Life Cycle Sustainability Assessment*. Retrieved from https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011 - Towards LCSA.pdf

United Nations. (2019). Sustainable Development Goals. Goal 11: Sustanaible cities and communities. Retrieved from https://unstats.un.org/sdgs/report/2018/goal-11/

Ureña-Sánchez, R., Callejón-Ferre, Á. J., Pérez-Alonso, J., & Carreño-Ortega, Á. (2012). Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. *Scientia Agricola*, *69*(4), 233–239. https://doi.org/10.1590/s0103-90162012000400001

Wei, B., Guo, S., Wang, J., Li, J., Wang, J., Zhang, J., … Sun, J. (2016). Thermal performance of single span greenhouses with removable back walls. *Biosystems Engineering*, *141*, 48–57. https://doi.org/10.1016/j.biosystemseng.2015.11.008

Yano, A., Onoe, M., & Nakata, J. (2014). Prototype semi-transparent photovoltaic modules for greenhouse roof applications. *Biosystems Engineering*, *122*, 62–73. https://doi.org/10.1016/j.biosystemseng.2014.04.003

ANNEX

Table 15. Life Cycle Inventory (LCI) of RTG.

LIFE CYCLE INVENTORY (LCI) - ROOFTOP GREENHOUSE						
STRUCTURE						
Construction						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Galvanised Steel 85	5133,0	kg	41,8	0,8	50	Sanyé-Mengual
Concrete	0,6	kg	0,0	0,2	50	Sanyé-Mengual
LDPE	36,8	kg	0,3	0,0	4	Sanyé-Mengual
Polyester	4,9	kg	0,0	0,0	5	Sanyé-Mengual
Aluminium	4,9	Kg	0,0	0,0	5	Sanyé-Mengual
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Metal working	5133,0	kg	41,8	0,8	50	Sanyé-Mengual
Zinc coat, coils	182,3	m2	1,5	0,0	50	Calculated (Ecoinvent)
Injection moulding	36,8	kg	0,3	0,0	4	Sanyé-Mengual
Polar fleece production	4,9	kg	0,0	0,0	5	Sanyé-Mengual
Sheet rolling, aluminium	4,9	kg	0,0	0,0	5	Sanyé-Mengual
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Galvanised Steel	Lorry 16-32t, EURO5	Martorell, Espanya	77	km	395,2	Sanyé-Mengual
Concrete	Lorry 16-32t, EURO6	Barcelona, Espanya	40	km	0,0	Sanyé-Mengual
LDPE	Lorry 16-32t, EURO7	Tarragona, Espanya	101	km	3,7	Sanyé-Mengual
Polyester	Lorry 16-32t, EURO8	Hellevoetsluis, Països Baixos	1487	km	7,3	Sanyé-Mengual
Aluminium	Lorry 16-32t, EURO9	Hellevoetsluis, Països Baixos	1487	km	7,3	Sanyé-Mengual
Greenhouse Construction						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery	2,5	kWh	0,0	0,0		Sanyé-Mengual
Maintenance						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
LDPE	442,1	kg	3,6	0,1	4	Sanyé-Mengual
Polyester	43,0	kg	0,4	0,0	5	Sanyé-Mengual

Aluminium	43,0	kg	0,4	0,0	5	Sanyé-Mengual
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Injection moulding	442,1	kg	3,6	0,1	4	Sanyé-Mengual
Polar fleece production	43,0	kg	0,4	0,0	5	Sanyé-Mengual
Sheet rolling, aluminium	43,0	kg	0,4	0,0	5	Sanyé-Mengual
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
LDPE	Lorry 16-32t, EURO5	Tarragona, Espanya	101	km	44,7	Sanyé-Mengual
Polyester	Lorry 16-32t, EURO6	Hellevoetsluis, Països Baixos	1487	km	63,9	Sanyé-Mengual
Aluminium	Lorry 16-32t, EURO7	Hellevoetsluis, Països Baixos	1487	km	63,9	Sanyé-Mengual
Maintenance						
Greenhouse Maintenance						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery	47054,2	kWh	941,1	7,7		Antón
End of life						
Deconstruction						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery used to demolish	1,2	kWh	0,0	0,0		Ribas
Waste treatment						
Concept	Weight	Units	Unit/m2	Unit/m2·year		Source
Waste	5708,3	kg	46,5	0,9		Calculated from Sanyé-Mengual excluding Polycarbonate
Waste transport						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Waste	Transport, lorry 16-32t	Bellaterra, Spain	30	km	171,2500174	Sanyé-Mengual
RAINWATER HARVESTING (RH)						
Construction						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Glass Fiber Reinforced Polymers	4051,7	kg	33,0	0,7	50	Sanjuan-Delmás
Cast iron	65,8	kg	0,5	0,0	10	Sanjuan-Delmás
Steel	7,7	kg	0,1	0,0	10	Sanjuan-Delmás
HDPE	305,0	kg	2,5	0,0	10	Sanjuan-Delmás
Processes materials						

Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Injection moulding	4051,7	kg	33,0	0,7	50	Sanjuan-Delmás
Extrusion, plastic pipes	305,0	kg	2,5	0,0	10	Sanjuan-Delmás
Metal working	73,5	kg	0,6	0,0	10	Sanjuan-Delmás
Transport materials						
Conecept	**Method of transport**	**Origin**	**Distance**	**Units**	**tkm**	**Source**
Glass Fiber Reinforced Polymers	Lorry 3.5-7.5 metric ton	Unknown	60	km	486,2	Sanjuan-Delmás
Cast iron + Steel + HDPE	Light commercial vehicle	Unknown	60	km	45,4	Sanjuan-Delmás
RH Installation						
Machinery use	**Energy**	**Units**	**Unit/m2**	**Unit/m2·year**		**Source**
Excavation, hydraulic digger	100,0	m3	0,8	0,0		Sanjuan-Delmás
End of life						
Deconstruction						
Machinery use	**Energy**	**Units**	**Unit/m2**	**Unit/m2·year**		**Source**
Machinery used to demolish	12,8	kWh	0,1	0,0		Sanjuan-Delmás
Waste treatment						
Concept	**Weight**	**Units**	**Unit/m2**	**Unit/m2·year**		**Source**
Municipal solid waste	305,0	kg	2,5	0,0		Sanjuan-Delmás
Waste transport						
Conecept	**Method of transport**	**Origin**	**Distance**	**Units**	**tkm**	**Source**
Waste	Lorry 3.5-7.5 metric ton	Bellaterra, Spain	30	km	265,8	Sanjuan-Delmás
AUXILIARY EQUIPMENT						
Installation						
Materials						
Concept	**Weight**	**Units**	**Unit/m2**	**Unit/m2·year**	**Lifespan**	**Source**
Cast iron	44,0	kg	0,4	0,0	10	Sanjuan-Delmás
Steel	5,0	kg	0,0	0,0	10	Sanjuan-Delmás
HDPE	2,5	kg	0,0	0,0	10	Sanjuan-Delmás
PE	40,5	kg	0,3	0,0	10	Sanjuan-Delmás
PE	75,0	kg	0,6	0,0	10	Sanjuan-Delmás
Polypropylene	8,0	kg	0,1	0,0	10	Sanjuan-Delmás
Cast iron	24,0	kg	0,2	0,0	10	Sanjuan-Delmás
HDPE	1,5	kg	0,0	0,0	10	Sanjuan-Delmás
HDPE	2,5	kg	0,0	0,0	10	Sanjuan-Delmás
Electronics	0,0	kg	0,0	0,0	10	Sanjuan-Delmás
PVC	41,0	kg	0,3	0,0	10	Sanjuan-Delmás

LDPE	27,5	kg	0,2	0,0	10	Sanjuan-Delmás
PE	1,5	kg	0,0	0,0	10	Sanjuan-Delmás
PVC	7,5	kg	0,1	0,0	10	Sanjuan-Delmás
LDPE	35,0	kg	0,3	0,0	5	Sanjuan-Delmás
EPS	482,0	kg	3,9	0,1	5	Sanjuan-Delmás
HDPE	40,0	kg	0,3	0,0	5	Sanjuan-Delmás
Steel	39,0	kg	0,3	0,0	5	Sanjuan-Delmás
Polypropylene	38,0	kg	0,3	0,0	5	Sanjuan-Delmás
Adhesive	1,0	mL	0,0	0,0	10	Sanjuan-Delmás
Solvent	2,0	mL	0,0	0,0	10	Sanjuan-Delmás
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Metal working	49,0	kg	0,4	0,1	10	Sanjuan-Delmás
Wire drawing	39,0	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	5,0	kg	0,0	0,0	10	Sanjuan-Delmás
Injection moulding	40,0	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	117,5	kg	1,0	0,2	10	Sanjuan-Delmás
Injection moulding	8,0	kg	0,1	0,0	10	Sanjuan-Delmás
Injection moulding	38,0	kg	0,3	0,0	5	Sanjuan-Delmás
Extrusion, plastic pipes	24,5	kg	0,2	0,0	10	Sanjuan-Delmás
Extrusion, plastic pipes	27,5	kg	0,2	0,0	10	Sanjuan-Delmás
Injection moulding	24,0	kg	0,2	0,0	10	Sanjuan-Delmás
Extrusion, plastic film	35,0	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	482,0	kg	3,9	0,4	5	Sanjuan-Delmás
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
All materials	Light commercial vehicle	Unknown	30	kg	37,5	Sanjuan-Delmás
End of life						
Waste treatment						
Concept	Weight	Units	Unit/m2	Unit/m2·year		Source
Waste	372,5	kg	3,0	0,1		Sanjuan-Delmás
Waste transport						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Waste	Light commercial vehicle	Bellaterra, Spain	30	km	32,5	Sanjuan-Delmás
PRODUCTION						
Installation						

Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
LDPE	39,9	kg	0,3	0,0	5	Sanjuan-Delmás
Perlite	3420,0	kg	27,9	0,6	3	Sanjuan-Delmás
N	1190,0	kg	9,7	0,2	1	Sanjuan-Delmás
P2O5	255,0	kg	2,1	0,0	1	Sanjuan-Delmás
K2O	2167,5	kg	17,7	0,4	1	Sanjuan-Delmás
Insecticide	1,7	kg	0,0	0,0	1	Sanjuan-Delmás
Fungicide	11,9	kg	0,1	0,0	1	Sanjuan-Delmás
Water	2319,8	m3	0,5	0,4	1	Sanjuan-Delmás
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Extrusion, plastic film	39,9	kg	0,3	0,0	5	Sanjuan-Delmás
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
All materials less perlite	Light commercial vehicle	Unknown	30	km	108,8	EUPHOROS
Perlite bags	Light commercial vehicle	Almeria	850	km	2940,9	EUPHOROS + (Llorach-Massana et al., 2017)
End of life						
Waste treatment						
Concept	Weight	Units	Unit/m2	Unit/m2·year		Source
Waste	47029,1	kg	383,0	7,7		Calculated
Waste transport						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Waste	Light commercial vehicle	Bellaterra, Spain	30	km	1410,9	Calculated

The cover material is excluded for a specific LCI is relocated specifically for all cover materials in the study.

Table 16. Life Cycle Inventory (LCI) of Conventional Greenhouse.

LIFE CYCLE INVENTORY (LCI) - ROOFTOP GREENHOUSE						
STRUCTURE						
Construction						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Galvanised steel	4043,0	kg	16,8	0,8	50	Ribas
Concrete	0,8	kg	0,0	0,0	50	Ribas
Iron	24,0	kg	0,1	0,0	50	Ribas
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Zinc coat, coils	143,7	m2	0,6	0,0	50,0	Calculated
Metal working	4067,0	kg	16,9	0,3	50,0	Calculated
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Galvanised steel	Lorry 16-32t, EURO5	Almeria, Spain	813	km	3287,0	Calculated
Concrete	Lorry 16-32t, EURO6	Barcelona, Espanya	40	km	0,0	Calculated
Iron	Lorry 16-32t, EURO5	Almeria, Spain	813	km	19,5	Calculated
Greenhouse Construction						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery use	2,5	kWh	0,0	0,0		Ribas
Maintenance						
Greenhouse Maintenance						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery use	1,4	kWh	0,0	0,0		Antón
End of life						
Deconstruction						
Machinery use	Energy	Units	Unit/m2	Unit/m2·year		Source
Machinery used to demolish	0,6	kWh	0,0	0,0		Ribas
Waste treatment						
Concept	Weight	Units	Unit/m2	Unit/m2·year		Source
Recycling process	4067,8	kg	16,9	0,3		Own elaboration
Waste transport						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Waste	Transport, lorry 16-32t	Bellaterra, Spain	30	km	122,03	Own elaboration
AUXILIARI EQUIPMENT						

Installation						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Cast iron	85,9	kg	0,4	0,0	10	Sanjuan-Delmás
Steel	9,8	kg	0,0	0,0	10	Sanjuan-Delmás
HDPE	4,9	kg	0,0	0,0	10	Sanjuan-Delmás
PE	79,1	kg	0,3	0,0	10	Sanjuan-Delmás
PE	146,5	kg	0,6	0,0	10	Sanjuan-Delmás
Polypropylene	15,6	kg	0,1	0,0	10	Sanjuan-Delmás
Cast iron	46,9	kg	0,2	0,0	10	Sanjuan-Delmás
HDPE	2,9	kg	0,0	0,0	10	Sanjuan-Delmás
HDPE	4,9	kg	0,0	0,0	10	Sanjuan-Delmás
Electronics	0,0	kg	0,0	0,0	10	Sanjuan-Delmás
PVC	80,1	kg	0,3	0,0	10	Sanjuan-Delmás
LDPE	53,7	kg	0,2	0,0	10	Sanjuan-Delmás
PE	2,9	kg	0,0	0,0	10	Sanjuan-Delmás
PVC	14,6	kg	0,1	0,0	10	Sanjuan-Delmás
LDPE	68,4	kg	0,3	0,0	5	Sanjuan-Delmás
EPS	941,3	kg	3,9	0,1	5	Sanjuan-Delmás
HDPE	78,1	kg	0,3	0,0	5	Sanjuan-Delmás
Steel	76,2	kg	0,3	0,0	5	Sanjuan-Delmás
Polypropylene	74,2	kg	0,3	0,0	5	Sanjuan-Delmás
Adhesive	2,0	mL	0,0	0,0	10	Sanjuan-Delmás
Solvent	3,9	mL	0,0	0,0	10	Sanjuan-Delmás
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Metal working manufacturing	95,7	kg	0,4	0,0	10	Sanjuan-Delmás
Wire drawing	76,2	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	9,8	kg	0,0	0,0	10	Sanjuan-Delmás
Injection moulding	78,1	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	229,5	kg	1,0	0,0	10	Sanjuan-Delmás
Injection moulding	15,6	kg	0,1	0,0	10	Sanjuan-Delmás
Injection moulding	74,2	kg	0,3	0,0	5	Sanjuan-Delmás
Extrusion, plastic pipes	47,8	kg	0,2	0,0	10	Sanjuan-Delmás
Extrusion, plastic pipes	53,7	kg	0,2	0,0	10	Sanjuan-Delmás
Injection moulding	46,9	kg	0,2	0,0	10	Sanjuan-Delmás

