F-CUBED

Report on Life Cycle Assessment and Socio-Economic Impact of the F-CUBED Production System for pulp & paper bio-sludge, virgin olive pomace and fruit & vegetable biogenic residues

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Executive summary

This report describes the work performed for Tasks 5.4 and 5.5 of Work Package 5 (WP5) of the F-CUBED (Future Feedstock Flexible Carbon Upgrading to Bio Energy Carriers) project. The F-CUBED project aims to convert wet biogenic residues into intermediate bioenergy carriers (fuel pellets) via hydrothermal treatment (TORWASH). The selected biogenic residues include paper bio-sludge, olive pomace and orange peels. The overall F-CUBED process consists of TORWASH treatment and filter press dewatering, to produce a solid product (converted into fuel pellets via drying and pelletization) and a liquid product (anaerobically digested to produce biogas).

In WP5 of the project, a comprehensive attributional cradle-to-gate life cycle assessment (LCA) was carried out to analyse environmental (E-LCA) and socio-economic aspects (S-LCA) on an industrial scale application of the F-CUBED process. The LCAs have been executed in compliance with the ISO standards of the 14040 series. In the LCA studies the conceptual process design and modelling for the F-CUBED Production System, has been analysed for three case studies, one for each of the wet biogenic residue streams.
The E-LCA study has also been conducted, with comparative purposes, for the Reference Cases (RCs) of the different biogenic residue streams. The RC refers to the practices applied at the F-CUBED project partners' site, respectively Smurfit Kappa in Sweden, Frantoio Oleario Chimienti (APPO Mill) in Italy and Delafruit in Spain, where the residues are generated.

For the present study, the Functional Unit (FU) correspond to 1 kWh of dispatchable electricity and all environmental impact indicators are reported per kWh of power produced. However, to facilitate comparative assessment while leading to a better understanding of the studied system against other systems and avoiding biased outcomes, the results have also been explore in reference to the overall process, considering the amount (on a wet basis) of biogenic residues treated.

The Life Cycle Inventory phase was conducted for each phase of the F-CUBED Production System, consisting of 10 production steps for Pulp & Paper Bio-sludge and 9 production steps for Olive Pomace and Orange Peels. Overall, 9 LCA models have been implemented using over 1700 data points that were subjected to iterative check and recalculation for the duration of the project.

The Life Cycle Impact Assessment (LCIA) was conducted with the ReCiPe method to evaluate the environmental impact of the F-CUBED Production System for different biogenic residue streams. The aim was to understand the scale and importance of potential environmental impacts. Specific impact categories relevant to bioenergy and the F-CUBED system were selected, focusing on 10 out of 18 impact categories based on different compartments of action. To ensure the reliability of their categorization, the study conducted a sensitivity analysis through a Monte Carlo simulation. This analysis was applied to the LCA model itself, as well as to specific data related to the biogenic residue streams, to account for uncertainty and ensure the accuracy of the findings. The LCA results for F-CUBED Production System and Reference Case were compared. A further comparison with Electricity country mix impacts was provided to demonstrate how the country-specific electricity impact intensity can affect the final outcomes.

The reliability of different impact categories varies between cases/biogenic residue stream. The following conclusions about impact categories for each residue can be drawn:

- For the paper bio-sludge case study three impact categories are reliable for the F-CUBED Production System: particulate matter formation (12.0%), terrestrial acidification (12.1%) and climate change (19.1%).

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- For the Olive Pomace case study four impact categories guarantee reliability: fossil depletion (13.18%), climate change (15.41%), terrestrial acidification (17.68%) and particulate matter formation (17.69%).
- For the Fruit & Vegetable (Orange Peels) case study, five impact categories guarantee reliability: terrestrial acidification (6.5%), particulate matter formation (6.77%), photochemical oxidant formation (12.42%), fossil depletion (17.09%) and climate change (-21.99%).

These results make clear that to describe the environmental performance of the F-CUBED Production System, the main impact categories to use as a reference of performance are climate change, particulate matter formation and terrestrial acidification, which are representative of the air compartment, human health and soil compartment, respectively.

The results of LCIA provide insights into the environmental impacts of the F-CUBED Production System on the respective biogenic residues sectors. The climate change impact category provides the following results with respect to emissions from the process:

- Pulp & Paper Bio-sludge: 17.9 kg CO2 eq./t residue treated
- Virgin Olive Pomace: -1.290 kg CO2 eq./t residue treated (negative value due to GHG saving)
- Orange Peels: -1.300 kg CO2 eq./t residue treated (negative value due to GHG saving)

For every case study, the hydrothermal treatment results in a significant reduction in carbon emissions when compared with the reference case. This is especially notable for olive pomace and orange peels, where the process is effectively providing a GHG emissions saving to the atmosphere, contributing to a negative carbon footprint. This outcome aligns well with climate change mitigation goals of the F-CUBED Project.

In summary, the environmental perspective on these LCA results shows that the hydrothermal treatment of the investigated biogenic residues can have several positive environmental impacts, such as carbon sequestration and reduced fossil resource use. However, there are variations in the environmental performance of the three residues, suggesting that specific mitigation strategies may be needed for certain environmental categories. Additionally, water use and land occupation should be carefully managed to minimize their environmental footprint of the overall value chain. Moreover, the results of the comparison between the F-CUBED Production System and Reference Cases show that in the paper bio-sludge case study, the F-CUBED Production System performs better in all impact categories than the Reference case. On the contrary, the olive pomace and orange peels case studies report better values only for three impact categories: climate change, fossil depletion and freshwater eutrophication. Results are also compared with impacts of the country of residue production's (Sweden, Italy, Spain) electricity mix impacts. This further demonstrates how the environmental impacts of electricity production differs in carbon intensity and how this affects comparisons with the F-CUBED process.

Finally, as sustainability issues play a central role in bioenergy applications and the Renewable Energy Directive (RED II) has extended the sustainability criteria to solid and gaseous biomass fuels used for heat and power production, for these reasons, the RED II methodology for the calculation of the GHG emission savings, stated in the Annex VI point B, has been applied to the F-CUBED Production System for the three different biogenic residue streams.
The GHG emissions savings calculated for the bio-pellets production, when compared to fossil fuel (i.e., 183 g CO2eq/MJ electricity) are 49%, 89% and 91%, for Pulp & Paper Bio-Sludge, Olive Pomace, and Orange Peels, respectively. In comparison, the default values of GHG emissions saving for electricity production, provided from DIRECTIVE (EU) 2018/2001 (RED II) (European Commission 2018), for wood briquettes or pellets from forest residues, referred to the biomass fuel production system belonging to the Case 2a, range between 45% and 59%.

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Social Life Cycle Assessment (S-LCA) has been performed to assess the socio-economic impacts of the F-CUBED Production System from extraction of raw material to the dispatch of the products, i.e., pellets, heat & electricity. For modelling the background dataset, a database and software have been used, i.e., Social Hotspot Database and SimaPro. This dataset has been integrated and enhanced by modelling the foreground system to cover the complete F-CUBED production system. The Social Hotspot 2022 Category Method for quantifying the impact assessment, was used in the present S-LCA. It refers to the Reference Scale Assessment (RS S-LCIA) and aims to assess social performance or social risk. This method includes characterization of different risk levels within each subcategory, followed by a damage assessment step that aggregates subcategory results to the category level.

The three selected case studies of biogenic residues stream treatments, have been investigated in the respective EU countries, i.e., Sweden, Italy and Spain. The social footprint of the F-CUBED Production System has been described for each country, by four different data visualizations. The social footprint was first calculated aggregating the social impacts associated with each country-specific economic sector by impact category. Then, the social impact categories were assessed identifying the contribution to the overall social risk of each economic sector representing every production step of the supply chain of a specific biogenic residue stream and country. Finally, to facilitate data interpretation, a more detailed analysis of the social impacts of the Case Studies was carried out through the breakdown of the sub-categories which make up the before-mentioned impact categories and the contribution analysis of each economic sector to the total social impacts by impact sub-category, on the basis of the characterization factors that describe the severity of a serious situation or opportunity/benefits. An ordinal scale with 1 to 4 performance reference points (PRPs, from “low risk” to “very high risk”) serves as the reference scale for impact assessment in the current investigation.

The results of the S-LCA show that in Sweden and Spain the treatment of the respective residues, Pulp & Paper Bio-sludge and Orange Peels, provides large benefits and low risk, with the exception for economic sector of bio-pellets production and electricity generation in Spain, where the risk level has been classified as medium for both. In contrast, the Olive Pomace case study in Italy demonstrates predominantly negative influences on social risks across the majority of impact sub-categories. Nevertheless, the overall social risk level remains within the "medium" range.

In Sweden, the social impacts related to the implementation of F-CUBED Production System for the Pulp & paper Case Study, is concentrated in the bio-pellets production and the Torwash & Dewatering treatments that give a small adverse contributions to social impacts, ranging between 8% and 11% and 4% and 7%, respectively. On the other hand, the Electricity production steps both by bio-pellets and biogas give large benefits to the different Impact categories. For the Olive Pomace Case Study, the bio-pellets production and the Electricity production steps by bio-pellets in Italy, provide the most adverse contributions ranging between 44-47% and 36-39% of total social impact, respectively, depending on the social category. However, for the Olive Pomace Case Study, the subcategories Smallholder vs. Commercial Farms and Labour Laws & Conventions represent opportunities for positive social impact.

For the Orange Peels Case Study, the bio-pellets production and the preconditioning phase, connected to the economic sector of Lumber and wood products production and to the Vegetables, fruits, nuts growing in Spain, respectively, provide small relatively adverse contributions to the social impacts. Through a more in-depth analysis, it becomes apparent that the initial contributions to the overall social risk are at a medium level, specifically for sub-categories 1A, 1E, and 1F. Conversely, the steps involved in electricity production using bio-pellets and biogas, as observed in electricity generation in Spain, yield substantial social advantages across various impact categories. This approach enables the anticipation and formulation of targeted measures to mitigate and enhance specific sub-categories affected by medium-level social risk.

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In general, the F-CUBED production process offers environmental benefits, in particular related to climate change (GHG emissions reduction relative to the current reference case), for treatment of the target wet residue streams of paper bio-sludge, olive pomace and orange peels. Social impacts of the F-CUBED production process are largely related to the country where the residue stream is produced and processed, i.e., Sweden, Italy and Spain. The most significant positive social impacts with the lowest risk are found for the treatment of the paper bio-sludge in Sweden and the orange peels in Spain.

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Acronyms

AD	Anaerobic digestion
ALO	Agriculture land Occupation
ar	As received
BMP	Biomethane potential
CC	Climate Change
CFC	Chlorofluorocarbons
CHP	Combined heat and power
COD	Chemical oxygen demand
db	Dry basis
DCB	Dichlorobenzene
DfE	Design for Environment
DM	Dry matter
ECM	Electricity Country Mix
EPD	Environmental Product Declarations
FD	Fossil Depletion
FEUT	Freshwater Eutrophication
FETX	Freshwater Ecotoxicity
GHG	Greenhouse gas
GWP	Global Warming Potential
HTX	Human Toxicity
HV	High Voltage
IEA	International Energy Agency
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle Engineering
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower heating value
MD	Metal Depletion
MV	Medium Voltage
NLT	Natural land Transformation
NMVOC	Non-Methane Volatile Organic Compounds
OD	Ozone Depletion
OP	Olive pomace
ORP	Orange peels
PE	Polyelectrolyte
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
PPB	Pulp & Paper bio-sludge
PPF	Pulp & Paper fiber sludge
PS	Production System
RC	Reference Case
RED	Renewable Energy Directives
S	Sulphur
SFK	Smurfit Kappa
TA	Terrestrial Acidification

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TEA	Techno-economic analysis
TETX	Terrestrial Ecotoxicity
wb	Wet basis
WD	Water Depletion
WWTP	Wastewater treatment plant

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1. Introduction

This report refers to deliverable D5.2. “Report on Life Cycle Assessment and Socio-Economic Impact of the production of solid bioenergy carriers from pulp & paper bio-sludge, virgin olive pomace and fruit & vegetable residues by means of F-CUBED treatment” of the F-CUBED project.

It describes the activities performed in the Task 5.4 and Task 5.5 of work package five (WP5), aiming to assess the environmental impact of the F-CUBED pre-treatment process introduced in the three studied value chains on produced unit of dispatchable electricity and evaluate the socio-economic impacts with particular attention to the potential improvement of social conditions and of the overall socio-economic performance.

The present work gathers the data produced in the whole cluster of the technical WPs of the F-CUBED Project, from the experimental data provided by the WP2. WP3 and WP4 and from the work developed in WP5. in the Tasks 5.1. 5.2 and 5.3. regarding the process design, modelling and technical evaluation of the F-CUBED process for treatment of three residual biomasses (pulp & paper bio-sludge, olive pomace and orange peels). Therefore, given the magnitude of the data collection and the large variety of topics treated, the present Deliverable is divided in two parts, distinct but logically integrated:

- Part A, concerning the E-LCA and the environmental impact assessment;
- Part B, concerning the S-LCA and socio-economic aspects.

1.1 Background

The threat of climate change resulting from human activities and the need to ensure environmental sustainability are now a global priority (United Nations; 2015). Much attention is now focused on the energy sector due to the prominence as the largest emitter of greenhouse gases and due to the related geopolitical tensions. It is nowadays urgent to limit reliance on energy imports and discover new/enhanced forms of energy production to improve energy security. The European Union initiative called “Fit for 55”, within the recent European Green Deal climate actions, sets a maximum emissions threshold to be met by 2030. corresponding to 55% of the Figures recorded in 1990. This program involves particularly the energy sector, which must increase the share of renewable energy to 40% in the same period (European Commission; 2019). This is a rather ambitious target considering that, by 2017. renewable energies provided just 17.6% of the total energy supply in the EU. Consequently, this decision has also informed the targets for the share of renewable energy established by the Renewable Energy Directive II, moving them from 32 to 40% by 2030. In fact in July 2021. the Commission proposed another revision of the directive, raising the target to 40% (up from 32%). Less than a year later, in view of the Russian invasion of Ukraine and the need to further step up our energy independence from fossil fuels, the Commission proposed to further increase this target to 45% by 2030. On 30 March 2023. a provisional agreement was reached, for a binding target for 2030 of at least 42.5%, but aiming for 45%.

In the framework of sustainable energy production, biomass is considered an important renewable energy source. In particular, the use of residual biomasses for energy purposes is regarded as one of the most promising solutions by policymakers and the scientific community to achieve the goal of reducing net CO_2 emissions, contributing to climate change mitigation (Lo, et al. 2021; Scarlat, et al. 2019; Chia, et al. 2020). Bioenergy is nowadays one of the main contributors to the renewable energy market and biomass-based energy production and is expected to increase in the next decades, expanding its role in the EU’s renewable energy mix and harnessing its potential contribution to a low carbon economy, for which sustainability issues play a central role in bioenergy applications. Indeed the revised Renewable Energy Directive (RED II) has extended the sustainability criteria to solid and gaseous biomass fuels used for heat and power production (Toscano, et al. 2018). The demand for renewable energy is expected to increase remarkably in the next

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years. Indeed, due to a significant number of competing production plants which are anticipated to come online within the near future, the access to the residual biomasses is very likely to become increasingly challenging (E4tech 2017). Particularly, within the next 10 years, the biomass potential is expected to become a relevant constraint for the continuous operation of the biorefineries (Ugolini, et al. 2022).

The total sources of biomass, which includes domestic production and net imports, in the EU-27 amounts to approximately 1 billion tons of dry matter (tDM), whereas the uses amount to 1.2 billion tDM. The additional biomass in uses with respect to the sources, which is domestic production plus net-imports, is due to the recovery of waste from industry and households. Almost 70% of the biomass supply is from the agricultural sector, which includes food, residues collected and grazed biomass (Avitabile, et al. 2023). The trend in biomass supply is increasing from both primary domestic production and secondary sources; most of the uses of biomass are for food and feed production, whereas for non-food products, materials account for 28% and energy for 22%. The increasing trend is most pronounced for biomass uses for bioenergy, followed by material uses, while food uses remain largely constant. When assessing all biomass production, supply, uses, demand, flows and impact at once, in many there is progress in terms of resource efficiency; on the other hand there is an overall increased use of biological resources because they are in fact more efficiently produced, less expensive, and their diversification in uses are encouraged. For all these reasons, the impact on biomass supply systems is increasing and residues have to be preferred for bioenergy production (Avitabile, et al. 2023). Moreover, traditional biomass sources alone will hardly satisfy sustainability criteria and meet future energy needs. This implies the need to draw from the widened field of agricultural residues, by-products, and wastes from the agroforestry and agro-industrial sectors (Toscano, et al. 2018).

Biogenic residues and wastes are often difficult to utilize as energy sources due to several challenges, including heterogeneity of the material, high moisture content, poor biological stability, and low energy density (Toscano, et al. 2015; Oh, et al. 2018; Aravani, et al. 2022). Particularly limited bulk and energy densities affecting the harvest phase and logistic costs and partly limit its energy and environmental sustainability (Ko, Lautala and Handler 2018; Duca, et al. 2022). Moreover, despite the numerous strengths, there are also critical issues related to the general sustainability of the conversion system process of biomass and the nature of the biomass from which bioenergy derives, also raising several ethical and social issues (Mai-Moulin, et al. 2021; Toscano, et al. 2018). In addition, heterogeneity in physical properties and chemical composition can affect a biomass power plant combustion efficiency, maintenance, and logistics, partly limiting its energy and environmental sustainability.

Therefore, novel technology solutions in the bioenergy sector are crucial to guarantee biomass upgrading, increasing the biomass utilization efficiency in the energetic conversion step and a higher degree of efficiency in the whole supply chain. This includes initiatives such as hydrothermal pre-treatment and densification of the biomass, such as the pelletization of biogenic residues, to improve the logistics and sustainability aspects of the supply chain and the quality of the resulting products (Toscano, et al. 2018; Duca, et al. 2022; Toscano, et al. 2019). In addition, these techniques can tackle problems related to the complexity of the chemical structure of biomass, providing rapid results and representing useful solutions for the different stakeholders involved in the bioenergy chain (Mancini, et al. 2018).

1.2 Environmental and Socio Economic Assessment of the F-CUBED Production System

The F-CUBED (Future Feedstock Flexible Carbon Upgrading to Bio Energy Carriers) Horizon 2020 project funded by European Commission (G.A. 884226) aims to convert wet biogenic residues into intermediate bioenergy carriers (fuel pellets) via hydrothermal treatment (TORWASH), as outlined in Figure 1.

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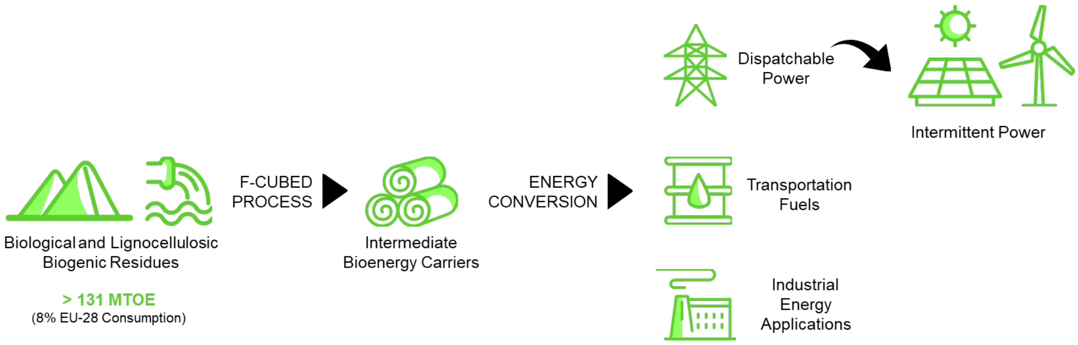

Figure 1 - F-CUBED Production System converts low quality biogenic residues to superior intermediate bioenergy carriers, increasing the flexibility of a renewable energy system.

The selected wet biogenic residues include pulp & paper bio-sludge, virgin olive pomace and fruit & vegetable (orange peels) biogenic residues. The main stream processes of the F-CUBED Product System consist of TORWASH hydrothermal treatment and filter press dewatering, to produce a solid product, converted into solid densified fuel, such as bio-pellets, via drying and pelletization. A secondary integrated stream deals with the filtrate (liquid fraction) processing, anaerobically digested to produce biogas.

In the F-CUBED Project the analysis of the environmental impacts and socio-economic assessment of the novel technology and production system are crucial items. In particular, one of the strategic objectives of the project deals with the climate change impact category. This topic has been widely investigated by the scientific community, as Carbon dioxide is one of the major by-products when it comes to combustion and also the main contributor to climate change and greenhouse gas effect (Thakur, et al. 2017). Indeed its potential effects are playing a significant role towards the world's economy, ecosystem services, and societal structures. In order to reduce the undesirable consequences of climate change and global warming, adaptation and mitigation technologies and policies must be implemented (Kumar, Ogita and Yau 2018). Therefore, there is an urgent need to develop viable alternatives and energy sources with lower environmental impact (Andersen 2013).

For the purpose of reducing the various emissions from the bioenergy production process, as first step, it is important to quantify them. The quantification can be performed by using specific tools and methodologies such as LCA. Life cycle assessment is one of the most complex, powerful and recognized tools to quantify the environmental assessment and sustainability of various products that otherwise may not be adequately accounted for. In fact, LCA is a standardized tool that can determine and compute the potential environmental impacts caused by the emissions of substances into the air, water, and soil and resources used throughout the life cycle of a product or process, from raw material extraction to waste management (Finnveden, et al. 2009). Relevant emissions and resources/raw-materials that are consumed and/or released during a process or manufacturing of a product are quantified in the environmental evaluation. This methodology can be seen as a complement to the technological approach as it highlights, in priority order, which steps in the production process should be improved (Jolliet, et al. 2015). Additionally, LCA can be used to evaluate whether the employed technology is more environmentally friendly compared to other conventional treatment processes (Foteinis, et al. 2020).

LCA is based on several principles and it should take into account all stages of a product life. Details regarding methodological principles and each step involved in the LCA are reported in Chapter 3.

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1.3 The biogenic residues streams and environmental issues

This section describes the main characteristics and features of the residue streams used in the present research and why they have been chosen as objects of the three case studies of the F-CUBED Project and analysed in the life cycle assessment.

1.3.1 Pulp & Paper Bio-sludge Residue Stream

A large variety of external treatment technologies are being used for pulp and paper mill effluents. The water that is withdrawn for usage in the pulp and paper industry is mainly used as process water. The most water-consuming processes are cooking and bleaching, where the water becomes contaminated by contact with raw materials, by-products, and residues (Fig. 2).

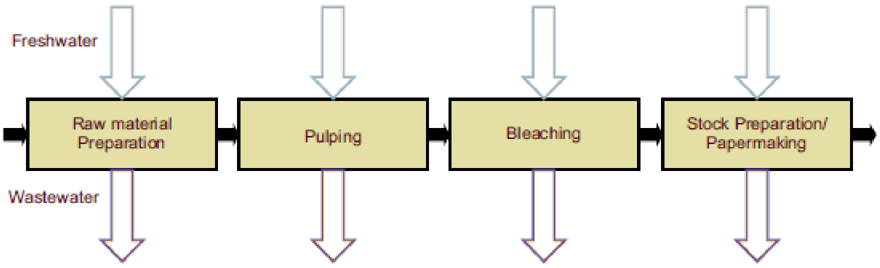

Figure 2- Water flows in the pulp and papermaking process (Source: Bajpai, 2022)

Reclamation of the effluent is economically important, as the gross usage of water in the industry is very high and the cost of effluent treatment for all water assigned to drain would be very expensive. This would also involve a loss of raw materials. A proportion of the water is recycled for use in dilution or other processes (Bajpai 2022). Residues related to the Pulp & Paper Sector (PPS) are of various types: sludge (bio-sludge from wastewater treatment, fibrous sludge, deinking sludge, etc.) from both virgin pulp production and/or processing paper for recycling and own pulp or paper mill residues (rejects, non-recyclable paper for recycling, plastics). The sludge may be stabilised, dewatered or dried. The pre-treatment steps necessary to optimise the combustion phase of the bio-sludge are case-specific, but the general aim of pre-treatment is the removal of unwanted materials (e.g. water), a reduction of pollutants and the homogenisation of the fuels with respect to calorific value, size and other physical parameters (such as density) (Suhr, et al. 2015).

In terms of fuels utilised, grate-fired boilers or fluidised bed combustion plants may be charged with fossil fuels (lignite and coal, fuel oil, natural gas), biogas, biomass (e.g., bark), wood residues, wood waste and other internal production residues and sometimes also external waste or refuse-derived fuel. In addition, various types of sludge (e.g. sludge from biological wastewater treatment) may be co-incinerated. In most cases, the energy content of dehydrated sewage sludge (20 – 40 % dry solids) is just sufficient to cover the flue-gas losses of the flue-gas produced by burning the sewage sludge (Suhr, et al. 2015). The mechanically dewatered pulp sludge has a lower calorific value amounting to 2.5-6.0 MJ/kg due to its often higher moisture and ash content, whilst the calorific value of dry pulp waste can reach over 20 MJ/kg. The higher the humidity of the fuel, the lower the overall energy economy of the boiler and also the more difficult the operability unless efficient technology is applied.

1.3.2 Virgin Olive Pomace Residue Stream

The olive oil industry represents one of the fastest-growing industrial sectors worldwide, being of great importance in the economy of European countries, such as Spain, Greece, and Italy.
The volume of processed olives in the main olive oil producer countries, such as Spain, leads to the generation of about 4–5 million metric tons of annual waste (Alonso-Fariñas, et al. 2020).

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The olive pomace is a by-product of olive oil production, obtained after milling operations. The milling process can be done by traditional pressing operations, or through centrifugation (that occurs in two or three phases). Depending on the process used and on the number of phases, the olive pomace has a different moisture content and requires different amounts of energy to be dried. In olive mills that use the two-outlet decanter, the most used system for olive oil extraction, the olive pomace is the biogenic residues waste mainly produced. Its moisture content is usually varying between 70-80% and beyond.

In general, the virgin olive pomace is transported to the olive pomace mill for the extraction of the crude pomace oil, mainly by organic solvents (technical hexane) (García Martín, et al. 2020). Before extraction, a drying phase is necessary to reduce the moisture and volatile matter of the olive mill solid waste (between 65 and 75%) to less than 8%. This drying phase involves the highest energy consumption of the whole process of pomace oil extraction, and it is normally fed by natural gas or by the resulting extracted pomace from pomace oil extraction. On completion of this stage, the residual oil (up to 4 % by weight) is extracted through a mixture of steam and hexane. The drying and the extraction phase are both obtained using hot air and superheated steam produced in a boiler, which uses exhausted pomace (oil-free pomace) at the end of the process.

However, recent LCA studies suggest that anaerobic digestion was the best alternative, with a global environmental impact reduction of 88.1 and 85.9% with respect to crude olive pomace oil extraction using natural gas and extracted pomace, respectively, as fuel (Alonso-Fariñas, et al. 2020). Mediterranean countries are responsible for a large part of the world olive oil production. Therefore, for these countries, environmentally friend disposal of the olive pomace requires the implementation of waste-to-energy strategies through novel technology solutions.

1.3.3 Fruit & Vegetables (Orange Peels) Residue Stream

Orange as the main citrus fruit is one of top-five fruit commodities that dominate the global fruit market. According to Eurostat Data Browser, the largest orange producers in Europe are Spain, Italy, Greece, Portugal and in these countries European orange production reached 6.5 million tons in 2021 (Eurostat 2017). However, citrus fruits are traded and consumed as fresh fruits, even in regions that don't produce citrus fruits. This is due to the extraordinary stability during the post-harvest of citrus that promotes global trade (Suri, Singh and Nema 2022). Therefore also global data are of interest in this case study. Around 18% of the global citrus fruit production, are utilized for industrial usage (FAO, 2017), especially for juice production, but also in the canning industry for the preparation of marmalade, mandarin segments as well as for recovery of bioactive essential oils and flavonoid compounds (Izquierdo and Sendra 2003).

Besides its industrial interest for utilization of citrus fruits, the number of wastes is also relatively increasing, leading to the environmental burden. Indeed global citrus fruit processing generates approximately 10 million tons of waste each year (Zema, et al. 2018), creating a serious ecological issue. The generation of waste correspond to 50% of the total fresh fruit mass including peels (50–55%), seeds (20–40%), pomace, and wastewater which covers portions of spoiled fruit, seeds, pulp, and peels. Particularly citrus peels, containing around 80% water, rot quickly, invite microbes, flies, mold, and produce mycotoxins, etc. Therefore, the treatment and proper disposal of citrus peels is highly necessary for waste management (Berk 2016) and requires significant investment to avoid soil and water pollution, further destroying the aquatic ecosystem (Zema, et al. 2018). More effective and sustainable alternatives for using orange peel wastes are highly desirable.

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Part A – Environmental Life Cycle Assessment

2. Case studies of the present research

2.1 Case studies considered in the LCA for F-CUBED

This section describes the conceptual process design and modelling for the F-CUBED Production System, in three case studies which have been analysed in the LCA study. For more detailed information see deliverable D5.1. The F-CUBED project aims to convert wet biogenic residues into intermediate bioenergy carriers (fuel pellets) via hydrothermal treatment (TORWASH). The selected biogenic residues include paper bio-sludge, olive pomace and orange peels. The overall F-CUBED process consists of TORWASH treatment and filter press dewatering, to produce a solid product (converted into fuel pellets via drying and pelletization) and a liquid product (anaerobically digested to produce biogas). The block flow diagram for the F-CUBED Production System is reported in Figure 3.

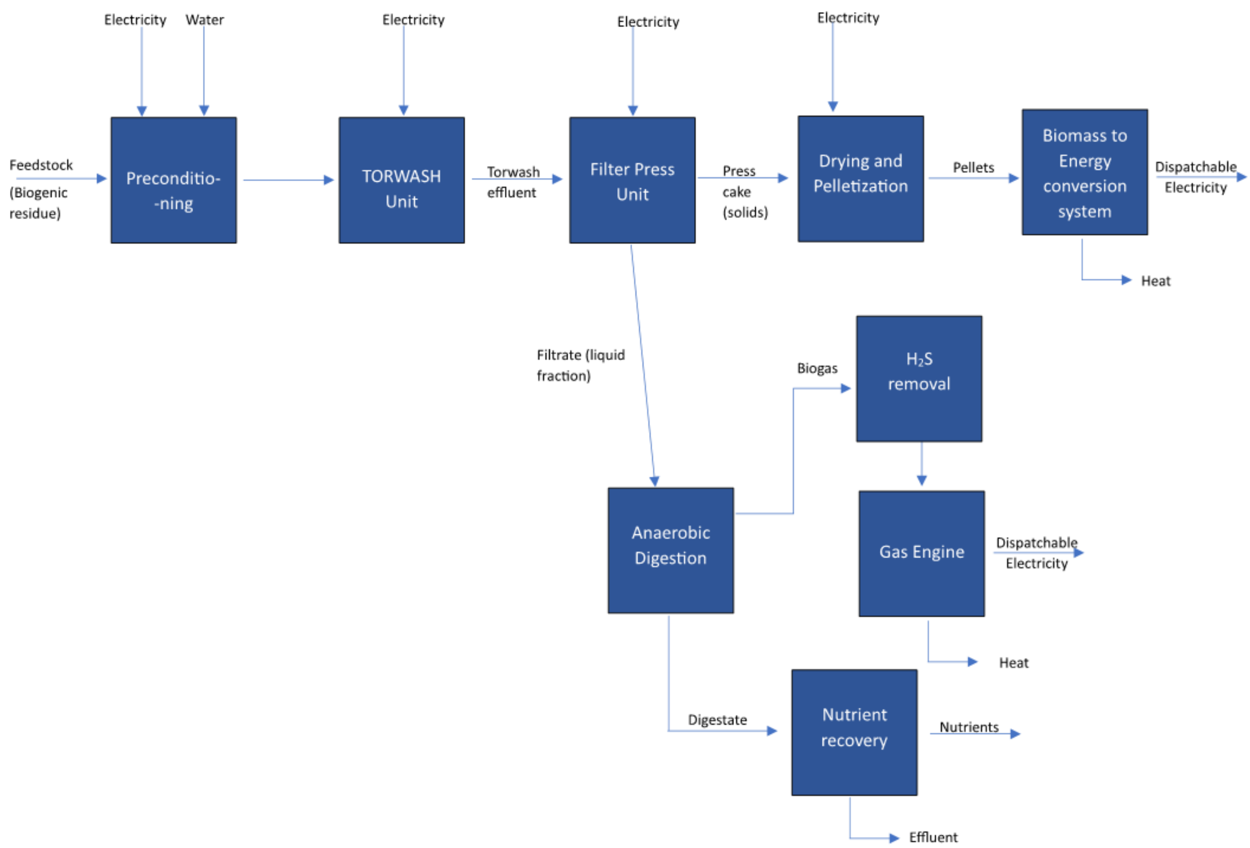

Figure 3 - Representation of the constituent processes of the F-CUBED Production System

The case studies considered in the LCA are:

- F-CUBED Production System for Pulp & Paper Bio-sludge (DM 3.5%);
- F-CUBED Production System for Virgin Olive Pomace (DM 19.6%);
- F-CUBED Production System for Fruit & Vegetable (Orange Peels [DM 20.0%]).