Extrusion, plastic film	68,4	kg	0,3	0,0	5	Sanjuan-Delmás
Injection moulding	941,3	kg	3,9	0,1	5	Sanjuan-Delmás
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
All materials	Light commercial vehicle	Unknown	30	kg	9,0	Sanjuan-Delmás
End of life						
Waste treatment						
Concept	Weight	Units	Unit/m2	Unit/m2·year		Source
Sanitary landfill	1791,8	kg	7,5	0,1		Sanjuan-Delmás
Waste transport						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
Waste	Light commercial vehicle	Bellaterra, Spain	30	km	9,0	Sanjuan-Delmás
PRODUCTION						
Installation						
Materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
LDPE	77,7	kg	0,3	0,0	5	EUPHOROS + (Llorach-Massana et al., 2017)
Perlite	6660,0	kg	27,8	0,6	3	EUPHOROS + (Llorach-Massana et al., 2017)
N	13,3	kg	0,1	0,0	1	EUPHOROS + (Llorach-Massana et al., 2017)
P2O5	415,0	kg	1,7	0,0	1	EUPHOROS + (Llorach-Massana et al., 2017)
K2O	1328,0	kg	5,5	0,1	1	EUPHOROS + (Llorach-Massana et al., 2017)
Insectiside	3,3	kg	0,0	0,0	1	EUPHOROS + (Llorach-Massana et al., 2017)
Fungicide	23,2	kg	0,1	0,0	1	EUPHOROS + (Llorach-Massana et al., 2017)
Water	3940,8	m3	0,5	0,3	1	Sanjuan-Delmás
Processes materials						
Concept	Weight	Units	Unit/m2	Unit/m2·year	Lifespan	Source
Extrusion, plastic film	77,7	kg	0,3	0,0	5	EUPHOROS
Transport materials						
Conecept	Method of transport	Origin	Distance	Units	tkm	Source
All materials less perlite	Light commercial vehicle	Unknown	30,0	km	53,5	EUPHOROS

Perlite bags	Light commercial vehicle	Almeria	850,0	km	5727,0	EUPHOROS + Sanjuan
End of life						
Waste treatment						
Concept	**Weight**	**Units**	**Unit/m2**	**Unit/m2·year**		**Source**
Sanitary landfill	62306,9	kg	259,6	5,2		Calculated
Waste transport						
Conecept	**Method of transport**	**Origin**	**Distance**	**Units**	**tkm**	**Source**
Waste	Light commercial vehicle	Bellaterra, Spain	30	km	1869,2	Calculated

The cover material is excluded for a specific LCI is relocated specifically for all cover materials in the study

Table 17. Life Cycle Inventory (LCI) adapted from Table 15 and *Table 16 and used for this thesis.*

STRUCTURE		RTG	CONVENTIONAL GREENHOUSE
CONSTRUCTION + MAINTENENCE			
Materials/assemblies - STRUCTURE (Rainwater Harvesting only for RTG)	**Unit**	**Value**	**Value**
Steel, low-alloyed {GLO}| market for | APOS, U	kg	5140,7	4043,0
Concrete, normal {CH}| unreinforced concrete production, with cement CEM II/A | APOS, U	m3	0,6	0,8
Polyethylene, low density, granulate {RER}| production | APOS, U	kg	478,9	0,0
Polyester resin, unsaturated {RER}| production | APOS, U	kg	47,9	0,0
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | APOS, U	kg	47,9	0,0
Glass fibre {RER}| production | APOS, U	kg	4051,7	0,0
Cast iron {RER}| production | APOS, U	kg	65,8	0,0
Polyethylene, high density, granulate {RER}| production | APOS, U	kg	305,0	0,0
Steel, unalloyed {RER}| steel production, converter, unalloyed | APOS, U	kg	0,0	24,0
Processes - STRUCTURE (Rainwater Harvesting only for RTG)	**Unit**	**Value**	**Value**
Metal working, average for metal product manufacturing {RER}| processing | APOS, U	kg	5206,5	4067,0
Zinc coat, coils {GLO}| market for | APOS, U	m2	182,3	143,7
Sheet rolling, aluminium {RER}| processing | APOS, U	kg	47,9	0,0
Polar fleece production, energy use only {RER}| production | APOS, U	kg	47,9	0,0

Injection moulding {RER}| processing | APOS, U	kg	4530,6	0,0
Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U	kg	305,0	0,0
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	MJ (construction)	2,5	2,5
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	MJ (maintenence)	47054,2	1,4
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	MJ (demolish)	14,0	0,6
Excavation, hydraulic digger {RER}| processing | APOS, U	m3	100,0	0,0
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	tkm	750,0	3428,5
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U	tkm	752,0	0,0
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | APOS, U	tkm	45,4	0,0
INSTALLATION + MAINTENANCE			
Materials/assemblies - AUXILIARY EQUIPMENT	**Unit**	**Value**	**Value**
Cast iron {RER}| production | APOS, U	kg	68,0	132,8
Steel, low-alloyed {GLO}| market for | APOS, U	kg	44,0	85,9
Polyethylene, high density, granulate {RER}| production | APOS, U	kg	46,5	90,8
Polyethylene, low density, granulate {RER}| production | APOS, U	kg	62,5	122,1
Polyethylene terephthalate, granulate, amorphous {RoW}| production | APOS, U	kg	117,0	228,5
Polypropylene, granulate {RER}| production | APOS, U	kg	46,0	89,8
Electronics, for control units {RER}| production | APOS, U	kg	0,0	0,0
Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U	kg	48,5	94,7
Polystyrene, expandable {RER}| production | APOS, U	kg	482,0	941,3
Epoxy resin, liquid {RER}| production | APOS, U	kg	1,0	2,0
1-propanol {RER}| production | APOS, U	kg	2,0	3,9

Processes - AUXILIARY EQUIPMENT	Unit	Value	Value
Metal working, average for metal product manufacturing {RER}| processing | APOS, U	kg	49,0	95,7
Wire drawing, steel {RER}| processing | APOS, U	kg	39,0	76,2
Injection moulding {RER}| processing | APOS, U	kg	714,5	1395,4
Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U	kg	52,0	101,6
Extrusion, plastic film {RER}| production | APOS, U	kg	35,0	68,4
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | APOS, U	tkm	70,0	17,9
PRODUCTIVITY		**RTG**	**CONVENTIONAL GREENHOUSE**
OPERATION			
Materials/assemblies - PRODUCTIVITY	**Unit**	**Value**	**Value**
Polyethylene, low density, granulate {RER}| production | APOS, U	kg	39,9	78
Expanded perlite {CH}| production | APOS, U	kg	3420,0	6660
Nitrogen fertiliser, as N {GLO}| nutrient supply from manure, solid, cattle | APOS, U	kg	1190,0	13
Phosphate fertiliser, as P2O5 {GLO}| nutrient supply from poultry manure, dried | APOS, U	kg	255,0	415
Potassium fertiliser, as K2O {GLO}| nutrient supply from poultry manure, dried | APOS, U	kg	2167,5	1328
Application mix, pesticides/kg/CH U	kg	2331,7	27
Processes - PRODUCTIVITY	**Unit**	**Value**	**Value**
Extrusion, plastic film {RER}| production | APOS, U	kg	39,9	78
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | APOS, U	tkm	4460,6	7650
Irrigation {ES}| processing | APOS, U	m3	2319,8	3941

Table 18. LCI of the cover materials studied adapted to the RTG

<table>
<tr><th colspan="7">RTG</th></tr>
<tr><td rowspan="18">COVERING MATERIALS</td><th colspan="6">INSTALLATION</th></tr>
<tr><th>Materials/assemblies - COVERING MATERIAL</th><th>Weight</th><th>Extrusion, plastic film {RER}| production | APOS, U</th><th>Electricity grid mix, AC, consumption mix, at consumer, 230V ES S</th><th>Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U</th><th>Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U</th></tr>
<tr><th></th><th>kg</th><th>kg</th><th>MJ</th><th>tkm</th><th>tkm</th></tr>
<tr><td>Polycarbonate {RER}| production | APOS, U</td><td>204,8</td><td>204,8</td><td rowspan="5">Assuming energy to collocate the envelope in the energy to build the greenhouse</td><td>203,1</td><td>206,5</td></tr>
<tr><td>Polyethylene, low density, granulate {RER}| production | APOS, U</td><td>42,1</td><td>42,1</td><td>4,3</td><td>-</td></tr>
<tr><td>Polyethylene, low density, granulate {RER}| production | APOS, U</td><td>84,3</td><td>84,3</td><td>8,5</td><td>-</td></tr>
<tr><td>Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U</td><td>1491,3</td><td>-</td><td>1816,4</td><td>-</td></tr>
<tr><td>Ethylene-tetrafluoroethylene copolymers (ETFE), at plant</td><td>49,1</td><td>49,1</td><td>75,4</td><td>-</td></tr>
<tr><th colspan="6">MAINTENANCE</th></tr>
<tr><th>Materials/assemblies - COVERING MATERIAL</th><th>Weight</th><th>Extrusion, plastic film {RER}| production | APOS, U</th><th>Electricity grid mix, AC, consumption mix, at consumer, 230V ES S</th><th>Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U</th><th>Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U</th></tr>
<tr><th></th><th>kg</th><th>kg</th><th>MJ</th><th>tkm</th><th>tkm</th></tr>
<tr><td>Polycarbonate {RER}| production | APOS, U</td><td>819,2</td><td>819,2</td><td>31,5</td><td>812,4</td><td>826,1</td></tr>
<tr><td>Polyethylene, low density, granulate {RER}| production | APOS, U</td><td>484,5</td><td>484,5</td><td>13,7</td><td>48,9</td><td>-</td></tr>
<tr><td>Polyethylene, low density, granulate {RER}| production | APOS, U</td><td>968,9</td><td>968,9</td><td>13,7</td><td>97,9</td><td>-</td></tr>
</table>

	Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	984,3	-	6,3	1198,8	-
	Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	0,0	0,0	0,0	0,0	-
	END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)					
	Materials/assemblies - COVERING MATERIAL	Weight	Electricity grid mix, AC, consumption mix, at consumer, 230V ES S		Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	
		kg	MJ		tkm	
	Polycarbonate {RER}| production | APOS, U	1024,0	Assuming energy to demolish the envelope in the RTG LCI		30,7	
	Polyethylene, low density, granulate {RER}| production | APOS, U	526,6			15,8	
	Polyethylene, low density, granulate {RER}| production | APOS, U	1053,2			31,6	
	Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	2475,6			74,3	
	Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	49,1			1,5	

Table 19. LCI of the cover materials studied adapted to the CG

CONVENTIONAL GREENHOUSE						
	INSATLLATION					
COVERING MATERIALS	Materials/assemblies - COVERING MATERIAL	Weight	Extrusion, plastic film {RER}| production | APOS, U	Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U
		kg	kg	MJ	tkm	tkm
	Polycarbonate {RER}| production | APOS, U	822,4	822,4	Assuming energy to collocate the envelope in the energy to build the greenhouse	815,6	829,3
	Polyethylene, low density, granulate {RER}| production | APOS, U	77,1	77,1		7,8	-
	Polyethylene, low density, granulate {RER}| production | APOS, U	154,2	154,2		15,6	-
	Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	2729,3	-		3324,3	-
	Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	90,0	90,0		138,1	-
	MAINTENANCE					
	Materials/assemblies - COVERING MATERIAL	Weight	Extrusion, plastic film {RER}| production | APOS, U	Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U
		kg	kg	MJ	tkm	tkm
	Polycarbonate {RER}| production | APOS, U	3289,6	3289,6	31,5	3262,3	3317,2
	Polyethylene, low density, granulate {RER}| production | APOS, U	886,7	886,7	13,7	89,6	-

Polyethylene, low density, granulate {RER}| production | APOS, U	1773,3	1773,3	8,4	179,1	-
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	1801,4	-	6,3	2194,1	-
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	0,0	0,0	0,0	138,1	-
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)					
Materials/assemblies - COVERING MATERIAL	**Weight**	**Electricity grid mix, AC, consumption mix, at consumer, 230V ES S**		**Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U**	
	kg	**MJ**		**tkm**	
Polycarbonate {RER}| production | APOS, U	822,4	Assuming energy to demolish the envelope in the energy to demolish the greenhouse		24,7	
Polyethylene, low density, granulate {RER}| production | APOS, U	963,8			28,9	
Polyethylene, low density, granulate {RER}| production | APOS, U	1927,5			57,8	
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	4530,7			135,9	
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	90,0			2,7	

Table 20. Characterization values for all impact categories ReCiPe (hierarchical, midpoint). Calculated with SimaPro 9.0.

IMPACT CATEGORIES + CED	GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Total	**3,43E+02**	**1,42E-04**	**2,45E+01**	**7,59E-01**	**1,26E-01**	**7,80E-01**	**1,06E+00**	**1,78E-01**	**2,17E-02**	**2,57E+03**	**2,80E+01**	**9,93E+00**	**1,31E-01**	**7,74E+00**	**1,30E+01**	**2,19E+00**	**6,17E+01**	**7,14E+00**	**2,96E+03**
Steel, low-alloyed {GLO}| market for | APOS, U	2,04E+00	3,76E-07	6,29E-02	4,76E-03	2,45E-03	4,94E-03	6,05E-03	1,62E-03	5,01E-05	5,45E+00	2,33E-01	7,91E-02	1,53E-03	9,91E-02	3,39E-02	6,16E-02	3,69E-01	1,33E-02	1,70E+01
Polyethylene, low density, granulate {RER}| production | APOS, U	3,08E+00	3,83E-09	4,06E-04	4,67E-03	1,76E-04	5,21E-03	6,42E-03	3,65E-05	1,83E-06	1,05E-02	5,38E-03	1,78E-03	1,96E-05	6,44E-04	2,34E-04	5,42E-04	1,55E+00	1,76E-02	7,07E+01
Polyester resin, unsaturated {RER}| production | APOS, U	6,80E+00	3,54E-05	2,92E-01	1,04E-02	2,32E-03	1,12E-02	1,66E-02	1,49E-03	1,55E-04	5,16E+00	1,08E-01	3,62E-02	2,69E-03	9,90E-02	9,76E-02	9,51E-03	2,18E+00	9,16E-02	9,99E+01
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | APOS, U	8,89E+00	2,36E-06	1,95E+00	1,84E-02	3,59E-03	1,86E-02	4,41E-02	4,90E-03	4,42E-04	4,78E+00	3,52E-01	1,28E-01	4,37E-03	9,08E-02	1,25E-01	1,19E-01	1,69E+00	3,12E-01	7,76E+01
Glass fibre {RER}| production | APOS, U	2,48E+00	2,38E-06	3,88E-01	8,26E-03	7,28E-04	8,37E-03	1,14E-02	9,29E-04	7,86E-05	1,95E+00	5,01E-02	1,69E-02	1,83E-03	2,43E-02	4,25E-02	7,49E-03	6,79E-01	2,27E-02	3,10E+01
Cast iron {RER}| production | APOS, U	2,02E+00	3,17E-07	1,28E-01	4,11E-03	1,55E-03	4,33E-03	5,36E-03	6,73E-04	4,32E-05	3,85E+00	7,53E-02	2,90E-02	8,31E-04	3,57E-02	2,71E-02	3,34E-02	3,53E-01	1,12E-02	1,63E+01
Polyethylene, high density, granulate {RER}| production | APOS, U	2,78E+00	4,62E-09	3,70E-04	4,04E-03	1,64E-04	4,52E-03	5,27E-03	2,78E-05	2,16E-06	8,73E-03	4,45E-03	1,45E-03	2,57E-05	5,87E-04	2,12E-04	3,28E-04	1,57E+00	1,36E-02	7,16E+01
Polyethylene terephthalate, granulate, amorphous {RoW}| production | APOS, U	3,92E+00	4,90E-07	1,32E-01	6,43E-03	1,55E-03	6,74E-03	9,85E-03	8,67E-04	5,58E-05	4,02E+00	6,85E-02	2,33E-02	8,91E-04	2,78E-02	4,64E-02	5,62E-03	1,60E+00	3,64E-02	7,32E+01
Polypropylene, granulate {RER}| production | APOS, U	2,69E+00	3,60E-09	2,87E-04	3,96E-03	1,51E-04	4,36E-03	4,99E-03	6,50E-05	1,00E-05	6,93E-03	3,95E-03	1,28E-03	2,63E-05	5,31E-04	1,67E-04	2,94E-04	1,54E+00	1,56E-02	7,04E+01
Electronics, for control units {RER}| production | APOS, U	3,93E+01	1,56E-05	3,37E+00	1,14E-01	3,74E-02	1,17E-01	1,88E-01	1,10E-01	3,29E-03	2,27E+02	1,77E+01	5,92E+00	2,36E-02	3,05E+00	1,50E+00	1,33E+00	9,37E+00	3,24E-01	4,30E+02
Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U	2,33E+00	4,00E-07	2,16E-03	5,35E-03	1,86E-04	5,95E-03	4,56E-03	7,02E-05	3,24E-05	8,43E-01	1,33E-02	4,46E-03	2,67E-03	7,36E-03	4,18E-03	1,03E-03	1,07E+00	1,86E-01	4,89E+01
Polystyrene, expandable {RER}| production | APOS, U	5,28E+00	1,20E-07	7,73E-04	5,83E-03	2,30E-04	6,40E-03	8,81E-03	1,13E-04	1,47E-05	4,90E-01	1,48E-02	4,72E-03	3,04E-04	2,38E-03	4,73E-04	5,34E-04	1,87E+00	6,48E-02	8,55E+01
Epoxy resin, liquid {RER}| production | APOS, U	4,61E+00	1,06E-06	2,62E-01	7,87E-03	2,33E-03	8,51E-03	1,12E-02	1,36E-03	9,43E-05	4,00E+00	1,68E-01	3,50E-02	5,69E-03	5,96E-02	5,93E-02	7,53E-03	1,57E+00	4,74E-02	7,18E+01
1-propanol {RER}| production | APOS, U	3,97E+00	1,03E-06	5,55E-01	1,34E-02	9,58E-04	1,75E-02	1,41E-02	1,59E-03	1,11E-04	3,73E+00	8,96E-02	3,02E-02	8,73E-04	3,43E-02	1,71E-01	6,80E-03	1,84E+00	8,92E-02	8,41E+01
Polycarbonate {RER}| production | APOS, U	1,19E+01	5,41E-06	1,16E-03	1,29E-02	2,04E-03	1,34E-02	2,01E-02	2,14E-04	4,88E-06	6,92E-01	1,63E-02	5,44E-03	3,55E-03	2,49E-02	6,72E-04	5,39E-04	2,19E+00	5,26E-02	9,99E+01
Steel, unalloyed {RER}| steel production, converter, unalloyed | APOS, U	2,31E+00	2,80E-07	4,74E-02	4,35E-03	1,71E-03	4,61E-03	5,56E-03	7,92E-04	3,59E-05	1,59E+00	3,21E-02	1,10E-02	7,41E-04	1,50E-02	2,37E-02	4,69E-02	3,39E-01	1,40E-02	1,56E+01
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	1,31E+02	3,96E-03	1,06E+00	1,39E-02	2,39E-03	1,45E-02	3,59E-02	3,47E-03	2,66E-04	1,30E+01	2,78E-01	9,67E-02	5,94E-01	7,21E+00	1,81E-01	2,62E-02	2,91E+00	1,81E-01	1,34E+02
Expanded perlite {CH}| production | APOS, U	4,23E-01	4,66E-07	4,86E-02	1,32E-03	2,25E-04	1,36E-03	1,85E-03	1,24E-04	5,75E-05	5,37E-01	1,19E-02	3,87E-03	1,96E-04	4,91E-03	6,15E-02	6,89E-03	1,29E-01	9,99E-03	5,88E+00
Nitrogen fertiliser, as N {GLO}| nutrient supply from manure, solid, cattle | APOS, U	6,04E+00	1,55E-05	5,72E-02	6,47E-03	1,70E-03	6,66E-03	1,89E-02	5,54E-04	4,76E-03	4,20E+00	5,00E-02	1,71E-02	2,17E-03	2,81E-02	2,78E+00	4,48E-03	3,62E-01	7,11E-02	1,66E+01
Phosphate fertiliser, as P2O5 {GLO}| nutrient supply from poultry manure, dried | APOS, U	3,71E+00	1,45E-05	1,51E-01	6,38E-03	2,41E-03	6,55E-03	4,05E-02	1,20E-03	4,71E-03	2,19E+00	7,04E-02	2,19E-02	1,40E-03	3,31E-02	2,29E+00	4,22E-03	5,61E-01	2,61E-01	2,58E+01
Potassium fertiliser, as K2O {GLO}| nutrient supply from poultry manure, dried | APOS, U	2,89E+00	1,13E-05	1,18E-01	4,98E-03	1,88E-03	5,11E-03	3,16E-02	9,37E-04	3,67E-03	1,71E+00	5,50E-02	1,71E-02	1,09E-03	2,58E-02	1,78E+00	3,29E-03	4,38E-01	2,04E-01	2,01E+01
Application mix, pesticides/kg/CH U	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,09E+03	5,06E+00	2,25E+00	4,46E-04	2,50E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Metal working, average for metal product manufacturing {RER}| processing | APOS, U	2,43E+00	8,81E-07	3,69E-01	4,84E-03	1,72E-03	4,97E-03	1,48E-02	3,33E-03	3,01E-04	2,87E+01	5,53E-01	1,84E-01	2,19E-03	2,21E-01	8,31E-02	4,81E-02	5,14E-01	2,12E-02	2,35E+01
Sheet rolling, aluminium {RER}| processing | APOS, U	5,60E-01	1,65E-07	1,30E-01	1,03E-03	2,22E-04	1,10E-03	1,80E-03	3,03E-04	2,39E-05	2,46E-01	1,58E-02	5,15E-03	1,40E-04	3,54E-03	1,30E-02	1,67E-03	1,40E-01	6,45E-03	6,41E+00
Polar fleece production, energy use only {RER}| production | APOS, U	4,94E+00	1,61E-06	1,89E+00	9,64E-03	1,84E-03	9,73E-03	2,16E-02	4,10E-03	2,94E-04	2,74E+00	1,46E-01	4,68E-02	1,57E-03	3,53E-02	2,67E-01	5,29E-03	1,17E+00	6,76E-02	5,37E+01
Injection moulding {RER}| processing | APOS, U	1,11E+00	3,97E-07	3,41E-01	1,85E-03	3,54E-04	1,93E-03	3,63E-03	7,13E-04	5,38E-05	4,66E-01	2,85E-02	9,17E-03	3,37E-04	6,70E-03	8,01E-02	2,00E-03	3,56E-01	1,71E-02	1,63E+01
Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U	3,37E-01	1,07E-07	1,16E-01	6,64E-04	1,38E-04	6,74E-04	1,39E-03	2,57E-04	1,93E-05	2,30E-01	1,04E-02	3,36E-03	1,42E-04	2,63E-03	5,51E-02	7,26E-04	8,22E-02	1,19E-02	3,76E+00
Extrusion, plastic film {RER}| production | APOS, U	4,45E-01	1,45E-07	1,77E-01	7,98E-04	1,76E-04	8,14E-04	1,57E-03	3,20E-04	2,69E-05	3,03E-01	1,42E-02	4,54E-03	2,05E-04	3,46E-03	7,45E-02	9,72E-04	1,12E-01	2,33E-02	5,14E+00
Wire drawing, steel {RER}| processing | APOS, U	3,62E-01	9,02E-08	3,82E-02	4,64E-04	1,32E-04	4,86E-04	7,76E-04	1,52E-04	2,22E-05	1,86E-01	1,26E-02	4,38E-03	2,97E-04	2,62E-03	1,47E-02	2,46E-03	5,33E-02	1,66E-02	2,44E+00

Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,72E-01	8,48E-08	2,73E-03	5,26E-04	6,15E-05	5,39E-04	4,12E-04	1,31E-05	1,06E-06	9,53E-01	2,36E-03	9,96E-04	3,41E-05	2,23E-03	6,92E-03	2,16E-04	5,77E-02	4,70E-04	2,64E+00
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U	5,34E-01	2,37E-07	9,36E-03	1,41E-03	1,67E-04	1,44E-03	1,25E-03	5,56E-05	4,26E-06	1,91E+00	1,12E-02	4,18E-03	1,01E-04	6,64E-03	1,46E-02	1,04E-03	1,72E-01	1,53E-03	7,87E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	1,18E-02	3,86E-09	4,17E-04	1,47E-04	6,72E-06	1,48E-04	1,90E-04	1,53E-06	1,07E-07	9,39E-03	7,37E-05	2,78E-05	1,53E-06	3,86E-05	7,62E-05	9,38E-06	3,60E-03	3,37E-05	1,65E-01
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	1,45E-01	1,85E-08	2,56E-03	5,67E-06	1,62E-05	9,13E-06	4,98E-04	6,04E-09	2,11E-07	1,12E-02	5,41E-06	7,66E-06	2,79E-05	3,09E-04	7,61E-05	1,68E-04	3,39E-02	1,21E-02	1,72E+00
Excavation, hydraulic digger {RER}| processing | APOS, U	5,58E-01	2,20E-07	7,59E-03	6,26E-03	6,04E-04	6,36E-03	2,96E-03	3,66E-05	2,38E-06	2,39E-01	3,27E-03	1,19E-03	5,22E-05	2,23E-03	1,65E-03	9,64E-04	1,77E-01	1,26E-03	8,09E+00
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | APOS, U	1,93E+00	7,87E-07	8,57E-02	8,28E-03	9,86E-04	8,55E-03	6,29E-03	4,01E-04	2,76E-05	4,37E+00	9,61E-02	3,27E-02	9,29E-03	2,86E-02	5,37E-02	5,28E-03	6,24E-01	7,26E-03	2,86E+01
Irrigation {ES}| processing | APOS, U	3,17E-01	6,93E-08	5,56E-02	8,87E-04	2,02E-04	9,27E-04	1,23E-03	1,08E-04	8,07E-06	3,83E-01	1,23E-02	3,63E-03	9,81E-05	3,15E-03	2,50E-02	2,09E-03	8,77E-02	1,00E+00	4,02E+00
Concrete, normal {CH}| unreinforced concrete production, with cement CEM II/A | APOS, U	1,52E+02	1,35E-05	1,06E+01	2,88E-01	2,14E-02	2,91E-01	2,54E-01	2,52E-02	1,84E-03	1,06E+02	1,63E+00	5,49E-01	2,19E-02	7,29E-01	2,07E+00	2,59E-01	1,22E+01	3,45E+00	5,62E+02
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	5,96E+01	1,72E-05	3,12E+00	1,87E-01	3,42E-02	1,90E-01	2,92E-01	1,59E-02	1,42E-03	6,64E+01	1,28E+00	4,43E-01	3,95E-02	5,36E-01	1,19E+00	2,07E-01	1,47E+01	6,36E-01	6,71E+02
Zinc coat, coils {GLO}| market for | APOS, U	5,66E+00	2,13E-06	2,18E-01	1,68E-02	3,80E-03	1,71E-02	2,45E-01	4,14E-03	1,69E-04	1,22E+02	5,65E-01	2,30E-01	1,34E-03	5,26E-01	8,83E-02	2,80E-01	1,35E+00	5,39E-02	6,21E+01
Section bar rolling, steel {RER}| processing | APOS, U	1,81E-01	4,51E-08	1,91E-02	2,32E-04	6,58E-05	2,43E-04	3,88E-04	7,59E-05	1,11E-05	9,29E-02	6,30E-03	2,19E-03	1,49E-04	1,31E-03	7,36E-03	1,23E-03	2,66E-02	8,32E-03	1,22E+00

Table 21. Values for current scenario RTG per functional unit (kg of tomatoes produced in one year) for each category of impact and CED.