These case studies are briefly described in Table 1. They have been broadly described in the Deliverables of the WP2. WP3 and WP4. to which can be referred to, for further information.

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Table 1 - Biogenic residues case studies investigated by attributional LCA

Biogenic residue stream	Object of investigation	Facility and treatments description
Pulp & Paper Bio-sludge DM =3.5%	Reference case	Smurfit Kappa Kraftliner paper mill in Piteå, Sweden. The mill produces kraftliner as the main product. The wastewater streams from this mill are sent to the wastewater treatment plant (WWTP).
	F-CUBED Production System	Integration of the F-CUBED Technology at the site of Smurfit Kappa paper mill, for operational application with pulp & paper sludge (bio-sludge) as feedstock for the TORWASH hydrothermal treatment. Industrial scale operational scenario.
Virgin olive pomace DM = 19.63%	Reference case	Frantoio Oleario Chimienti (APPO) olive mill, in Sannicandro di Bari, Italy. In the mill the cleaned olives are processed for the extraction of the extra virgin olive oil. The olive pomace is sent to the AD reactor for biogas generation.
	F-CUBED Production System	Integration of the F-CUBED Technology at the site of APPO olive mill, for operational application with virgin olive pomace as feedstock for the TORWASH hydrothermal treatment. Industrial scale operational scenario.
Orange peels DM=20%	Reference case	Delafruit's food processing plant, in Reus, Spain. In the plant, the fresh oranges are squeezed to get orange juice which is used for different purposes. The orange peels are sent to the AD reactor for biogas generation.
	F-CUBED Production System	Integration of the F-CUBED Technology at the site of Delafruit's facility, for operational application with orange peels as feedstock for the TORWASH hydrothermal treatment. Industrial scale operational scenario.

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2.2 Summary of the Reference Cases

This section describes the Reference Cases (RCs) for the different biogenic residues streams which have been analysed in the LCA study. They represent the actual or conventional treatments of the selected biogenic residue streams to which the environmental impacts of F-CUBED Production System have been respectively compared. Each reference case is based on commercially available technologies using advanced and integrated concepts. The RCs to whom F-CUBED is compared to, are summarized in Table 2. The block flow diagrams of the RCs are also presented in Figures 4 to 6.

The RC refers to the practices applied at the F-CUBED project partners' site, i.e. Smurfit Kappa, Frantoio Oleario Chimienti (APPO Mill) and Delafruit, where the feedstocks are generated. For Pulp & Paper Bio-sludge the RC corresponds to the current scenario; for Virgin Olive Pomace and Orange Peels case studies, nowadays no energy generation is foreseen in the conventional practices. Hence, in order to make LCA analysis and comparison with the F-CUBED Production System, the conversion system of biogenic residues into energy has been included. Between the conventional options of incineration and anaerobic digestion (AD) to biogas generation, AD is chosen since incineration of such wet streams is highly inefficient (Shah 2022), and AD is a promising alternative to valorise agrifood wastes, which is gaining interest under an environmental sustainability overview (Alonso-Fariñas, et al. 2020). The anaerobic digestion process consists of the production of biogas from the wet biogenic residue/ waste, heat and electricity cogeneration by the combustion of the generated biogas, and landfarming of the anaerobic digestate. Moreover, since the Reference Cases are used to compare the environmental performances to their F-CUBED counterparts, the materials and energy inputs for conditioning the biogenic residues stream (Table 2) and the electricity generated have been considered for the life cycle analysis and the necessary assumptions (Chapter 4) applied.

Table 2-Input data for the biogenic residues Reference Cases (Source: Shah 2022)

Residue Stream	Input	Mass/Energy flow rate	Additional Information
Pulp & Paper Bio-sludge	Fiber sludge	3375 t (db)/y (1.65% DM)	T – 25°C, P – 1 atm
	Bio-sludge	2250 t (db)/y (3.5% DM)	T – 25°C, P – 1 atm
	Polyelectrolyte	25 t/y	
	Ferrous salt solution	170 t/y	Added as 40 % solution
	Nutrients added in WWTP	P – 30 t/y N – 170 t/y	P and N are added as an acid solution and urea salt respectively
	Yearly operating hours	8600 hr	Obtained from F-CUBED partners
Virgin Olive Pomace	Olive pomace	9600 t (ar)/y (19.63% DM)	T – 15°C, P – 1 atm
	Preparation of waste stream for AD	Dilution of stream to 9% DM and heat to 30°C for AD reactions	
	BMP of olive pomace	216 cm^3 CH_4/g volatile solids	
	Yearly operating hours	960 hr	Obtained from F-CUBED partners
Orange Peels	Orange peels waste stream	2300 t (wb)/y (20% DM)	T – 15°C, P – 1 atm
	Preparation of waste stream for AD	Dilution of stream to 10% DM and heat to 55°C for AD reactions	
	BMP of orange peels	0.061 Nm^3 CH_4/kg volatile solids	
	Yearly operating hours	3200 hr	Obtained from F-CUBED partners

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2.2.1 Pulp & Paper Bio-sludge reference case

The project partner Smurfit Kappa, Kraftliner paper mill, in Piteå (Sweden) has been considered representative of the Scandinavian Pulp & Paper Mill sector. The mill produces kraftliner as the main product. In this mill the long duration test of the F-CUBED Production System (pilot plant) has been carried out.

The wastewater streams from this mill are sent to the wastewater treatment plant (WWTP). In the WWTP, additional nutrients are added i.e. Phosphorous and Nitrogen. The treated water from this mill is then discharged to the environment. Two types of sludge are generated in this mill a) paper fiber sludge from the mill and b) paper biological sludge from the WWTP. The fiber sludge and bio-sludge are mixed. The fiber sludge is mixed to aid the dewatering of the bio-sludge. This mixed paper sludge is then sent to a gravity table for dewatering and increase the dry matter (DM) content to 8%. The dewatering is further aided by adding polyelectrolyte (PE) and ferrous sulphate salt. The concentrated sludge is sent to a screw press to increase the DM to 30%. This stream is sent to the onsite biomass boiler where steam is generated. The water effluent from this operation has negligible dry matter content and is sent to the WWTP. The block flow diagram for Reference Case is depicted in Figure 4.

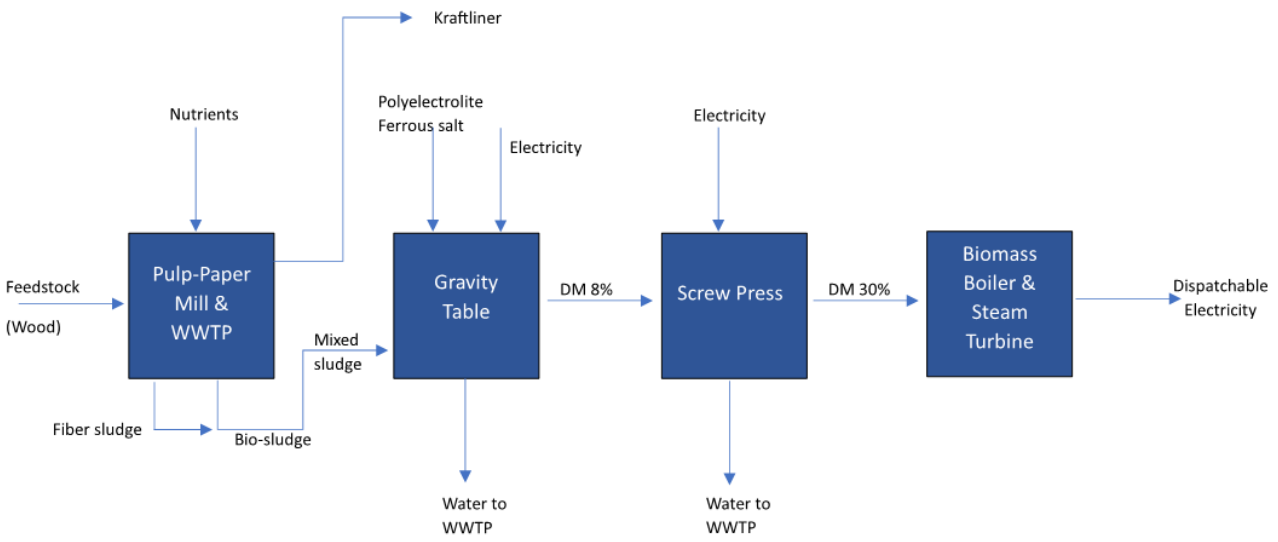

Figure 4- Representation of relevant processes considered as Reference Cases for Pulp & Paper Bio-sludge

The RC for pulp & paper sludge has been modelled considering the following assumptions:

- the wastewater treatment phase has a flow rate of 18 t/t_{ADp} representing an average value of the range 9-27 t/t_{ADp} valid for a plant capacity of about 650 kt_{ADp}/y, and an electricity consumption of 8 kWh/t_{ADp}, based on BAT for Pulp, Paper and Board (Suhr, et al. 2015);
- the biological sludge is mixed with the fiber sludge and then treated by a gravity table and dewatered by a screw press characterized by the efficiency of mechanical separation of the suspended solids of about 95% (Visigalli 2020) and an energy consumption of 10 kWh/t (Suhr, et al. 2015);
- the press cake feeding the biomass boiler is modelled with data collected in BAT for Waste Incineration (Neuwahl, et al. 2019), setting the inputs of sodium hydroxide, ammonia, water for gas cleaning and electricity requirement; and
- the produced steam is converted into energy through a turbine characterised by a power efficiency of 20% and heat surplus to be used outside the system.

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2.2.2 Virgin Olive Pomace reference case

For olive pomace, the current operational site of project partner APPO, Frantoio Oleario G. Chimienti olive mill, in Sannicandro di Bari (Italy), has been considered representative of the overall sector. In this mill the long duration test of the F-CUBED Production System (pilot plant) has been carried out. In the specific case study, the milling process has been followed by centrifugation that occurs in two phases and the resulting olive pomace has a moisture content of about 80%, and contains residual oil up to 4 % by weight (De Marco, Riemma and Iannone 2017). Therefore this biogenic residue stream consists mainly of the WET olive pomace and no other chemicals.

Unlike the conventional utilization of olive pomace for the crude olive pomace oil extraction through a mixture of steam and hexane, in the present reference case the resulting residues of virgin olive pomace are used for biogas generation by anaerobic digestion. The content of H_2S in the biogas is removed using iron sponge technology. The cleaned biogas is burned in a cogeneration unit with a gas engine generating electricity and heat. It is intended to represent the production of grid-connected electricity with biogas. The main product is then considered to be electricity at high voltage, while heat is produced as a co-product.
The last step of the process deals with the transformation of electricity voltage from high to medium voltage, including the losses during voltage transformation. On the contrary the process doesn't include the transformer station itself as this is considered included in the transmission network. This theoretical alternative, used as a reference case for the Olive Pomace stream, is particularly interesting because it represents a technical solution exploitable at mill level (or associated mills) differently from the conventional olive pomace exploitation involving a third party industrial entity.

The Reference Case process is outlined in Figure 5.

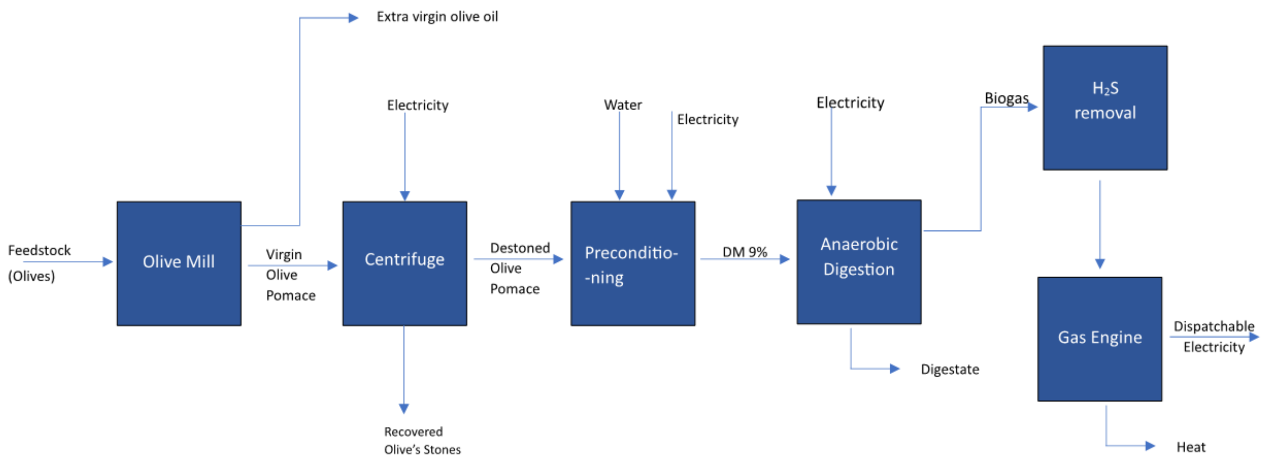

Figure 5- Representation of relevant processes considered as Reference Cases for Virgin Olive Pomace

In this RC, the virgin olive pomace is preconditioned with the destoning and dilution phases; then it is treated in an anaerobic digester producing biogas and digestate. Particularly, this scenario uses the output value of the produced biogas with specific lower heating value (LHV) for scaling the process contained in the Ecoinvent database and describing a commercial plant for biogas production through the anaerobic digestion of manure. The biogas production yield has been collected from the literature (Batuecas, et al. 2019).
The process also includes the cleaning treatment for removing the H_2S from the flue gas, based on the stoichiometric reactions illustrated in Shelford and Gooch (2017).

No credits for the nutrients potentially contained in the digestate have been considered: the anaerobic reactor has been hypothesised with a large scale and the residues inlet are characterised by low homogeneity and significant variations of physicochemical parameters (e.g. limited changes of suspended/dissolved solids, heavy metals, BOD, COD, etc.). Therefore the digestate can be considered for soil improvement, but not as

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fertiliser; the amount of diesel consumption due to the spreading on soil has been taken into account, inserting the Ecoinvent process for landfarming.

2.2.3 Fruit & Vegetable (Orange Peels) reference case

For the orange peels case study, the current operational site of project partner Delafruit, in La Selva del Camp, Tarragona (Spain), has been considered as representative of the overall sector. In Delafruit, the long duration test of the F-CUBED Production System (pilot plant) has been carried out. In the food processing plant, the fresh oranges are squeezed to get orange juice which is used for different purposes in the agro-food industry. In the RC the resulting orange peels are used as feedstock for biogas generation by anaerobic digestion. H_2S in the biogas is removed using iron sponge technology. The cleaned flue biogas is burned in a cogeneration unit with a gas engine generating electricity and heat. It is intended to represent the production of grid-connected electricity with biogas. The main product is then considered to be electricity at high voltage, while heat is produced as a co-product. The last step of the process deals with the transformation of electricity voltage from high to medium voltage, including the losses during voltage transformation. On the contrary the process doesn't include the transformer station itself as this is considered included in the transmission network.

The Reference case process is depicted in Figure 6.

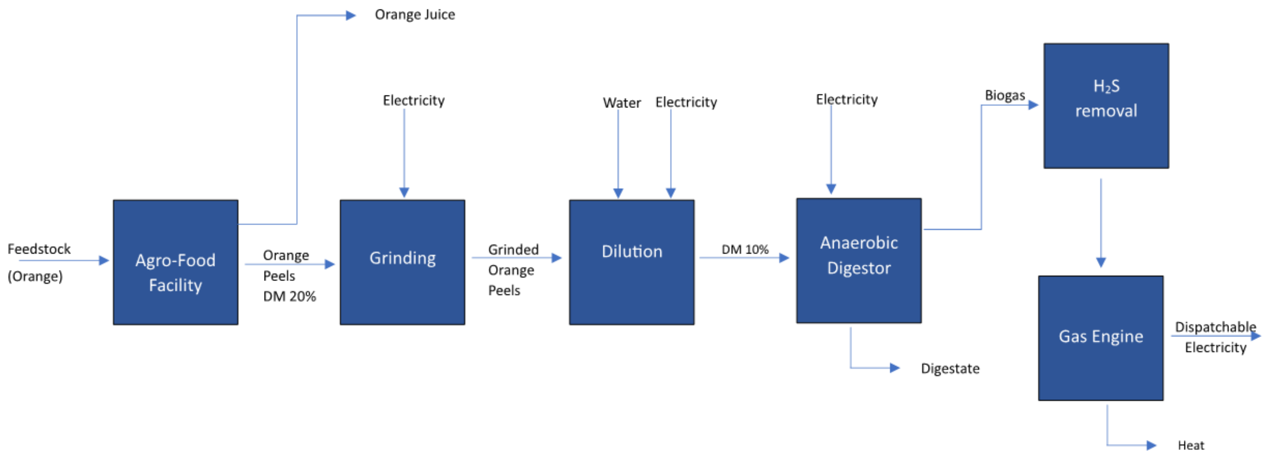

Figure 6- Representation of relevant processes considered as Reference Cases for Fruit & Vegetable (Orange Peels) residues

In this RC, the orange peels are preconditioned with the grinding and dilution phases; then they are treated in an anaerobic digester producing biogas and digestate. Particularly, this scenario uses the output value of the produced biogas with specific LHV for scaling the process contained in the Ecoinvent database and describing a commercial plant for biogas production through the anaerobic digestion of manure. The data concerning the biogas characterisation and production has been collected from literature (Zoair, et al. 2016; Ortiz, et al. 2020). The process also includes the cleaning treatment for removing the H_2S from the flue gas, based on the stoichiometric reactions illustrated in Shelford and Gooch (2017).

No credits for the nutrients potentially contained in the digestate have been considered: the anaerobic reactor has been hypothesised with a large scale and the residues inlet are characterised by low homogeneity and significant variations of physicochemical parameters (e.g. limited changes of suspended/dissolved solids, heavy metals, BOD, COD, etc.). Therefore the digestate can be considered for soil improvement, but not as fertiliser; the amount of diesel consumption due to the spreading on soil has been taken into account, inserting the Ecoinvent process for landfarming.

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3. LCA Methodology for F-CUBED Production System Analysis

Life cycle assessment is one of the most complex, powerful and recognized tools to quantify the environmental assessment and sustainability of various products. In fact, LCA is a standardized tool that can determine and compute the potential environmental impacts caused by the emissions of substances into the air, water, and soil and resources used throughout the life cycle of a product or process, from raw material extraction to waste management (Finnveden, et al. 2009). Particularly, it is a well-known method for assessing the environmental impacts of bioenergy production, allowing identification of the sources and causes of the environmental impacts of bioenergy production systems (Hosseinzadeh-Bandbafha etal. 2021). Since it can specify the environmental issues at each production stage, LCA represents a suitable tool for investigating and comparing novel bioenergy production systems to conventional systems of bioenergy production from environmental point of view.

Despite significant advantages, there are still limitations that have to be faced and mitigate applying LCA method properly: appropriate assumptions, diligent inventory data, choice of right method of impact assessment, and uncertainty analysis may increase accuracy and reliability of bioenergy product systems' life cycle assessment results. Moreover, four features make LCA a complete and robust tool, which supports companies and markets in sustainability commitments: *i)* takes a life cycle perspective, *ii)* covers a broad range of environmental issues, *iii)* quantitative approach, and *iv)* it is science-based (Bjørn, et al. 2018). According to the definitions provided by the International Organization of Standardization (ISO) through ISO:14040:2021 – Principles and Framework (ISO 2022) and ISO:14044:2021 – Requirements and Guidelines (ISO 2023), the LCA applied in the present study, consists of four phases: 1) Goal and scope definition; 2)Life cycle inventory (LCI), 3) Life cycle impact assessment (LCIA), and 4) Interpretation of the results. The relation between the above-mentioned phases is outlined in Figure7.

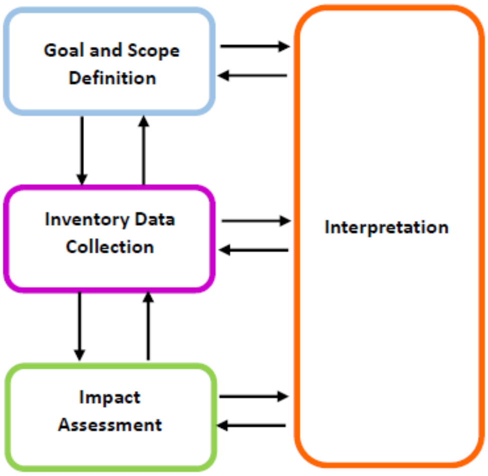

Figure 7- – LCA methodology according to ISO guidelines

Each phase, performed in the F-CUBED Production System LCA study, is described in detailed manner in the next sections.

3.1 Goal and scope definition of F-CUBED LCA study

In the goal and scope definition phase of the LCA study, goal, functional unit (FU), system boundaries, and allocation approach are reported and analysed. The present LCA study can be classified as attributional LCA that describes the environmental impacts of flows to/from a life cycle and its sub-systems and aims to

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quantify the environmental impacts of all relevant resource and material inputs according to the status quo or mean data within a constrained boundary (Lee, et al. 2020).

3.1.1 Goal and scope definition

The goal of the present study is to quantify and assess the environmental burden of the F-CUBED Production System applied to three different wet biogenic residue streams (paper sludge, olive pomace, orange peels), characterized by low economic value, and compare the F-CUBED technology with conventional technologies for their treatment. The F-CUBED system proposes the novel TORWASH technology integrated with other technologies in a process flow that aims to improve the conversion steps of secondary biomass to intermediate bioenergy carries in an environmental efficient and cost-effective manner. For comparison, Reference Cases are developed to highlight the potential improvements brought by the F-CUBED Production system.

The study addresses primarily to the EU-Commission which funded F-CUBED project through H2020 programme (G.A. 884226). The target audience of the study also includes members of the agro-food industries and forest-based products as the pulp and paper industry. Moreover, this study will be available for the interested public (technical and non-technical), while the findings of the research can serve as valuable information for decision-makers in the above-mentioned industrial sectors.

3.1.2 Functional unit

The functional unit (FU) is a quantified description of the performance of the analysed production system to which all outputs and inputs to/from the system itself are referred (Flysjö 2011). For the present study, the FU is output unit related, and corresponds to 1 kWh of dispatchable electricity. All environmental impact indicators are reported per kWh of power produced. However, to facilitate comparative assessment while leading to a better understanding of the studied system against other systems and avoiding biased outcomes, the results have also been examined in relation to the amount (wet basis) of biogenic residues treated.

3.1.3 System boundaries

The system boundaries are defined as the interface between the set of unit processes under investigation and the environment or other processes. Therefore they define which processes will be included or excluded from the system. Depending on the goal of the LCA, the limits of the system are referred to the cradle-to-gate option. This approach is suitable to compare options to make the same bioenergy from different feedstock (Hosseinzadeh-Bandbafha, et al. 2021), thus covering all production steps from raw materials point of extraction (i.e., biogenic residues) up to the finished product (i.e., renewable electricity) ready to be dispatched.

As illustrated in Figure 8. system boundaries include four meta-groups of processes:
1) **Upstream Processes**: residue extraction, eventually transport to the F-CUBED plant and preconditioning of the residues;
2) **Main Stream Processes**: TORWASH hydrothermal treatment, dewatering, drying and pelletizing;
3) **Downstream Processes**: transport to the power plant, biomass to energy conversion system; and
4) **Secondary Liquid Fraction Processing**: Anaerobic digestion, biogas to energy conversion system.

Regarding the geographical limitations, the system foresees that the plant is located in Northern Sweden for Pulp & Paper Bio-sludge scenario, in Spain for the fruit and vegetables residues case study and in Italy, for the virgin olive pomace case study. A plant lifetime of 15 years is considered. The period over which the time-dependent characteristics of the object of the assessment are analysed is one year.

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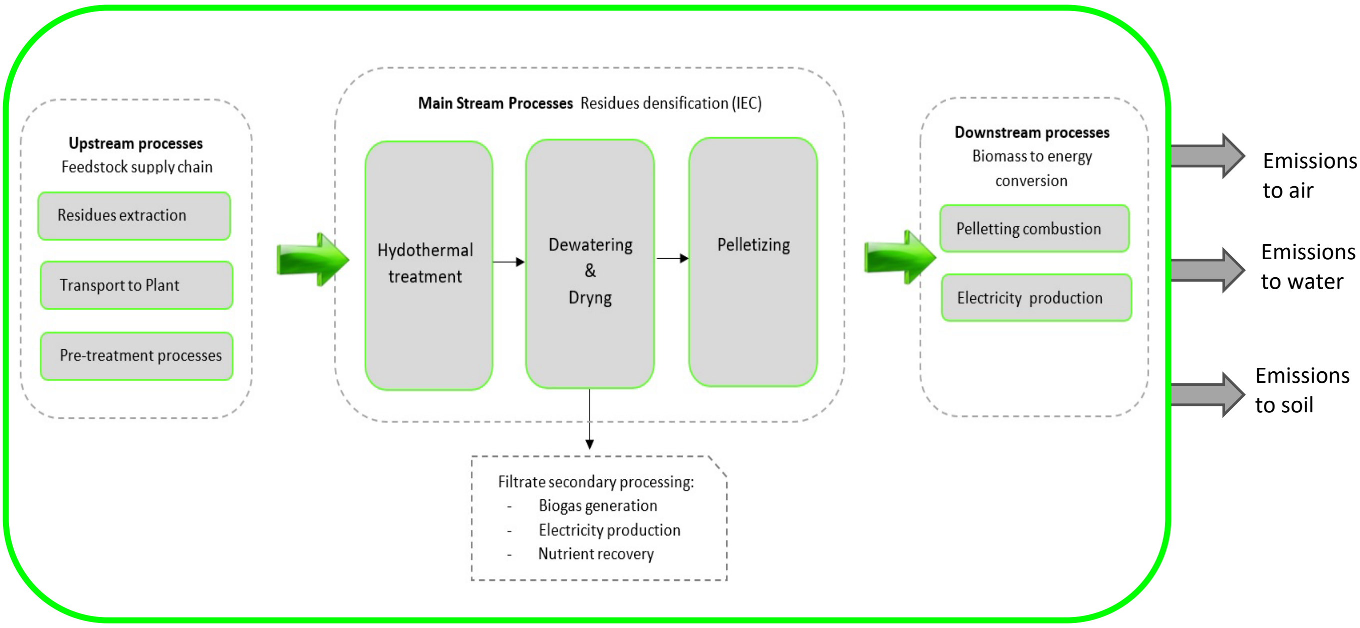

Figure 8 - System boundaries for F-CUBED Production System

3.1.4 Allocation approach

F-CUBED is multifunctional bioenergy production systems in which co-products occur as outputs, they are: intermediate energy carriers (e.g. pellets), electricity and biogas. Therefore environmental load of the process needs to be allocated over the different outputs. According to the International Organization for Standardization (ISO 2022), allocation is "partitioning the input or output flows of a process or a production system between the product system under study and one or more other product systems." Because of the many concerns about allocating the environmental impacts in bioenergy product systems, in the present LCA, in compliance with the same ISO, allocation is avoided by "system expansion" consisting in the extension of the system boundaries by including secondary processes that would be needed to make a similar output in respect of the co-product. It is the case of the anaerobic digestion of the filtrate after dewatering step. Here the results based on system expansion can be considered accurate because the data on the effects of the exported functions are available, by project partners, as foreground data. In situations where it was not possible to avoid the allocation of the environmental load, the allocation has been based on a physical relationship, such as mass or energy content of the outputs. For example, the case of the olive stones separated from the olive pomace in the upstream processes of the Olive Pomace case study.

In addition to the above-mentioned approach, the Allocation at the point of substitution (APOS) system model has been chosen. To set the methodological rules to calculate the database, in the way of treating waste and recyclable materials, it uses expansion of product systems to avoid allocation within treatment systems. The APOS model is therefore performing an expansion of the allocation system to include all treatment processes required for any by-products be they wastes or recyclable. However, addressing multi-functional problems in LCA analysis is one of the most significant sources of uncertainty (Cherubini, et al. 2018). Accordingly, a sensitivity analysis has been conducted.

3.2 Life cycle inventory

Life cycle inventory (LCI) is the second phase of the LCA study that consists of the inventory of input and output data flows of the production system. During this phase, the data of resource, energy consumption

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and the contaminant discharged into the environment, in each stage of an LCA, have been collected and processed. The data collection includes raw resources or materials, energy by type, water consumption and emissions to air, water and soil by specific substance (Heijungs,, et al. 2003). The LCI is built on the basis of unit processes; a unit process represents "the smallest element considered in the life cycle inventory analysis for which input and output data are quantified" (ISO 2022). It is the least aggregated process level in the production system and the building blocks of the process-based LCA. Inputs come in several types of products (including components, materials and services), waste for treatment and natural resources (i.e., fossils, ore, biotic resources). Outputs come in different forms as well: products (including components, materials and services), waste for treatment and residuals to the environment (including pollutants to air, water and soil) (Curran 2012). LCI data have been categorized into two types:

• *Foreground data*: primary data, collected from interviews, questionnaires, on-site measurements, online and offline data collection.
• *Background data*: secondary data, derived from calculations, estimations, databases, scientific reports, statistics, and scientific literature.

Both categories of data have been used in the present study. The correctness of the LCA results depends directly on the quality of the inventory (Ren e Toniolo 2019). The data required in the LCI of the current investigated systems were retrieved from interviews with experts (i.e., pelletizing phase), process modelling and simulation (i.e., TORWASH and dewatering phases). Especially the modelling of the system process has been considered as foreground data because the technology object of study is actually at pilot scale and not yet developed at industrial scale. The mass and energy balance data for the main processes, power generation from pellet production technology, were provided by project partner TNO using modelling and simulation tools. More details are reported in the deliverable D5.1. Usually, the LCI data are gathered and presented in table format. This approach was also used in the present deliverable. The tables and descriptions of the overall LCI are reported in Chapter 3.

3.2.1 Importance of data source and data quality

Assuring the reliability and validity of the findings and drawing insightful conclusions depend on the quality and integrity of the data. Quality has many different aspects that depend on the priorities, demands, and viewpoints of the users. The management of data quality across the whole data collection process is discussed in this section. According to ISO 14044:2021 (ISO 2023) the unit processes of LCI may include a combination of measured, calculated and/or estimated data. The quality of these data is an important aspect in LCI. All data should address the following quality requirements: time-related, geographical and technology coverage, precision, completeness, representativeness, consistency, reproducibility, source, and uncertainty of information. Considerations about data quality are fundamental for identifying the data uncertainties and the range of variation of their values in order to carry out an adequate sensitivity analysis of the results.

In the present study, data validation has been performed during data collection to affirm and prove that the data quality requirements were fulfilled. This was done, for example, by mass/energy balances and/or comparative analysis of release factors. Moreover, data checks were performed as an iterative process. On one hand, because it is connected to the other LCA's phases, e.g. if LCIA phase showed unreasonable impact result, the LCI analysis have been revisited to improve the data coverage and/or quality. On the other hand, being based on continuous communication with the project partners to clarify any queries or inconsistencies about the data. The data quality evaluation is particularly important for the background data coming from life cycle databases, literature sources (e.g., from searches of results in published papers), and other past work. For instance, typical trade-offs to accessibility are that the secondary data identified is for a different country, a slightly different process, or averaged across similar machinery. That does not mean the data cannot be used but a careful evaluation must be carried out highlighting the differences between the process

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data used and the specific process needed in the study. On the other hand, in some cases, background data may be of comparable or higher quality than primary data. Indeed, they can typically be found because it has been published by the original author who generated it as primary data for their own peer-reviewed study, thus it is assumed of good quality. In any case, it is important to report details about the secondary source and to quantitatively maintain the correct units for the inputs and outputs of the unit process (Scott, Hendrickson and Matthews 2014). In the present LCA, the overall data quality of the described systems is considered to be high and representative in terms of technology coverage and resource supply chain.

3.3 Life cycle impact assessment

LCIA, as the third phase of an LCA study, assesses the potential environmental impacts by converting the inventory data into specific impact indicators (Rosenbaum, et al. 2018). During this stage, the effect of substances on the selected impact categories is quantified highlighting the processes that contribute the most. Among the impact assessment method available for LCA in bioenergy production systems, the ReCiPe method (Huijbregts, et al., 2017) is the most used LCIA method (Hosseinzadeh-Bandbafha, et al., 2021). Details regarding this impact assessment method and the motivation of its choice are provided in section 3.3.1. In the case of generally accepted and straightforward impact categories, for which characterization factors have already been derived, all inventory results are pre-classified to preselected impact categories already available in different LCA software tools, e.g., GaBi or SimaPro (Hauschild e Huijbregts 2015).