RTG – CURRENT SCENARIO Functional unit: kg tomatoes produced over 1 year		GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
		kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
STRUCTURE + RAINWATER HARVESTING	Materials/assemblies - STRUCTURE + RH	2,05E-01	1,15E-07	1,73E-02	5,43E-04	1,38E-04	5,59E-04	7,34E-04	1,07E-04	5,24E-06	3,15E-01	1,23E-02	4,18E-03	1,35E-04	5,33E-03	3,10E-03	3,06E-03	5,22E-02	1,68E-03	2,39E+00
	Processes - STRUCTURE + RH	2,28E-01	6,92E-08	3,24E-02	3,44E-04	1,07E-04	3,56E-04	1,42E-03	1,86E-04	1,61E-05	1,52E+00	2,70E-02	9,01E-03	1,30E-04	1,12E-02	7,42E-03	2,75E-03	5,53E-02	6,65E-03	2,60E+00
	TOTAL STRUCTURE + RAINWATER HARVESTING	4,33E-01	1,84E-07	4,97E-02	8,87E-04	2,44E-04	9,15E-04	2,15E-03	2,94E-04	2,14E-05	1,83E+00	3,92E-02	1,32E-02	2,65E-04	1,65E-02	1,05E-02	5,81E-03	1,08E-01	8,33E-03	4,99E+00
AUXILIARY EQUIPMENT	Materials/assemblies - AUXILIARY EQUIPMENT	3,27E-02	1,51E-09	2,48E-04	4,30E-05	4,67E-06	4,68E-05	6,15E-05	2,47E-06	1,83E-07	1,08E-02	2,77E-04	9,45E-05	4,42E-06	1,01E-04	8,27E-05	5,18E-05	1,22E-02	4,17E-04	5,60E-01
	Processes - AUXILIARY EQUIPMENT	9,39E-03	3,40E-09	2,42E-03	1,91E-05	3,64E-06	1,98E-05	3,36E-05	6,28E-06	4,98E-07	1,78E-02	4,79E-04	1,57E-04	8,80E-06	1,54E-04	6,11E-04	3,71E-05	2,87E-03	1,36E-04	1,31E-01
	TOTAL AUXILIARY EQUIPMENT	4,20E-02	4,92E-09	2,66E-03	6,20E-05	8,31E-06	6,66E-05	9,52E-05	8,75E-06	6,80E-07	2,86E-02	7,55E-04	2,52E-04	1,32E-05	2,55E-04	6,93E-04	8,89E-05	1,51E-02	5,53E-04	6,91E-01
PRODUCTION	Materials/assemblies - PRODUCTION	1,37E-01	4,14E-07	4,54E-03	2,13E-04	6,44E-05	2,19E-04	9,27E-04	2,94E-05	1,29E-04	3,39E-01	2,63E-03	9,18E-04	5,13E-05	1,28E-03	6,84E-02	3,19E-04	1,74E-02	5,39E-03	7,97E-01
	Processes - PRODUCTION	8,03E-02	3,16E-08	4,45E-03	3,35E-04	4,18E-05	3,46E-04	2,66E-04	1,76E-05	1,23E-06	1,75E-01	3,93E-03	1,32E-03	3,58E-04	1,16E-03	2,58E-03	2,44E-04	2,57E-02	2,03E-02	1,18E+00
	TOTALPRODUCTION	2,17E-01	4,46E-07	8,99E-03	5,48E-04	1,06E-04	5,65E-04	1,19E-03	4,70E-05	1,30E-04	5,14E-01	6,56E-03	2,24E-03	4,09E-04	2,43E-03	7,09E-02	5,63E-04	4,31E-02	2,56E-02	1,97E+00
CURRENT COVERING - POLYCARBONATE	Materials/assemblies - COVERING	1,05E-01	4,75E-08	1,02E-05	1,13E-04	1,80E-05	1,18E-04	1,76E-04	1,88E-06	4,29E-08	6,08E-03	1,43E-04	4,78E-05	3,12E-05	2,19E-04	5,91E-06	4,74E-06	1,92E-02	4,62E-04	8,78E-01
	Processes - COVERING	5,56E-03	2,05E-09	1,59E-03	1,29E-05	2,15E-06	1,32E-05	1,92E-05	2,94E-06	2,47E-07	1,11E-02	1,46E-04	4,89E-05	2,12E-06	5,03E-05	7,16E-04	1,06E-05	1,53E-03	2,13E-04	7,02E-02
	TOTAL COVERING	1,10E-01	4,96E-08	1,60E-03	1,26E-04	2,01E-05	1,31E-04	1,96E-04	4,82E-06	2,90E-07	1,71E-02	2,89E-04	9,67E-05	3,33E-05	2,69E-04	7,22E-04	1,53E-05	2,08E-02	6,75E-04	9,48E-01
TOTAL		8,02E-01	6,85E-07	6,30E-02	1,62E-03	3,79E-04	1,68E-03	3,63E-03	3,54E-04	1,53E-04	2,39E+00	4,69E-02	1,58E-02	7,20E-04	1,95E-02	8,29E-02	6,47E-03	1,86E-01	3,52E-02	8,60E+00

Table 22. Values for current scenario CG per functional unit (kg of tomatoes produced in one year) for each category of impact and CED.

CG – CURRENT SECENARIO Functional unit: kg tomatos produced over 1 year		GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
		kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
STRUCTURE	Materials/assemblies - STRUCTURE	4,43E-02	8,09E-09	1,39E-03	1,03E-04	5,23E-05	1,07E-04	1,30E-04	3,47E-05	1,08E-06	1,17E-01	4,96E-03	1,69E-03	3,27E-05	2,11E-03	7,33E-04	1,32E-03	7,94E-03	2,99E-04	3,65E-01
	Processes - STRUCTURE	5,93E-02	2,20E-08	8,12E-03	1,26E-04	4,07E-05	1,29E-04	5,10E-04	7,47E-05	6,59E-06	7,23E-01	1,23E-02	4,12E-03	4,86E-05	5,16E-03	1,97E-03	1,24E-03	1,31E-02	5,03E-04	5,98E-01
	TOTAL STRUCTURE	1,04E-01	3,01E-08	9,50E-03	2,29E-04	9,30E-05	2,36E-04	6,40E-04	1,09E-04	7,66E-06	8,40E-01	1,73E-02	5,81E-03	8,12E-05	7,28E-03	2,70E-03	2,56E-03	2,10E-02	8,01E-04	9,64E-01
AUXILIARY EQUIPMENT	Materials/assemblies - AUXILIARY EQUIPMENT	3,91E-02	1,81E-09	2,96E-04	5,14E-05	5,59E-06	5,61E-05	7,36E-05	2,96E-06	2,19E-07	1,30E-02	3,31E-04	1,13E-04	5,29E-06	1,21E-04	9,90E-05	6,20E-05	1,47E-02	4,99E-04	6,70E-01
	Processes - AUXILIARY EQUIPMENT	1,00E-02	3,58E-09	2,84E-03	1,76E-05	3,74E-06	1,83E-05	3,63E-05	7,27E-06	5,78E-07	1,86E-02	5,13E-04	1,68E-04	4,72E-06	1,67E-04	6,97E-04	4,11E-05	3,04E-03	1,58E-04	1,39E-01
	AUXILIARY EQUIPMENT	4,91E-02	5,39E-09	3,13E-03	6,91E-05	9,33E-06	7,44E-05	1,10E-04	1,02E-05	7,97E-07	3,15E-02	8,44E-04	2,81E-04	1,00E-05	2,88E-04	7,96E-04	1,03E-04	1,77E-02	6,57E-04	8,09E-01
PRODUCTION	Materials/assemblies - PRODUCTIVITY	4,48E-02	1,28E-07	4,54E-02	9,74E-05	2,65E-05	1,00E-04	3,78E-04	1,35E-05	3,83E-05	3,27E-01	1,67E-03	6,19E-04	1,77E-05	7,76E-04	1,98E-02	2,74E-04	9,44E-03	2,36E-03	4,33E-01
	Processes - PRODUCTIVITY	8,44E-02	3,32E-08	4,67E-03	3,52E-04	4,39E-05	3,64E-04	2,79E-04	1,85E-05	1,29E-06	1,84E-01	4,13E-03	1,39E-03	3,76E-04	1,22E-03	2,71E-03	2,56E-04	2,70E-02	2,11E-02	1,24E+00
	PRODUCTIVITY	1,29E-01	1,61E-07	4,67E-03	4,50E-04	7,05E-05	4,64E-04	6,57E-04	3,20E-05	3,96E-05	5,11E-01	5,80E-03	2,01E-03	3,94E-04	1,99E-03	2,25E-02	5,30E-04	3,64E-02	2,34E-02	1,67E+00
CURRENT COVERING - POLYETHYLENE	Materials/assemblies - COVERING	1,56E-02	9,02E-06	3,31E-06	5,69E-06	2,34E-06	4,63E-06	9,34E-06	7,05E-07	4,33E-08	3,39E-05	4,21E-05	5,05E-06	1,36E-03	8,87E-04	8,00E-05	1,35E-06	6,33E-04	7,15E-06	2,87E-02
	Processes - COVERING	2,38E-03	7,91E-10	9,01E-04	4,39E-06	9,36E-07	4,48E-06	8,25E-06	1,63E-06	1,37E-07	2,17E-03	7,34E-05	2,37E-05	1,07E-06	1,91E-05	3,82E-04	5,08E-06	6,11E-04	1,19E-04	2,80E-02
	TOTAL COVERING	1,80E-02	9,02E-06	9,05E-04	1,01E-05	3,27E-06	9,11E-06	1,76E-05	2,34E-06	1,80E-07	2,20E-03	1,15E-04	2,87E-05	1,36E-03	9,06E-04	4,62E-04	6,44E-06	1,24E-03	1,27E-04	5,66E-02
TOTAL		3,00E-01	9,21E-06	3,29E-01	7,57E-04	1,76E-04	7,83E-04	1,43E-03	1,54E-04	4,82E-05	1,38E+00	2,40E-02	8,13E-03	1,85E-03	1,05E-02	2,65E-02	3,20E-03	7,64E-02	2,50E-02	3,50E+00

Table 23. Values per functional unit (kg of tomatoes produced in one year) for each covering material. Adapted to RTG.

RTG																					
POLYCARBONATE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polycarbonate {RER}| production | APOS, U	2,05E+02	kg	2,09E-02	9,51E-09	2,04E-06	2,27E-05	3,60E-06	2,35E-05	3,53E-05	3,76E-07	8,58E-09	1,22E-03	2,87E-05	9,56E-06	6,24E-06	4,38E-05	1,18E-06	9,47E-07	3,85E-03	9,25E-05	1,76E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	2,05E+02	kg	7,83E-04	2,54E-10	3,12E-04	1,40E-06	3,10E-07	1,43E-06	2,75E-06	5,63E-07	4,73E-08	5,32E-04	2,49E-05	7,99E-06	3,61E-07	6,09E-06	1,31E-04	1,71E-06	1,98E-04	4,10E-05	9,04E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	2,03E+02	tkm	3,00E-04	1,48E-10	4,76E-06	9,16E-07	1,07E-07	9,41E-07	7,19E-07	2,29E-08	1,85E-09	1,66E-03	4,11E-06	1,74E-06	5,95E-08	3,88E-06	1,21E-05	3,76E-07	1,01E-04	8,20E-07	4,61E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	2,07E+02	tkm	2,10E-05	6,84E-12	7,39E-07	2,60E-07	1,19E-08	2,63E-07	3,36E-07	2,71E-09	1,89E-10	1,66E-05	1,31E-07	4,93E-08	2,71E-09	6,85E-08	1,35E-07	1,66E-08	6,39E-06	5,97E-08	2,93E-04
TOTAL			2,20E-02	9,92E-09	3,19E-04	2,52E-05	4,03E-06	2,61E-05	3,91E-05	9,65E-07	5,79E-08	3,43E-03	5,78E-05	1,93E-05	6,66E-06	5,38E-05	1,44E-04	3,05E-06	4,15E-03	1,34E-04	1,90E-01
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polycarbonate {RER}| production | APOS, U	8,19E+02	kg	8,37E-02	3,80E-08	8,15E-06	9,06E-05	1,44E-05	9,40E-05	1,41E-04	1,51E-06	3,43E-08	4,87E-03	1,15E-04	3,82E-05	2,50E-05	1,75E-04	4,72E-06	3,79E-06	1,54E-02	3,70E-04	7,02E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	8,19E+02	kg	3,13E-03	1,02E-09	1,25E-03	5,61E-06	1,24E-06	5,72E-06	1,10E-05	2,25E-06	1,89E-07	2,13E-03	9,96E-05	3,19E-05	1,44E-06	2,44E-05	5,24E-04	6,84E-06	7,91E-04	1,64E-04	3,62E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	3,15E+01	MJ	3,92E-05	2,44E-11	1,03E-05	1,26E-07	3,56E-08	1,32E-07	2,10E-07	4,11E-08	6,02E-09	5,03E-05	3,41E-06	1,18E-06	8,04E-08	7,10E-07	3,98E-06	6,65E-07	1,44E-05	4,50E-06	6,61E-04
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	8,12E+02	tkm	1,20E-03	5,91E-10	1,91E-05	3,67E-06	4,29E-07	3,76E-06	2,87E-06	9,16E-08	7,39E-09	6,65E-03	1,65E-05	6,95E-06	2,38E-07	1,55E-05	4,83E-05	1,51E-06	4,03E-04	3,28E-06	1,84E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	8,26E+02	tkm	8,40E-05	2,74E-11	2,96E-06	1,04E-06	4,76E-08	1,05E-06	1,35E-06	1,08E-08	7,57E-10	6,66E-05	5,23E-07	1,97E-07	1,08E-08	2,74E-07	5,41E-07	6,65E-08	2,56E-05	2,39E-07	1,17E-03
TOTAL			8,82E-02	3,97E-08	1,29E-03	1,01E-04	1,61E-05	1,05E-04	1,57E-04	3,90E-06	2,38E-07	1,38E-02	2,35E-04	7,85E-05	2,67E-05	2,16E-04	5,82E-04	1,29E-05	1,66E-02	5,42E-04	7,59E-01
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Polycarbonate {RER}| production | APOS, U	1,02E+03	kg	1,05E-01	4,75E-08	1,02E-05	1,13E-04	1,80E-05	1,18E-04	1,76E-04	1,88E-06	4,29E-08	6,08E-03	1,43E-04	4,78E-05	3,12E-05	2,19E-04	5,91E-06	4,74E-06	1,92E-02	4,62E-04	8,78E-01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	3,07E+01	tkm	4,53E-05	2,24E-11	7,21E-07	1,39E-07	1,62E-08	1,42E-07	1,09E-07	3,46E-09	2,79E-10	2,51E-04	6,22E-07	2,63E-07	9,00E-09	5,87E-07	1,82E-06	5,69E-08	1,52E-05	1,24E-07	6,97E-04

TOTAL			4,53E-05	2,24E-11	7,21E-07	1,39E-07	1,62E-08	1,42E-07	1,09E-07	3,46E-09	2,79E-10	2,51E-04	6,22E-07	2,63E-07	9,00E-09	5,87E-07	1,82E-06	5,69E-08	1,52E-05	1,24E-07	6,97E-04
TOTAL GLOBAL			1,10E-01	4,96E-08	1,61E-03	1,26E-04	2,02E-05	1,31E-04	1,96E-04	4,87E-06	2,96E-07	1,74E-02	2,93E-04	9,81E-05	3,34E-05	2,70E-04	7,28E-04	1,60E-05	2,08E-02	6,76E-04	9,49E-01

POLYETHYLENE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polyethylene, low density, granulate {RER}| production | APOS, U	4,21E+01	kg	1,11E-03	1,38E-12	1,47E-07	1,69E-06	6,38E-08	1,88E-06	2,32E-06	1,32E-08	6,62E-10	3,78E-06	1,94E-06	6,43E-07	7,07E-09	2,33E-07	8,45E-08	1,96E-07	5,59E-04	6,38E-06	2,56E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	4,21E+01	kg	1,61E-04	5,23E-11	6,42E-05	2,89E-07	6,38E-08	2,94E-07	5,66E-07	1,16E-07	9,73E-09	1,09E-04	5,12E-06	1,64E-06	7,43E-08	1,25E-06	2,70E-05	3,52E-07	4,07E-05	8,43E-06	1,86E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	4,25E+00	tkm	6,28E-06	3,10E-12	9,98E-08	1,92E-08	2,25E-09	1,97E-08	1,51E-08	4,80E-10	3,87E-11	3,48E-05	8,62E-08	3,64E-08	1,25E-09	8,14E-08	2,53E-07	7,88E-09	2,11E-06	1,72E-08	9,66E-05
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			1,28E-03	5,68E-11	6,44E-05	2,00E-06	1,30E-07	2,20E-06	2,90E-06	1,29E-07	1,04E-08	1,48E-04	7,15E-06	2,32E-06	8,26E-08	1,57E-06	2,73E-05	5,56E-07	6,02E-04	1,48E-05	2,75E-02
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	4,84E+02	kg	1,28E-02	1,59E-11	1,69E-06	1,94E-05	7,34E-07	2,17E-05	2,67E-05	1,52E-07	7,62E-09	4,35E-05	2,24E-05	7,39E-06	8,13E-08	2,68E-06	9,72E-07	2,26E-06	6,43E-03	7,33E-05	2,94E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	4,84E+02	kg	1,85E-03	6,02E-10	7,38E-04	3,32E-06	7,34E-07	3,38E-06	6,51E-06	1,33E-06	1,12E-07	1,26E-03	5,89E-05	1,89E-05	8,54E-07	1,44E-05	3,10E-04	4,04E-06	4,68E-04	9,70E-05	2,14E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	1,37E+01	MJ	1,70E-05	2,17E-12	3,00E-07	6,65E-10	1,90E-09	1,07E-09	5,84E-08	7,08E-13	2,48E-11	1,31E-06	6,34E-10	8,99E-10	3,27E-09	3,62E-08	8,92E-09	1,97E-08	3,98E-06	1,42E-06	2,01E-04
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	4,89E+01	tkm	7,22E-05	3,56E-11	1,15E-06	2,21E-07	2,58E-08	2,27E-07	1,73E-07	5,52E-09	4,45E-10	4,00E-04	9,91E-07	4,18E-07	1,43E-08	9,36E-07	2,91E-06	9,06E-08	2,43E-05	1,98E-07	1,11E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			1,47E-02	6,55E-10	7,41E-04	2,30E-05	1,49E-06	2,53E-05	3,35E-05	1,49E-06	1,20E-07	1,70E-03	8,22E-05	2,67E-05	9,53E-07	1,81E-05	3,14E-04	6,41E-06	6,93E-03	1,72E-04	3,17E-01
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	5,27E+02	kg	1,39E-02	1,73E-11	1,84E-06	2,11E-05	7,98E-07	2,35E-05	2,90E-05	1,65E-07	8,28E-09	4,73E-05	2,43E-05	8,03E-06	8,84E-08	2,91E-06	1,06E-06	2,45E-06	6,99E-03	7,97E-05	3,19E-01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight,	1,58E+01	tkm	2,33E-05	1,15E-11	3,71E-07	7,13E-08	8,34E-09	7,32E-08	5,59E-08	1,78E-09	1,44E-10	1,29E-04	3,20E-07	1,35E-07	4,63E-09	3,02E-07	9,38E-07	2,93E-08	7,83E-06	6,38E-08	3,59E-04

lorry 16-32 metric ton, EURO5 | APOS, U																				
TOTAL			2,33E-05	1,15E-11	3,71E-07	7,13E-08	8,34E-09	7,32E-08	5,59E-08	1,78E-09	1,44E-10	1,29E-04	3,20E-07	1,35E-07	4,63E-09	3,02E-07	9,38E-07	2,93E-08	7,83E-06	6,38E-08	3,59E-04
TOTAL GLOBAL			1,61E-02	7,24E-10	8,06E-04	2,51E-05	1,63E-06	2,75E-05	3,64E-05	1,62E-06	1,30E-07	1,98E-03	8,97E-05	2,92E-05	1,04E-06	1,99E-05	3,42E-04	6,99E-06	7,54E-03	1,87E-04	3,45E-01

POLYETHYLENE DOUBLE-LAYER			IMPACT CATEGORIES																	
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polyethylene, low density, granulate {RER}| production | APOS, U	8,43E+01	kg	2,23E-03	2,77E-12	2,94E-07	3,38E-06	1,28E-07	3,77E-06	4,65E-06	2,64E-08	1,32E-09	7,57E-06	3,89E-06	1,29E-06	1,41E-08	4,66E-07	1,69E-07	3,92E-07	1,12E-03	1,28E-05	5,11E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	8,43E+01	kg	3,22E-04	1,05E-10	1,28E-04	5,77E-07	1,28E-07	5,89E-07	1,13E-06	2,31E-07	1,95E-08	2,19E-04	1,02E-05	3,29E-06	1,49E-07	2,51E-06	5,39E-05	7,03E-07	8,14E-05	1,69E-05	3,72E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	8,51E+00	tkm	1,26E-05	6,19E-12	2,00E-07	3,84E-08	4,49E-09	3,94E-08	3,01E-08	9,59E-10	7,74E-11	6,96E-05	1,72E-07	7,28E-08	2,49E-09	1,63E-07	5,06E-07	1,58E-08	4,22E-06	3,44E-08	1,93E-04
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			2,56E-03	1,14E-10	1,29E-04	4,00E-06	2,60E-07	4,39E-06	5,81E-06	2,59E-07	2,09E-08	2,96E-04	1,43E-05	4,64E-06	1,65E-07	3,14E-06	5,46E-05	1,11E-06	1,20E-03	2,97E-05	5,50E-02
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	9,69E+02	kg	2,56E-02	3,18E-11	3,38E-06	3,89E-05	1,47E-06	4,33E-05	5,34E-05	3,03E-07	1,52E-08	8,70E-05	4,47E-05	1,48E-05	1,63E-07	5,36E-06	1,94E-06	4,51E-06	1,29E-02	1,47E-04	5,88E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	9,69E+02	kg	3,71E-03	1,20E-09	1,48E-03	6,64E-06	1,47E-06	6,77E-06	1,30E-05	2,66E-06	2,24E-07	2,52E-03	1,18E-04	3,78E-05	1,71E-06	2,88E-05	6,20E-04	8,08E-06	9,36E-04	1,94E-04	4,28E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	1,37E+01	MJ	1,70E-05	2,17E-12	3,00E-07	6,65E-10	1,90E-09	1,07E-09	5,84E-08	7,08E-13	2,48E-11	1,31E-06	6,34E-10	8,99E-10	3,27E-09	3,62E-08	8,92E-09	1,97E-08	3,98E-06	1,42E-06	2,01E-04
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	9,79E+01	tkm	1,44E-04	7,12E-11	2,30E-06	4,42E-07	5,16E-08	4,53E-07	3,46E-07	1,10E-08	8,90E-10	8,01E-04	1,98E-06	8,37E-07	2,87E-08	1,87E-06	5,81E-06	1,81E-07	4,85E-05	3,95E-07	2,22E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			2,95E-02	1,31E-09	1,48E-03	4,60E-05	2,99E-06	5,05E-05	6,69E-05	2,98E-06	2,40E-07	3,41E-03	1,64E-04	5,34E-05	1,90E-06	3,61E-05	6,28E-04	1,28E-05	1,39E-02	3,42E-04	6,33E-01
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	1,05E+03	kg	2,78E-02	3,46E-11	3,67E-06	4,23E-05	1,60E-06	4,71E-05	5,81E-05	3,30E-07	1,66E-08	9,46E-05	4,86E-05	1,61E-05	1,77E-07	5,82E-06	2,11E-06	4,91E-06	1,40E-02	1,59E-04	6,39E-01
Processes	Value	Unit																			

Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	3,16E+01	tkm	4,66E-05	2,30E-11	7,41E-07	1,43E-07	1,67E-08	1,46E-07	1,12E-07	3,56E-09	2,87E-10	2,58E-04	6,40E-07	2,70E-07	9,26E-09	6,04E-07	1,88E-06	5,85E-08	1,57E-05	1,28E-07	7,17E-04
TOTAL			4,66E-05	2,30E-11	7,41E-07	1,43E-07	1,67E-08	1,46E-07	1,12E-07	3,56E-09	2,87E-10	2,58E-04	6,40E-07	2,70E-07	9,26E-09	6,04E-07	1,88E-06	5,85E-08	1,57E-05	1,28E-07	7,17E-04
TOTAL GLOBAL			3,21E-02	1,45E-09	1,61E-03	5,01E-05	3,26E-06	5,51E-05	7,28E-05	3,24E-06	2,61E-07	3,96E-03	1,79E-04	5,83E-05	2,08E-06	3,98E-05	6,84E-04	1,40E-05	1,51E-02	3,72E-04	6,89E-01

HORTICULTURE GLASS			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	1,49E+03	kg	7,63E-01	2,20E-07	4,00E-02	2,40E-03	4,38E-04	2,43E-03	3,75E-03	2,04E-04	1,82E-05	8,50E-01	1,64E-02	5,68E-03	5,06E-04	6,86E-03	1,52E-02	2,65E-03	1,88E-01	8,15E-03	8,59E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,82E+03	tkm	2,68E-03	1,32E-09	4,26E-05	8,20E-06	9,59E-07	8,41E-06	6,43E-06	2,05E-07	1,65E-08	1,49E-02	3,68E-05	1,55E-05	5,32E-07	3,47E-05	1,08E-04	3,37E-06	9,00E-04	7,33E-06	4,12E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			7,66E-01	2,21E-07	4,00E-02	2,41E-03	4,39E-04	2,44E-03	3,75E-03	2,04E-04	1,82E-05	8,65E-01	1,65E-02	5,69E-03	5,07E-04	6,89E-03	1,53E-02	2,65E-03	1,89E-01	8,15E-03	8,64E+00
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	9,84E+02	kg	5,04E-01	1,45E-07	2,64E-02	1,58E-03	2,89E-04	1,61E-03	2,47E-03	1,34E-04	1,20E-05	5,61E-01	1,08E-02	3,75E-03	3,34E-04	4,53E-03	1,00E-02	1,75E-03	1,24E-01	5,38E-03	5,67E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	6,30E+00	MJ	7,84E-06	1,00E-12	1,39E-07	3,07E-10	8,76E-10	4,94E-10	2,69E-08	3,27E-13	1,14E-11	6,06E-07	2,93E-10	4,15E-10	1,51E-09	1,67E-08	4,12E-09	9,08E-09	1,83E-06	6,54E-07	9,29E-05
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,20E+03	tkm	1,77E-03	8,72E-10	2,81E-05	5,41E-06	6,33E-07	5,55E-06	4,24E-06	1,35E-07	1,09E-08	9,81E-03	2,43E-05	1,02E-05	3,51E-07	2,29E-05	7,12E-05	2,22E-06	5,94E-04	4,84E-06	2,72E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			5,06E-01	1,46E-07	2,64E-02	1,59E-03	2,90E-04	1,61E-03	2,48E-03	1,35E-04	1,20E-05	5,71E-01	1,09E-02	3,76E-03	3,34E-04	4,55E-03	1,01E-02	1,75E-03	1,24E-01	5,38E-03	5,70E+00
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			

Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	2,48E+03	kg	1,27E+00	3,65E-07	6,64E-02	3,98E-03	7,27E-04	4,04E-03	6,22E-03	3,38E-04	3,01E-05	1,41E+00	2,73E-02	9,42E-03	8,40E-04	1,14E-02	2,53E-02	4,40E-03	3,11E-01	1,35E-02	1,43E+01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	7,43E+01	tkm	1,10E-04	5,40E-11	1,74E-06	3,35E-07	3,92E-08	3,44E-07	2,63E-07	8,37E-09	6,75E-10	6,08E-04	1,50E-06	6,35E-07	2,18E-08	1,42E-06	4,41E-06	1,38E-07	3,68E-05	3,00E-07	1,69E-03
TOTAL			1,10E-04	5,40E-11	1,74E-06	3,35E-07	3,92E-08	3,44E-07	2,63E-07	8,37E-09	6,75E-10	6,08E-04	1,50E-06	6,35E-07	2,18E-08	1,42E-06	4,41E-06	1,38E-07	3,68E-05	3,00E-07	1,69E-03
TOTAL GLOBAL			1,27E+00	3,67E-07	6,65E-02	4,00E-03	7,28E-04	4,05E-03	6,23E-03	3,39E-04	3,02E-05	1,44E+00	2,73E-02	9,45E-03	8,41E-04	1,14E-02	2,55E-02	4,40E-03	3,13E-01	1,35E-02	1,43E+01

ETFE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	4,91E+01	kg	5,51E-02	1,67E-06	4,46E-04	5,86E-06	1,01E-06	6,12E-06	1,52E-05	1,47E-06	1,12E-07	5,50E-03	1,17E-04	4,08E-05	2,50E-04	3,04E-03	7,66E-05	1,11E-05	1,23E-03	7,64E-05	5,64E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	4,91E+01	kg	1,88E-04	6,10E-11	7,49E-05	3,37E-07	7,44E-08	3,43E-07	6,61E-07	1,35E-07	1,13E-08	1,28E-04	5,97E-06	1,92E-06	8,67E-08	1,46E-06	3,14E-05	4,10E-07	4,75E-05	9,84E-06	2,17E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	7,54E+01	tkm	1,11E-04	5,49E-11	1,77E-06	3,40E-07	3,98E-08	3,49E-07	2,67E-07	8,51E-09	6,86E-10	6,17E-04	1,53E-06	6,45E-07	2,21E-08	1,44E-06	4,48E-06	1,40E-07	3,74E-05	3,05E-07	1,71E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			5,54E-02	1,67E-06	5,22E-04	6,53E-06	1,12E-06	6,81E-06	1,61E-05	1,61E-06	1,24E-07	6,25E-03	1,25E-04	4,34E-05	2,51E-04	3,04E-03	1,12E-04	1,16E-05	1,31E-03	8,65E-05	6,03E-02
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	0,00E+00	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

TOTAL			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	4,91E+01	kg	5,51E-02	1,67E-06	4,46E-04	5,86E-06	1,01E-06	6,12E-06	1,52E-05	1,47E-06	1,12E-07	5,50E-03	1,17E-04	4,08E-05	2,50E-04	3,04E-03	7,66E-05	1,11E-05	1,23E-03	7,64E-05	5,64E-02
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,47E+00	tkm	2,18E-06	1,07E-12	3,46E-08	6,65E-09	7,78E-10	6,83E-09	5,22E-09	1,66E-10	1,34E-11	1,21E-05	2,99E-08	1,26E-08	4,32E-10	2,82E-08	8,76E-08	2,73E-09	7,31E-07	5,95E-09	3,35E-05
TOTAL			2,18E-06	1,07E-12	3,46E-08	6,65E-09	7,78E-10	6,83E-09	5,22E-09	1,66E-10	1,34E-11	1,21E-05	2,99E-08	1,26E-08	4,32E-10	2,82E-08	8,76E-08	2,73E-09	7,31E-07	5,95E-09	3,35E-05
TOTAL GLOBAL			5,54E-02	1,67E-06	5,22E-04	6,54E-06	1,12E-06	6,82E-06	1,61E-05	1,61E-06	1,24E-07	6,26E-03	1,25E-04	4,34E-05	2,51E-04	3,04E-03	1,13E-04	1,16E-05	1,32E-03	8,66E-05	6,04E-02

Table 24.Values per functional unit (kg of tomatoes produced in one year) for each covering material. Adapted to CG.