For the purpose of this work, SimaPro 9.1. was chosen as LCA software tool. SimaPro is a modular software with a parameterized architecture. It contains all the elements to model products and systems from a life cycle perspective. The software incorporates access to several available databases, such as Ecoinvent 3.8. and SHDB, and data about material elaboration, production and use of fuels and electricity, transport of goods, waste treatment covering a wide range of the customer's needs. Simple or more complex processes and various production alternatives can be modelled using this specific tool. SimaPro serves for efficient completion of tasks such as: Life Cycle Assessment (LCA) according to ISO 14040 & 14044. Life Cycle Engineering (LCE), Product and Process Optimization, Design for Environment (DfE), Environmental Product Declarations (EPD), Sustainability Assessment – environmental /economic/ social, Life Cycle Costing (LCC), Energy and Resource Efficiency Analysis, Material Flow Analysis, Greenhouse Gas Accounting, Sustainability Benchmarking.

3.3.1 Impact assessment method and impact categories

As previously mentioned, the ReCiPe method was selected as the impact assessment method because of its completeness and universality. The number of substances covered by this method is more than 3000 (Aghbashlo, et al. 2021). Moreover, the method is regularly updated, therefore it provides the most relevant results from the environmental perspective. The ReCiPe impact assessment method is applied based on Hierarchist perspectives, at midpoint level in the current study. Midpoint characterization methods lead to more accurate results and reduce the uncertainty. ReCiPe2016 produces 18 midpoint indicators. The life cycle inventories for the investigated three case studies, thus have been converted into a number of harmonized impact scores at midpoint level. The main environmental impact categories and the respective characterization factor, further considered in the present LCIA, are listed in Table 3.

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Table 3 - Overview of the midpoint categories and characterisation factors (Source: Goedkoop et al., 2009. modified)

Impact category	Abbreviation	Unit (compartment)	Characterisation factor	Abbreviation
Climate change	CC	kg CO_2 (to air)	global warming potential	GWP
Ozone depletion	OD	kg CFC-11[5] (to air)	ozone depletion potential	ODP
Terrestrial acidification	TA	kg SO_2 (to air)	terrestrial acidification potential	TAP
Freshwater eutrophication	FEUT	kg P (to freshwater)	freshwater eutrophication potential	FEP
Marine eutrophication	ME	kg N (to freshwater)	marine eutrophication potential	MEP
Human toxicity	HTX	kg 14DCB (to urban air)	human toxicity potential	HTP
Photochemical oxidant formation	POF	kg NMVOC[6] (to air)	photochemical oxidant formation potential	POFP
Particulate matter formation	PMF	kg PM_{10} (to air)	particulate matter formation potential	PMFP
Terrestrial ecotoxicity	TETX	kg 14DCB (to industrial soil)	terrestrial ecotoxicity potential	TETP
Freshwater ecotoxicity	FETX	kg 14DCB (to freshwater)	freshwater ecotoxicity potential	FETP
Marine ecotoxicity	METX	kg 14-DCB[7] (to marine water)	marine ecotoxicity potential	METP
Ionising radiation	IR	kg U^{235} (to air)	ionising radiation potential	IRP
Agricultural land occupation	ALO	m^2yr (agricultural land)	agricultural land occupation potential	ALOP
Urban land occupation	ULO	m^2yr (urban land)	urban land occupation potential	ULOP
Natural land transformation	NLT	m^2 (natural land)	natural land transformation potential	NLTP
Water depletion	WD	m^3 (water)	water depletion potential	WDP
Mineral depletion	MRD	kg Fe	mineral depletion potential	MDP
Fossil depletion	FD	kg oil[†]	fossil depletion potential	FDP

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3.4 Interpretation of the results

The fourth phase of an LCA study is the interpretation of the results of LCI and LCIA phases by which the findings of the previous phases are checked and discussed in depth to form the basis for conclusions and recommendations for decision-makers in accordance with the Goal and Scope. The interpretation phase plays a crucial role in the quality and consistency of LCA studies. It gives meaning to the study results by conclusions and explaining limitations. Particularly, in LCA studies of F-CUBED Production Systems, the interpretation phase aims to justify the production and use of bioenergy and recommends strategies to further increase the environmental sustainability of products.

3.5 Sensitivity analysis

In LCA, uncertainty exists as a result of incompleteness of the model (i.e. choice of cut-offs), using inputs or methods that imperfectly capture the characteristics of the product system: the data itself could be unavailable or of questionable quality; the methods may similarly be imperfect; geospatial information may be incorrect or non-site-specific for key processes; technological progresses cannot be fully represented, as reported in Williams, Weber and Hawkins (2009). In the present work we refer to the parameter uncertainty, defined as error in parametric quantities, inadequate or outdated measurements (corresponding to unrepresentativeness of the data), or no data (generally corresponding to lack of data). It refers to the uncertainty in seen or measured values caused by the stochastic nature of the system, as well as data quality uncertainty. Theoretically, any deviations in inventory development from the LCA principles, e.g., excluding relevant input-output data, can move the calculated scores away from the actual values. If the inventory phase ignores some data affecting the results, conclusions could be not robust and interpretations biased. Moreover, variability in LCA occurs as a result of randomness in the data, because of heterogeneity or diversity of the values. In fact all data used in LCA studies is inherently uncertain: by a heuristic approach, the LCA results can be assumed reliable if by forcing variability ranges of +/- 20% of the input data, then relatively small differences would be noted in the calculated impacts (Scott, Hendrickson and Matthews 2014).

In the present work, the method used for parameter uncertainty analysis is Monte Carlo simulation.
Monte Carlo is one of the more well-adopted methods used by the LCA community for parameter uncertainty propagation (Igos, et al. 2018). It randomly changes uncertain parameters; however, the variation is limited by the distributions specified for the considered parameter. Repeated calculations provide an expected output value distribution that represents the combined parameter uncertainty (Mahmood, et al. 2022). Another important tool here used in understanding the uncertainty of the obtained results is the use of the contribution analysis for determining which processes are playing a significant role in the results. Therefore, when the sensitivity analysis shows the uncertainty of a specific indicator, a contribution analysis can be executed in order to deeply highlight the most critical process and their inputs/outputs. As a consequence the assumptions of these processes are analysed and evaluated in order to establish if some changes in the inventory have to be done, with a recalculation of the LCA results.

4. Life Cycle Inventory

In the present chapter the life cycle inventory phase (LCI) for the F-CUBED Production System is described together with the respective assumptions considered for every biogenic residue stream objective of the present research. The LCI refers firstly to 1 ton of the specific biogenic residue and in the further elaboration is referred to the FU of 1 kWh_{el} of the dispatchable electricity. The inventory has been modelled for Europe and the specific country of biogenic residues' origin (Figure 9) for a Time period of one year and Macro-economic scenario of Business-as-Usual. Data inventory for RCs are reported in Appendix A.

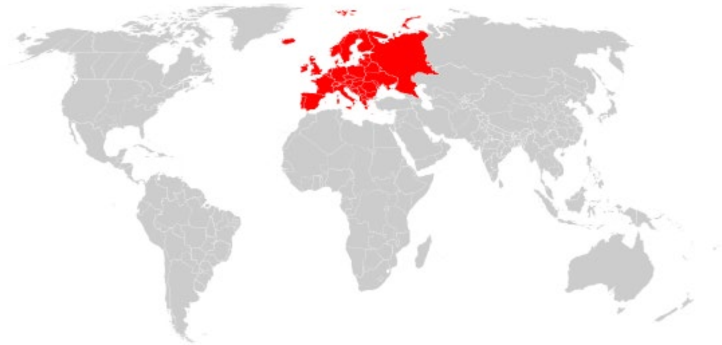

Figure 9 - Geographic reference of the LCI data collection (Source: Ecoinvent 3.9.1)

Some of the unit processes of the inventory phase have been designed by proxy-process of the Ecoinvent 3.8 database, describing specific commercial dataset coherent and as much closer as possible to the unit process object of analysis. The use of proxy-processes contributes to reduce the risk of data lack in the inventory phase, for instance because a product or emissions is missing, and increases the completeness of the LCA datasets. For calibrating the proxy-process to the experimental one, an input value from experimental data is chosen and the proxy-process is scaled accordingly, e.g. electricity consumption, energy content of the product or digestate output. Ideally this input data has been provided, from a project partner who is specialized in the specific operations of the unit process in question.

4.1. LCI of F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

In the present section the LCI phase of Pulp & Paper Bio-sludge case study is described.

The F-CUBED Production System for Pulp & Paper Bio-sludge consists of 10 production steps:

1. Biological sludge extraction (DM 3.5%). It includes the WWT and the separation of the treated water stream;
2. Enhanced (thickened) Bio-sludge production (DM 10%) by decanter-centrifuge;
3. TORWASH pre-treatment and production of TORWASH effluent (DM 8.5%);
4. Dewatering by Membrane Filter Press (Limburg Filter Ltd), production of press cake (solids, DM 42.3%) and filtrate (liquid fraction, DM 3%);
5. Pelletization by CPM operational scheme and pellets production (MC 8%);
6. Heat, central or small-scale for heat production from pellets;
7. Electric power production (MV) by steam turbine;
8. Biogas generation by anaerobic digestion (LHV 19.69 MJ/Nm^3) and digestate production step;

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9. Electricity production (HV) by heat and power co-generation, biogas gas engine, Sweden case;
10. Electricity voltage transformation from high to medium voltage, Sweden scenario.

The table of data inventory (Table 4a & 4b) and the description of the assumptions complete the description of the data collection for Pulp & Paper Bio-sludge case study (Section 4.1.1).

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Table 4- Life Cycle Inventory of F-CUBED Production System for Pulp & Paper Bio-sludge Case Study (a)

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
UPSTREAM	Waste Water Treaatment	Land Use Change	Forest land transormation	8,46E-03	m2	Foreground	Biological sludge (3,5%, DM)	Product	9,89E-02	t wb/tADp	Foreground
			Occupation, industrial area	1,55E-04	m2a	Foreground	Treated water stream	Product	1,79E+01	t/tADp	Background
		WWT	Waste water from idustrial process	1,80E+01	t/tADp	Background					
			Urea (46%)	5,69E-01	kg/tADp	Foreground					
			Phosphoric acid (85%)	1,72E-01	kg/tADp	Foreground					
			Building construction	1,55E-04	m2/tADp	Foreground					
			Pipeline long distance	1,26E-07	km/tADp	Foreground					
		Electricity/heat	Electricity, medium voltage, Sweden country-mix	8,00E+00	kWh/tADp	Background					
	Enhanced Bio-sludge	Biogenic residues	Biological sludge (3,5%, DM)	9,89E-02	t wb/tADp	Foreground	Enhanced Bio-sludge by screew press (DM 10%)	Product	3,29E-02	t wb/tADp	Foreground
		Decanter-centrifuge ANDRITZ D-Series	Steel, low-alloyed	3,08E-04	kg/tADp	Background	Liquid fraction (waste water from decanter-centrifuge)	Product	6,60E-02	t wb/tADp	Calculated
			Electricity, medium voltage, Sweden country-mix	1,10E-01	kWh/tADp	Background					
MAIN STREAM	TORWASH pretreatment	Biogenic residues	Enhanced Bio-sludge by screew press (DM 10%)	3,29E-02	t wb/tADp	Foreground	TORWASH effluent (8,5%)	Product	3,87E-02	t wb/tADp	Foreground
		Tap water	additional diluition	5,80E-03	t wb/tORP	Calculated	Hydrogen sulfide	Emission to Air	2,71E-03	kg/tADp	Foreground
		Torwash reactor	Steel low alloyed	3,08E-04	kg/tADp	Background					
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	4,25E-03	kgFe2O3/tADp	Foreground					
			Silica sand	1,60E-03	kgSiO2/tADp	Foreground					
			Oxygen, liquid	1,28E-03	kgO2/tADp	Foreground					
		Electricity/heat	Electricity, medium voltage, Sweden country-mix	2,26E-01	kWh/tADp	Calculated					
	Dewatering by Limburg Filter-Press	Feedstock	TORWASH effluent (DM 8,5%)	3,87E-02	t wb/tADp	Foreground	SOLIDS (42,3% DM), press cake	Product	1,14E-02	t wb/tADp	Foreground
			Fiber sludge stream (DM 1,65%)	9,32E-02	t wb/tADp	Foreground	FILTRATE (3 % DM), Liquid frac	Product	1,21E-01	t wb/tADp	Calculated
		Limburg Filter-Press	Steel, low-alloyed	1,21E-03	t db/tADp	Background/Foreground					
			Polypropylene, granulate	2,76E-04	kg db/tADp	Background/Foreground					
			Electricity, medium voltage, Sweden country-mix	1,73E-01	kWh/tADp	Foreground					
	Pelletizing	CMP Pellet production	SOLIDS (42,3% DM), press cake	1,14E-02	t wb/tADp	Foreground	Pellet (MC 8%; DM 92%)	Product	5,25E-03	t wb/tADp	Foreground
			Wood pellet production/kwh	4,45E-01	kWh/tADp	Foreground	Water evaporated	Emission to Air	6,16E-03	t /tADp	Foreground
		Transport to the plant	Transport, freight, lorry >32 metric ton, EURO4	9,13E-01	tkm/tADp	Background	Water evaporated	Emission to Water	6,16E-03	t /tADp	Foreground
		Storage and handling at the plant	Skid-steer loader 155 kW, Load capacity 5 m3	1,63E-02	m3/tADp	Foreground/Background					

Table 4 - - Life Cycle Inventory of F-CUBED Production System for Pulp & Paper Bio-sludge Case Study (b)

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
DOWNSTREAM	Biomass boiler	Combustion in boiler	Pellet (MC 8%; DM 92%)	5,25E-03	t wb/tADp	Foreground	Energy-Heat-Steam	Product	8,21E+01	MJ/tADp	Foreground
			Transport, freight, lorry 16-32 metric ton, EURO4	5,25E-01	tkm/tADp	Background	Ash from paper production sludge	Waste to treatment	1,98E-03	t/tADp	Foreground
			Heat, central or small-scale, other than natural gas for heat production, wood pellet, at furnace 300kW /kg pellet (LHV specific)	5,25E+00	kg wb/tADp	Background/Calculated					
		Electricity/heat	Included in the energy consumption of the Heat Central Small Scale unit process								
	Electric power production by Steam Turbine	Steam Turbine	Steel, low-alloyed	8,50E-04	kg/t ADp	Background	Electric power production	Product	4,56E+00	kWh/tADp	Background
		Electricity/heat	Energy-Heat-Steam	8,21E+01	MJ/tADp	Foreground	Heat, central or small-scale, natural gas	Avoided products	1,40E+01	kWh/tADp	Background/Calculated
FILTRATE PROCESSING	Anaerobic digestion	Feedstock	FILTRATE_LMF-press (Liquid fraction), DM 3%	1,21E-01	twb/TADp	Foreground	Biogas from anaerobic digestion	Products	5,10E-01	Nm3/tADp	Foreground
		Biogas production process proxy	Biogas anaerobic digestion of manure /kg dig.	7,47E-03	kg/tADp	Foreground	Digestate	Products	7,47E-03	kg/tADp	Foreground
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	7,09E-03	kgFe2O3/tADp	Foreground	Urea as N	Avoided products	1,25E-01	kg/tADp	Background
			Silica sand	2,66E-03	kgSiO2/tADp	Foreground	Phosphate fertiliser, as P2O5	Avoided products	2,05E-01	kg/tADp	Background
			Oxygen, liquid	2,13E-03	kgO2/tADp	Foreground	Potassium sulfate, as K2O	Avoided products	2,74E-02	kg/tADp	Background
	Electricity production from biogas	Feedstock	Biogas from anaerobic digestion	5,10E-01	m3/tADp	Calculated/Foreground	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE-100%	Product	1,13E+01	kWh/tADp	Background
		Gas engine	Electricity, high voltage (SE) heat and power co-generation, biogas, gas engine/m3 BIOGAS	5,10E-01	m3/tADp	Background	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	1,95E+01	kWh/tADp	Background
								Avoided product - Scenario 54%	1,05E+01	kWh/tADp	Background
	Transformation from High to Medium Voltage	Electricity High Voltage	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	1,13E+01	kWh/tADp	Background	Electricity medium voltage from heat and power co-generation	Product	1,126E+01	kWh/tADp	Background
		Electricity transforation	Electricity voltage transformation from high to medium voltage (SE)	1,13E+01	kWh/tADp	Background					

4.1.1 Main Assumptions in the F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

The main assumptions considered in the LCI phase for the F-CUBED Production System of Pulp & Paper Bio-sludge (PPB), are described in this section.

4.1.1.1 Wastewater Treatment [PPB]

The wastewater flow has been set equal to 18 t/t_{ADp} as average value of the range 9-27 t/t_{ADp} valid for a plant capacity of about 700 kt_{ADP}/y, as indicated in BAT for Pulp, Paper and Board (Suhr, et al. 2015). The electricity consumption of 8 kWh/tADp has been collected from BAT for Pulp, Paper and Board (Suhr, et al. 2015). The treated water stream has been calculated as a difference between the biological sludge (foreground data) and the wastewater flows.

4.1.1.2 Enhanced Bio-Sludge UPR (decanter centrifuge) [PPB]

The decanter centrifuge has been modelled based on the technical specifications of the commercial Andritz decanter D3. with the hydraulic capacity ranging from 1 to 30 m^3/h. For calculating the electricity consumption the average operative power of 24 kW for about 8000 hours/year has been assumed. For calculating the construction steel, the weight of 1800 kg has been considered with an average life time of 15 years. The output liquid fraction has been calculated considering the efficiency of mechanical separation of the suspended solids of about 95% as reported in Andritz technical specifications and (Visigalli 2020). The impacts associated with the outputs of this process (enhanced bio-sludge and liquid fraction) have been shared using the mass balance criteria and considering the suspended solids content (%) of the enhanced bio-sludge and the wastewater.

4.1.1.3 TORWASH [PPB]

The Torwash reactor has been modelled based on the commercial scale data of Industry standards for reactor construction, such as American Society of Mechanical Engineers (ASME) and the European Committee for Standardization (EN). The construction steel has been estimated starting from the weight of 4000 kg and considering an average life time of 15 years. A H_2S scavenger system was used, i.e., an iron sponge as cleaning treatment for removing the H_2S from the flue gas, due to its technological maturity and ability to handle low H_2S flows (Ghimire, et al. 2021); (Shah 2022). It has been modelled on the basis of the stoichiometric reactions illustrated in (Shelford and Gooch 2017); the inlets for iron pellets, silica sand and liquid oxygen have been considered in the UPR modelling. The impacts of the process have been totally put in charge to the Torwash effluent because the H_2S is classified as a waste (pollutant emissions to air). A specific amount of tap water has been considered as input even if no dilution is carried out in this phase, as described in Section 7.1. The electricity consumption for the Torwash system has been estimated adjusting the requirement for the filter press by a coefficient (D=4.5) to take into account the discontinuous operational mode.

4.1.1.4 Dewatering by Limburg Filter Press [PPB]

The electricity consumption from foreground data is 1.3 kWh/m3 feed (Torwash effluent). It results lower with respect to the value reported in BAT for Pulp, Paper and Board (2015) (see Table 2.11. page 84) indeed this latter takes into account also the energy due to the transport of the fiber sludge stream with pumps (3.5 kWh/t_{ADp}). The construction materials (i.e. steel and polypropylene) have been calculated starting from the technical data supplied by partner (LMF) for the membrane filter press used in the long duration tests and from technical specification of Yuwei Filtration Equipment Co. Ltd., membrane filter press steel low-alloyed, 45 plates, Model: Xam G60/870-Ubk. The filtrate flow has been calculated as a difference between the Torwash effluent inlet and the output press cake, considering a solid capture index of the press equal to 100% (foreground data). The impacts associated with the outputs of this process (solids and filtrate) have been shared using the mass balance criteria and considering the suspended solids content (%) of the two fractions.

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4.1.1.5 Pelletizing [PPB]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing a commercial plant for wood pellet production. The proxy-process considers the dataset of the inputs and outputs of materials and energy for wood pellets production such as the electricity medium voltage, the water, the waste mineral oil, etc. It is valid for pellets produced in a pellets factory which uses residue as raw materials. The raw materials are firstly pre-treated and dried, then comminuted and mixed. In the end they are pelletized, cooled and stored. The pellets produced match the characteristics of the German standard of quality DIN-plus (certification). The input value chosen for calibrating the proxy-process to the experimental one is the overall electricity consumption for pelletizing step which takes into account the different phases of pre-treatment, drying, comminution, pelletizing, cooling and silage storage. This data has been gathered, for pre-treatment, comminution and pelletizing, from project partner CPM, who is specialize in pelletization operations as foreground data and from (Buratti and Fantozzi 2010) for the remaining sub-phases. The transport distance from the origination site of the solid biomass to the Pelletizing plant has been set equal to 80 km, based on (Buratti and Fantozzi 2010). The storage and handling of the cakes from dewatering step at the plant has been modelled on the process of the Ecoinvent database skid-steer loader 155 kW with a capacity volume of 5 m^3 and considering the density of 700 kg/m3 from (Shah 2022). No wastes are generated during the process: the residues are continuously reused feeding the plant (internal reuse); only the evaporated water is considered.

4.1.1.6 Pellet Combustion In Biomass Boiler [PPB]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing heat production from wood pellets in a furnace (300 kW). The proxy-process introduces in the LCA model the dataset valid for boilers with nominal capacities in the approximate range of 100 to 500 kW. The activity represents average annual operation including start/stop (warm up and cool down), which reduces the efficiency compared to rated values provided by boiler manufacturers and increases some emissions factors such as CO. Air emissions factors as well as other exchanges correspond to Ecoinvent v2.2 except of PM, CO, NOx, CH_4 and NMVOC. These key emissions factors are considered updated based on latest available information. The input value chosen for calibrating the proxy-process to the experimental one is the mass flow of the pellets feeding the boiler with their specific LHV of 18.2 MJ/kg (for MC 7%) derived as foreground data from project partner TNO. From ASPEN Plus simulations based on lab experiment performance (lb) case, the bio-pellet compositions and energy efficiencies for various feedstocks have been calculated (Dijkstra, et al. 2023). The transport distance from the Pelletizing plant to the conversion plant has been set equal to 100 km, based on Buratti and Fantozzi (2010) and considering the bulk density of pellets of 650 kg/m^3 from IRENA (2018). The heat generated (i.e. steam) by pellet combustion has been calculated using the foreground data of LHV for pulp and paper sludge and considering a combustion efficiency of 86%. This data has been provided by the project partner Smurfit Kappa as foreground data.

4.1.1.7 Electric Power Production [PPB]

The electricity is produced by a steam turbine modelled with technical data of a commercial turbine (ABB Stal back pressure turbine, 27 MW), considering an electric efficiency of 20%. The conversion energy system has an overall efficiency of 81.5% (average value from 72% to 91%), including the production of electricity ($\eta_{el} = 20\%$) and heat ($\eta_{th} = 61.5\%$), as reported in BAT for Waste Incineration (Neuwahl, et al. 2019). The process model hypothesised the 54% of exported heat outside the system, i.e. surplus not used by the mill and/or the auxiliary processes as the wastewater treatment, as reported in the BAT for Pulp, Paper and Board (Suhr, et al. 2015).

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4.1.1.8 Anaerobic Digestion [PPB]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing a commercial plant for biogas production through the anaerobic digestion of manure. This proxy-process introduces in the LCA model the inventory for the anaerobic fermentation, such as the anaerobic digestion plant for agriculture, with methane recovery, the electricity low voltage, as well as for the storage of the substrates The dataset includes the input for storage of substrate as well as the storage of digestate after fermentation. Indeed, the emissions of CO_2. CH_4. NH_3 and N_2O to air due to the storage of the substrates before the AD process as well as from storage of the digestate after the AD process, are incorporates. Water content of digestate is 95% in wet weight basis. The storage of the substrate before the AD process is assumed to be an undercover system. The activity ends with the biogas and digestate being available at the biogas plant. The input value chosen for calibrating the proxy-process to the experimental one is the digestate production (0.01% mass). This data has been gathered, as foreground data, from project partner PAQUES based on their BIOPAQ ICX process of which process conditions and process performance parameters have been provided.

A H_2S scavenger system was used i.e. an iron sponge as cleaning treatment for removing the H_2S from the flue gas, due to its technological maturity and ability to handle low H_2S flows (Ghimire, et al. 2021); (Shah 2022). It has been modelled on the basis of the stoichiometric reactions illustrated in (Shelford and Gooch 2017); the inlets for iron pellets, silica sand and liquid oxygen have been considered in the UPR modelling.

The digestate has been considered as possible substituted product of specific nutrients. The use of the digestate can allow the reduction of the use of specific fertiliser: starting from the digestate amount indicated by partners, the calculation of the avoided quantities of the traditional fertilisers has been carried out based on (Herrera, et al. 2022) and the associated credits for their avoided production have been included in the LCA model. Particularly, the contributions for the avoided urea, phosphate fertiliser and potassium sulphate have been estimated. On the other hand the diesel consumption due to the digestate spreading has been computed in the SimaPro model; the amount of the required diesel of 25.5 l/ha has been based on the literature (ENAMA 2005) for Italy.

4.1.1.9 Electricity (HV) Production From Biogas [PPB]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing a commercial gas engine producing electricity at high voltage. This proxy-process introduces in the LCA model the inventory for the production of electricity and heat from a biogas mix from different sources (biowaste, sewage sludge) when burning it in a cogeneration unit with gas engine. The main product is then considered to be electricity at high voltage, while heat is produced as a co-product. The cogeneration unit has a capacity of 160 kW_{el}; the degrees of efficiency are as follows: $\eta_{el} = 0.37$ and $\eta_{th} = 0.53$. A mix of biogas is treated in this dataset with an average lower heating value of 22.73 MJ/Nm3. The dataset provides the overall inputs from Technosphere such as heat and power co-generation unit, 160kW electrical, components for heat and electricity, lubricating oil, waste mineral oil, etc. This activity ends with the production of electricity high voltage, corresponding to the treatment of $1m^3$ of biogas in a cogeneration unit and includes emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure.

The input value chosen for calibrating the proxy-process to the experimental one is the produced biogas from anaerobic digestion for the specific biogenic residue stream whose lower heating value (LHV 19.69 MJ/Nm3) has been calculated on the basis of the biogas composition provided by project partner PAQUES based on their BIOPAQ ICX process, as before mentioned. The process hypothesised the 54% of exported heat outside the system (i.e. surplus not used by the mill and/or the auxiliary processes as the wastewater treatment) as reported in the BAT for Pulp, Paper and Board (Suhr, et al. 2015).

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4.1.1.10 Transformation From High To Medium Voltage [PPB]

This dataset represents the transformation of electricity voltage from high to medium voltage for Sweden. It includes the losses during voltage transformation but doesn't the transformer station itself as this is included in the dataset for the transmission network. The conversion factor is 1.01 kWh_{HV}/kWh_{MV}. This value compensates for the losses during transformation from high to medium voltage. The calculation is made based on total electricity losses between net electricity available at the busbar and the use of electricity calculated based on the IEA electricity information. The transformation of electricity voltage from HV to MV compliances the efficiency of about 99.5% reported by Borgato (2015).

4.2. LCI of F-CUBED Production System for Virgin Olive Pomace Case Study

In the present section the LCI phase for Virgin Olive Pomace case study is described.

F-CUBED Production System for Virgin Olive Pomace consists of 9 production steps:

1. Virgin Olive Pomace extraction (DM 19.36%) and preconditioning (destoning and dilution, DM 5.75%);
2. TORWASH pre-treatment and production of TORWASH effluent (DM 4.5%);
3. Dewatering by Membrane Filter Press (Limburg Filter Ltd), production of press cake (solids, DM 58.36%) and filtrate (liquid fraction, DM 1.8%);
4. Pelletization by CPM operational scheme and pellets production (MC 8%);
5. Production of heat and electricity from pellets by co-generation unit, Italy case;
6. Electricity voltage transformation from high to medium voltage, scenario for Italy;
7. Biogas generation by anaerobic digestion (LHV 20.59 MJ/Nm^3) and digestate production;
8. Electricity production (HV) by heat and power co-generation, biogas gas engine, Italy case;
9. Electricity voltage transformation from high to medium voltage, Italy scenario.

The table of data inventory (Table 5a & 5b) and the description of the assumptions complete the description of the data collection for Virgin Olive Pomace case study (Section 4.2.1).

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Table 5- Life Cycle Inventory of the F-CUBED Production System for Virgin Olive Pomace Case Study (a)

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
UPSTREAM	**Preconditioning**	**Feedstock as received**	Olive pomace (DM 19,63%)	1,00E+00	t OP	Foreground	Pre-conditioned olive pomace (destoned and diluited), DM 5,75%	Product	2,01E+00	t wb/tOP	Foreground/Calculated
		Destoning	Steel, low-alloyed	6,94E-03	kg/tOP	Background	Olive's stones	Product	8,05E-02	t wb/tOP	Background
		Diluition	Tap water	1,09E+00	kg/Top	Background					
		Electricity/heat	Electricity, medium voltage, Italy country-mix	6,34E+00	kWh/top	Background/Foreground					
MAIN STREAM	**TORWASH pretreatment**	**Biogenic residues**	Pre-conditioned olive pomace (destoned and diluited), DM 5,75%	2,01E+00	t wb/tOP	Foreground	TORWASH effluent (DM 4,5 %)	Product	2,57E+00	t wb/tOP	Foreground
		Tap water	additional dilution	5,59E-01	t wb/tORP	Calculated	Hydrogen sulfide	Emission to Air	1,98E-03	kg/tOP	Foreground
		Hydrothermal treatment plant	Steel, low-alloyed	1,03E-02	kg/tOP	Background					
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	6,56E-03	kgFe2O3/tOP	Calculated					
			Silica sand	2,46E-03	kgSiO2/tOP	Calculated					
			Oxygen, liquid	1,97E-03	kgO2/tOP	Calculated					
		Electricity/heat	Electricity, medium voltage, IT country-mix	1,09E+01	kWh/tOP	Calculated					
	Dewatering	**Dewatering by Limburg Filter-Press**	TORWASH effluent (DM 4,5 %)	2,57E+00	t wb/tOP	Foreground	SOLIDS (58,36% DM), press cake	Product	1,98E-01	t wb/tOP	Foreground
							FILTRATE (1,8 % DM), Liquid fraction	Product	2,37E+00	t wb/tOP	Foreground/Calculated
		Limburg Filter-Press	Steel, low-alloyed	2,39E-02	kg/tOP	Background					
			Polypropylene, granulate	2,47E-02	kg/t ORP	Background					
		Electricity/heat	Electricity, medium voltage, IT country-mix	3,09E+00	kWh/tOP	Foreground					
	Pelletting	**CMP Pellet production**	SOLIDS (58,36% DM), press cake	1,98E-01	t wb/tOP	Foreground	Pellet (MC 8%; DM 92%)	Product	1,26E-01	t wb/tOP	Foreground
			Wood pellet production/kwh	7,95E+00	kWh/tOP	Foreground/Background	Water evaporated	Emission to Air	7,25E-02	t /tORP	Calculated
		Transport to the plant	Transport, freight, lorry >32 metric ton, EURO4	1,59E+01	tkm/tOP	Background	Water evaporated	Emission to Water	7,25E-02	t /tORP	Calculated
		Storage and handling at the plant	Skid-steer loader 155 kW, Load capacity 5 m3	3,31E-01	m3/tORP	Foreground					

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Table 5 - Life Cycle Inventory of the F-CUBED Production System for Virgin Olive Pomace Case Study (b)

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
DOWNSTREAM	**Electricity production from pellet**	**Feedstock**	Pellet (MC 8%; DM 92%)	1,26E-01	t wb/tOP	Foreground	Electricity high voltage from heat and power co-generation	Product	1,61E+03	kWh el/tOP	Foreground/Calculated
		Biomass conversion process	Electricity, high voltage {IT}| heat and power co-generation, wood chips/MJ	3,31E+03	MJ/tOP	Calculated	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	4,83E+03	kWh th/tOP	Background
								Avoided product - Scenario80%	3,86E+03	kWh th/tOP	Background
	Transformation from High to Medium Voltage	**Electricity High Voltage**	Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage	1,61E+03	kWh/tORP	Background	Electricity medium voltage from heat and power co-generation	Product	1,60E+03	kWh/tOP	Background
		Electricity transforation	Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage	1,61E+03	kWh/tORP	Background					
FILTRATE PROCESSING	**Anaerobic digestion**	**Feedstock**	FILTRATE (1,8 % DM), Liquid fraction	2,37E+00	t wb/tOP	Foreground/Calculated	Biogas from anaerobic digestion	Products	2,39E+01	Nm3/tOP	Foreground/Calculated
		Biogas production process proxy	Biogas anaerobic digestion of manure /kg dig.	1,06E-03	kg/tOP	Foreground	Digestate	Products	1,06E-03	kg/tOP	Foreground
		Digestate spreading	Fertilising, by broadcaster/kg diesel	4,70E-04	kg/t OP	Background	Urea as N	Avoided products	1,77E-05	kg/tOP	Background
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	9,45E-03	kgFe2O3/tOP	Foreground	Phosphate fertiliser, as P2O5	Avoided products	2,91E-05	kg/tOP	Background
			Silica sand	3,55E-03	kgSiO2/tOP	Foreground	Potassium sulfate, as K2O	Avoided products	3,89E-06	kg/tOP	Background
			Oxygen, liquid	2,84E-03	kgO2/tOP	Foreground					
	Electricity production from biogas	**Feedstock**	Biogas from anaerobic digestion	2,39E+01	Nm3/tOP	Calculated/Foreground	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	Product	4,67E+02	kWh/tOP	Background
		Gas engine	Electricity, high voltage (IT) heat and power co-generation, biogas, gas engine/m3 BIOGAS	2,39E+01	Nm3/tOP	Background	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	8,03E+02	kWh/tOP	Background
								Avoided product - Scenario 80%	6,42E+02	kWh/tOP	Background
	Transformation from High to Medium Voltage	**Electricity High Voltage**	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	4,67E+02	kWh/tOP	Background	Electricity medium voltage from heat and power co-generation	Product	4,65E+02	kWh/tOP	Background
		Electricity transforation	Electricity voltage transformation from high to medium voltage (IT)	4,67E+02	kWh/tOP	Background					

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4.2.1 Main Assumptions in the F-CUBED Production System for Virgin Olive Pomace

The main assumptions considered in the LCI phase for the F-CUBED Production System of Virgin Olive Pomace (OP) are described in this section.