CG																					
POLYCARBONATE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polycarbonate {RER}| production | APOS, U	8,22E+02	kg	5,15E-02	2,34E-08	5,01E-06	5,58E-05	8,85E-06	5,78E-05	8,68E-05	9,26E-07	2,11E-08	2,99E-03	7,06E-05	2,35E-05	1,53E-05	1,08E-04	2,91E-06	2,33E-06	9,47E-03	2,28E-04	4,32E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	8,22E+02	kg	1,93E-03	6,26E-10	7,67E-04	3,45E-06	7,63E-07	3,52E-06	6,78E-06	1,38E-06	1,16E-07	1,31E-03	6,13E-05	1,97E-05	8,89E-07	1,50E-05	3,22E-04	4,20E-06	4,87E-04	1,01E-04	2,23E-02
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	8,16E+02	tkm	7,37E-04	3,64E-10	1,17E-05	2,26E-06	2,64E-07	2,31E-06	1,77E-06	5,63E-08	4,54E-09	4,09E-03	1,01E-05	4,27E-06	1,46E-07	9,56E-06	2,97E-05	9,26E-07	2,48E-04	2,02E-06	1,13E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	8,29E+02	tkm	5,17E-05	1,68E-11	1,82E-06	6,41E-07	2,93E-08	6,46E-07	8,27E-07	6,67E-09	4,66E-10	4,10E-05	3,21E-07	1,21E-07	6,67E-09	1,68E-07	3,33E-07	4,09E-08	1,57E-05	1,47E-07	7,20E-04
TOTAL			5,42E-02	2,44E-08	7,86E-04	6,21E-05	9,90E-06	6,43E-05	9,62E-05	2,37E-06	1,42E-07	8,43E-03	1,42E-04	4,76E-05	1,64E-05	1,32E-04	3,55E-04	7,50E-06	1,02E-02	3,31E-04	4,66E-01
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polycarbonate {RER}| production | APOS, U	3,29E+03	kg	2,06E-01	9,36E-08	2,00E-05	2,23E-04	3,54E-05	2,31E-04	3,47E-04	3,70E-06	8,44E-08	1,20E-02	2,82E-04	9,41E-05	6,14E-05	4,31E-04	1,16E-05	9,32E-06	3,79E-02	9,10E-04	1,73E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	3,29E+03	kg	7,71E-03	2,50E-09	3,07E-03	1,38E-05	3,05E-06	1,41E-05	2,71E-05	5,54E-06	4,65E-07	5,24E-03	2,45E-04	7,86E-05	3,55E-06	6,00E-05	1,29E-03	1,68E-05	1,95E-03	4,03E-04	8,90E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	3,15E+01	MJ	2,40E-05	3,06E-12	4,25E-07	9,40E-10	2,69E-09	1,51E-09	8,26E-08	1,00E-12	3,50E-11	1,86E-06	8,97E-10	1,27E-09	4,62E-09	5,12E-08	1,26E-08	2,78E-08	5,62E-06	2,00E-06	2,85E-04
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	3,26E+03	tkm	2,95E-03	1,45E-09	4,69E-05	9,02E-06	1,06E-06	9,26E-06	7,07E-06	2,25E-07	1,82E-08	1,64E-02	4,05E-05	1,71E-05	5,86E-07	3,82E-05	1,19E-04	3,70E-06	9,91E-04	8,07E-06	4,54E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	3,32E+03	tkm	2,07E-04	6,73E-11	7,28E-06	2,56E-06	1,17E-07	2,58E-06	3,31E-06	2,67E-08	1,86E-09	1,64E-04	1,29E-06	4,86E-07	2,67E-08	6,74E-07	1,33E-06	1,64E-07	6,29E-05	5,88E-07	2,88E-03
		TOTAL	2,17E-01	9,76E-08	3,14E-03	2,48E-04	3,96E-05	2,57E-04	3,85E-04	9,49E-06	5,70E-07	3,37E-02	5,69E-04	1,90E-04	6,56E-05	5,30E-04	1,42E-03	3,00E-05	4,09E-02	1,32E-03	1,87E+00
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Polycarbonate {RER}| production | APOS, U	8,22E+02	kg	5,15E-02	2,34E-08	5,01E-06	5,58E-05	8,85E-06	5,78E-05	8,68E-05	9,26E-07	2,11E-08	2,99E-03	7,06E-05	2,35E-05	1,53E-05	1,08E-04	2,91E-06	2,33E-06	9,47E-03	2,28E-04	4,32E-01
Processes	Value	Unit																			

Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	2,47E+01	tkm	2,23E-05	5,01E-13	5,41E-08	1,91E-08	8,72E-10	1,92E-08	2,46E-08	1,98E-10	1,39E-11	1,22E-06	9,56E-09	3,61E-09	1,99E-10	5,01E-09	9,90E-09	1,22E-09	4,68E-07	4,37E-09	2,14E-05
TOTAL			2,23E-05	5,01E-13	5,41E-08	1,91E-08	8,72E-10	1,92E-08	2,46E-08	1,98E-10	1,39E-11	1,22E-06	9,56E-09	3,61E-09	1,99E-10	5,01E-09	9,90E-09	1,22E-09	4,68E-07	4,37E-09	2,14E-05
TOTAL GLOBAL			2,71E-01	1,22E-07	3,93E-03	3,11E-04	4,95E-05	3,22E-04	4,81E-04	1,19E-05	7,12E-07	4,22E-02	7,11E-04	2,38E-04	8,20E-05	6,62E-04	1,78E-03	3,75E-05	5,11E-02	1,65E-03	2,33E+00

POLYETHYLENE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polyethylene, low density, granulate {RER}| production | APOS, U	7,71E+01	kg	1,25E-03	1,55E-12	1,65E-07	1,90E-06	7,16E-08	2,11E-06	2,60E-06	1,48E-08	7,43E-10	4,24E-06	2,18E-06	7,21E-07	7,93E-09	2,61E-07	9,48E-08	2,20E-07	6,27E-04	7,15E-06	2,87E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	7,71E+01	kg	1,81E-04	5,87E-11	7,19E-05	3,24E-07	7,15E-08	3,30E-07	6,35E-07	1,30E-07	1,09E-08	1,23E-04	5,74E-06	1,84E-06	8,33E-08	1,41E-06	3,02E-05	3,94E-07	4,56E-05	9,46E-06	2,09E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	7,79E+00	tkm	7,04E-06	3,47E-12	1,12E-07	2,15E-08	2,52E-09	2,21E-08	1,69E-08	5,38E-10	4,34E-11	3,90E-05	9,66E-08	4,08E-08	1,40E-09	9,12E-08	2,83E-07	8,84E-09	2,37E-06	1,93E-08	1,08E-04
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			1,44E-03	6,37E-11	7,22E-05	2,24E-06	1,46E-07	2,46E-06	3,26E-06	1,45E-07	1,17E-08	1,66E-04	8,02E-06	2,60E-06	9,26E-08	1,76E-06	3,06E-05	6,23E-07	6,75E-04	1,66E-05	3,09E-02
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	8,87E+02	kg	1,44E-02	1,78E-11	1,89E-06	2,18E-05	8,23E-07	2,43E-05	3,00E-05	1,70E-07	8,54E-09	4,88E-05	2,51E-05	8,29E-06	9,12E-08	3,00E-06	1,09E-06	2,53E-06	7,21E-03	8,22E-05	3,30E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	8,87E+02	kg	2,08E-03	6,75E-10	8,27E-04	3,72E-06	8,23E-07	3,80E-06	7,31E-06	1,49E-06	1,25E-07	1,41E-03	6,60E-05	2,12E-05	9,58E-07	1,62E-05	3,48E-04	4,53E-06	5,25E-04	1,09E-04	2,40E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	1,37E+01	MJ	1,04E-05	1,33E-12	1,84E-07	4,07E-10	1,16E-09	6,56E-10	3,58E-08	4,34E-13	1,52E-11	8,05E-07	3,89E-10	5,51E-10	2,00E-09	2,22E-08	5,47E-09	1,21E-08	2,44E-06	8,68E-07	1,23E-04
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	8,96E+01	tkm	8,10E-05	3,99E-11	1,29E-06	2,48E-07	2,90E-08	2,54E-07	1,94E-07	6,19E-09	4,99E-10	4,49E-04	1,11E-06	4,69E-07	1,61E-08	1,05E-06	3,26E-06	1,02E-07	2,72E-05	2,21E-07	1,25E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		TOTAL	1,65E-02	7,34E-10	8,31E-04	2,58E-05	1,68E-06	2,83E-05	3,75E-05	1,67E-06	1,34E-07	1,91E-03	9,22E-05	2,99E-05	1,07E-06	2,02E-05	3,52E-04	7,18E-06	7,77E-03	1,92E-04	3,55E-01
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					

Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	9,64E+02	kg	1,56E-02	1,94E-11	2,06E-06	2,37E-05	8,94E-07	2,64E-05	3,26E-05	1,85E-07	9,29E-09	5,31E-05	2,73E-05	9,01E-06	9,91E-08	3,26E-06	1,18E-06	2,75E-06	7,84E-03	8,94E-05	3,58E-01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	2,89E+01	tkm	2,61E-05	1,29E-11	4,16E-07	7,99E-08	9,35E-09	8,20E-08	6,27E-08	2,00E-09	1,61E-10	1,45E-04	3,59E-07	1,51E-07	5,19E-09	3,39E-07	1,05E-06	3,28E-08	8,78E-06	7,15E-08	4,02E-04
TOTAL			2,61E-05	1,29E-11	4,16E-07	7,99E-08	9,35E-09	8,20E-08	6,27E-08	2,00E-09	1,61E-10	1,45E-04	3,59E-07	1,51E-07	5,19E-09	3,39E-07	1,05E-06	3,28E-08	8,78E-06	7,15E-08	4,02E-04
TOTAL GLOBAL			1,80E-02	8,10E-10	9,03E-04	2,81E-05	1,83E-06	3,09E-05	4,08E-05	1,82E-06	1,46E-07	2,22E-03	1,01E-04	3,27E-05	1,17E-06	2,23E-05	3,84E-04	7,83E-06	8,45E-03	2,09E-04	3,86E-01

POLYETHYLENE DOUBLE-LAYER			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Polyethylene, low density, granulate {RER}| production | APOS, U	1,54E+02	kg	2,50E-03	3,10E-12	3,30E-07	3,79E-06	1,43E-07	4,22E-06	5,21E-06	2,96E-08	1,49E-09	8,49E-06	4,36E-06	1,44E-06	1,59E-08	5,22E-07	1,90E-07	4,40E-07	1,25E-03	1,43E-05	5,73E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	1,54E+02	kg	3,61E-04	1,17E-10	1,44E-04	6,47E-07	1,43E-07	6,60E-07	1,27E-06	2,60E-07	2,18E-08	2,46E-04	1,15E-05	3,68E-06	1,67E-07	2,81E-06	6,04E-05	7,88E-07	9,12E-05	1,89E-05	4,17E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,56E+01	tkm	1,41E-05	6,94E-12	2,24E-07	4,31E-08	5,04E-09	4,42E-08	3,38E-08	1,08E-09	8,68E-11	7,81E-05	1,93E-07	8,16E-08	2,80E-09	1,82E-07	5,67E-07	1,77E-08	4,73E-06	3,85E-08	2,17E-04
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			2,87E-03	1,27E-10	1,44E-04	4,48E-06	2,91E-07	4,93E-06	6,51E-06	2,90E-07	2,34E-08	3,32E-04	1,60E-05	5,21E-06	1,85E-07	3,52E-06	6,12E-05	1,25E-06	1,35E-03	3,33E-05	6,17E-02
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	1,77E+03	kg	2,87E-02	3,57E-11	3,79E-06	4,36E-05	1,65E-06	4,86E-05	5,99E-05	3,40E-07	1,71E-08	9,76E-05	5,02E-05	1,66E-05	1,82E-07	6,01E-06	2,18E-06	5,06E-06	1,44E-02	1,64E-04	6,59E-01
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	1,77E+03	kg	4,15E-03	1,35E-09	1,65E-03	7,44E-06	1,65E-06	7,59E-06	1,46E-05	2,99E-06	2,51E-07	2,82E-03	1,32E-04	4,24E-05	1,92E-06	3,23E-05	6,95E-04	9,07E-06	1,05E-03	2,17E-04	4,80E-02
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	8,41E+00	MJ	6,40E-06	8,17E-13	1,13E-07	2,51E-10	7,16E-10	4,04E-10	2,20E-08	2,67E-13	9,34E-12	4,95E-07	2,39E-10	3,39E-10	1,23E-09	1,37E-08	3,37E-09	7,42E-09	1,50E-06	5,34E-07	7,59E-05
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32	1,79E+02	tkm	1,62E-04	7,99E-11	2,57E-06	4,95E-07	5,79E-08	5,08E-07	3,88E-07	1,24E-08	9,98E-10	8,98E-04	2,22E-06	9,38E-07	3,22E-08	2,10E-06	6,52E-06	2,03E-07	5,44E-05	4,43E-07	2,49E-03

metric ton, EURO5 | APOS, U																					
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			3,30E-02	1,47E-09	1,66E-03	5,15E-05	3,35E-06	5,67E-05	7,49E-05	3,34E-06	2,69E-07	3,82E-03	1,84E-04	5,99E-05	2,13E-06	4,04E-05	7,04E-04	1,43E-05	1,55E-02	3,83E-04	7,10E-01
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Polyethylene, low density, granulate {RER}| production | APOS, U	1,93E+03	kg	3,12E-02	3,88E-11	4,12E-06	4,74E-05	1,79E-06	5,28E-05	6,51E-05	3,70E-07	1,86E-08	1,06E-04	5,45E-05	1,80E-05	1,98E-07	6,53E-06	2,37E-06	5,50E-06	1,57E-02	1,79E-04	7,17E-01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	5,78E+01	tkm	5,23E-05	2,58E-11	8,31E-07	1,60E-07	1,87E-08	1,64E-07	1,25E-07	3,99E-09	3,22E-10	2,90E-04	7,18E-07	3,03E-07	1,04E-08	6,78E-07	2,10E-06	6,56E-08	1,76E-05	1,43E-07	8,04E-04
TOTAL			5,23E-05	2,58E-11	8,31E-07	1,60E-07	1,87E-08	1,64E-07	1,25E-07	3,99E-09	3,22E-10	2,90E-04	7,18E-07	3,03E-07	1,04E-08	6,78E-07	2,10E-06	6,56E-08	1,76E-05	1,43E-07	8,04E-04
TOTAL GLOBAL			3,60E-02	1,62E-09	1,81E-03	5,62E-05	3,66E-06	6,18E-05	8,16E-05	3,63E-06	2,93E-07	4,44E-03	2,01E-04	6,54E-05	2,33E-06	4,46E-05	7,67E-04	1,56E-05	1,69E-02	4,16E-04	7,72E-01