4.2.1.1 Preconditioning [OP]

The virgin olive pomace is destoned, filtrated, diluted and mixed before feeding the TORWASH treatment process. For the destoning phase, based on Leone, et al. (2015) the olives stones have been calculated considering a number of stones of about 11.9% in weight of the olives and a separation coefficient of the equipment of 58%. The electricity consumption of the destoning machine has been set equal to 24.70 kWh as reported in Leone, et al. (2015). For calculating the construction steel, the machine Clemente model Galaxy 2 has been used as a reference considering an average life time of 15 years: the machine treats 4 t/h of 2-phases olive pomace and has a weight of 1000 kg. The electricity requirement for moving the pomace from the oil mill to the pre-conditioning phase and then to the TORWASH unit, has been calculated hypothesising an average pomace density of 1.09 kg/l as indicated in Nastri, et al. (2006) and the use of the piston pump Mori-TEM model PP.210 with a flow rate of 1500 l/min and a power of 7.5 kW. The amount of added water has been calculated starting from the foreground data of the long duration tests where the dry matter content of the pomace has been monitored: the virgin olive pomace is characterised by the 19.36 % DM when produced and by the 5.75 % DM after the dilution. The preconditioned olive pomace quantity has been calculated as a difference between the diluted pomace and the separated stones. The impacts associated with the outputs of this process (preconditioned olive pomace and stones) have been shared using the mass balance criteria.

4.2.1.2 TORWASH [OP]

This unit process has been modelled as described for the PPB case study. Therefore the same assumptions apply to this production step of the OP case study.

4.2.1.3 Dewatering by Limburg Filter Press [OP]

The electricity consumption is 1.2 kWh/m^3_{feed} (Torwash effluent). The electrical energy requirement has been estimated by project partner Limburg Filter and provided as foreground data. The construction materials (i.e. steel and polypropylene) have been calculated starting from the technical data supplied by partner (LMF) for the membrane filter press used in the long duration tests and from technical specification of Yuwei Filtration Equipment Co. Ltd., membrane filter press steel low-alloyed, 45 plates, Model: Xam G60/870-Ubk. The filtrate flow has been calculated as a difference between the Torwash effluent inlet and the output press cake, considering a solid capture index of the press equal to 100% as indicated by project partner Limburg Filter and provided as foreground data.

4.2.1.4 Pelletizing [OP]

This unit process has been modelled as described for the PPB case study. Therefore the same assumptions apply to this production step of the OP case study.

4.2.1.5 Electricity (HV) Production From Pellet [OP]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing the production of heat and electricity with wood chips in co-generation plant with a capacity of 6667 kW (referring to fuel input) valid for in Italy. This proxy-process introduces in the LCA model the inventory for the electricity (HV) produced with an organic Rankine cycle (ORC) steam generator (1000 kW electrical). Wood chips are burned in a boiler (furnace 5000 kW, with silo) at a temperature of 800-1300 °C under excess air conditions and

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turned into carbon dioxide and water. The produced heat can be used directly or for steam production in order to generate electricity with a turbine.

Emissions vary with quality of the combustion (temperature, mixing of the combustion gases and the added fresh air, retention time of gases in the combustor), filter technologies and with the efficiency of the plant, for which has been considered an electricity production yield of 15% and a heat production yield of 45%. Emissions data in this dataset are taken from measurements and literature. The input value from experimental data that has been chosen for calibrating the proxy-process to the experimental one is the difference between the energy content of the F-CUBED pellets (LHV 26.3 MJ/kg, at MC 6%) in respect of the wood-chips used in CHP unit (LHV 18.9 MJ/kg). This data has been provided by project partner TNO which has calculated the bio-pellet composition by ASPEN Plus simulations based on the lab experiment performance (lb) case (Dijkstra, et al. 2023). The transport distance from the Pelletizing plant to the conversion plant has been set equal to 100 km from Buratti and Fantozzi (2010)., considering the bulk density of pellets of 650 kg/m^3 (IRENA 2018). The process hypothesised the 80% of exported heat outside the system (i.e. surplus not used by the mill and/or other auxiliary processes). This amount is higher than for the other biogenic streams case studies because the plant size of the Italian olive mills is usually small and no significant heat consumptions are required in the chain for the olive oil production, as hot water for the malaxing phase of a typical 2-phase plant.

4.2.1.6 Transformation From High To Medium Voltage (from pellets) [OP]

This dataset represents the transformation of electricity voltage from high to medium voltage for Italy. It includes the losses during voltage transformation but doesn't the transformer station itself as this is included in the dataset for the transmission network. The conversion factor is 1.01 kWh_{HV}/kWh_{MV}. This value compensates for the losses during transformation from high to medium voltage. The calculation is made based on total electricity losses between net electricity available at the busbar and the use of electricity calculated based on the IEA electricity information. The transformation of electricity voltage from HV to MV compliances the efficiency of about 99.5% reported by Borgato (2015).

4.2.1.7 Anaerobic Digestion [OP]

This unit process has been modelled as described for the PPB case study. Therefore the same assumptions apply to this production step of the OP case study. In the OP case study the LHV of the biogas has been calculated from biogas composition provided as foreground data from project partner PAQUES based on their BIOPAQ ICX process.

4.2.1.8 Electricity (HV) Production From Biogas [OP]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing a commercial gas engine producing electricity at high voltage. This proxy-process introduces in the LCA model the inventory for the production of electricity and heat from a biogas mix from different sources (biowaste, sewage sludge) when burning it in a cogeneration unit with gas engine. The main product is then considered to be electricity at high voltage, while heat is produced as a co-product. The cogeneration unit has a capacity of 160 kW_{el}; the degrees of efficiency are as follows: $\eta_{el} = 0.37$ and $\eta_{th} = 0.53$. A mix of biogas is treated in this dataset with an average lower heating value of 22.73 MJ/Nm^3. The dataset provides the overall inputs from Technosphere such as heat and power co-generation unit, 160kW electrical, components for heat and electricity, lubricating oil, waste mineral oil, etc. This activity ends with the production of electricity high voltage, corresponding to the treatment of 1m^3 of biogas in a cogeneration unit and includes emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure.

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The input value chosen for calibrating the proxy-process to the experimental one is the produced biogas from anaerobic digestion for the specific biogenic residue stream whose lower heating value (LHV 20.59 MJ/Nm3) has been calculated on the basis of the biogas composition provided by project partner PAQUES based on their BIOPAQ ICX process, as before mentioned. In the OP case study the LHV of the biogas has been cautiously set at the minimum score (LHV 17.31 MJ/Nm3) considering that the concentrations of polyphenols can determine a significant inhibition of methanogenesis (Micoli, et al. 2023) and to take into account the heterogeneity of the substrate in the actual digester. The process hypothesised the 80% of exported heat outside the system (i.e. surplus not used by the mill and/or other auxiliary processes). This amount is higher than for the other biogenic streams case studies, because the plant size of the Italian olive mills is reduced and no significant heat consumptions are required in the chain for the olive oil production, as hot water for the malaxing phase of a typical 2-phases plant.

4.2.1.9 Transformation From High To Medium Voltage (From Biogas) [OP]

This unit process has been modelled as described for the PPB case study. Therefore the same assumptions apply to this production step of the OP case study.

4.3. LCI of F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study

In the present section the LCI phase of Fruit & Vegetable (Orange Peels) case study is described.

The F-CUBED Production System for Fruit & Vegetable (Orange Peels) consists of 9 production steps:

1. Orange peels extraction (DM 20%) and preconditioning (grinding and dilution, DM 3.86%);
2. TORWASH pre-treatment and production of TORWASH effluent (DM 2.63%);
3. Dewatering by Membrane Filter Press (Limburg Filter Ltd), production of press cake (solids, DM 42.0%) and filtrate (liquid fraction, DM 1.6%);
4. Pelletization by CPM operational scheme and pellets production (MC 8%);
5. Production of heat and electricity from pellets with co-generation unit, Spain case ;
6. Electricity voltage transformation from high to medium voltage, Spain scenario;
7. Biogas generation by anaerobic digestion (LHV 19.33 MJ/Nm^3) and digestate production;
8. Electricity production (HV) by heat and power co-generation, biogas gas engine, Spain case;
9. Electricity voltage transformation from high to medium voltage, Spain scenario.

The table of data inventory (Table 6a & 6b) and the description of the assumptions complete the description of the data collection for the Fruit & Vegetable (Orange Peels) case study (Section 4.3.1).

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Table 6- Life Cycle Inventory of F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study (a)

	Process	Sub-process	Unit process - Input	Values	Units	Type of Source	Unit process - Output	Sub-process	Values	Units	Type of source
UPSTREAM	Preconditioning	Feedstock as received	Oramge peels (DM 20%)	1,00E+00	t ORP	Foreground	Pre-conditioned orange peels (grinded and diluited) DM 3,86%	Product	5,18E+00	t wb/tORP	Foreground/Calculated
		Grinding	Steel, low-alloyed	2,90E-02	kg/tORP	Background					
		Diluition	Tap water	4,18E+00	kg/tORP	Calculated					
		Electricity/heat	Electricity, medium voltage, Spain country-mix	5,13E+00	kWh/tORP	Background/Foreground					
MAIN STREAM	TORWASH pretreatment	Biogenic residues	Pre-conditioned orange peels (grinded and diluited) DM 3,86%	5,18E+00	t wb/tORP	Foreground	TORWASH effluent (DM 2,63 %)	Product	7,60E+00	t wb/tORP	Foreground
			Tap water	2,42E+00	t wb/tORP	Calculated	Hydrogen sulfide	Emission to Air	4,00E-02	kg/tORP	Foreground
		Hydrothermal treatment plant	Steel, low-alloyed	1,68E-02	kg/tOP	Background					
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	6,28E-02	kgFe2O3/tORP	Foreground					
			Silica sand	2,36E-02	kgSiO2/tORP	Foreground					
			Oxygen, liquid	1,89E-02	kgO2/tORP	Foreground					
		Electricity/heat	Electricity, medium voltage, Spain country-mix	2,80E+01	kWh/tORP	Calculated					
	Dewatering	Dewatering by Limburg Filter-Press	TORWASH effluent (DM 2,63 %)	7,60E+00	t wb/tORP	Foreground	SOLIDS (42% DM), press cake	Product	4,76E-01	t wb/tORP	Foreground
							FILTRATE (1,59 % DM), Liquid fraction	Product	7,13E+00	t wb/tORP	Foreground/Calculated
		Limburg Filter-Press	Steel, low-alloyed	9,99E-02	kg/tORP	Background					
			Polypropylene, granulate	1,10E-01	kg/t ORP	Background					
		Electricity/heat	Electricity, medium voltage, Spain country-mix	9,13E+00	kWh/tOP	Foreground					
	Pelletization	CMP Pellet production	SOLIDS (42% DM), press cake	4,76E-01	t wb/tORP	Foreground	Pellet (MC 8%; DM 92%)	Product	2,17E-01	t wb/tORP	Foreground
			Wood pellet production/kwh	2,04E+01	t wb/tORP	Foreground/Backgro	Water evaporated	Emission to Air	2,59E-01	t /tORP	Calculated
		Transport to the plant	Transport, freight, lorry >32 metric ton, EURO4	3,81E+01	t wb/tORP	Background	Water evaporated	Emission to Water	2,59E-01	t /tORP	Calculated
		Storage and handling at the plant	Skid-steer loader 155 kW, Load capacity 5 m3	7,94E-01	t wb/tORP	Foreground					

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Table 6 - Life Cycle Inventory of F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study (b)

	Process	Sub-process	Unit process - Input	Values	Units	Type of Source	Unit process - Output	Sub-process	Values	Units	Type of source
DOWNSTREAM	Electricity production from pellet	Feedstock	Pellet (MC 8%; DM 92%)	2,17E-01	t wb/tORP	Foreground	Electricity high voltage from heat and power co-generation	Product	2,35E+03	kWh el/tORP	Foreground/Calculated
		Biomass conversion process	Electricity, high voltage {ES}| heat and power co-generation, wood chips/MJ	4,83E+03	MJ/tORP	Calculated	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	7,04E+03	kWh th/tORP	Background
								Avoided product - Scenario 54%	3,80E+03	kWh th/tORP	Background
	Transformation from High to Medium Voltage	Electricity High Voltage	Electricity, medium voltage {ES}| electricity voltage transformation from high to medium voltage	2,35E+03	kWh/tORP	Background	Electricity medium voltage from heat and power co-generation	Product	2,33E+03	kWh/tORP	Background
		Electricity transforation	Electricity, medium voltage {ES}| electricity voltage transformation from high to medium voltage	2,35E+03	kWh/tORP	Background					
FILTRATE PROCESSING	Anaerobic digestion	Feedstock	FILTRATE (1,59 % DM), Liquid fraction	7,13E+00	t wb/tORP	Foreground/Calculated	Biogas from anaerobic digestion	Products	1,63E+02	Nm3/tORP	Foreground/Calculated
		Biogas production process proxy	Biogas anaerobic digestion of manure /kg dig.	4,16E-01	kg/tORP	Foreground	Digestate	Products	4,16E-01	kg/tORP	Foreground
		IRON SPONGE BED technology for H_2S Gas Cleaning	Iron pellet	2,88E-01	kgFe_2O_3/tORP	Foreground	Urea as N	Avoided products	6,96E-03	kg/tORP	Background
			Silica sand	1,08E-01	kgSiO_2/tORP	Foreground	Phosphate fertiliser, as P_2O_5	Avoided products	1,14E-02	kg/tORP	Background
			Oxygen, liquid	8,66E-02	kgO_2/tORP	Foreground	Potassium sulfate, as K_2O	Avoided products	1,52E-03	kg/tORP	Background
		Digestate landfarming	Fertilising, by broadcaster/kg diesel	1,84E-04	kg/t ORP	Background					
	Electricity production from biogas	Feedstock	Biogas from anaerobic digestion	1,63E+02	Nm3/tORP	Calculated/Foreground	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	Product	2,90E+03	kWh/tORP	Background
		Gas engine	Electricity, high voltage (ES) heat and power co-generation, biogas, gas engine/m3 BIOGAS	1,63E+02	Nm3/tORP	Background	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	4,99E+03	kWh/tORP	Background
								Avoided product - Scenario 54%	2,69E+03	kWh/tORP	Background
	Transformation from High to Medium Voltage	Electricity High Voltage	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	2,90E+03	kWh/tORP	Background	Electricity medium voltage from heat and power co-generation	Product	2,89E+03	kWh/tORP	Background
		Electricity transforation	Electricity voltage transformation from high to medium voltage (ES)	2,90E+03	kWh/tORP	Background					

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4.3.1 Main Assumptions in the F-CUBED Production System for Fruit & Vegetable (Orange peels)

The main assumptions considered in the LCI phase for the F-CUBED Production System of Orange Peels (ORP) are described in this section.

4.3.1.1 Preconditioning [ORP]

The orange peels are ground up and diluted before feeding the Torwash treatment process. The overall electricity consumption of the pre-conditioning process has been set equal to 5.13 kWh/t_{ORP} as resulted from: the electricity requirements for DM% dilution of the feedstock "ar" with water to the desired DM% for TORWASH using a mixer as reported in (Shah 2022); the electricity requirements for a shredder pump (type CRI-MAN PTS 25 – 100k); the electricity requirement for moving the orange peels from the production plant to the preconditioning phase and then to the TORWASH plant, which has been calculated hypothesising an average pomace density of 1.09 kg/l (Nastri, et al. 2006) and the use of the piston pump Mori-TEM model PP.210 with a flow rate of 1500 l/min and a power of 7.5 kW. The electricity consumption includes also the heating from 15 to 55 °C. For calculating the construction steel, the machine Clemente model Galaxy 2 has been used as a reference considering an average life time of 15 years: the machine treats 4 t/h of 2-phases olive pomace and has a weight of 1000 kg. The amount of added water for dilution has been calculated starting from the foreground data of the long duration tests where the dry matter content of the orange peels has been monitored: the orange peels are characterised by DM 20% when produced and by DM 3.86% after the dilution.

4.3.1.2 TORWASH [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study.

4.3.1.3 Dewatering by Limburg Filter Press [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study.

4.3.1.4 Pelletizing [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study.

4.3.1.5 Electricity (HV) Production From Pellet [ORP]

This unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing the production of heat and electricity with wood chips in co-generation plant with a capacity of 6667 kW (referring to fuel input) valid for Spain. This proxy-process introduces in the LCA model the inventory for the electricity (HV) produced with an organic Rankine cycle (ORC) steam generator (1000 kW electrical). Wood chips are burned in a boiler (furnace 5000 kW, with silo) at a temperature of 800-1300 °C under excess air conditions and turned into carbon dioxide and water. The produced heat can be used directly or for steam production in order to generate electricity with a turbine. Emissions vary with quality of the combustion (temperature, mixing of the combustion gases and the added fresh air, retention time of gases in the combustor), filter technologies and with the efficiency of the plant, for which has been considered an electricity production yield of 15% and a heat production yield of 45%. Emissions data in this dataset are taken from measurements and literature.

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The input value from experimental data that has been chosen for calibrating the proxy-process to the experimental one is the difference between the energy content of the F-CUBED pellets (LHV 22.2 MJ/kg, at MC 6%) in respect of the wood-chips used in CHP unit (LHV 18.9 MJ/kg). This data has been provided by project partner TNO which has calculated the bio-pellet composition by ASPEN Plus simulations based on lab experiment performance (lb) case (Dijkstra, et al. 2023). The transport distance from the Pelletizing plant to the conversion plant has been set equal to 100 km (Buratti and Fantozzi 2010), considering the bulk density of pellets of 650 kg/m^3 (IRENA 2018). The process hypothesised the 54% of exported heat outside the system (i.e. surplus not used by the mill and/or other auxiliary processes). This amount is lower than for the OP biogenic streams case studies and similar to PPB one because the activity refers to an industrial scale exploitation.

4.3.1.6 Transformation From High To Medium Voltage (From Pellets) [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study.

4.3.1.7 Anaerobic Digestion [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study. In the ORP case study the biogas LHV has been calculated from biogas composition provided as foreground data from project partner PAQUES based on their BIOPAQ ICX process.

4.3.1.8 Electricity (HV) Production From Biogas [ORP]3

Similarly to OP case study, this unit process has been designed by proxy-process of Ecoinvent 3.8 database, describing a commercial gas engine producing electricity at high voltage. This proxy-process introduces in the LCA model the inventory for the production of electricity and heat from a biogas mix from different sources (biowaste, sewage sludge) when burning it in a cogeneration unit with gas engine. The main product is then considered to be electricity at high voltage, while heat is produced as a co-product. The cogeneration unit has a capacity of 160 kW$_{el}$; the degrees of efficiency are as follows: $\eta_{el} = 0.37$ and $\eta_{th} = 0.53$. A mix of biogas is treated in this dataset with an average lower heating value of 22.73 MJ/Nm^3. The dataset provides the overall inputs from Technosphere such as heat and power co-generation unit, 160kW electrical, components for heat and electricity, lubricating oil, waste mineral oil, etc. This activity ends with the production of electricity high voltage, corresponding to the treatment of 1m^3 of biogas in a cogeneration unit and includes emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure. The input value chosen for calibrating the proxy-process to the experimental one is the produced biogas from anaerobic digestion for the specific biogenic residue stream whose lower heating value (LHV 19.33 MJ/Nm3) has been calculated on the basis of the biogas composition provided by project partner PAQUES based on their BIOPAQ ICX process, as before mentioned.

In the ORP case study the LHV has been further set at the minimum score (LHV 15.79 MJ/Nm3) considering that the concentrations of D-limonene can determine a significant inhibition of the anaerobic digestion (Lukitawesa, et al. 2018) and to take into account the heterogeneity of the substrate in the actual digester.
The process hypothesised the 54% of exported heat outside the system (i.e. surplus not used by the mill and/or other auxiliary processes). This amount is lower than for the OP biogenic streams case studies and similar to PPB because this activity refers to an industrial scale exploitation.

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4.3.1.9 TRANSFORMATION FROM HIGH TO MEDIUM VOLTAGE (from biogas) [ORP]

This unit process has been modelled as described for the PPB and OP case studies. Therefore the same assumptions apply to this production step of the ORP case study.

5. Life Cycle Impact Assessment

In the present chapter the life cycle impact assessment (LCIA) phase conducted with ReCiPe impact assessment method (Huijbregts et al., 2017) is reported, aiming to describe the magnitude and significance of the potential environmental impacts of the F-CUBED Production System applied to the biogenic residue streams, objective of the present research: Pulp & Paper Bio-sludge, Virgin Olive Pomace and Fruit & Vegetable residue stream (Orange Peels).

Moreover the sensitivity analysis is described. It has been carried out by Monte Carlo method in two subsequent steps: the first step dealt with the sensitivity analysis of the LCA model inherently to the unit processes of Ecoinvent data base; successively a second analysis has been conducted to take in consideration the uncertainty introduced by foreground sensitive data for each specific biogenic residue stream.

The cross-check of the impact assessment with sensitivity analysis allowed to improve the accuracy in selecting the relevant impact categories (IC) for the LCA study. In fact, the value of the Coefficient of Variation and its behaviour in the two subsequent sensitivity analysis give information about the reliability of the IC for the specific biogenic residue stream. The LCIA refers to 1 ton of the specific biogenic residue.
The results of LCIA for Reference Cases are reported in Section 6.2

5.1 LCIA of the F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

In the present section the life cycle impact assessment for Pulp & Paper Bio-sludge case study (PPB) is described. The data are stated in Tables 7 and 8 which report the absolute (Table 7) and percentage (Table 8) total values of 14 impact categories from ReCiPe method and their breakdown into the 10 production steps of the F-CUBE Production System for the PPB case study. The detailed contribution of production steps for every impact category is graphically illustrated in Figure 10.

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Table 7- Impact assessment per ton of residue of F-CUBED Production System in the Pulp & Paper Bio-sludgeCase Study

			Upstream processes				Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
Impact category	**Unit**	**Total**	**Biological sludge**	**Treated water stream**	**Enhanced Bio-sludge**	**Waste water from decanter-centrifuge**	**TORWASH effluent**	**Dewatering PRESS CAKE (Solids)**	**Dewatering FILTRATE (Liquid fraction)**	**PELLETIZING phase**	**Biomass boiler (combustion)**	**Electricity production system**	**Anaerobic digestion**	**Digestate**	**ELECTRICITY generation from biogas (HV)**	**ELECTRICITY voltage transformation (MV)**
Climate change	kg CO2 eq	1,79E+01	2,83E+00	-	2,69E+00	1,42E-01	2,71E+00	2,72E+00	-	3,43E+00	4,45E+00	7,94E-01	-8,86E-01	-	-9,01E-01	-6,77E-02
Ozone depletion	kg CFC-11 eq	4,88E-06	6,61E-07	-	6,33E-07	3,33E-08	6,45E-07	6,53E-07	-	7,45E-07	8,85E-07	5,60E-07	-8,48E-08	-	-1,74E-07	3,27E-07
Terrestrial acidification	kg SO2 eq	2,02E-01	1,80E-02	-	1,71E-02	9,01E-04	1,72E-02	1,73E-02	-	2,19E-02	3,23E-02	2,89E-02	-7,78E-03	-	2,47E-02	3,18E-02
Freshwater eutrophication	kg P eq	2,89E-01	9,03E-04	-	8,61E-04	4,53E-05	8,70E-04	8,78E-04	-	1,28E-03	1,33E-01	1,33E-01	-4,94E-04	-	8,45E-03	1,04E-02
Human toxicity	kg 1,4-DB eq	1,46E+01	1,12E+00	-	1,07E+00	5,61E-02	1,08E+00	1,09E+00	-	1,50E+00	2,93E+00	2,71E+00	-4,44E-01	-	1,42E+00	2,07E+00
Photochemical oxidant formation	kg NMVOC	1,08E-01	8,35E-03	-	7,95E-03	4,19E-04	8,02E-03	8,07E-03	-	1,39E-02	2,97E-02	2,58E-02	-4,12E-03	-	3,71E-03	6,64E-03
Particulate matter formation	kg PM10 eq	7,89E-02	6,92E-03	-	6,59E-03	3,47E-04	6,64E-03	6,67E-03	-	9,45E-03	1,92E-02	1,81E-02	-3,11E-03	-	3,20E-03	4,93E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	-2,16E-01	7,81E-04	-	7,43E-04	3,91E-05	7,47E-04	7,50E-04	-	1,54E-03	2,67E-03	2,48E-03	-7,25E-02	-	-6,96E-02	-8,34E-02
Freshwater ecotoxicity	kg 1,4-DB eq	1,67E+00	1,44E-01	-	1,37E-01	7,22E-03	1,39E-01	1,41E-01	-	1,64E-01	2,21E-01	1,93E-01	-6,61E-02	-	2,57E-01	3,32E-01
Agricultural land occupation	m2a	6,36E+01	9,31E-01	-	8,95E-01	4,71E-02	9,20E-01	9,38E-01	-	1,07E+01	2,17E+01	2,17E+01	-2,49E-01	-	2,37E+00	3,65E+00
Natural land transformation	m2	9,08E-03	7,82E-04	-	7,45E-04	3,92E-05	7,50E-04	7,54E-04	-	1,84E-03	2,95E-03	2,43E-03	-4,20E-04	-	-4,71E-04	-3,18E-04
Water depletion	m3	1,45E+00	1,88E-01	-	1,79E-01	9,43E-03	1,87E-01	1,88E-01	-	1,90E-01	2,06E-01	2,04E-01	-4,91E-02	-	3,64E-02	1,16E-01
Metal depletion	kg Fe eq	3,84E+00	5,88E-01	-	5,60E-01	2,95E-02	5,67E-01	5,73E-01	-	6,36E-01	7,40E-01	6,92E-01	-2,66E-01	-	-1,64E-01	-1,14E-01
Fossil depletion	kg oil eq	4,43E+00	9,66E-01	-	9,19E-01	4,84E-02	9,23E-01	9,27E-01	-	1,15E+00	1,46E+00	1,80E-01	-2,94E-01	-	-9,73E-01	-8,72E-01

Table 8 - Impact assessment of F-CUBED Production System in the Pulp & Paper Bio-sludge Case Study – Percentage contributions of the unit processes

			Upstream processes				Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
Impact category	**Unit**	**Total**	**Biological sludge**	**Treated water stream**	**Enhanced Bio-sludge**	**Waste water from decanter-centrifuge**	**TORWASH effluent**	**Dewatering PRESS CAKE (Solids)**	**Dewatering FILTRATE (Liquid fraction)**	**PELLETIZING phase**	**Biomass boiler (combustion)**	**Electricity production system**	**Anaerobic digestion**	**Digestate**	**ELECTRICITY generation from biogas (HV)**	**ELECTRICITY voltage transformation (MV)**
Climate change	%	100	15,78	-	15,02	0,79	15,12	15,21	-	19,14	24,87	4,43	-4,94	-	-5,03	-0,38
Ozone depletion	%	100	13,54	-	12,97	0,68	13,20	13,38	-	15,25	18,12	11,46	-1,74	-	-3,55	6,69
Terrestrial acidification	%	100	8,89	-	8,46	0,45	8,50	8,54	-	10,80	15,95	14,31	-3,85	-	12,19	15,74
Freshwater eutrophication	%	100	0,31	-	0,30	0,02	0,30	0,30	-	0,44	46,00	45,96	-0,17	-	2,93	3,61
Human toxicity	%	100	7,66	-	7,30	0,38	7,38	7,45	-	10,28	20,09	18,59	-3,04	-	9,76	14,15
Photochemical oxidant formation	%	100	7,70	-	7,33	0,39	7,39	7,45	-	12,83	27,36	23,81	-3,80	-	3,42	6,12
Particulate matter formation	%	100	8,77	-	8,34	0,44	8,41	8,45	-	11,96	24,33	22,94	-3,94	-	4,06	6,25
Terrestrial ecotoxicity	%	-100	0,36	-	0,34	0,02	0,35	0,35	-	0,71	1,24	1,15	-33,61	-	-32,26	-38,64
Freshwater ecotoxicity	%	100	8,62	-	8,22	0,43	8,31	8,44	-	9,81	13,26	11,55	-3,96	-	15,43	19,89
Agricultural land occupation	%	100	1,46	-	1,41	0,07	1,45	1,48	-	16,79	34,15	34,12	-0,39	-	3,72	5,74
Natural land transformation	%	100	8,61	-	8,20	0,43	8,26	8,30	-	20,27	32,44	26,80	-4,62	-	-5,18	-3,50
Water depletion	%	100	12,91	-	12,31	0,65	12,83	12,91	-	13,10	14,19	14,02	-3,37	-	2,50	7,95
Metal depletion	%	100	15,30	-	14,58	0,77	14,77	14,91	-	16,56	19,27	18,00	-6,93	-	-4,26	-2,97
Fossil depletion	%	100	21,79	-	20,74	1,09	20,84	20,93	-	25,92	32,91	4,05	-6,63	-	-21,96	-19,68

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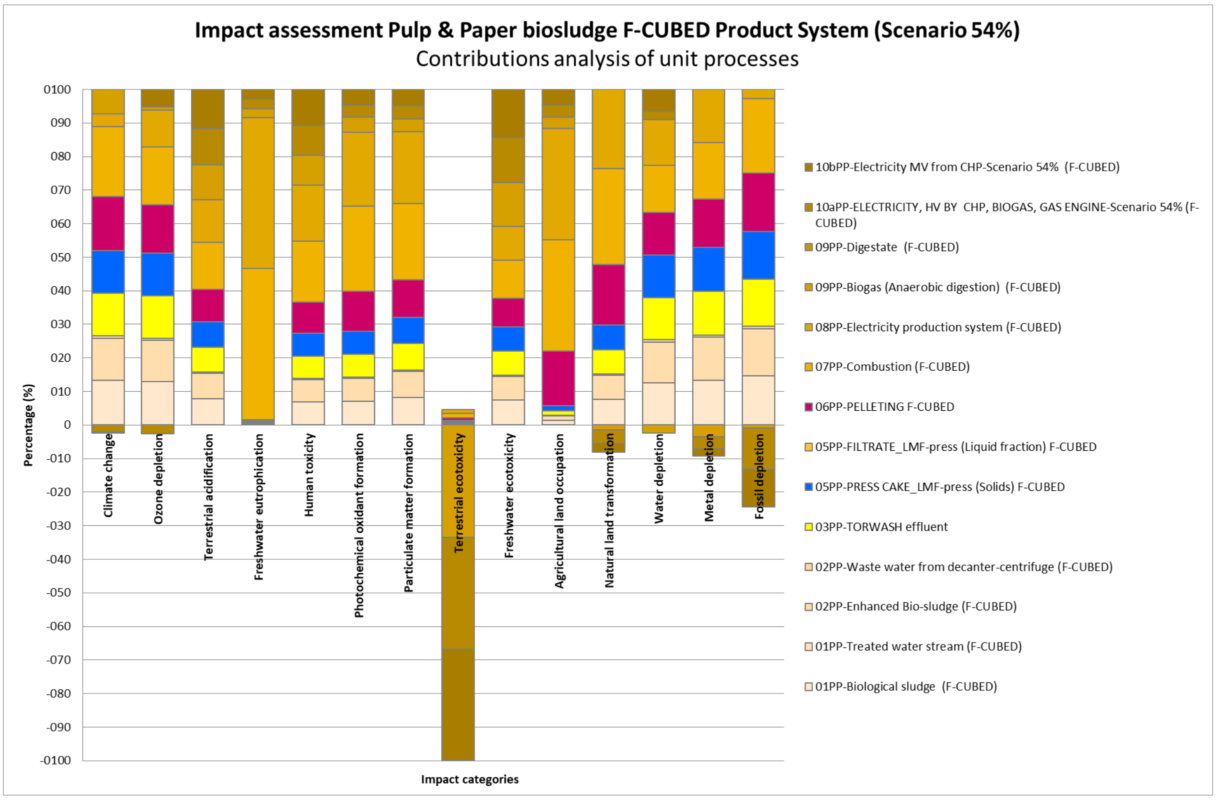

Figure 10 - Impact Assessment of F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

The relative weight of the main F-CUBED processes on the overall impact category is very limited for the indicators Freshwater eutrophication and Terrestrial ecotoxicity, which are mainly influenced by the energy conversion phases (downstream processes and filtrate processing). Moreover, the relative weight of the boiler combustion phase of the produced pellets is relevant for almost all the considered impacts: this critical aspect is probably due to the Ecoinvent process chosen for the phase modelling that considers a small-sized plant[1] for wood pellet combustion with reduced optimisations from the energetic and logistic points of view.