HORTICULTURE GLASS			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	2,73E+03	kg	8,56E-01	2,47E-07	4,49E-02	2,69E-03	4,91E-04	2,73E-03	4,20E-03	2,29E-04	2,04E-05	9,53E-01	1,84E-02	6,37E-03	5,68E-04	7,69E-03	1,71E-02	2,97E-03	2,10E-01	9,13E-03	9,64E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	3,32E+03	tkm	3,01E-03	1,48E-09	4,78E-05	9,19E-06	1,08E-06	9,43E-06	7,21E-06	2,30E-07	1,85E-08	1,67E-02	4,13E-05	1,74E-05	5,97E-07	3,90E-05	1,21E-04	3,77E-06	1,01E-03	8,22E-06	4,62E-02
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			8,59E-01	2,48E-07	4,49E-02	2,70E-03	4,92E-04	2,74E-03	4,21E-03	2,29E-04	2,04E-05	9,70E-01	1,85E-02	6,38E-03	5,68E-04	7,73E-03	1,72E-02	2,98E-03	2,11E-01	9,14E-03	9,68E+00
MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	1,80E+03	kg	5,65E-01	1,63E-07	2,96E-02	1,78E-03	3,24E-04	1,80E-03	2,77E-03	1,51E-04	1,34E-05	6,29E-01	1,22E-02	4,20E-03	3,75E-04	5,08E-03	1,13E-02	1,96E-03	1,39E-01	6,03E-03	6,36E+00
Processes	Value	Unit																			

Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	6,30E+00	MJ	4,80E-06	6,13E-13	8,49E-08	1,88E-10	5,37E-10	3,03E-10	1,65E-08	2,00E-13	7,00E-12	3,71E-07	1,79E-10	2,54E-10	9,25E-10	1,02E-08	2,52E-09	5,56E-09	1,12E-06	4,00E-07	5,69E-05
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	2,19E+03	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			5,65E-01	1,63E-07	2,96E-02	1,78E-03	3,24E-04	1,80E-03	2,77E-03	1,51E-04	1,34E-05	6,29E-01	1,22E-02	4,20E-03	3,75E-04	5,08E-03	1,13E-02	1,96E-03	1,39E-01	6,03E-03	6,36E+00
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Glazing, double, U<1.1 W/m2K, laminated safety glass {GLO}| market for | APOS, U	4,53E+03	kg	1,42E+00	4,10E-07	7,45E-02	4,47E-03	8,15E-04	4,53E-03	6,97E-03	3,79E-04	3,38E-05	1,58E+00	3,06E-02	1,06E-02	9,42E-04	1,28E-02	2,83E-02	4,93E-03	3,49E-01	1,52E-02	1,60E+01
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,36E+02	tkm	1,23E-04	6,06E-11	1,95E-06	3,76E-07	4,40E-08	3,86E-07	2,95E-07	9,39E-09	7,57E-10	6,81E-04	1,69E-06	7,12E-07	2,44E-08	1,59E-06	4,95E-06	1,54E-07	4,13E-05	3,36E-07	1,89E-03
TOTAL			1,23E-04	6,06E-11	1,95E-06	3,76E-07	4,40E-08	3,86E-07	2,95E-07	9,39E-09	7,57E-10	6,81E-04	1,69E-06	7,12E-07	2,44E-08	1,59E-06	4,95E-06	1,54E-07	4,13E-05	3,36E-07	1,89E-03
TOTAL GLOBAL			1,42E+00	4,11E-07	7,45E-02	4,48E-03	8,16E-04	4,54E-03	6,98E-03	3,80E-04	3,38E-05	1,60E+00	3,06E-02	1,06E-02	9,43E-04	1,28E-02	2,85E-02	4,94E-03	3,50E-01	1,52E-02	1,60E+01

ETFE			IMPACT CATEGORIES																		
INSTALLATION			GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
Materials/assemblies	Value	Unit	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	9,00E+01	kg	6,18E-02	1,87E-06	5,00E-04	6,57E-06	1,13E-06	6,86E-06	1,70E-05	1,64E-06	1,26E-07	6,17E-03	1,32E-04	4,58E-05	2,81E-04	3,41E-03	8,58E-05	1,24E-05	1,38E-03	8,57E-05	6,33E-02
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	9,00E+01	kg	2,11E-04	6,84E-11	8,39E-05	3,78E-07	8,35E-08	3,85E-07	7,41E-07	1,51E-07	1,27E-08	1,43E-04	6,70E-06	2,15E-06	9,72E-08	1,64E-06	3,53E-05	4,60E-07	5,32E-05	1,10E-05	2,43E-03
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	1,38E+02	tkm	1,25E-04	6,16E-11	1,98E-06	3,82E-07	4,47E-08	3,92E-07	2,99E-07	9,54E-09	7,69E-10	6,92E-04	1,71E-06	7,23E-07	2,48E-08	1,62E-06	5,03E-06	1,57E-07	4,19E-05	3,42E-07	1,92E-03
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			6,21E-02	1,87E-06	5,86E-04	7,33E-06	1,26E-06	7,64E-06	1,80E-05	1,81E-06	1,39E-07	7,01E-03	1,40E-04	4,86E-05	2,81E-04	3,41E-03	1,26E-04	1,30E-05	1,47E-03	9,71E-05	6,76E-02

MAINTENANCE																					
Materials/assemblies	Value	Unit																			
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Processes	Value	Unit																			
Extrusion, plastic film {RER}| production | APOS, U	0,00E+00	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Electricity grid mix, AC, consumption mix, at consumer, 230V ES S	0,00E+00	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Transport, freight, sea, transoceanic ship {GLO}| processing | APOS, U	0,00E+00	tkm	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
TOTAL			0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
END OF LIFE (DEMOLITION + TRANSPORT TO WASTE TREATMENT)																					
Materials/assemblies	Value	Unit																			
Ethylene-tetrafluoroethylene copolymers (ETFE), at plant	9,00E+01	kg	6,18E-02	1,87E-06	5,00E-04	6,57E-06	1,13E-06	6,86E-06	1,70E-05	1,64E-06	1,26E-07	6,17E-03	1,32E-04	4,58E-05	2,81E-04	3,41E-03	8,58E-05	1,24E-05	1,38E-03	8,57E-05	6,33E-02
Processes	Value	Unit																			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	2,70E+00	tkm	2,44E-06	1,20E-12	3,88E-08	7,46E-09	8,73E-10	7,66E-09	5,85E-09	1,86E-10	1,50E-11	1,35E-05	3,35E-08	1,41E-08	4,85E-10	3,16E-08	9,82E-08	3,06E-09	8,20E-07	6,67E-09	3,75E-05
TOTAL			2,44E-06	1,20E-12	3,88E-08	7,46E-09	8,73E-10	7,66E-09	5,85E-09	1,86E-10	1,50E-11	1,35E-05	3,35E-08	1,41E-08	4,85E-10	3,16E-08	9,82E-08	3,06E-09	8,20E-07	6,67E-09	3,75E-05
TOTAL GLOBAL			6,21E-02	1,87E-06	5,86E-04	7,33E-06	1,26E-06	7,64E-06	1,81E-05	1,81E-06	1,39E-07	7,02E-03	1,40E-04	4,86E-05	2,81E-04	3,41E-03	1,26E-04	1,30E-05	1,47E-03	9,71E-05	6,77E-02

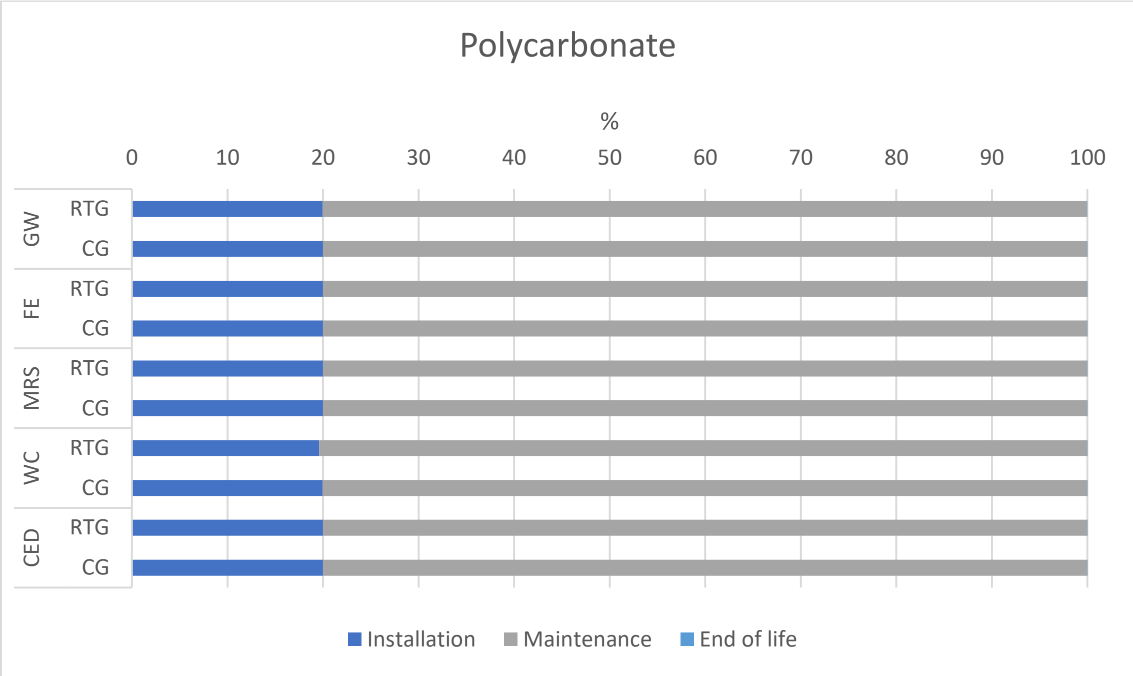

Figure 33. Representation of the impact of the polycarbonate life cycle for each stage of the life cycle, distinguishing between greenhouses and for all impact categories.

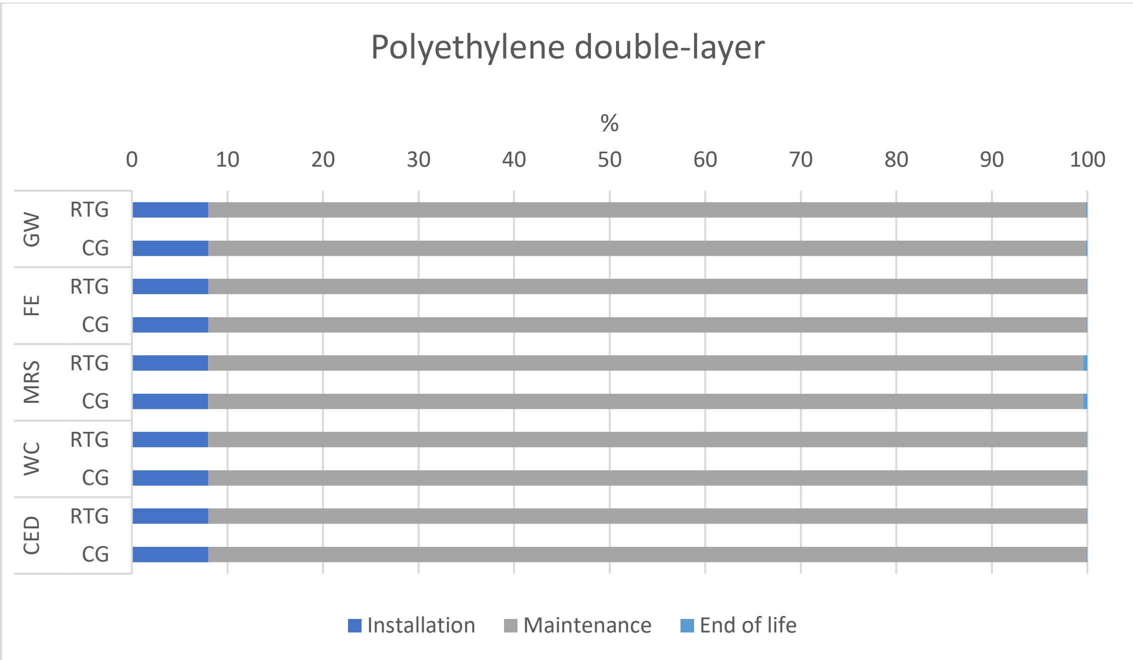

Figure 34. Representation of the impact of the polyethylene doble-layer life cycle for each stage of the life cycle, distinguishing between greenhouses and for all impact categories.

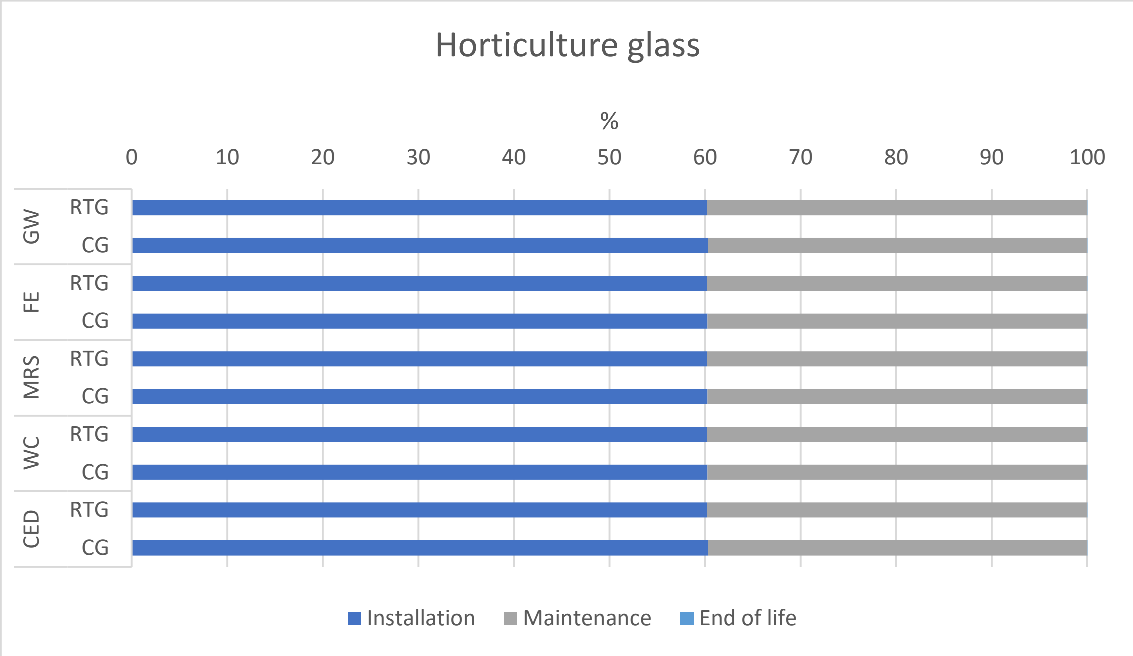

Figure 35. Representation of the impact of the horticulture glass life cycle for each stage of the life cycle, distinguishing between greenhouses and for all impact categories.