According to the choices carried out in the inventory construction and considering the assumptions and limitations definition, no significant effects on the impact categories are determined by credits attribution: only the Terrestrial ecotoxicity benefits from the avoided production and use of traditional fertilisers due to the spreading of the digestate, while the Fossil depletion takes advantage from the heat recovery scenario (Section 4.1.1.7).

5.1.1 Sensitivity analysis for Pulp & Paper Bio-sludge Case Study

The first step of sensitivity analysis identifies seven reliable impact categories out of fourteen, which have a coefficient of variation (CV%) ≤ 20%: TETX, PMF, TA, CC, FD, OD, MD. On the contrary, as depicted in Figure 11. five impact categories are affected by a coefficient of variation over 20% up to 100% and classified as unreliable: POF, ALO, HTX, FETX, FEUT. Two impact categories present CV's outliers and therefore have been classified as absolutely inconsistent[2]: they are NLT and WD.

[1] furnace pellets with silo, 300kW, valid for boilers with nominal capacities in the approximate range of 100 to 500 kW.

[2] Inconsistent data is here defined as a data without solidity and foundation, which does not stand the test or refutation.

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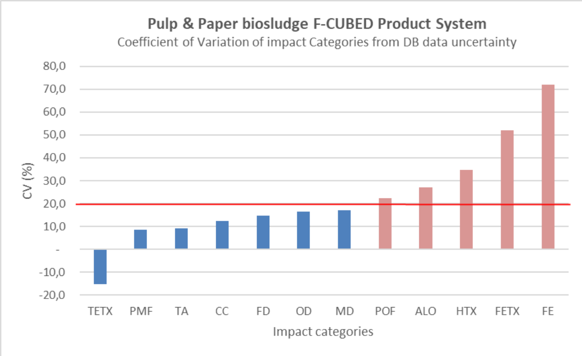

Figure 11 - Coefficient of Variation of Impact Categories from database uncertainty

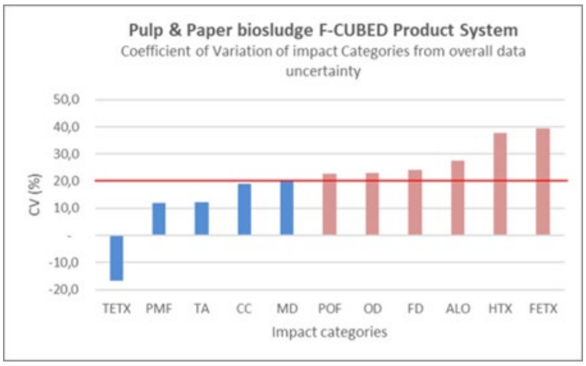

Figure 12 - Coefficient of Variation of Impact Categories from foreground data uncertainty

The second step of the sensitivity analysis considers the uncertainty introduced by the foreground data for the specific biogenic residues stream. In the Pulp & Paper Bio-sludge case study, four critical data have been identified (Table 9): Biological sludge DM (%), Torwash Electricity consumption (kWh/t $_{ADp}$), Pellet MC (%), Filtrate DM (%). These data have been used as parameter for the sensitivity analysis and variated between the minimum and maximum values provided as foreground data or according to Scott, Hendrickson and Matthews (2014).

Table 9- Relevant parameters for sensitivity analysis in the Pulp & Paper Bio-sludge Case Study

Meta-process	Data input	Value	Min.	Max.	Source
Upstream	Biological sludge DM (%)	3.5%[1]	2.8%[2]	4.2%[2]	[1]Questionnaire by TNO [2] Scott Mathius, 2014
Main stream	Torwash Electricity consumption (MV) kWh/t ADP	0.226 [1]	0.181[2]	0.271[2]	[1] estimated [2] Scott Mathius, 2014
	Pellet MC (%)	8% [1]	7% [2]	10% [2]	[1] meeting CPM; [2] D5.1
Secondary filtrate processing	Filtrate DM (%)	3 [1]	0.85 [2]	5.3 [3]	[1] average value [2] D2.1 [3] Questionnaire

The uncertainty introduced by these foreground data makes the sensitivity scenario change, as illustrated by Figure 12. On the basis of the coefficient of variation (CV%), five impact categories guarantee a sufficient reliability: TETX (16.8%), PMF (12.0%), TA (12.1%), CC (19.1%), MD (20.4%). On the contrary, the inconsistent impact categories are FEUT (528%), NLT (2.202.01%) and WD (2.924.6%). Six categories are classified as unreliable: POF (22.7%), OD (23%) FD (24%), ALO (27.5%) HTX (37.8%) FETX (39.3%).

In Table 10 every impact category is described by statistical indicators: media, median, standard deviation, coefficient of variation, limits of the 95% confidence interval, standard error of the mean. Yellow background groups unreliable categories and dark yellow the inconsistent categories.

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Table 10- Sensitivity analysis of Impact Categories from foreground data uncertainty in the PPB Case Study

Impact category	Units	Media	Mediana	SD	CV (%)	2,5%	97,5%	SEM
Terrestrial ecotoxicity	kg 1,4-DB eq	-1,96E-01	-1,92E-01	3,29E-02 -	**16,8**	-2,81E-01	-1,34E-01	3,29E-03
Particulate matter formation	kg PM10 eq	8,49E-02	8,42E-02	1,02E-02	**12,0**	6,67E-02	1,08E-01	1,02E-03
Terrestrial acidification	kg SO2 eq	2,29E-01	2,26E-01	2,78E-02	**12,1**	1,88E-01	2,99E-01	2,78E-03
Climate change	kg CO2 eq	2,13E+01	2,10E+01	4,08E+00	**19,1**	1,39E+01	3,12E+01	4,08E-01
Metal depletion	kg Fe eq	3,98E+00	3,89E+00	8,14E-01	**20,4**	2,76E+00	6,06E+00	8,14E-02
Photochemical oxidant formation	kg NMVOC	1,19E-01	1,13E-01	2,71E-02	**22,7**	8,36E-02	2,00E-01	2,71E-03
Ozone depletion	kg CFC-11 eq	5,01E-06	4,89E-06	1,15E-06	**23,0**	3,05E-06	8,17E-06	1,15E-07
Fossil depletion	kg oil eq	5,04E+00	4,85E+00	1,21E+00	**24,0**	3,07E+00	8,08E+00	1,21E-01
Agricultural land occupation	m2a	6,30E+01	6,01E+01	1,73E+01	**27,5**	3,86E+01	1,17E+02	1,73E+00
Human toxicity	kg 1,4-DB eq	1,64E+01	1,46E+01	6,21E+00	**37,8**	8,55E+00	3,44E+01	6,21E-01
Freshwater ecotoxicity	kg 1,4-DB eq	1,84E+00	1,68E+00	7,24E-01	**39,3**	9,83E-01	4,08E+00	7,24E-02
Freshwater eutrophication	kg P eq	6,74E-01	2,28E-01	3,56E+00	**528,8**	4,29E-02	1,59E+00	3,56E-01
Natural land transformation	m2	1,06E-02	-1,53E-02	2,34E-01	**2.202,1**	-3,02E-01	7,09E-01	2,34E-02
Water depletion	m3	5,58E+00	5,45E+00	1,63E+02	**2.924,6**	-3,30E+02	3,26E+02	1,63E+01

5.2 LCIA of the F-CUBED Production System for Virgin Olive Pomace Case Study

The data in Tables 11 and 12 report the absolute (Table 11) and percentage (Table 12) total values of 14 impact categories from the ReCiPe method and their breakdown into the 9 production steps of the F-CUBED Production System for the OP case study. The detailed contribution of production steps for every impact category is graphically illustrated in Figure 13.

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Table 11 - Impact assessment per ton of residue of F-CUBED Production System in the Virgin Olive Pomace Case Study

			Upstream processes	Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
Impact category	**Unit**	**Total**	**Pre-conditioning**	**TORWASH effluent**	**PRESS CAKE_dewatering (Solids)**	**FILTRATE_dewatering (Liquid fraction)**	**PELLETING**	**Electricity production system**	**Voltage transformation**	**Anaerobic digestion**	**Digestate**	**ELECTRICITY generation, HV, BIOGAS-Scenario 80%**	**ELECTRICITY generation, MV, BIOGAS-Scenario 80%**
Climate change	kg CO2 eq	-1,30E+03	2,67E+00	7,46E+00	8,90E+00	-	2,15E+01	-9,73E+02	-2,79E+02	2,01E-02	-	-1,45E+02	5,68E+01
Ozone depletion	kg CFC-11 eq	-6,50E-05	4,01E-07	1,12E-06	1,33E-06	-	2,97E-06	-8,26E-05	1,09E-05	2,81E-09	-	-1,31E-05	1,40E-05
Terrestrial acidification	kg SO2 eq	2,99E+00	1,07E-02	2,98E-02	3,55E-02	-	1,18E-01	-4,57E-01	2,21E+00	1,42E-04	-	1,34E-01	9,08E-01
Freshwater eutrophication	kg P eq	3,49E-01	7,89E-04	2,21E-03	2,64E-03	-	9,86E-03	-2,04E-02	1,84E-01	5,31E-06	-	5,53E-02	1,15E-01
Human toxicity	kg 1,4-DB eq	1,50E+02	5,80E-01	1,62E+00	1,96E+00	-	9,33E+00	-2,78E+01	1,13E+02	5,79E-03	-	5,25E+00	4,61E+01
Photochemical oxidant formation	kg NMVOC	1,02E+00	6,43E-03	1,80E-02	2,16E-02	-	1,26E-01	-5,51E-01	1,07E+00	2,16E-04	-	-7,60E-02	3,96E-01
Particulate matter formation	kg PM10 eq	9,29E-01	3,35E-03	9,36E-03	1,12E-02	-	6,09E-02	-1,26E-01	7,04E-01	9,50E-05	-	1,24E-02	2,53E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	1,26E-01	2,53E-04	7,10E-04	8,48E-04	-	1,50E-02	-2,02E-02	3,92E-02	-7,89E-06	-	3,66E-02	5,38E-02
Freshwater ecotoxicity	kg 1,4-DB eq	-2,26E+00	4,94E-02	1,36E-01	1,67E-01	-	5,76E-01	-6,98E+00	-4,28E-01	6,26E-04	-	1,16E+00	3,06E+00
Agricultural land occupation	m2a	1,60E+03	3,36E-01	9,43E-01	1,11E+00	-	1,75E+02	6,46E+02	7,19E+02	1,31E-03	-	1,88E+01	4,03E+01
Natural land transformation	m2	-1,24E-01	3,75E-04	1,05E-03	1,25E-03	-	2,07E-02	-1,16E-01	-2,12E-02	5,94E-06	-	-1,92E-02	8,22E-03
Water depletion	m3	2,56E+01	5,74E-02	1,60E-01	1,89E-01	-	2,75E-01	-3,74E-01	1,43E+01	9,37E-05	-	3,35E+00	7,62E+00
Metal depletion	kg Fe eq	-6,17E+00	8,87E-02	2,28E-01	3,18E-01	-	1,45E+00	-1,11E+01	4,58E-01	1,10E-02	-	-4,76E-01	2,89E+00
Fossil depletion	kg oil eq	-4,99E+02	8,34E-01	2,34E+00	2,81E+00	-	6,77E+00	-3,41E+02	-1,23E+02	6,12E-03	-	-5,55E+01	7,91E+00

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Table 12 - Impact assessment of F-CUBED Production System in the Virgin Olive Pomace Case Study – Percentage contributions of the unit processes

Impact category	Unit	Total	Upstream processes	Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
			Pre-conditioning	TORWASH effluent	Dewatering PRESS CAKE (Solids)	Dewatering FILTRATE (Liquid fraction)	PELLETIZING phase	ELECTRICITY generation from pellets (HV)	ELECTRICITY voltage transformation (MV)	Anaerobic digestion	Digestate	ELECTRICITY generation from biogas (HV)	ELECTRICITY voltage transformation (MV)
Climate change	%	-100,0	0,21	0,57	0,69	-	1,65	-74,88	-21,48	0,00	-	-11,13	4,37
Ozone depletion	%	-100,0	0,62	1,73	2,05	-	4,56	-127,09	16,78	0,00	-	-20,21	21,56
Terrestrial acidification	%	100,0	0,36	1,00	1,19	-	3,93	-15,30	73,95	0,00	-	4,48	30,39
Freshwater eutrophication	%	100,0	0,23	0,63	0,75	-	2,82	-5,84	52,75	0,00	-	15,82	32,83
Human toxicity	%	100,0	0,39	1,08	1,31	-	6,21	-18,49	75,28	0,00	-	3,50	30,73
Photochemical oxidant formation	%	100,0	0,63	1,77	2,12	-	12,44	-54,28	105,78	0,02	-	-7,48	39,00
Particulate matter formation	%	100,0	0,36	1,01	1,21	-	6,56	-13,54	75,78	0,01	-	1,34	27,27
Terrestrial ecotoxicity	%	100,0	0,20	0,56	0,67	-	11,88	-16,03	31,07	-0,01	-	28,99	42,67
Freshwater ecotoxicity	%	-100,0	2,18	6,01	7,37	-	25,44	-308,62	-18,90	0,03	-	51,18	135,31
Agricultural land occupation	%	100,0	0,02	0,06	0,07	-	10,94	40,30	44,91	0,00	-	1,18	2,51
Natural land transformation	%	-100,0	0,30	0,85	1,00	-	16,64	-92,91	-17,07	0,00	-	-15,42	6,60
Water depletion	%	100,0	0,22	0,62	0,74	-	1,07	-1,46	55,95	0,00	-	13,09	29,76
Metal depletion	%	-100,0	1,44	3,69	5,16	-	23,49	-180,52	7,42	0,18	-	-7,71	46,87
Fossil depletion	%	-100,0	0,17	0,47	0,56	-	1,36	-68,38	-24,65	0,00	-	-11,11	1,58

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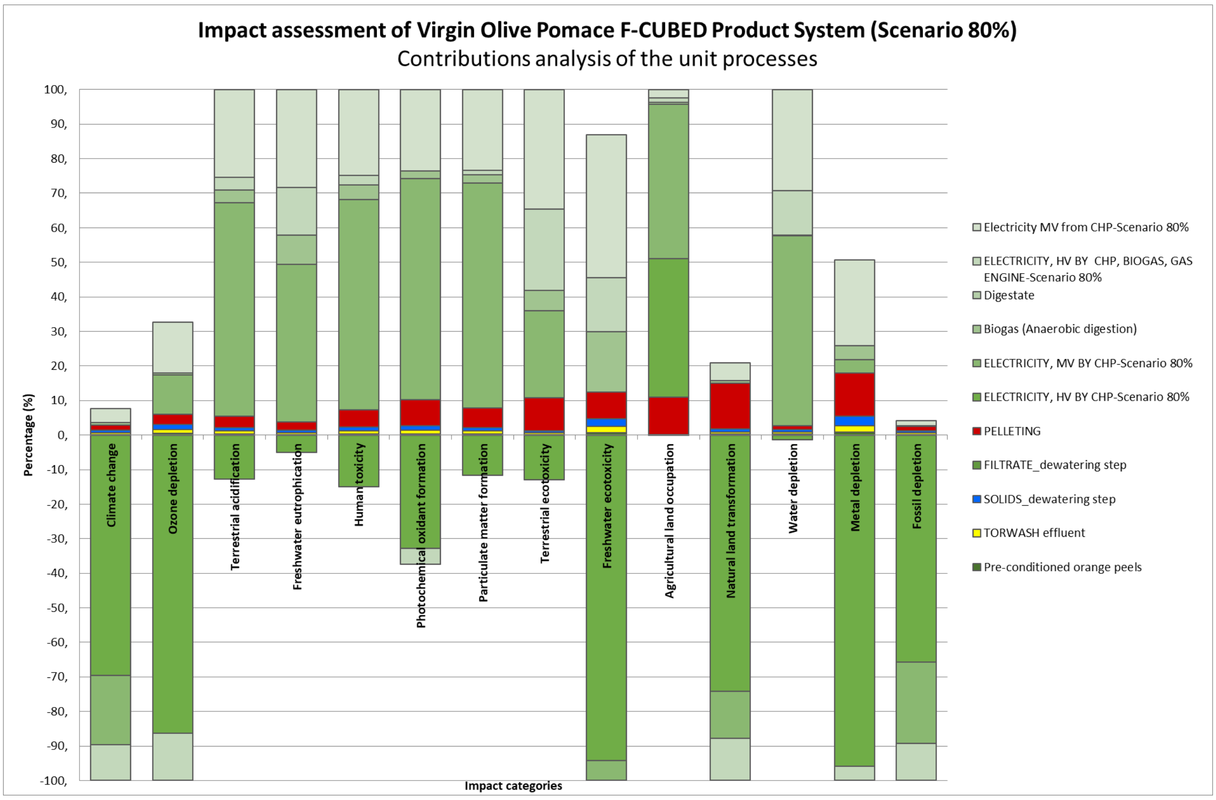

Figure 13 - Impact Assessment of F-CUBED Production System for Virgin Olive Pomace Case Study

The relative weight of the main stream processes on the obtained results is very limited for all the indicators, that are mainly influenced by the energy conversion phases (downstream processes and filtrate processing). Similar considerations can be carried out also for the pre-treatment processes. According to the choices carried out in the inventory construction and considering the assumptions and limitation definition, significant effects on the impact categories are determined by the credits attribution in the conversion phases (i.e. pellet and biogas utilisation), although the digestate spreading seems to produce reduced benefits.

5.2.1 Sensitivity analysis for F-CUBED Production System in the Virgin Olive Pomace Case Study

The first step of sensitivity analysis identifies five reliable impact categories out of fourteen, which have a coefficient of variation (CV%) ≤ 20%: CC, FD, TA, ALO, PMF. On the contrary as depicted in Figure 14. two impact categories are affected by a coefficient of variation over +/-20% up to +/-100% and classified as unreliable: POF and HTX. Seven impact categories present CV's outliers and therefore have been classified as absolutely inconsistent : they are FEUT, TETX, NLT, WD, FETX, MD and OD.

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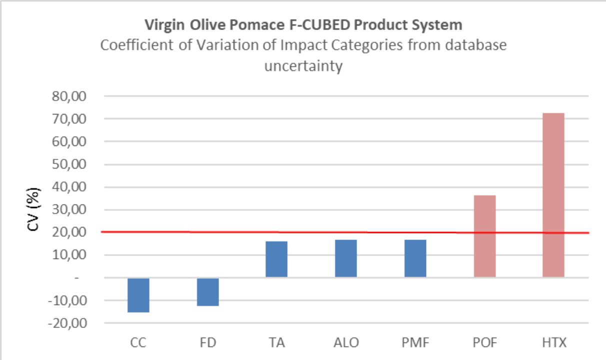

Figure 14 - Coefficient of Variation of Impact Categories from database uncertainty

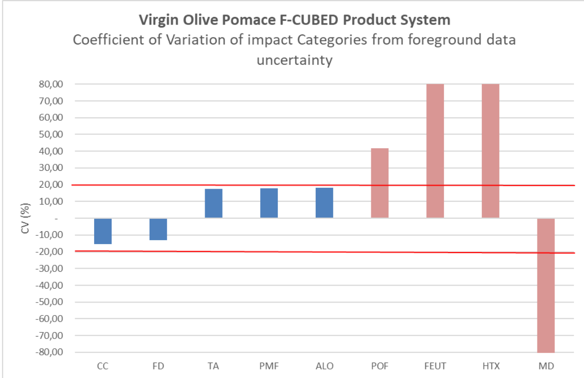

Figure 15 - Coefficient of Variation of Impact Categories from foreground data uncertainty

The second step of the sensitivity analysis considers the uncertainty introduced by the foreground data for the specific biogenic residues stream. In the Virgin Olive Pomace case study, three critical data have been identified (Tables 13): Torwash Electricity consumption (kWh/t $_{OP}$), Pellet MC (%), Biogas LHV (MJ/kg). These data have been used as parameter for the sensitivity analysis and variated between the minimum and maximum values provided as foreground data or according to Scott, Hendrickson and Matthews (2014).

Table 13 - Relevant parameters for sensitivity analysis in the Virgin Olive Pomas Case Study

Meta -process	Data input	Value	Min.	Max.	Source
Main stream	TORWASH Electricity consumption (kWh/t $_{OP}$)	10.87[1]	8.69[2]	13.04 [2]	[1] estimated [2] Scott Mathius, 2014
	Pellet MC (%)	8% [1]	6% [2]	10% [2]	[1] meeting CPM; [2] D5.1
Downstream	Biogas LHV (MJ/kg)	17.31	13.85	20.77	[1] calculated [2] Scott Mathius, 2014

The uncertainty introduced by these foreground data makes the sensitivity scenario change, as illustrated by Figure 15. On the basis of the coefficient of variation (CV%), five impact categories guarantee a sufficient reliability: FD (13.18%), CC (15.41%), TA (17.68%), PMF (17.69%) and ALO (18.20%). On the contrary, the inconsistent impact categories are OD (-121.65%), TETX (195.60%), FETX (-535.53%), WD (1.664.99%) and NLT (4.297.85%). Finally four categories are classified as unreliable: POF (41.71%), FEUT (87.20%), HTX (96.14%) and MD (-97.46%).

In Table 14 every impact category is described by statistical indicators: media, median, standard deviation, coefficient of variation, limits of the 95% confidence interval, standard error of the mean.
Yellow background groups unreliable categories and dark yellow the inconsistent categories.

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Table 14 - - Sensitivity analysis of Impact Categories from foreground data uncertainty in OP Case Study

Impact category	Unit	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Climate change	kg CO2 eq	-1,30E+03	-1,31E+03	2,01E+02 -	**15,41**	-1,74E+03	-8,83E+02	2,01E+01
Fossil depletion	kg oil eq	-5,00E+02	-5,10E+02	6,59E+01 -	**13,18**	-6,28E+02	-3,66E+02	6,59E+00
Terrestrial acidification	kg SO2 eq	3,01E+00	3,06E+00	5,32E-01	**17,68**	1,71E+00	3,97E+00	5,32E-02
Particulate matter formation	kg PM10 eq	9,34E-01	9,33E-01	1,65E-01	**17,69**	6,01E-01	1,30E+00	1,65E-02
Agricultural land occupation	m2a	1,60E+03	1,57E+03	2,91E+02	**18,20**	1,16E+03	2,33E+03	2,91E+01
Photochemical oxidant formation	kg NMVOC	1,02E+00	1,01E+00	4,25E-01	**41,71**	2,96E-01	1,90E+00	4,25E-02
Freshwater eutrophication	kg P eq	3,18E-01	2,18E-01	2,78E-01	**87,20**	6,37E-02	1,12E+00	2,78E-02
Human toxicity	kg 1,4-DB eq	1,52E+02	1,30E+02	1,46E+02	**96,14**	-4,15E+01	5,98E+02	1,46E+01
Metal depletion	kg Fe eq	-5,51E+00	-4,54E+00	5,37E+00 -	**97,46**	-2,00E+01	3,38E+00	5,37E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	1,53E-01	1,85E-01	2,99E-01	**195,60**	-3,54E-01	7,44E-01	2,99E-02
Natural land transformation	m2	1,47E-01	7,89E-01	6,33E+00	**4.297,85**	-1,20E+01	1,22E+01	6,33E-01
Water depletion	m3	-6,93E+01	-1,29E+01	1,15E+03 -	**1.664,99**	-2,67E+03	1,89E+03	1,15E+02
Freshwater ecotoxicity	kg 1,4-DB eq	-1,29E+00	-2,49E+00	6,91E+00 -	**535,53**	-1,60E+01	1,32E+01	6,91E-01
Ozone depletion	kg CFC-11 eq	-5,58E-05	-3,83E-05	6,79E-05 -	**121,65**	-2,66E-04	2,71E-05	6,79E-06

5.3 LCIA of the F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study

The data in Tables 15 and 16 report the absolute (Table 15) and percentage (Table 16) total values of 14 impact categories from ReCiPe method and their breakdown into the 9 production steps of the F-CUBED Production System for the ORP case study. The detailed contribution of production steps for every impact category is graphically illustrated in Figure 16.

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Table 15- Impact assessment per ton of residue of F-CUBED Production System in the Fruit & Vegetable (Orange peels) Case Study

Impact category	Unit	Total	Upstream processes	Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
			Pre-conditioning	TORWASH effluent	Dewatering PRESS CAKE (Solids)	Dewatering FILTRATE (Liquid fraction)	PELLETIZING phase	ELECTRICITY generation from pellets (HV)	ELECTRICITY voltage transformation (MV)	Anaerobic digestion	Digestate	ELECTRICITY generation from biogas (HV)	ELECTRICITY voltage transformation (MV)
Climate change	kg CO2 eq	-1,30E+03	1,67E+00	1,13E+01	1,46E+01	-	4,65E+01	-9,26E+02	-2,04E+02	9,20E-02	-	-5,70E+02	3,23E+02
Ozone depletion	kg CFC-11 eq	-4,88E-06	2,41E-07	1,63E-06	2,07E-06	-	6,20E-06	-7,62E-05	3,15E-05	8,44E-09	-	-5,18E-05	8,14E-05
Terrestrial acidification	kg SO2 eq	1,35E+01	1,13E-02	7,54E-02	9,65E-02	-	3,05E-01	-9,81E-02	4,88E+00	7,32E-04	-	1,01E+00	7,17E+00
Freshwater eutrophication	kg P eq	1,31E+00	6,94E-04	4,87E-03	6,18E-03	-	2,47E-02	-8,11E-04	2,87E-01	2,05E-04	-	3,15E-01	6,71E-01
Human toxicity	kg 1,4-DB eq	6,56E+02	6,03E-01	4,29E+00	5,48E+00	-	2,43E+01	-9,84E-01	2,38E+02	6,19E-02	-	4,48E+01	3,40E+02
Photochemical oxidant formation	kg NMVOC	6,27E+00	6,66E-03	4,43E-02	5,72E-02	-	3,24E-01	-1,60E-01	2,72E+00	4,37E-04	-	-1,44E-01	3,42E+00
Particulate matter formation	kg PM10 eq	4,59E+00	4,23E-03	2,79E-02	3,59E-02	-	1,62E-01	3,49E-02	1,81E+00	8,75E-04	-	1,58E-01	2,35E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	6,18E-01	8,18E-05	6,08E-04	7,89E-04	-	3,69E-02	1,05E-02	4,13E-02	-3,98E-03	-	2,47E-01	2,85E-01
Freshwater ecotoxicity	kg 1,4-DB eq	2,91E+01	5,23E-02	3,01E-01	4,03E-01	-	1,45E+00	-5,83E+00	3,95E+00	5,05E-03	-	8,34E+00	2,04E+01
Agricultural land occupation	m2a	3,09E+03	1,52E-01	1,04E+00	1,32E+00	-	4,48E+02	1,14E+03	1,20E+03	4,07E-02	-	1,08E+02	1,90E+02
Natural land transformation	m2	-2,24E-02	2,29E-04	1,57E-03	2,00E-03	-	5,18E-02	-8,00E-02	2,08E-02	6,09E-06	-	-7,18E-02	5,30E-02
Water depletion	m3	7,52E+01	2,15E-02	2,55E+00	2,59E+00	-	2,73E+00	2,12E+00	9,75E+00	-9,97E-04	-	2,30E+01	3,25E+01
Metal depletion	kg Fe eq	4,67E+01	1,95E-01	8,45E-01	1,22E+00	-	4,11E+00	-7,64E+00	1,54E+01	2,22E-01	-	1,94E+00	3,04E+01
Fossil depletion	kg oil eq	-6,27E+02	4,63E-01	3,15E+00	4,18E+00	-	1,42E+01	-3,27E+02	-1,22E+02	1,50E-02	-	-2,27E+02	2,62E+01

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Table 16 - Impact assessment of F-CUBED Production System in the Fruit & Vegetable (Orange peels) Case Study – Percentage contributions of the unit processes

			Upstream processes	Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
Impact category	**Unit**	**Total**	**Pre-conditioning**	**TORWASH effluent**	**Dewatering PRESS CAKE (Solids)**	**Dewatering FILTRATE (Liquid fraction)**	**PELLETIZING phase**	**ELECTRICITY generation from pellets (HV)**	**ELECTRICITY voltage transformation (MV)**	**Anaerobic digestion**	**Digestate**	**ELECTRICITY generation from biogas (HV)**	**ELECTRICITY voltage transformation (MV)**
Climate change	%	- 100,00	0,13	0,87	1,12	-	3,57	- 71,10	- 15,68	0,01	-	- 43,75	24,84
Ozone depletion	%	- 100,00	4,93	33,46	42,38	-	127,00	- 1.560,20	644,34	0,17	-	- 1.060,36	1.668,27
Terrestrial acidification	%	100,00	0,08	0,56	0,72	-	2,27	- 0,73	36,25	0,01	-	7,54	53,31
Freshwater eutrophication	%	100,00	0,05	0,37	0,47	-	1,88	- 0,06	21,95	0,02	-	24,04	51,28
Human toxicity	%	100,00	0,09	0,65	0,84	-	3,70	- 0,15	36,21	0,01	-	6,83	51,83
Photochemical oxidant formation	%	100,00	0,11	0,71	0,91	-	5,16	- 2,56	43,39	0,01	-	- 2,30	54,57
Particulate matter formation	%	100,00	0,09	0,61	0,78	-	3,54	0,76	39,44	0,02	-	3,44	51,32
Terrestrial ecotoxicity	%	100,00	0,01	0,10	0,13	-	5,97	1,71	6,68	- 0,64	-	39,95	46,10
Freshwater ecotoxicity	%	100,00	0,18	1,03	1,38	-	4,97	- 20,03	13,56	0,02	-	28,65	70,23
Agricultural land occupation	%	100,00	0,00	0,03	0,04	-	14,50	36,80	38,97	0,00	-	3,48	6,16
Natural land transformation	%	- 100,00	1,02	6,99	8,90	-	230,69	- 356,64	92,70	0,03	-	- 319,93	236,24
Water depletion	%	100,00	0,03	3,39	3,44	-	3,63	2,81	12,96	- 0,00	-	30,58	43,15
Metal depletion	%	100,00	0,42	1,81	2,61	-	8,79	- 16,35	32,93	0,48	-	4,16	65,16
Fossil depletion	%	- 100,00	0,07	0,50	0,67	-	2,26	- 52,06	- 19,46	0,00	-	- 36,17	4,18

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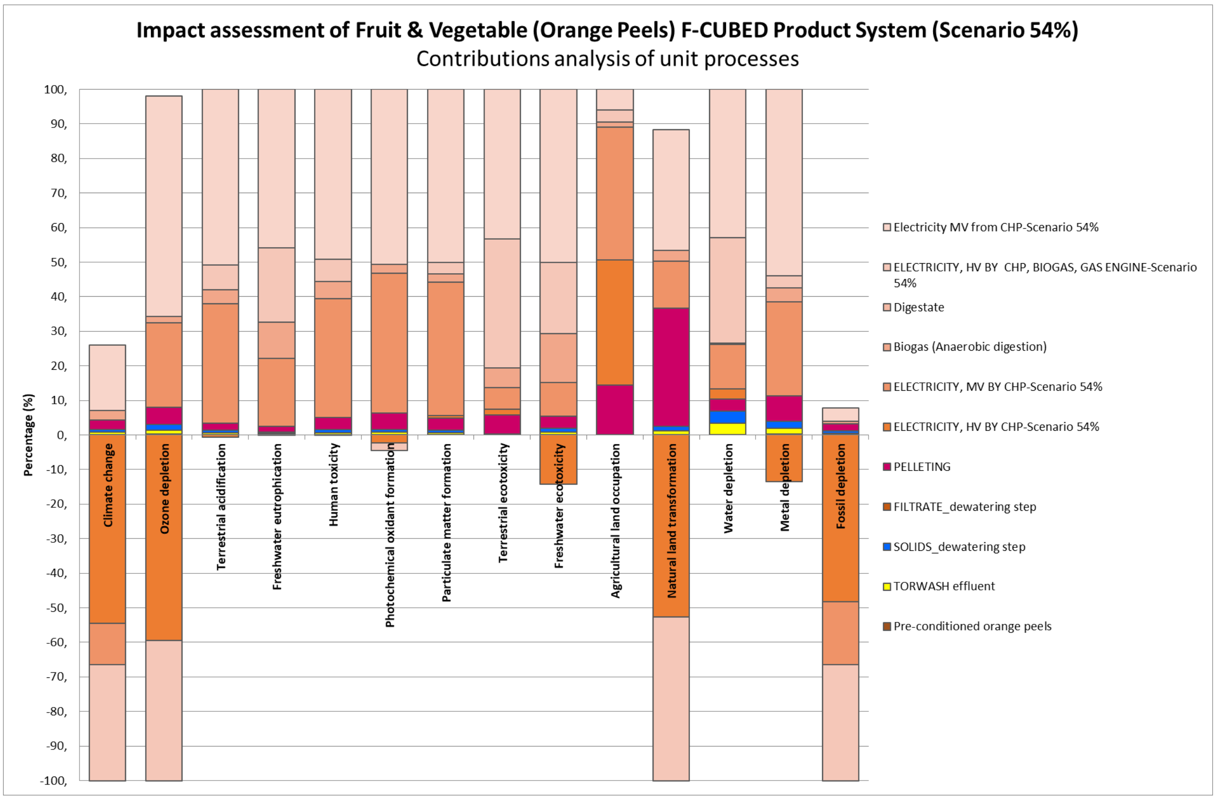

Figure 16 - Impact Assessment of F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study

The relative weight of the main stream processes on the obtained results is very limited for all the analysed indicators: only the Agricultural land occupation and Natural land transformation show significant contributions mainly due by the pelletizing phase. Similar considerations can be carried out also for the pre-treatment processes.

According to the choices carried out in the inventory construction and considering the assumptions and limitation definition, significant effects on the impact categories are determined by the credits attribution in the conversion phases (i.e. pellet and biogas utilisation), although the digestate spreading seems to produce reduced benefits.

5.3.1 Sensitivity analysis for Fruit & Vegetable (Orange Peels) Case Study

The first step of sensitivity analysis identifies seven reliable impact categories out of fourteen, which have a coefficient of variation (CV%) ≤ 20%: CC[3], FD, TA, ALO, PMF, MD and POF. On the contrary as depicted in Figure 17. three impact categories are affected by a coefficient of variation over 20% up to 100% and classified as unreliable: HTX, FETX and TETX. Finally, four impact categories present CV's outliers and therefore have been classified as absolutely inconsistent: they are FEUT, NLT, OD and WD.

[3] Actually CC is slightly above 20% (21, 62%).

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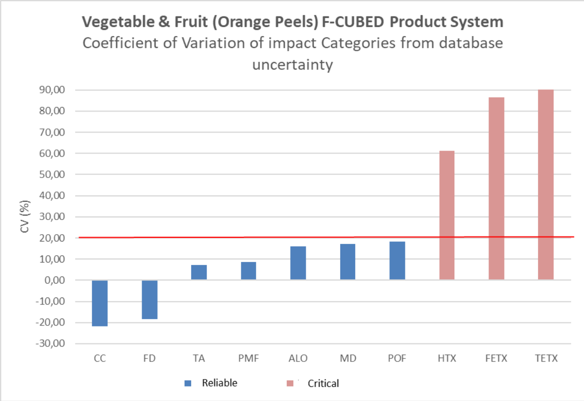

Figure 17 - Coefficient of Variation of Impact Categories from database uncertainty

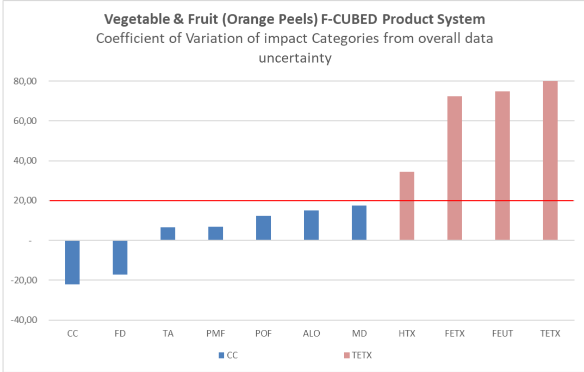

Figure 18 - Coefficient of Variation of Impact Categories from foreground data uncertainty

The second step of the sensitivity analysis considers the uncertainty introduced by the foreground data for the specific biogenic residues stream. In the ORP case study, four critical data have been identified (Tables 17): Torwash Electricity consumption (kWh/t $_{ORP}$), Pellet MC (%), Biogas LHV (MJ/kg).These data have been used as parameter for the sensitivity analysis and variated between the minimum and maximum values provided as foreground data or according to Scott, Hendrickson and Matthews (2014).

Table 17- Relevant parameters for sensitivity analysis of the Orange Peels Case Study

Meta system	UNIT process - input	Used value	Min.	Max.	Source
Main stream	TORWASH Electricity consumption (MV) (kWh/t $_{ORP}$)	27.98 [1]	22.38[2]	33.57 [2]	[1] estimated [2] Scott Mathius, 2014
	Pellet MC (%)	8% [1]	6% [2]	10% [2]	[1] meeting CPM; [2] D5.1
Downstream	Biogas LHV (MJ/kg)	15.79 [1]	18.95[2]	12.63 [3]	[1] calculated [2] Scott Mathius, 2014

The uncertainty introduced by these foreground data makes the sensitivity scenario change, as illustrated by Figure 18. On the basis of the coefficient of variation (CV%), the same seven impact categories guarantee a sufficient reliability, although with slightly difference in CV: TA (6.5%), PMF (6.77%), POF (12.42%), ALO (15.09), FD (-17.09), MD (17.64%) and CC (-21.99%). On the contrary, the inconsistent impact categories are OD (539.54%), NLT (981.74%) and WD (3.038.20%). Finally three categories are classified as unreliable: HTX (34.54%), FETX (72.30%), FEUT (74.95%) and TETX (89.29%).

In Table 18 every impact category is described by statistical indicators: media, median, standard deviation, coefficient of variation, limits of the 95% confidence interval, standard error of the mean.
Yellow background groups unreliable categories and dark yellow the inconsistent categories.

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Table 18 - Sensitivity analysis of Impact Categories from foreground data uncertainty for Fruit & Vegetable (Orange Peels)

Impact category	Unit	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Climate change	kg CO2 eq	-1,27E+03	-1,26E+03	2,79E+02 -	**22,00**	-1,92E+03	-7,47E+02	2,79E+01
Fossil depletion	kg oil eq	-6,41E+02	-6,34E+02	1,10E+02 -	**17,09**	-8,58E+02	-4,29E+02	1,10E+01
Terrestrial acidification	kg SO2 eq	1,39E+01	1,39E+01	9,02E-01	**6,50**	1,22E+01	1,58E+01	9,02E-02
Particulate matter formation	kg PM10 eq	4,65E+00	4,66E+00	3,15E-01	**6,77**	4,02E+00	5,43E+00	3,15E-02
Photochemical oxidant formation	kg NMVOC	6,23E+00	6,18E+00	7,74E-01	**12,42**	4,91E+00	8,13E+00	7,74E-02
Agricultural land occupation	m2a	3,14E+03	3,05E+03	4,75E+02	**15,09**	2,31E+03	4,21E+03	4,75E+01
Metal depletion	kg Fe eq	4,79E+01	4,75E+01	8,46E+00	**17,64**	2,92E+01	6,37E+01	8,46E-01
Human toxicity	kg 1,4-DB eq	6,74E+02	6,21E+02	2,33E+02	**34,54**	3,46E+02	1,33E+03	2,33E+01
Freshwater ecotoxicity	kg 1,4-DB eq	3,75E+01	3,17E+01	2,71E+01	**72,30**	1,14E+00	1,29E+02	2,71E+00
Freshwater eutrophication	kg P eq	9,70E-01	7,40E-01	7,27E-01	**74,95**	4,83E-01	4,05E+00	7,27E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	6,35E-01	6,04E-01	5,67E-01	**89,29**	-3,57E-01	1,84E+00	5,67E-02
Ozone depletion	kg CFC-11 eq	-2,29E-05	8,46E-06	1,23E-04 -	**539,54**	-4,63E-04	1,26E-04	1,23E-05
Natural land transformation	m2	1,21E+00	1,78E-01	1,19E+01	**981,74**	-2,65E+01	3,17E+01	1,19E+00
Water depletion	m3	7,84E+01	4,31E+02	2,38E+03	**3.038,20**	-5,89E+03	3,44E+03	2,38E+02

6. Results and Interpretation

Conducting an environmental life cycle assessment (LCA) is a crucial step in understanding the environmental impacts of a process like hydrothermal treatment of wet biogenic residues. In the present chapter the results of the Environmental Life Cycle Assessment (E-LCA) of the F-CUBED Production System applied to the three investigated biogenic residue streams are presented and discussed in a clear and comprehensive manner for the intended audience of the study.

Firstly the results of the F-CUBED Production Systems are reported. The focus is on the more significant impact categories accordingly to the goal of the E-LCA (see Chapter 2.1) considering the results reliability as obtained by sensitivity analysis. Moreover, the impact categories that are representative and relevant for the specific stream treatment (e.g. freshwater eutrophication, freshwater ecotoxicity and water depletion for Pulp and Paper Bio-sludge case study) and show high variability between the data, indicating a low reliability of the impact assessment results, require a deeper analysis: substance inventory and background unit process are investigated to analyse their distribution and contribution to the impacts generated.
For the evaluation of the environmental efficiency, the F-CUBED Production System is then compared to reference scenarios that represent the current use of the residue processing for bioenergy purposes, i.e., combustion of paper bio-sludge cakes and anaerobic digestion for olive pomace and orange peels case studies.

Finally the results interpretation is provided to draw a set of conclusions and recommendations after taking into consideration the most significant issues identified throughout the LCI and LCIA steps (ISO 2022).

6.1 Results of the F-CUBED Production Systems

In this section key LCIA results of the E-LCA are described. Table 19 reports a systemic view of the impact categories values for the three evaluated F-CUBED Production Systems, referred to each biogenic residue stream. As previously mentioned, the results were obtained using the ReCiPe impact assessment method (Huijbregts, et al., 2017), based on the LCI, its respective assumptions and sensitivity analysis.

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Table 19 - Results of the environmental life cycle assessment for the F-CUBED Production System of the investigated biogenic residue streams

Impact category	Unit	Pulp & Paper Bio-sludge	Virgin Olive Pomace	Orange Peels
Climate change	kg CO2 eq./ $t_{res.}$	1.79E+01	-1.29E+03	-1.30E+03
Ozone depletion	kg CFC-11 eq./ t_{res}	4.88E-06	-6.50E-05	-4.88E-06
Terrestrial acidification	kg SO2 eq./ t_{res}	2.02E-01	2.99E+00	1.35E+01
Freshwater eutrophication	kg P eq./ t_{res}	2.89E-01	3.49E-01	1.31E+00
Human toxicity	kg 1,4-DB eq./ t_{res}	1.46E+01	1.50E+02	6.56E+02
Photochemical oxidant formation	kg NMVOC/ t_{res}	1.08E-01	1.02E+00	6.27E+00
Particulate matter formation	kg PM10 eq./ t_{res}	7.89E-02	9.29E-01	4.59E+00
Terrestrial ecotoxicity	kg 1,4-DB eq./ t_{res}	-2.16E-01	1.26E-01	6.18E-01
Freshwater ecotoxicity	kg 1,4-DB eq./ t_{res}	1.67E+00	-2.26E+00	2.91E+01
Agricultural land occupation	m^2a/ t_{res}	6.36E+01	1.60E+03	3.09E+03
Natural land transformation	m^2/ t_{res}	9.08E-03	-1.24E-01	-2.24E-02
Water depletion	m^3/ t_{res}	1.45E+00	2.56E+01	7.52E+01
Metal depletion	kg Fe eq./ t_{res}	3.84E+00	-6.17E+00	4.67E+01
Fossil depletion	kg oil eq./ t_{res}	4.43E+00	-4.99E+02	-6.27E+02

Some impact categories of the PPB case study, e.g. CC and FD, are higher than in OP and ORP case studies. This can be referred to the more complex pre-treatment process which include the WWT. For the same reason, other impact categories, e.g. FEUT and HTX, present lower values because benefits of the reduction of the pollutants in the water compartment.

6.1.1 Identification of the most relevant impact categories for LCA study of F-CUBED Production System

The selection of impact categories is essential to capture the most significant environmental effects. Therefore, in the present section the impact categories most relevant to the environmental impacts associated with the F-CUBED Production System of the biogenic residues and their energy recovery are prioritized. Focusing on the impact pathways and affected areas of protection of the impact categories, the present LCA study will focus, accordingly to the goals and scope of LCA (Section 3.1), on the indicators described below for every single emissions compartment.

In the AIR compartment the most relevant impact categories analysed in the present study are Climate change (CC), Ozone depletion (OD) and Photochemical oxidant formation (POF).

Climate change (CC) concerns Carbon dioxide (fossil), Carbon dioxide from land transformation. Dinitrogen monoxide, Methane (biogenic and fossil). The characterization factor at midpoint level for CC is the widely used Global Warming Potential (GWP) which expresses the amount of additional radiative forcing integrated over time caused by emissions of 1 kg of GHG (W y m-2kg-1) relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of CO2. Indeed the various GHGs have different atmospheric lifetimes, resulting in time-horizon-dependent characterization factors. In the present study the value choices in the modelling of the effect of GHGs relates to Hierarchist category, with time horizon 100 years (see also Section 6.3.1). CC remains a crucial impact category because one of the strategic objectives and expected outcome of the F-CUBED project is the reduction of greenhouse gas (GHG) emissions by more than 50%, due to the residues processing, transportation and disposal.

Photochemical Ozone Formation (POF) impact category measures the potential to form ground-level ozone due to the reaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx) in the presence of sunlight. Ground-level ozone can lead to smog and respiratory issues. POF is related to photochemical reactions of NOx (NO, NO2. and NO3) and Non-Methane Volatile Organic Compounds (NMVOC). These reactions are responsible of Ozone formation, a non-linear process that depends on meteorological conditions and background concentrations of NOx and NMVOC and it is more intense in summer (Huijbregts et al. 2017). This impact indicator relates with air pollution that causes primary and secondary aerosols in the atmosphere and can have a substantial negative impact on human health because Ozone can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of respiratory distress in humans, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD) from respiratory symptoms to hospital admissions and death (Lelieveld , et al. 2015). Additionally, ozone can have a negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors (Gerosa, et al. 2015).

Ozone depletion is affected by the emissions of Ozone Depleting Substances (ODSs) which ultimately lead to damage to human health because of the resultant increase in UVB-radiation. Chemicals that deplete ozone are relatively persistent and have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere. After emissions of an ODS, the tropospheric concentrations of all ODSs increase and, after a time, the stratospheric concentration of ODS also increases. This leads to a decrease in the atmospheric ozone concentration, which in turn causes a larger portion of the UVB radiation to hit the earth. The increased radiation potentially originates increasing the incidence of skin cancer and cataracts (Huijbregts et al. 2017). The Ozone Depleting Potential (ODP), calculated by the World Meteorological Organization, quantifies the amount of ozone a substance can deplete relative to CFC-11 for a specific time horizon and is therefore largely related to the molecular structure of the ODS and especially to the number of chlorine and bromine groups in the molecule, as well as the atmospheric lifetime of the chemical. It is expressed in kg CFC-11 equivalents, and used as a characterization factor at the midpoint level (Huijbregts et al. 2017).

In the WATER compartment the most relevant impact categories analysed in the present study are Freshwater eutrophication (FEUT) and Freshwater ecotoxicity (FETX).

Freshwater eutrophication (FEUT). Agricultural residues like olive pomace and orange peels can contribute to nutrient runoff, potentially affecting water bodies. Evaluating eutrophication potential is relevant to ensure sustainable waste residues utilization. Indeed, FEUT occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen. Environmental impacts related to FEUT are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions to the fresh water, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae, and heterotrophic species such as fish and invertebrates. This ultimately leads to relative loss of species. In ReCiPe (Huijbregts et al. 2017), emissions impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction (PDF) following an increase in phosphorus concentrations in fresh water.

Freshwater ecotoxicity (FETX). Considering the high moisture content of the biogenic residues at the point of extraction (even beyond 70%), the relevance of freshwater ecotoxicity might be somewhat diminished compared to other impact categories. Indeed, freshwater ecotoxicity is often associated with the release of toxic substances into water bodies. Although the residues themselves might have high moisture content, the treatment process could involve conditions that lead to the release of potentially harmful compounds or substances into the water phase. These could include chemicals used in the treatment process or compounds that might become soluble under certain conditions. Therefore freshwater ecotoxicity could be relevant in this framework and assessing this impact category allows to ensure a comprehensive understanding of the potential environmental impacts associated with the specific residue's treatment processes and the potential for leaching or release of harmful substances into the water phase. Similarly to HTX, FETX impact category is related to the concept of bioconcentration, generally applicable for organic pollutants. The chemical 1.4-dichlorobenzene (1.4-DCB) is used as a reference substance in the midpoint calculations by dividing the calculated potential impact of the chemical by the potential impact of 1.4-DCB emitted to fresh water. The effect of ecotoxicity, expresses in cubic meter (m^3) of the medium per kg of chemicals emitted, represents the change in Potentially Disappeared Fraction (PDF) of species due to a change in the environmental concentration of a substance in the receiving compartment ((Huijbregts et al. 2017).

In SOIL compartment the most relevant impact category analysed in the present study is **Terrestrial Acidification (TA)**. Indeed the residues' composition could result in emissions that contribute to acidification of terrestrial ecosystems, particularly when considering the pulping process and potential emissions from orange peels (Suri, Singh and Nema 2022). Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in the acidity of the soil. For almost all plant species, there is a clearly defined optimum level of acidity. A serious deviation from this optimum level is harmful for that specific kind of species and is referred to as acidification. As a result, changes in levels of acidity will cause shifts in a species occurrence. Major acidifying emissions are NOx, NH3. or SO2 (Van Zelm, et al. 2013) This calculation of characterization factors for acidification for vascular plant species is based on fate factors, accounting for the environmental persistence of an acidifying substance, calculated with an atmospheric deposition model, combined with a geochemical soil acidification (Roy, et al. 2014). For acidification the modelling from emissions to damage consists of the following consecutive steps: emissions of NOx, NH3 or SO2 is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution H+ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear. To evaluate the Terrestrial acidification effects, the Acidification Potential (AP), expressed in kg SO_{2eq}, is calculated. Terrestrial acidification damage is expressed in species year/kg SO_{2eq} (Huijbregts et al. 2017).

As RESOURCE DEPLETION the most relevant impact categories analysed in the present study are Water depletion (WD) and Fossil depletion (FD).

Water depletion (WD). All water-related impacts, both on human health, terrestrial vegetation (ecosystem quality) and aquatic ecosystems, are based on water consumption. Water consumption is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds or disposed into the sea (Falkenmark and Rockstrom 2004). Water that has been consumed is thus not available anymore in the watershed of origin for humans nor for ecosystems. The modelling from water consumption to damage consists of the quantification of the reduction in freshwater availability. For humans, a reduction in freshwater availability leads to competition between different water uses. Too little irrigation will lead to reduced crop production and consequently to increased malnutrition among the local population with lower human development indexes (HDI). Impacts on terrestrial ecosystems are modelled via a potential reduction in vegetation and plant diversity. The line of reasoning is that a reduction in blue water (water in lakes, rivers, aquifers and precipitation) will potentially also reduce the available green water (soil moisture) and thus lead

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to a reduction in plant species. The fractions of freshwater fish that disappear due to water consumption are estimated based on species discharge relationships at river mouths. The characterization factor (CF) at midpoint level is cubic meter (m^3) of water consumed per m^3 of water extracted. Thus, for flows that are already given as consumptive water flows, the midpoint indicator coincides with the inventory. For water flows that are reported simply as withdrawal or as extracted water, a factor needs to be applied to account for the water-use efficiency. For agriculture, the consumptive part of the withdrawal can be estimated using water requirement ratios based on AQUASTAT (FAO 2022) and Döll and Siebert (Döll e Siebert 2002). Water consumption in industry (generalized) and for domestic water use is much lower. It is assumed that, on a global level, 5 to 10% of industrial water use is consumptive (i.e. there is a return flow of 90-95% of withdrawn water) and 10% of domestic water use is consumptive (Huijbregts et al. 2017). Based on this information, it is convenient to apply a water requirement ratio of 10% for both sectors.

Fossil Depletion (FD). The term fossil refers to a group of fuels/resources that contain hydrocarbons. The group ranges from volatile materials (like methane), to liquid petrol, to non-volatile materials (like coal). Evaluating the consumption of resources, especially non-renewable one such as resources of fossil origin, can provide insights into the sustainability of the process over the long term. The damage modelling is subdivided into several steps: It is assumed that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel extraction causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. In ReCiPe (Huijbregts et al. 2017), the damage to natural resource scarcity is estimated: when conventional fossil fuel production is limited by scarcity, new, so called unconventional sources will be needed to ensure sufficient supply. These unconventional sources can be unconventional fossil fuels, such as tar sands as well as “alternative” energy sources, such as uranium34. wind and solar. Also oil could be produced in alternative geographical locations with higher costs, such as Arctic regions (Vieira, et al. 2016). The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential of fossil resource (kg oil_{eq}/unit of resource), is defined as the ratio between the energy content of fossil resource x and the energy content of crude oil. The data used to derive the cost-cumulative production relationships for crude oil, natural gas and hard coal are retrieved from the International Energy Agency.

With specific focus on HUMAN HEALTH, at midpoint level, the most relevant impact categories analysed in the present study are Human toxicity and Particulate Matter Formation.

Human Toxicity (HTX): this category considers the potential impacts of emissions on human health from the residues' utilization, accounting for the toxicity of different pollutants. HTX is related to the concept of bioconcentration, generally applicable for organic pollutants. The characterization factor of human toxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical (Huijbregts et al. 2017). The chemical 1.4-dichlorobenzene (1.4-DCB) is used as a reference substance in the midpoint calculations by dividing the calculated potential impact of the chemical by the potential impact of 1.4-DCB emitted to urban air. To evaluate the human toxicity effects the human toxicity potential (HTPx,i) is used for carcinogenic or non-carcinogenic effects of a substance to a certain emissions compartment. To include the sensitivity of the human population intake fractions for metals in the calculations, different scenarios are assumed: in the egalitarian and hierarchic scenario human exposure occurs via all intake routes (air, drinking water, food). In contrast, the individualistic scenario assumes human exposure occurs via air and drinking water only.

Particulate Matter Formation (PMF). This category assesses the emissions that contribute to the formation of particulate matter, which can have negative effects on air quality and human health. Indeed, air pollution that causes primary and secondary aerosols in the atmosphere can have a substantial negative impact on human health, ranging from respiratory symptoms to hospital admissions and death. PM has both

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anthropogenic and natural sources. Although both may contribute significantly to PM levels in the atmosphere, this chapter focuses on attributive effects of PM from anthropogenic sources, since only this fraction may be influenced by human activity (Goedkoop, et al. 2009). Characterization factor at midpoint level for PMF is Particulate matter formation potential (PMFP) expressed in PM10-equivalent. PM10. the airborne fraction with a diameter of less than 10 µm, between 10 and 2.5 µm, represents a complex mixture of organic and inorganic substances (Manigrasso, et al. 2020), responsible of severe health problems as it reaches the upper part of the airways and lungs when inhaled and seems to have more visible impacts on respiratory morbidity. The effects of chronic PM exposure on mortality (life expectancy) seem instead to be attributable to fine particles, the airborne fraction below 2.5 µm (PM2.5) rather than to coarser particles. The modelling from emissions to damage is divided into five consecutive steps: emissions of NOx, NH3. SO2 or primary PM2.5 is followed by atmospheric fate and chemistry in the air; NOx, NH3. and SO2 are transformed in air to secondary aerosols. Subsequently, PM2.5 can be inhaled by the human population, leading to increased number of mortality cases in humans, and final damage to human health (Huijbregts et al. 2017).

Details and discussions in regards to the impact categories that exhibit the highest importance for the LCA of F-CUBED Production Systems of the investigated biogenic residue processing follow in the next sections.

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6.1.2 Pulp & Paper Bio-sludge (PPB)

The LCIA results for PPB case study are reported, as unit per ton of residue, in Table 20.

Table 20- Relevant impact categories for LCA study of F-CUBED Production System, in the PPB case study

Impact category	Unit	Value	CV (%)
Climate change	kg CO2 eq./ t_{ADp}	1.79E+01	19.1
Ozone depletion	kg CFC-11 eq./ t_{ADp}	4.88E-06	23.0
Terrestrial acidification	kg SO2 eq./ t_{ADp}	2.02E-01	12.1
Freshwater eutrophication	kg P eq./ t_{ADp}	2.89E-01	528.8
Human toxicity	kg 1,4-DB eq./ t_{ADp}	1.46E+01	37.8
Photochemical oxidant formation	kg NMVOC/ t_{ADp}	1.08E-01	22.7
Particulate matter formation	kg PM10 eq./ t_{ADp}	7.89E-02	12.0
Freshwater ecotoxicity	kg 1,4-DB eq./ t_{ADp}	1.67E+00	39.3
Water depletion	m^3/ t_{ADp}	1.45E+00	2924.6
Fossil depletion	kg oil eq./ t_{ADp}	4.43E+00	24

As mentioned in Section 5.1.1. the reliable impact categories are: Particulate matter formation (CV 12.0%), Terrestrial acidification (CV 12.1%), Climate change (CV 19.1%). On the contrary, the impact categories that present inconsistent data are Freshwater eutrophication (CV 528%) and Water depletion (CV 2924.6%).

Finally, Ozone depletion, Human toxicity, Photochemical oxidant formation and Freshwater ecotoxicity have high value of CV which implies a relatively large value of the standard deviation from the average value. Particularly Fossil depletion increase its CV up to 24% with respect to the database uncertainty with the introduction of foreground sensitivity data.

The detailed breakdown of these impact categories into the process steps of the F-CUBED Production System is explained in the following sub-sections.

6.1.2.1 Climate change Impact category

The Climate change impact category for PPB accounts for 17.91 kg $CO_{2\ eq.}$/ t_{ADp}. As displayed in Figure 19. combustion of the pellets in the biomass boiler (24.87%) and pelletizing phase (19.14%) provide the largest contributions to the CC impact category, releasing 4.45 and 3.43 kg $CO_{2\ eq.}$/ t_{ADp} respectively. In the main stream processes, Torwash treatment (15.12%; 2.71 kg $CO_{2\ eq.}$/ t_{ADp}) and the dewatering phase (15.21%; 2.72 kg $CO_{2\ eq.}$/ t_{ADp}) follow with equivalent contribution. Therefore the main stream processes alone account for 49.47% (8.86 kg $CO_{2\ eq.}$/ t_{ADp}).

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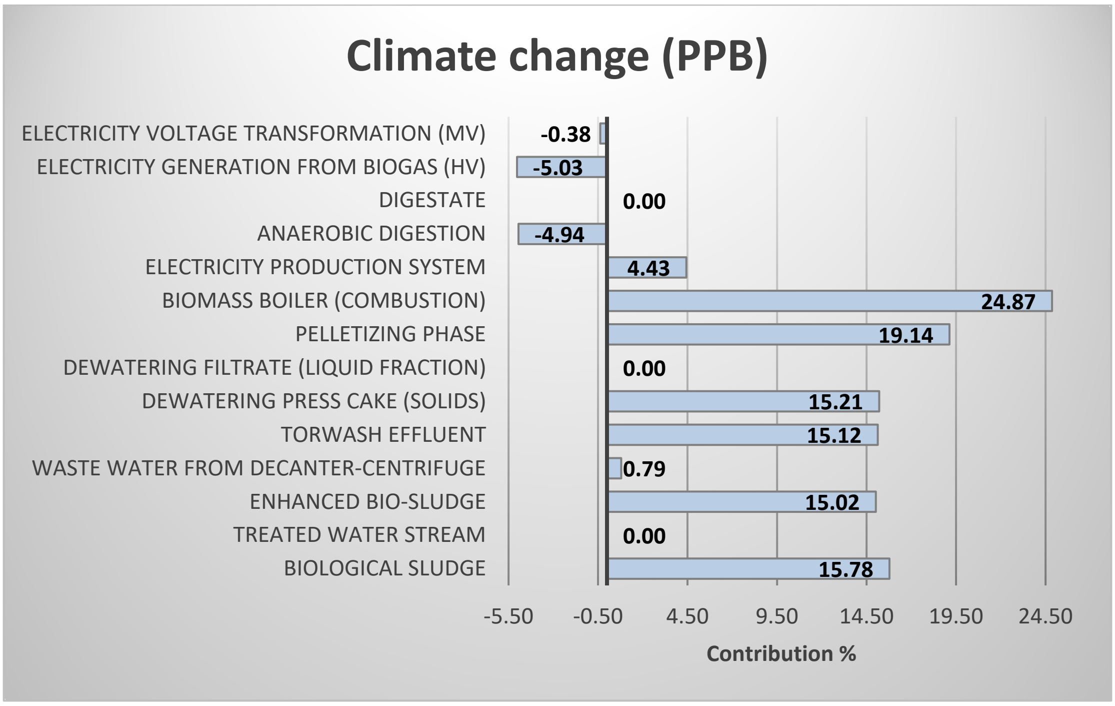

Figure 19 - Distribution of the CC impact category in the processes of the F-CUBED Production System for the PPB case study

Also the upstream pre-treatment processes, WWT and improvement/thickening of the bio-sludge with the decanter-centrifuge, give a significant contribution to the CC impact category, accounting for 31.59% (5.66 kg $CO_{2\ eq.}$/ t_{ADp}) when combined. Also note that AD, electricity generation from biogas (HV) and electricity voltage transformation (MV) account for negative emissions of -10.35%, corresponding to -1.85 kg $CO_{2\ eq.}$/ t_{ADp} of GHG emissions to the atmosphere as avoided product from Technosphere by heat recovery (scenario 54% heat exported outside the system).

The Climate change impact category for PPB, when compared to the OP and ORP case studies, is the only one resulting in positive emissions. Nonetheless, if we introduce in the LCA analysis the emissions saving resulting from the avoided treatment and disposal of the bio-sludge, the overall value of the CC impact category becomes negative, as extensively explained in Section 6.3.1.

6.1.2.2 Terrestrial Acidification Impact category

Terrestrial Acidification impact category for PPB case study accounts for 0.202 kg $SO_{2eq.}$/ t_{ADp}. As displayed in Figure 20. the TA impact category for PPB case study has its largest contributions from combustion of the pellets in the biomass boiler (15.95%) and in electricity from biogas voltage transformation (15.74%), releasing 0.0323 and 0.0318 kg $SO_{2\ eq.}$/ t_{ADp} respectively. The main stream processes, which include the novel TORWASH treatment, contribute with 27.85% and 0.0563 kg $SO_{2\ eq.}$/ t_{ADp}.