Table 25. Values for the optimal scenario RTG with ETFE per Functional unit (kg of tomatoes produced in one year) for each category of impact and CED.

RTG – OPTIMAL SCENARIO Functional unit: kg tomatoes produced over 1 year		GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
		kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
STRUCTURE + RAINWATER HARVESTING	Materials/assemblies - STRUCTURE + RH	2,05E-01	1,15E-07	1,73E-02	5,43E-04	1,38E-04	5,59E-04	7,34E-04	1,07E-04	5,24E-06	3,15E-01	1,23E-02	4,18E-03	1,35E-04	5,33E-03	3,10E-03	3,06E-03	5,22E-02	1,68E-03	2,39E+00
	Processes - STRUCTURE + RH	2,28E-01	6,92E-08	3,24E-02	3,44E-04	1,07E-04	3,56E-04	1,42E-03	1,86E-04	1,61E-05	1,52E+00	2,70E-02	9,01E-03	1,30E-04	1,12E-02	7,42E-03	2,75E-03	5,53E-02	6,65E-03	2,60E+00
	TOTAL STRUCTURE + RAINWATER HARVESTING	4,33E-01	1,84E-07	4,97E-02	8,87E-04	2,44E-04	9,15E-04	2,15E-03	2,94E-04	2,14E-05	1,83E+00	3,92E-02	1,32E-02	2,65E-04	1,65E-02	1,05E-02	5,81E-03	1,08E-01	8,33E-03	4,99E+00
AUXILIARY EQUIPMENT	Materials/assemblies - AUXILIARY EQUIPMENT	3,27E-02	1,51E-09	2,48E-04	4,30E-05	4,67E-06	4,68E-05	6,15E-05	2,47E-06	1,83E-07	1,08E-02	2,77E-04	9,45E-05	4,42E-06	1,01E-04	8,27E-05	5,18E-05	1,22E-02	4,17E-04	5,60E-01
	Processes - AUXILIARY EQUIPMENT	9,39E-03	3,40E-09	2,42E-03	1,91E-05	3,64E-06	1,98E-05	3,36E-05	6,28E-06	4,98E-07	1,78E-02	4,79E-04	1,57E-04	8,80E-06	1,54E-04	6,11E-04	3,71E-05	2,87E-03	1,36E-04	1,31E-01
	TOTAL AUXILIARY EQUIPMENT	4,20E-02	4,92E-09	2,66E-03	6,20E-05	8,31E-06	6,66E-05	9,52E-05	8,75E-06	6,80E-07	2,86E-02	7,55E-04	2,52E-04	1,32E-05	2,55E-04	6,93E-04	8,89E-05	1,51E-02	5,53E-04	6,91E-01
PRODUCTION	Materials/assemblies - PRODUCTION	1,37E-01	4,14E-07	4,54E-03	2,13E-04	6,44E-05	2,19E-04	9,27E-04	2,94E-05	1,29E-04	3,39E-01	2,63E-03	9,18E-04	5,13E-05	1,28E-03	6,84E-02	3,19E-04	1,74E-02	5,39E-03	7,97E-01
	Processes - PRODUCTION	8,03E-02	3,16E-08	4,45E-03	3,35E-04	4,18E-05	3,46E-04	2,66E-04	1,76E-05	1,23E-06	1,75E-01	3,93E-03	1,32E-03	3,58E-04	1,16E-03	2,58E-03	2,44E-04	2,57E-02	2,03E-02	1,18E+00
	TOTALPRODUCTION	2,17E-01	4,46E-07	8,99E-03	5,48E-04	1,06E-04	5,65E-04	1,19E-03	4,70E-05	1,30E-04	5,14E-01	6,56E-03	2,24E-03	4,09E-04	2,43E-03	7,09E-02	5,63E-04	4,31E-02	2,56E-02	1,97E+00
OPTIM COVERING - ETFE	Materials/assemblies - COVERING	1,04E+00	3,17E-05	8,45E-03	1,11E-04	1,92E-05	1,16E-04	2,88E-04	2,78E-05	2,13E-06	1,04E-01	2,22E-03	7,74E-04	4,75E-03	5,77E-02	1,45E-03	2,10E-04	2,33E-02	1,45E-03	1,07E+00
	Processes - COVERING	5,72E-03	2,22E-09	1,45E-03	1,30E-05	2,18E-06	1,33E-05	1,77E-05	2,73E-06	2,28E-07	1,44E-02	1,43E-04	4,88E-05	2,07E-06	5,56E-05	6,83E-04	1,05E-05	1,62E-03	1,92E-04	7,43E-02
	TOTAL COVERING	5,54E-02	1,67E-06	5,22E-04	6,54E-06	1,12E-06	6,82E-06	1,61E-05	1,61E-06	1,24E-07	6,26E-03	1,25E-04	4,34E-05	2,51E-04	3,04E-03	1,13E-04	1,16E-05	1,32E-03	8,66E-05	6,04E-02
TOTAL		7,48E-01	2,31E-06	6,19E-02	1,50E-03	3,60E-04	1,55E-03	3,46E-03	3,51E-04	1,52E-04	2,38E+00	4,67E-02	1,57E-02	9,38E-04	2,22E-02	8,23E-02	6,47E-03	1,67E-01	3,46E-02	7,71E+00

Table 26. Values for the optimal scenario (discarded) – CG with ETFE - per Functional unit (kg of tomatoes produced in one year) for each category of impact and CED.

CG – OPTIMAL SCENARIO (DISCARDED) Functional unit: kg tomatoes produced over 1 year		GW	SOD	IR	OF, HH	FP	OF, TE	TA	FE	ME	TEcotox	FEcotox	MEcotox	HCT	HnCT	LU	MRS	FRS	WC	CED
		kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3	MJ
STRUCTURE	Materials/assemblies - STRUCTURE + RH	4,43E-02	8,09E-09	1,39E-03	1,03E-04	5,23E-05	1,07E-04	1,30E-04	3,47E-05	1,08E-06	1,17E-01	4,96E-03	1,69E-03	3,27E-05	2,11E-03	7,33E-04	1,32E-03	7,94E-03	2,99E-04	3,65E-01
	Processes - STRUCTURE + RH	5,93E-02	2,20E-08	8,12E-03	1,26E-04	4,07E-05	1,29E-04	5,10E-04	7,47E-05	6,59E-06	7,23E-01	1,23E-02	4,12E-03	4,86E-05	5,16E-03	1,97E-03	1,24E-03	1,31E-02	5,03E-04	5,98E-01
	TOTAL STRUCTURE + RAINWATER HARVESTING	1,04E-01	3,01E-08	9,50E-03	2,29E-04	9,30E-05	2,36E-04	6,40E-04	1,09E-04	7,66E-06	8,40E-01	1,73E-02	5,81E-03	8,12E-05	7,28E-03	2,70E-03	2,56E-03	2,10E-02	8,01E-04	9,64E-01
AUXILIARY EQUIPMENT	Materials/assemblies - AUXILIARY EQUIPMENT	3,91E-02	1,81E-09	2,96E-04	5,14E-05	5,59E-06	5,61E-05	7,36E-05	2,96E-06	2,19E-07	1,30E-02	3,31E-04	1,13E-04	5,29E-06	1,21E-04	9,90E-05	6,20E-05	1,47E-02	4,99E-04	6,70E-01
	Processes - AUXILIARY EQUIPMENT	1,00E-02	3,58E-09	2,84E-03	1,76E-05	3,74E-06	1,83E-05	3,63E-05	7,27E-06	5,78E-07	1,86E-02	5,13E-04	1,68E-04	4,72E-06	1,67E-04	6,97E-04	4,11E-05	3,04E-03	1,58E-04	1,39E-01
	TOTAL AUXILIARY EQUIPMENT	4,91E-02	5,39E-09	3,13E-03	6,91E-05	9,33E-06	7,44E-05	1,10E-04	1,02E-05	7,97E-07	3,15E-02	8,44E-04	2,81E-04	1,00E-05	2,88E-04	7,96E-04	1,03E-04	1,77E-02	6,57E-04	8,09E-01
PRODUCTION	Materials/assemblies - PRODUCTION	4,48E-02	1,28E-07	0,00E+00	9,74E-05	2,65E-05	1,00E-04	3,78E-04	1,35E-05	3,83E-05	3,27E-01	1,67E-03	6,19E-04	1,77E-05	7,76E-04	1,98E-02	2,74E-04	9,44E-03	2,36E-03	4,33E-01
	Processes - PRODUCTION	8,44E-02	3,32E-08	4,67E-03	3,52E-04	4,39E-05	3,64E-04	2,79E-04	1,85E-05	1,29E-06	1,84E-01	4,13E-03	1,39E-03	3,76E-04	1,22E-03	2,71E-03	2,56E-04	2,70E-02	2,11E-02	1,24E+00
	TOTALPRODUCTION	1,29E-01	1,61E-07	4,67E-03	4,50E-04	7,05E-05	4,64E-04	6,57E-04	3,20E-05	3,96E-05	5,11E-01	5,80E-03	2,01E-03	3,94E-04	1,99E-03	2,25E-02	5,30E-04	3,64E-02	2,34E-02	1,67E+00
OPTIM COVERING - ETFE	Materials/assemblies - COVERING	6,18E-02	1,87E-06	5,00E-04	6,57E-06	1,13E-06	6,86E-06	1,70E-05	1,64E-06	1,26E-07	6,17E-03	1,32E-04	4,58E-05	2,81E-04	3,41E-03	8,58E-05	1,24E-05	1,38E-03	8,57E-05	6,33E-02
	Processes - COVERING	4,63E-04	1,93E-10	8,79E-05	1,15E-06	1,74E-07	1,18E-06	1,35E-06	1,71E-07	1,43E-08	1,54E-03	1,02E-05	3,61E-06	1,47E-07	4,91E-06	4,54E-05	7,76E-07	1,38E-04	1,17E-05	6,31E-03
	TOTAL COVERING	6,22E-02	1,87E-06	5,88E-04	7,71E-06	1,31E-06	8,03E-06	1,84E-05	1,81E-06	1,40E-07	7,71E-03	1,42E-04	4,94E-05	2,81E-04	3,42E-03	1,31E-04	1,32E-05	1,52E-03	9,74E-05	6,96E-02
TOTAL		3,44E-01	2,07E-06	1,79E-02	7,55E-04	1,74E-04	7,82E-04	1,43E-03	1,53E-04	4,82E-05	1,39E+00	2,41E-02	8,15E-03	7,66E-04	1,30E-02	2,61E-02	3,21E-03	7,66E-02	2,50E-02	3,51E+00

Table 27. Economic data for current RTG with polycarbonate and optimal RTG with ETFE.

	Unit	RTG POLYCARBONATE			RTG ETFE		
		Unit per m²	Price (€)	€/m2	Unit per m²	Price (€)	€/m2
Materials							
Structure							
Galvanised steel	kg	0,87	3,12	2,70	0,87	3,12	2,70
Concrete	m³	0,00	60,56	0,01	0,00	60,56	0,01
Polyethylene	kg	0,08	2,87	0,22	0,08	2,87	0,22
Covering	kg	1,67	7,47	12,46	0,40	280,00	112,07
Polyesther	Kg	0,01	0,39	0,00	0,01	0,39	0,00
Aluminium	Kg	0,01	23,61	0,18	0,01	23,61	0,18
Rainwater system	Unit	0,01	1447,81	11,79	0,01	1447,81	11,79
Pump	Unit	0,01	422,56	3,44	0,01	422,56	3,44
Auxiliary equipment							
Pump + pressure switch	Unit	0,01	423,56	3,45	0,01	423,56	3,45
Nutrient tanks	Unit	0,02	32,00	0,52	0,02	32,00	0,52
Water tanks	Unit	0,02	32,00	0,52	0,02	32,00	0,52
DOSATRON	Unit	0,02	552,70	9,00	0,02	552,70	9,00
Flow meter	Unit	0,01	124,00	1,01	0,01	124,00	1,01
Digital timer	Unit	0,01	275,00	2,24	0,01	275,00	2,24
Pipes and joints – headboard	m	0,07	2,47	0,16	0,07	2,47	0,16
Pipes - distribution	m	0,02	13,13	0,28	0,02	13,13	0,28
Drippers + tubes	m	0,00	2,47	0,00	0,00	2,47	0,00
Leachate trays	m²	0,15	1,07	0,17	0,15	1,07	0,17
Production							
LDPE	Kg	0,01	13,13	0,09	0,01	13,13	0,09
Expanded perlite	Kg	0,46	69,32	32,18	0,46	69,32	32,18
Fertiliser	Kg	0,59	6,63	3,90	0,59	6,63	3,90
Pesticides	kg	0,00	70,89	0,16	0,00	70,89	0,16
Construction							
Top official	h	96,00	21,49	16,80	96,00	21,49	16,80
Workman	h	192,00	11,72	18,32	192,00	11,72	18,32
Machinery							
Forklift	h	96,00	39,24	30,68	96,00	39,24	30,68
Tower crane	h	96,00	2,43	1,90	96,00	2,43	1,90
Concrete mixer	h	3,00	1,42	0,03	3,00	1,42	0,03
Electricity	kWh	0,00	0,12	0,00	0,00	0,12	0,00
Transport	Km	32,90	0,19	0,05	33,50	0,19	8,91
Maintenance							
Aluminum + Polyester							
Top official	h	16,00	21,49	0,00	16,00	21,49	0,00
Workman	h	16,00	11,72	1,53	16,00	11,72	1,53
Machinery	h	0,00	0,00	0,00	0,00	0,00	0,00
Transport	km	0,52	0,19	0,00	0,52	0,19	0,02
Covering material							
Top official	h	8,00	21,49	1,40	0,00	21,49	0,00
Workman	h	24,00	11,72	2,29	0,00	11,72	0,00
Machinery	h	0,00	0,12	0,00	0,00	0,12	0,00
Transport	km	13,34	0,19	2,54	0,00	0,19	0,00
Electricity	kWh	2,13	0,12	0,00	2,13	0,12	0,00
Deconstruction							
Top official	h	48,00	21,49	8,40	48,00	21,49	8,40 €
Workman	h	96,00	11,72	9,16	96,00	11,72	9,16 €
Transport	h	15,44	0,19	0,02	15,32	0,19	0,05
Electricity	kWh	0,00	0,12	0,00	0,00	0,12	0,00
Machinery							
Forklift	h	48,00	39,24	15,34	48,00	39,24	15,34