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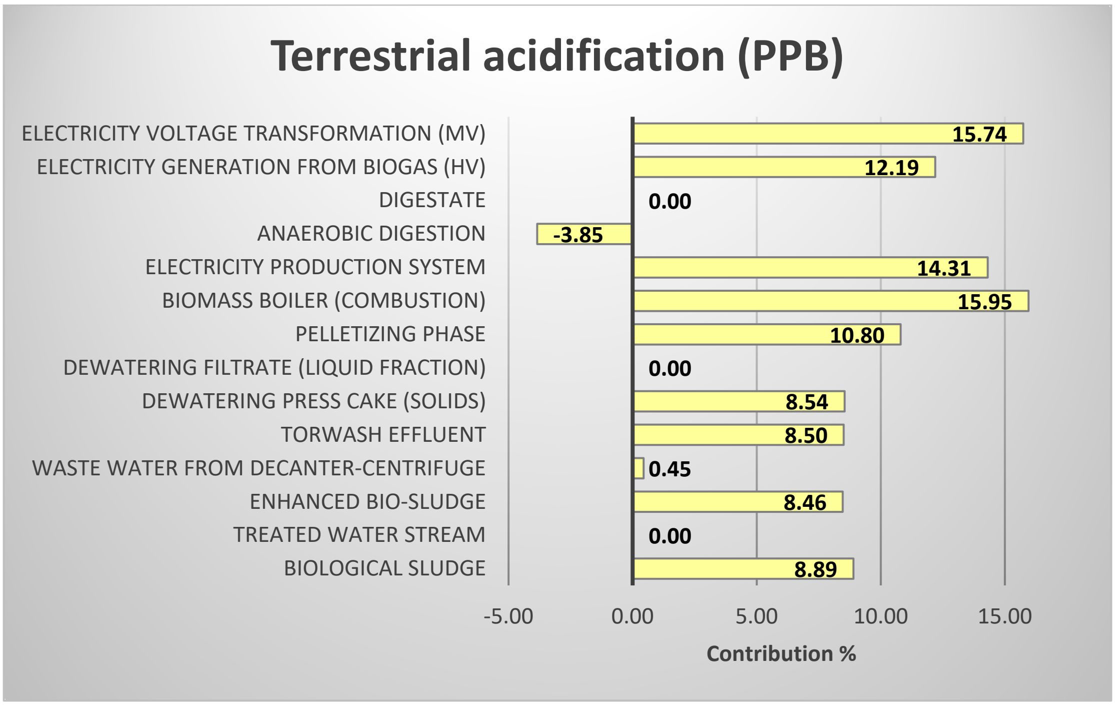

Figure 20 - Distribution of the TA impact category in the processes of the F-CUBED Production System for the PPB case study

Also the upstream pre-treatment processes, WWT and improvement/thickening of the bio-sludge with decanter-centrifuge, give a significant contribution to the TA impact category, accounting for 17.80% (0.0360 kg $SO_{2\ eq.}$/ t_{ADp}) when combined. However at a glance, it is clear that the contributions to the TA impact category are concentrated in the upper middle part of the chart (Fig. 19), in charge to downstream processes and anaerobic digestion. Nevertheless the AD process is in countertrend showing negative emissions share of -3.85% (-0.0078 kg $SO_{2\ eq.}$/ t_{ADp}).

6.1.2.3 Particulate Matter Formation Impact category

Particulate Matter Formation impact category for PPB case study accounts for 0.0789 kg $PM10_{eq.}$/ t_{ADp}. As displayed in Figure 21. the largest contributions to PMF impact category come from combustion of the pellets in the biomass boiler (24.33%) and in electricity production system (steam turbine) (22.94%), releasing 0.0192 and 0.0181 kg $PM10_{eq.}$/ t_{ADp} respectively. Therefore, over 47% of the total emissions are due to these two processes. The main stream processes, which include the novel TORWASH treatment, contribute with 28.82% and 0.0228 kg $PM10_{eq.}$/ $t_{ADp.}$

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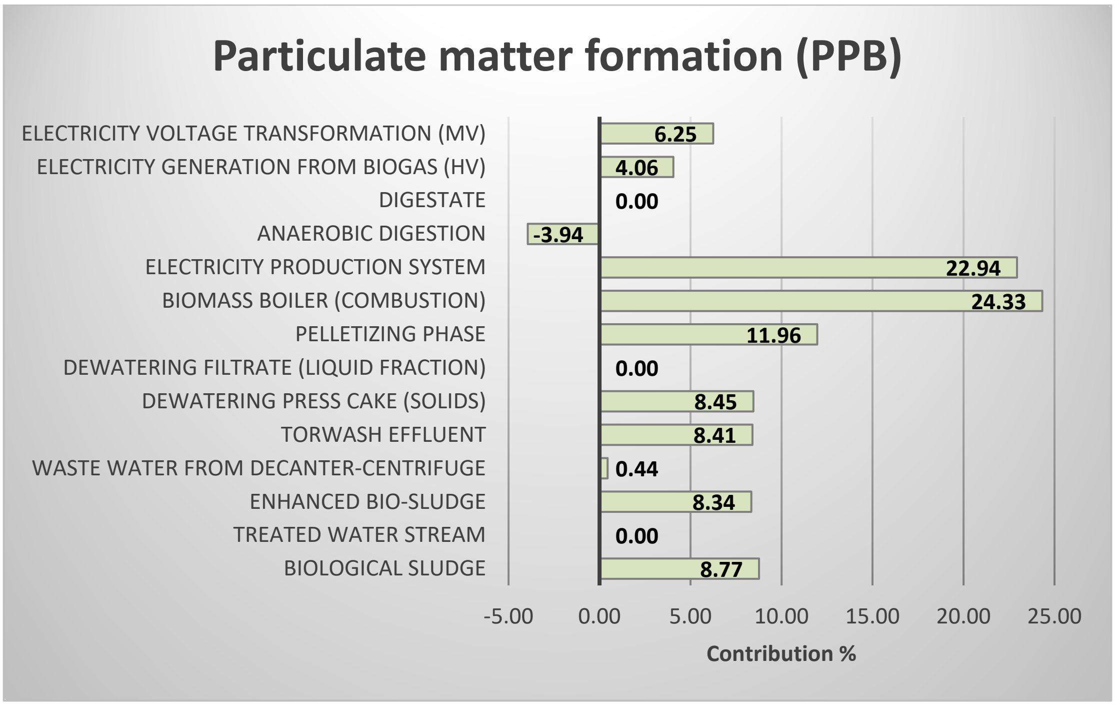

Figure 21 - - Distribution of the PMF impact category in the processes of the F-CUBED Production System for the PPB case study

In PPB case study, also the upstream pre-treatment processes, WWT and improvement of the bio-sludge with decanter-centrifuge, give a significant contribution to the PMF impact category, accounting for 17.55% (0.0139 kg PM10 $_{eq.}$/ t_{ADp}) when combined.

The only negative emissions of the production system are allocated in AD (- 3.94%; -0.0031 kg PM10 $_{eq.}$/ t_{ADp}).

6.1.2.4 Fossil Depletion Impact category

Fossil Depletion impact category for PPB case study accounts for 4.43 kg oil $_{eq.}$/ t_{ADp}. As displayed in Figure 22. FD has its bigger contributions from combustion of the pellets in the biomass boiler (32.91%) and in pelletizing phase (25.92%) releasing 1.46 and 1.15 kg oil $_{eq.}$/ t_{ADp} respectively. The main stream processes, which include the novel TORWASH treatment, contribute with 67.69% and 3.00 kg oil $_{eq.}$/ t_{ADp}.

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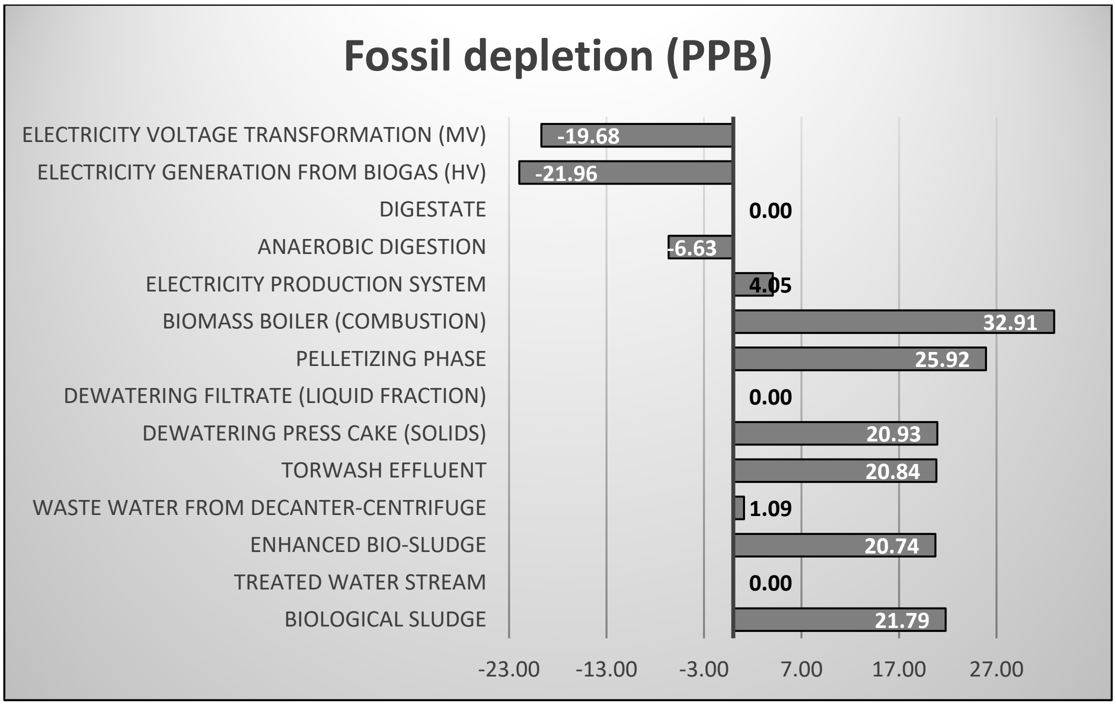

Figure 22 - Distribution of the FD impact category in the processes of the F-CUBED Production System for the PPB case study

In the PPB case study, WWT and improvement of the bio-sludge with decanter-centrifuge, as upstream pre-treatment processes, give a significant contribution to the FD impact category, accounting for over 43% (1.93 kg oil $_{eq.}$/ t_{ADp}) when combined. Secondary filtrate processing accounts for negative emissions of -48.26%, corresponding to -2.14 kg oil $_{eq.}$/ t_{ADp} as avoided product from Technosphere by heat recovery and nutrient recovery from digestate utilization.

6.1.2.5 Photochemical oxidant formation Impact category

Photochemical oxidant formation impact category uses NMVOC (Non Methane Volatile Organic Compounds) as a reference and provides 0.108 kg NMVOC / t_{ADp}. As displayed in Figure 23, POF impact category for PPB case study, derives its relevant contributions from combustion of the pellets in the biomass boiler (27.36%) and in electricity production system (steam turbine) (23.81%) releasing 0.0297 and 0.0258 kg NMVOC/ t_{ADp} respectively.

The main stream processes, which include the novel TORWASH treatment, contribute 27.67% and 0.0300 kg NMVOC/ t_{ADp}.

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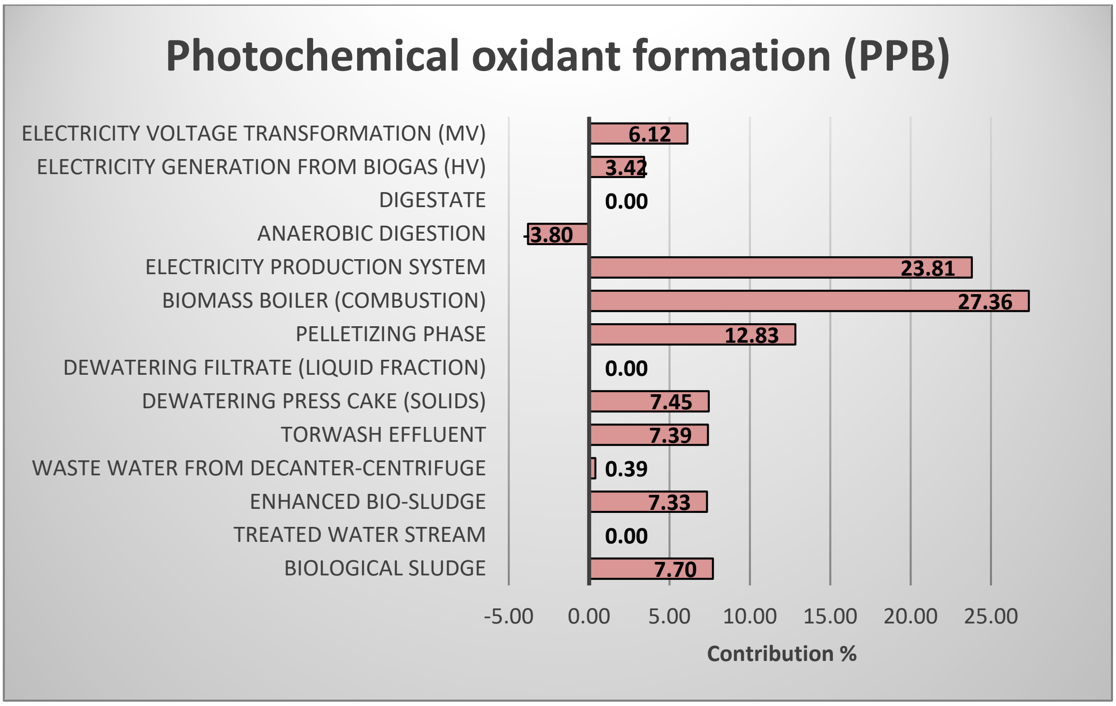

Figure 23 - Distribution of the FD impact category in the processes of the F-CUBED Production System for the PPB case study

The upstream pre-treatment processes, WWT and improvement of the bio-sludge with decanter-centrifuge, contribute to the POF impact category with over 15% of the overall emissions (0.0167 kg NMVOC/ t_{ADp}).

The filtrate processing secondary phase, in countertrend with respect to the previous impact categories account for the smallest share of impact of 5.74% (0.0062 kg NMVOC/ t_{ADp}).

6.1.2.6 Further analysis of the Impact categories for F-CUBED Production System in the Pulp & Paper Bio-sludge Case Study

Impact categories of relevance for LCA study of the F-CUBED Production System that show CV's value over 20% up to 100%, require deepening investigation. Indeed for them, the standard deviation is relatively large relative to the mean and therefore there is high variability between the data, indicating a low reliability of the impact assessment results.

For the F-CUBED Production System in the PPB case study these impacts are: Freshwater ecotoxicity (FETX) and Human toxicity (HTX). In these categories substance inventory and background unit process are investigate to analyse their distribution and contribution to the impacts generated. Data are reported in Table C1 (Appendix C).

HTX Impact category (CV 37.8%)

Human toxicity impact category for PPB case study accounts for overall 14.60 kg 1,4-DB $_{eq}$/ t_{ADp}. As displayed in Figure 24. HTX receives the more consistent contributions from the downstream processes: combustion of the pellets in the biomass boiler (20.09%) and electricity production system (steam turbine) (18.59%), releasing 2.93 and 2.71 kg 1,4-DB $_{eq.}$/ t_{ADp} respectively. The main stream processes, which include the novel TORWASH treatment, contribute with 25.11 % and 3.67 kg 1,4-DB eq/ t_{ADp}.

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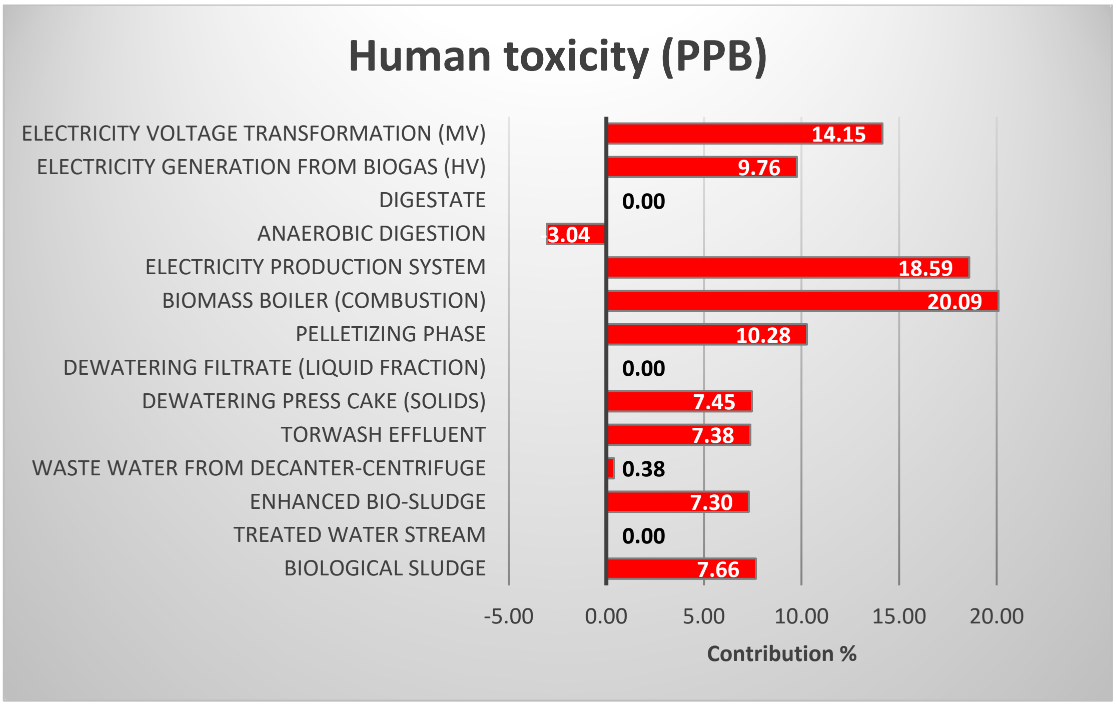

Figure 24- Distribution of the HTX impact category in the processes of the F-CUBED Production System for the PPB case study

The pre-treatment processes, WWT and improvement of the bio-sludge with decanter-centrifuge, contribute to the HTX impact category with about 15.34% of the overall emissions (2.24 kg 1,4-DB$_{eq}$./ t$_{ADp}$), while secondary filtrate processing, contributes to the HTX impact category with about 21% of the overall emissions (3.05 kg 1,4-DB$_{eq}$./ t$_{ADp}$).

HTX concerns chemical elements such as Antimony, Arsenic, Lead, Mercury, Vanadium, in air compartment and Arsenic, Barium, Lead, Manganese, Molybdenum, Zinc, in the water compartment. Respectively they account for 3.25 and 10.28 kg 1,4-DB eq/ t$_{ADp}$. It demonstrates that the water compartment is the most vulnerable to the HTX impact category for Pulp & Paper Bio-sludge case study.

FETX Impact category (CV 39.3%)

Freshwater ecotoxicity impact category for PPB case study accounts for overall 1.67 kg 1,4-DB $_{eq}$/ t$_{ADp}$.

As displayed in Figure 25. secondary filtrate processing provides the largest contribution which accounts for 31.36 % of the overall impact, corresponding to of 0.523 kg 1,4-DB $_{eq.}$/ t$_{ADp}$ emissions. Downstream and Main stream processes contribute almost equally with 24.81% and 25.56% of the overall emissions, releasing 0.41 and 0.44 kg 1,4-DB $_{eq}$/ t$_{ADp}$ respectively.

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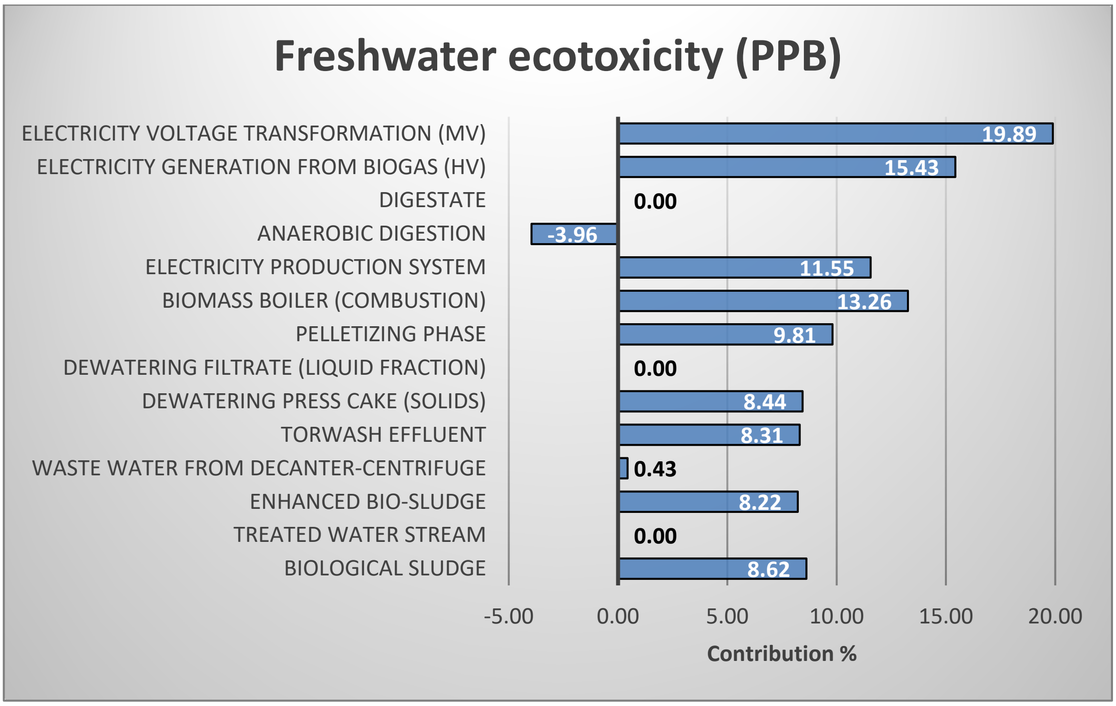

Figure 25- Distribution of the FETX impact category in the processes of the F-CUBED Production System for the PPB case study

The upstream pre-treatment processes, WWT and improvement of the bio-sludge with decanter-centrifuge, contribute to the HTX impact category with about 17.27 % of the overall emissions, realising 0.288 kg 1,4-DB $_{eq}$/ t_{ADp} . The Table C1 (Appendix C) shows that **Freshwater ecotoxicity** impact category concerns chemical elements such as Copper, Manganese, Nickel, Vanadium, Zinc, that provide a contribution of 1.64 kg 1,4-DB $_{eq}$/ t_{ADp} in water compartment. Their distribution in the production phases is in accordance with the impact distribution before mentioned. The overall positive emissions are slightly compensated by anaerobic digestion which contributes by -3.96% (-0.066 kg 1,4-DB $_{eq}$/ t_{ADp}).

For the PPB case study also Ozone depletion and Agricultural land occupation requires a brief explanation.

OD Impact category (CV 23.0 %)

OD impact category is shifted from the reliable category to unreliable category when uncertainty calculation has included the sensitive foreground data (Table 9). OD concerns Chlorine atoms in chlorofluorocarbons (CFC) and bromine atoms in halons which are effective in degrading ozone due to heterogeneous catalysis, and leads to a slow depletion of stratospheric ozone around the globe. The OD impact category uses CFC-11 (trichlorofluoromethane) as a reference and it provides a contribution of 4.88^10^{-6} kg CFC-11 eq/ t_{ADp}. The main stream processes of the F-CUBED Production System are the largest contributors (41.83%). As depicted in Figure 26. the Uranium enriched in U235 and its compounds; plutonium and its compounds; alloys, dispersions, ceramic products are responsible of this impact.

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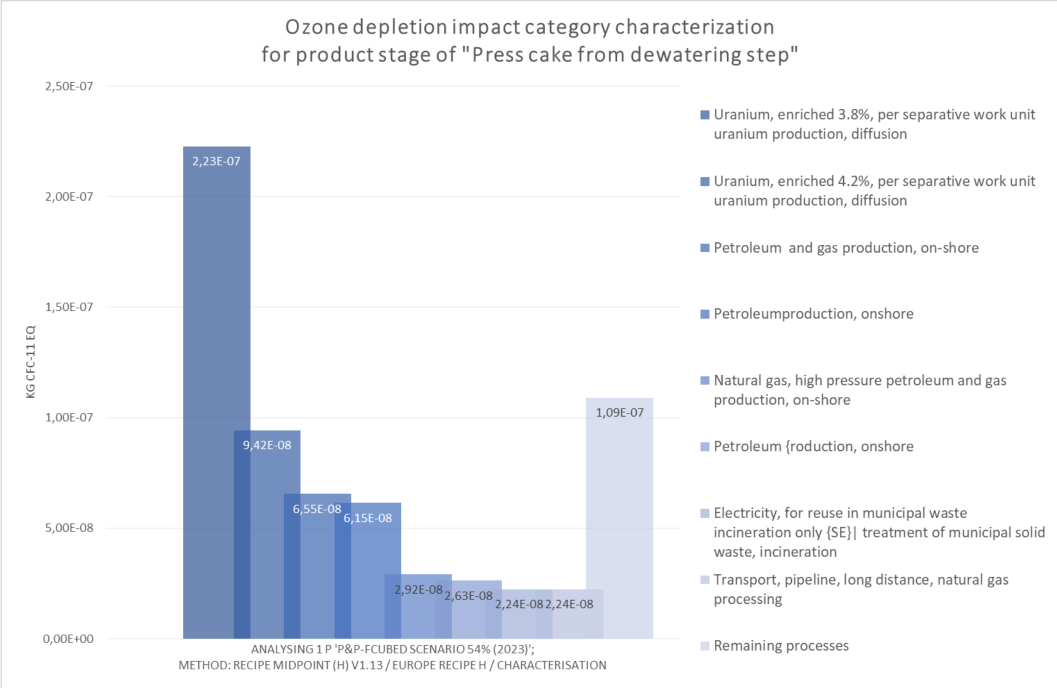

Figure 26 - Ozone depletion impact category characterization. Torwash and Pelletization steps show the same scenario

They refer to the electricity consumption and background UPR nested in the specific electricity country mix for Sweden. This item will be explained more extensively in Section 6.2.1. where the results of the LCIA for F-CUBED Production System, Reference Case and Electricity Country Mix will be compared.

ALO Impact category (CV 27.5 %)

The Agriculture Land Occupation impact category uses the amount of agricultural area occupied or transformed [m2.yr] as a reference and reflects the damage to ecosystems due to the effects of occupation and transformation of land. Although there are many links between the way land is used and the loss of biodiversity, this category concentrates on the following mechanisms (Huijbregts, et al., 2017) :

1. occupation of a certain area of land during a certain time;
2. transformation of a certain area of land.

In the PPB case study, ALO provides an overall impact of 63.58 m^2a/ t_{ADp}, mostly in charge of occupation forest intensive, unit process (88%). The downstream processes of the F-CUBED Production System are the largest contributors (43.41 m^2a/ t_{ADp}), but also Main Stream Processes contribute with 12.53 m^2a/ t_{ADp} (about 20%).

This result has to be explained because the F-CUBED technology (TORWASH and Membrane Filter Press), the most important part of the main stream processes, is assumed to be integrated in existing facilities, due to the challenges (and environmental impact) of transporting wet residue. As a consequence, the impact has to be attributed mainly to the occupation and transformation of a certain area of land by the stages like drying and pelletization which offer locational flexibility, suggesting the potential for a hub-based infrastructure, and to pellet energy conversion and biogas generation units, into electricity and voltage transformation.

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6.1.3 Virgin Olive Pomace (OP)

The LCIA results for the OP case study are reported, as unit per ton of residue, in Table 21.

Table 21 - Relevant impact categories for LCA study of F-CUBED Production System, OP case study

Impact category	Unit	Value	CV (%)
Climate change	kg CO2 eq./ $t_{OP.}$	-1.29E+03	-15.41
Ozone depletion	kg CFC-11 eq./ t_{OP}	-6.50E-05	121.65
Terrestrial acidification	kg SO2 eq./ t_{OP}	2.99E+00	17.68
Freshwater eutrophication	kg P eq./ t_{OP}	3.49E-01	87.20
Human toxicity	kg 1,4-DB eq./ t_{OP}	1.50E+02	96.14
Photochemical oxidant formation	kg NMVOC/ t_{OP}	1.02E+00	41.71
Particulate matter formation	kg PM10 eq./ t_{OP}	9.29E-01	17.69
Freshwater ecotoxicity	kg 1,4-DB eq./ t_{OP}	-2.26E+00	535.53
Water depletion	m^3/ t_{OP}	2.56E+01	1644.99
Fossil depletion	kg oil eq./ t_{OP}	-4.99E+02	13.18

As mentioned in Section 5.2.1. the reliable impact categories are: Fossil depletion (CV 13.18%), Climate change(CV 15.41%), Terrestrial acidification CV 17.68%), Particulate matter formation (CV17.69%). On the contrary, the inconsistent impact categories are: Water depletion (CV 1664.99%), Freshwater ecotoxicity (CV 535.53%) Ozone depletion (121. 65%). Finally, Freshwater eutrophication Human toxicity and Photochemical oxidant formation have high value of CV which implies a relatively large value of the standard deviation from the average value. Nevertheless, Freshwater eutrophication decreases its CV to 87.20% from inconsistent value of 150%. The detailed breakdown of these impact categories into the process steps of the F-CUBED Production System is explained in the following sub-sections.

6.1.3.1 Climate Change Impact category

The Climate change impact category for OP accounts for -1299.00 kg $CO_{2\ eq.}$/ t_{OP}. As displayed in Figure 27. CC has its major contributions in downstream processes, particularly by electricity generation from pellets (HV) (-74.88 %) releasing -972.69 kg $CO_{2\ eq.}$/ t_{OP} and electricity voltage transformation (MV) (21.48%; - 279.02 kg $CO_{2\ eq.}$/ t_{OP}); these two processes account for -96.36%, corresponding to emissions saving of -1251.71kg $CO_{2\ eq.}$/ t_{OP}, when combined. The main stream processes slightly contribute to CC with positive emissions for 2.91% (37.86 kg $CO_{2\ eq.}$/ t_{OP}).

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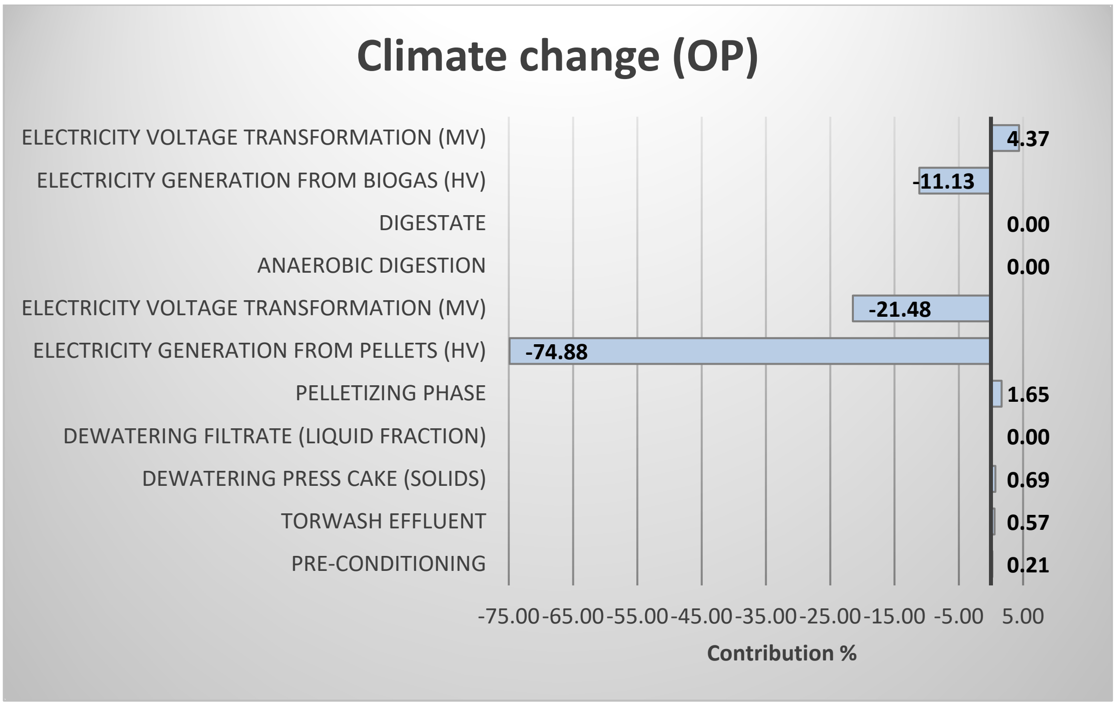

Figure 27- Distribution of the Climate change impact category in the processes of the F-CUBED Production System for the OP case study

In OP the pre-treatment processes, destoning and dilution, give a small contribution to the CC impact category, accounting for 0.21% (2.67 kg $CO_{2\ eq.}$/ t_{OP}) when combined. Note that electricity generation from biogas (HV) and its electricity voltage transformation (MV) account for -6.76% of negative emissions, corresponding to -87.81 kg $CO_{2\ eq.}$/ t_{OP} of GHG emissions to the atmosphere as avoided product from Technosphere by heat recovery (scenario 80% exported heat outside the system).

6.1.3.2 Terrestrial Acidification Impact category

Terrestrial Acidification impact category for OP case study accounts for 2.99 kg $SO_{2\ eq.}$/ t_{OP}.

As displayed in Figure 28. the major contributions come from electricity voltage transformation (MV) both from pellets (73.95%) and from biogas (30.29%) respectively releasing 2.210 and 0.908 kg $SO_{2\ eq.}$/ t_{OP}. Therefore, more than 100% of the overall emissions are due to these two processes. For this impact category and others that show the same impact behaviour, concentrated mainly in the electricity voltage transformation, the reason has to be referred to the considerable influence of the electricity country mix composition. Indeed, since Italy is assumed as plant location for OP case study, the electric grid mix is mainly based on fossil fuels (carbon intensity of electricity in Italy is 0.372 kg $CO_{2\ eq.}$/kWh). This effect is partially compensated by the heat and power co-generation unit, because it is assumed a heat recovery scenario of 80%, as avoided product from Technosphere.

The main stream processes, which include the novel TORWASH treatment, contribute with 6.12% and 0.183 kg $SO_{2\ eq.}$/ t_{OP}.

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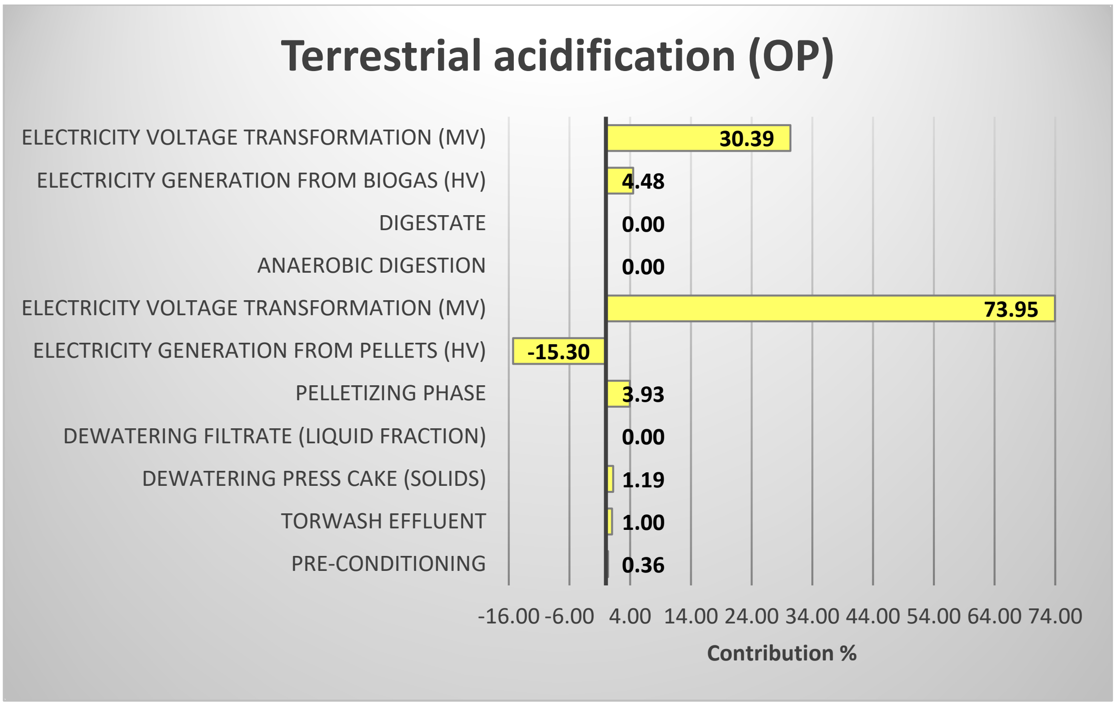

Figure 28 - Distribution of the TA impact category in the processes of the F-CUBED Production System for the OP case study

In OP the pre-treatment processes, destoning and dilution, give a small contribution to the TA impact category, accounting for 0.36% (0.011 kg $SO_{2\ eq.}$/ t_{OP}) when combined.

However at a glance, it is clear that the contributions to the TA impact category are concentrated in the upper middle part of the chart (Fig. 20) in charge to downstream processes and to the filtrate processing with electricity voltage transformation (MV) in both phases. Nevertheless in these two groups of processes, respectively, electricity generation from pellets (HV) accounts negative emissions of -15.30%, corresponding to -0.457 kg CO2 eq./ t_{OP} of GHG emissions to the atmosphere as avoided product from Technosphere by heat recovery (scenario 80%), and AD provide practically no contribution to the impact (1.4*10^-4 kg $SO_{2\ eq.}$/ t_{OP}).

6.1.3.3 ***Particulate Matter Formation*** *Impact category*

Particulate Matter Formation impact category for OP case study accounts for 0.93 kg PM10 $_{eq.}$/ t_{OP}. As displayed in Figure 29. PMF impact category for OP, has its major contributions from electricity voltage transformation (MV) both from pellets (75.78%) and biogas (27.27%) respectively releasing 0.7042 and 0.253 kg PM10 $_{eq.}$/ t_{OP}. Therefore, more than 100% of the overall impact is due to these two processes. The main processes stream, which include the novel TORWASH treatment, contribute with 8.78% and 0.0815 kg PM10 $_{eq.}$/ t_{OP}.

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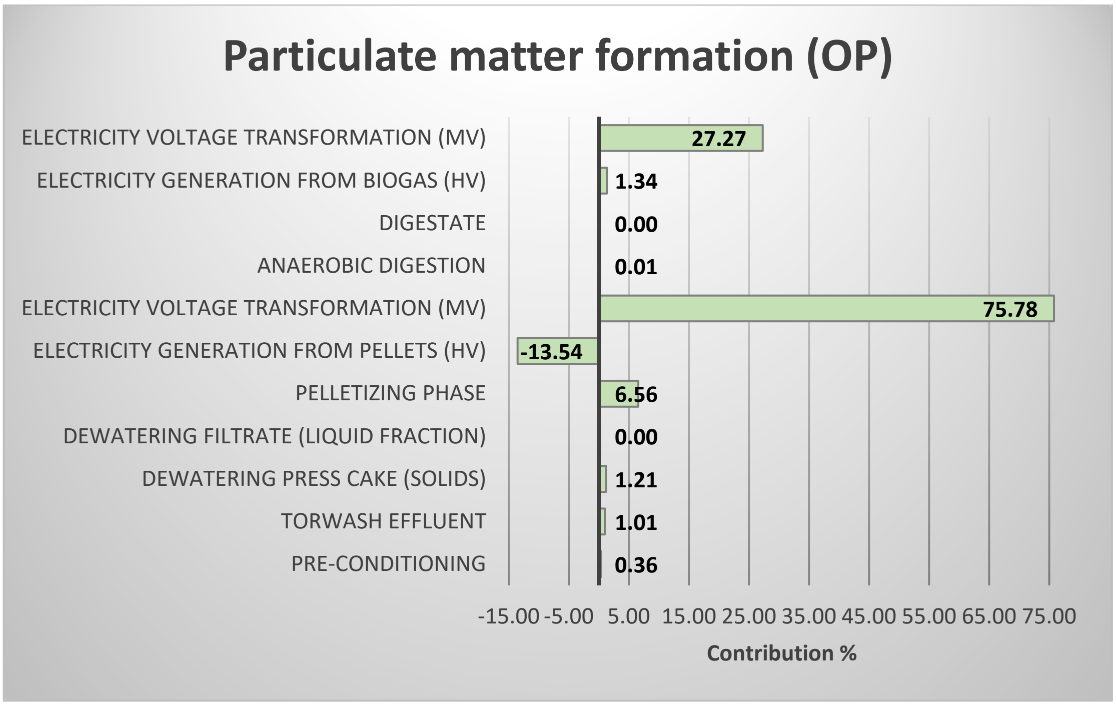

Figure 29 - - Distribution of the PMF impact category in the processes of the F-CUBED Production System for the OP case study

In OP the upstream pre-treatment processes, destoning and dilution, give a small contribution to the PMF impact category, accounting for 0.36% (0.0033 kg PM10 $_{eq.}$/ t_{OP}) when combined. Similar to TA, electricity generation from pellets (HV) accounts negative emissions of -0.126 kg PM10 $_{eq.}$/ t_{OP} (-13.54%) as avoided product from Technosphere by heat recovery scenario (80%).

6.1.3.4 Fossil Depletion Impact category

Fossil Depletion impact category for OP case study accounts for -499.24 kg oil $_{eq.}$/ t_{OP}. As displayed in Figure 30. FD has its major contributions in downstream processes: electricity generation from pellets (HV) (-68.38 %) releasing -341.26 kg oil $_{eq.}$/ t_{OP} and electricity voltage transformation (MV) (-24.65%; - 123.07 kg oil $_{eq.}$/ t_{OP}); these two processes account for -93.03%, corresponding to the saving of -464.43 kg oil $_{eq.}$/ t_{OP}, when combined. The main processes stream contributes with slightly positive emissions for 2.39% (11.92 kg oil $_{eq.}$/ t_{OP}).

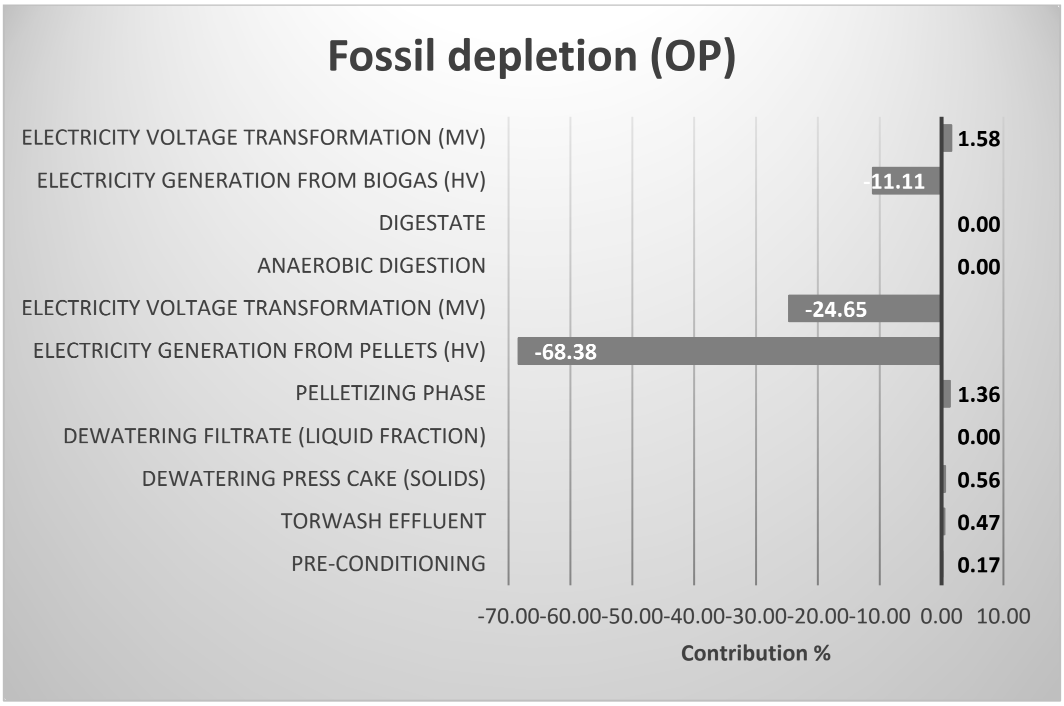

Figure 30 - Distribution of the FD impact category in the processes of the F-CUBED Production System for the OP case study

In the upstream pre-treatment processes, destoning and dilution, give a small contribution to the FD impact category, accounting for over 0.17% (0.834kg oil $_{eq.}$/ t_{OP}) when combined. The secondary filtrate processing accounts for overall negative emissions of about -11.11%, corresponding to -47.56 kg oil $_{eq.}$/ t_{OP} as avoided product from Technosphere by heat recovery and for the nutrient recovery from digestate utilization.

6.1.3.5 Further analysis of the Impact categories for F-CUBED Production System in the Virgin Olive Pomace Case Study

Impact categories of relevance for LCA study of the F-CUBED Production System that show CV's value over 20% up to 100%, require deepening investigation. Indeed for them, the standard deviation is relatively large relative to the mean and therefore there is high variability between the data, indicating a low reliability of the impact assessment results. For the F-CUBED Production System in the OP case study these impacts are: Freshwater eutrophication (FEUT), Human toxicity (HTX) and Photochemical oxidant formation (POF).

In these categories substance inventory and background unit process are investigate to analyse their distribution and contribution to the impacts generated. Data are reported in Table C2 (Appendix C).

FEUT Impact category (CV 87.20%)

Freshwater Eutrophication impact category for OP case study accounts for 0.35 kg P $_{eq}$/ t_{OP}. As displayed in Figure 31. the largest contributions to FEUT's impact are from electricity voltage transformation (MV) both from pellets (52.75%) and from biogas (32.83%) respectively releasing 0.184 and 0.115 kg P_2 $_{eq.}$/ t_{OP}. Therefore, about 85% of the total s emissions are due to these two processes.

These phases aren't related to the specific novel technology and could be improved with a tailor made modelling.

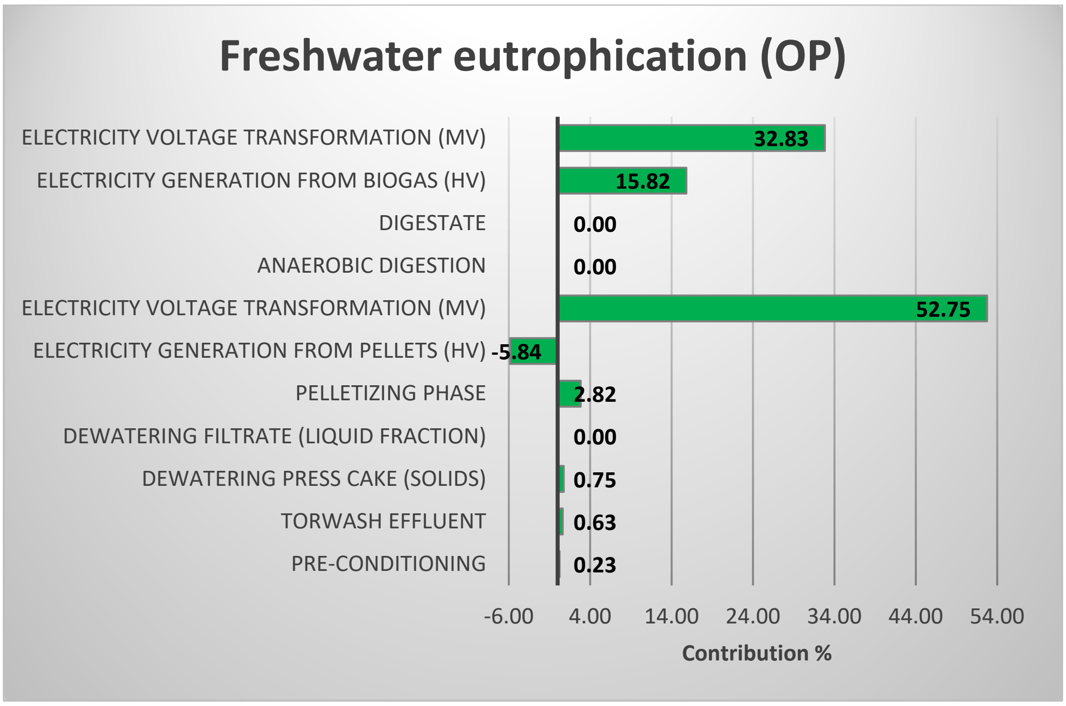

Figure 31 - Distribution of the FEUT impact category in the processes of the F-CUBED Production System for the OP case study

The main processes stream, which include the novel TORWASH treatment, provide a small contribute of 4.21 % and 0.0147 kg P $_{eq}$/ t_{OP}. The Table C2 shows that FEUT concerns the chemical molecules of Phosphate, in water compartment, and Phosphorus, in soil compartment, that provide respectively 0.366 and 0.0163 kg P $_{eq.}$/t $_{OP}$, generating 95% and 5% of the impact in their respective compartments. The Figure 32 depicts that the processes responsible for the FEUT impact category are related to the National Electricity Grid Mix of Italy, mainly based on fossils sources.

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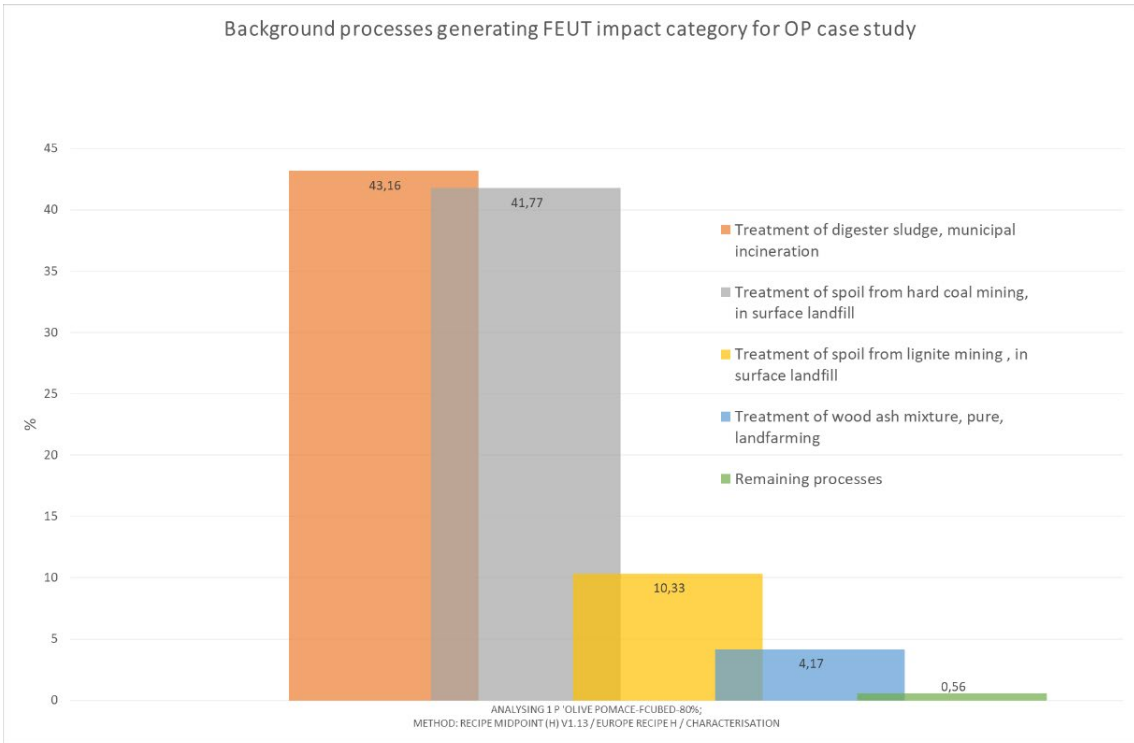

Figure 32- Background processes generating FEUT impact category for OP case study. They relate to the ECM

Also treatment of digester sludge and wood ash mixture are related to renewable share of ECM given the small contribution (respectively negative and close to zero) of AD and pellets combustion in the present impact category.

HTX Impact category (CV 96.1%)

Human toxicity impact category for OP case study accounts for overall 150.18 kg 1,4-DB $_{eq}$/ t_{OP}. As displayed in Figure 33, electricity voltage transformation (MV) both from pellets (71.67%) and from biogas (29.26%) provide the largest contributions, releasing 113.06 and 46.15 kg 1,4-DB $_{eq.}$/ t_{OP} respectively. Therefore, about 100 % of the overall emissions are due to these two processes.

The main stream processes, which include the novel TORWASH treatment, provide a contribute of 8.19 % and 12.91 kg 1,4-DB $_{eq.}$/ t_{OP} to the HTX overall impact.

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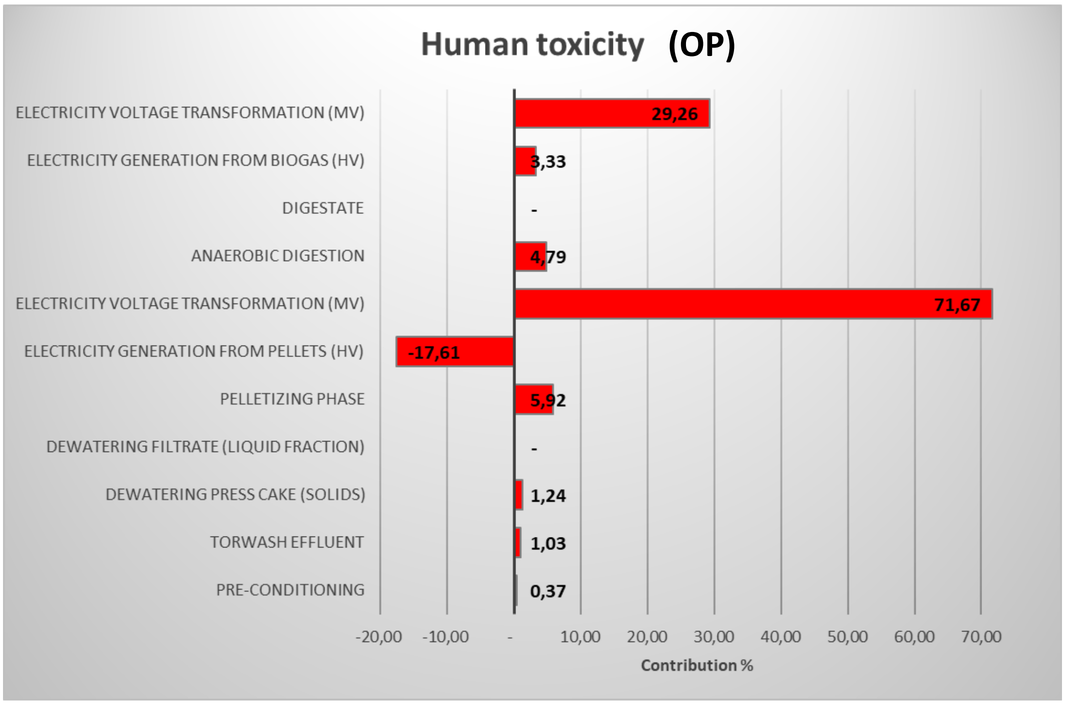

Figure 33 - Distribution of the HTX impact category in the processes of the F-CUBED Production System for the OP case study

HTX concerns chemical elements such as Antimony, Arsenic, Lead, Manganese, Mercury, Vanadium, in air compartment, Cadmium in soil, and Arsenic, Barium, Manganese, Selenium, in water compartment. Each compartment accounts for 18.93, 2.74 and 128.60 kg 1,4-DB eq/ t_{ADp} respectively. These values demonstrate that the water compartment is the most vulnerable to the HTX impact category for Virgin Olive Pomace case study. The downstream processes are the main contributors (54%), followed by the filtrate (liquid fraction) processing (37%), while the main stream processes contribute with about 8% to the HTX impact.

Among downstream processes, the UPR of conversion of pellets into energy, accounts negative emissions (-17.61%).

POF Impact category (CV 41.7%)

Photochemical oxidant formation impact category uses NMVOC (Non Methane Volatile Organic Compounds) as a reference and provides 1.05 kg NMVOC / t_{OP}. As displayed in Figure 34 POF impact category for OP case study, has its main contributions from electricity voltage transformation (MV) both from pellets (101.97%) and from biogas (37.59%) respectively releasing 0.396 and 1.074 kg NMVOC/ t_{OP}.

Referring to the stream of UPR, the downstream processes are the largest contributors (50%), followed by the filtrate (liquid fraction) processing (34%), while the main stream processes contribute with about 16% and 0.166 kg NMVOC/ t_{OP}. to the POF impact.

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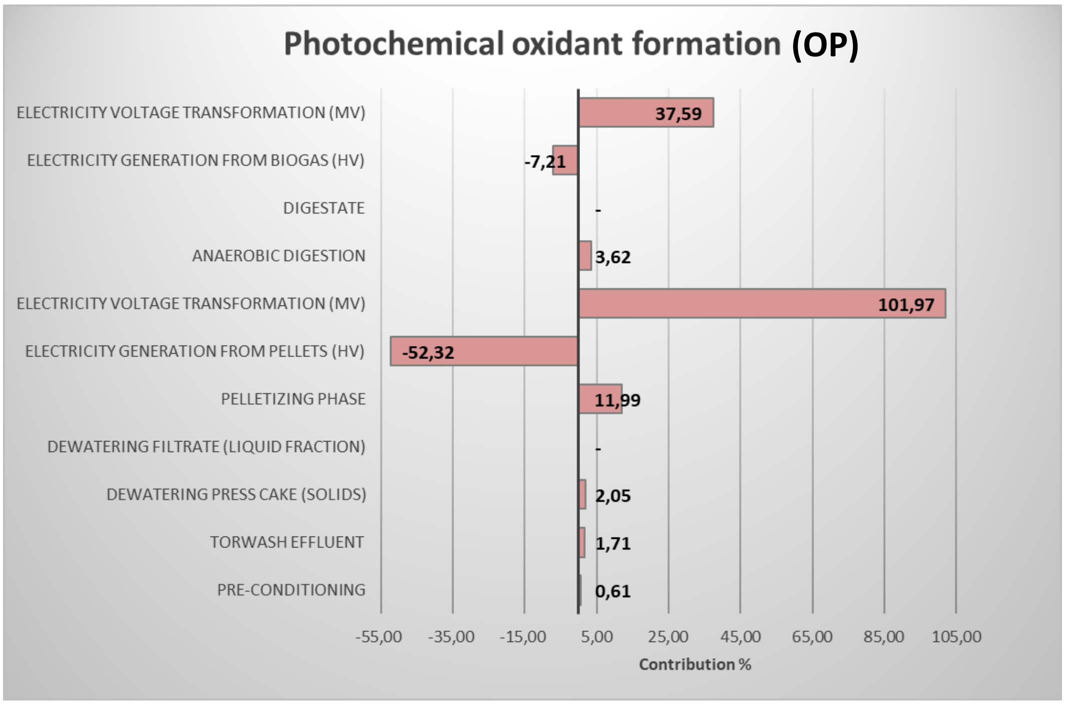

Figure 34- - Distribution of the FD impact category in the processes of the F-CUBED Production System for the OP case study

For OP case study, in addition to the impact categories discussed so far, also further comment for **Ozone depletion one**, is necessary because OD impact category has a mean value very close to zero. Therefore the value of the coefficient of variation tends to become very large [4] and this could cause problems for interpretation purposes.

Ozone depletion has worsened its reliability when the foreground data are considered in the sensitivity analysis.

OD impact category (CV 121.65%) concerns Chlorine atoms in chlorofluorocarbons (CFC) and bromine atoms in halons which are effective in degrading ozone due to heterogeneous catalysis, leading to a slow depletion of stratospheric ozone around the globe. The OD impact category uses CFC-11 (trichlorofluoromethane) as a reference and provides a negative contribution of -6.450^10^{-5} kg CFC-11 eq/t $_{OP}$. The downstream processes of the F-CUBED Production System are the only contributors to the OD impact (111.20% on the total value) which is slightly compensated by the favourable impact reduction of the other processes of the F-CUBED Production System.

[4] The closer the CV formula denominator approaches zero ($CV = \frac{SD}{\mu}$), the greater the CV value.

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6.1.4 Fruit & Vegetable – Orange Peels (ORP)

The LCIA results for ORP case study are reported, as unit per ton of residue, in Table 22.

Table 22 - Relevant impact categories for LCA study of F-CUBED Production System, in the ORP case study

Impact category	Unit.	Value	CV (%)
Climate change	kg CO2 eq./ t_{ORP}	-1.30E+03	21.99
Ozone depletion	kg CFC-11 eq./ t_{ORP}	-4.88E-06	539.54
Terrestrial acidification	kg SO2 eq./ t_{ORP}	1.35E+01	6.50
Freshwater eutrophication	kg P eq./ t_{ORP}	1.31E+00	74.95
Human toxicity	kg 1,4-DB eq./ t_{ORP}	6.56E+02	35.54
Photochemical oxidant formation	kg NMVOC/ t_{ORP}	6.27E+00	12.42
Particulate matter formation	kg PM10 eq./ t_{ORP}	4.59E+00	6.77
Freshwater ecotoxicity	kg 1,4-DB eq./ t_{ORP}	2.91E+01	72.30
Water depletion	m^3/ t_{ORP}	7.52E+01	3038.20
Fossil depletion	kg oil eq./ t_{ORP}	-6.27E+02	17.09

As mentioned in Section 5.3.1. the reliable impact categories for ORP case study are: Climate change(CV 21.99%), Particulate matter formation (CV 6.77%), Terrestrial acidification CV 6.50%) and Fossil depletion (CV 17.09%). On the contrary, inconsistent impact categories are Water depletion (CV 3038.20 %) and Ozone depletion (CV 539.54%). Finally, Freshwater eutrophication and Freshwater ecotoxicity have high value of CV which implies a relatively large value of the standard deviation from the average value. Nevertheless FEUT increase its reliability when the uncertainty of foreground data is considered in the sensitivity analysis and the CV shifts to 75.5% from inconsistent value of 101%. Moreover, Human toxicity shows worsen performance for the F-CUBED Production System compared to the Reference Case.
The detailed breakdown of these impact categories into the process steps of the F-CUBED Production System is explained in the following sub-sections. F-CUBED PS for OP and ORP case studies refers to similar schemes, in which the main differences, beyond the nature of residue, lie in the carbon intensity of the electricity country mix and in the heat recovery share.

6.1.4.1 Climate Change Impact category

The Climate change impact category for ORP accounts for -1301.61 kg $CO_{2\ eq.}$/ t_{ORP}. As displayed in Figure 35. they are mainly provided from electricity generation (HV) from pellets (-71.10 %) and from biogas (-43.75%) releasing -925.50 and - 204.11 kg $CO_{2\ eq.}$/ t_{ORP} respectively; these two processes account for about -115% of the overall impact, corresponding to GHG emissions saving of -1495.01 kg $CO_{2\ eq.}$/ t_{ORP} , when combined. These negative contributions refer to the GHG emissions savings generated from avoided product from Technosphere by heat recovery in the case study of Orange Peels (scenario 54% heat exported outside the system).

The main processes stream slightly contributes to CC impact with positive emissions for 5.56% (72.36 kg $CO_{2\ eq.}$/ t_{ORP}).

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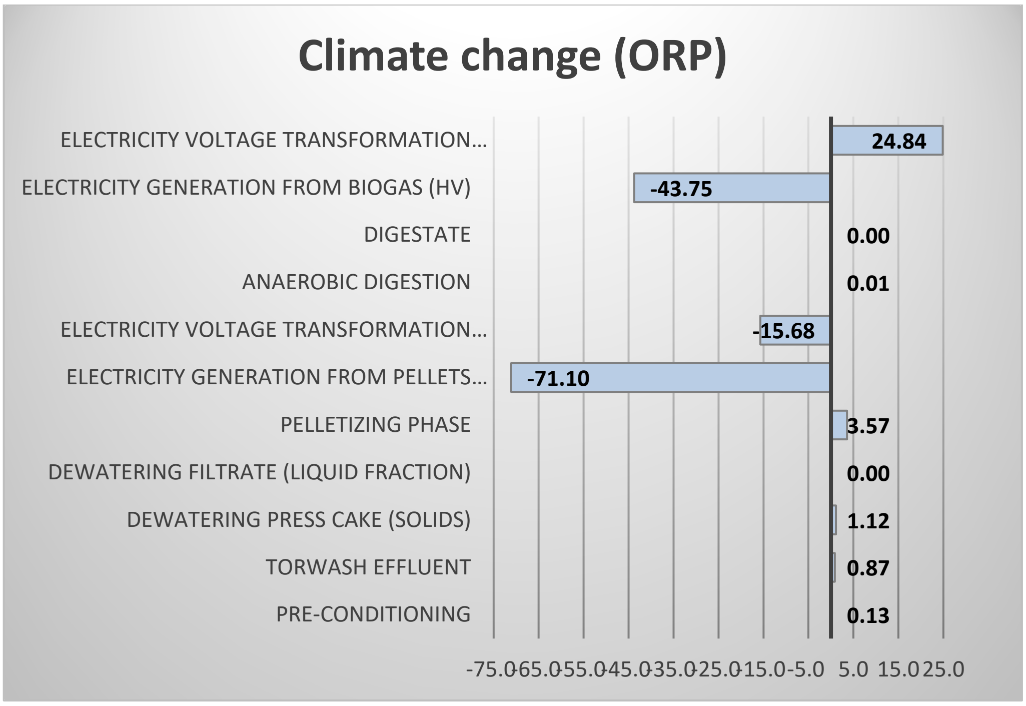

Figure 35 - Distribution of the CC impact category in the processes of the F-CUBED Production System for the ORP case study

In ORP the pre-treatment processes, comminution and dilution, give a small contribution to the CC impact category, accounting for 0.13% (1.67 kg $CO_{2\ eq.}$/ t_{ORP}) when combined. Electricity voltage transformation (MV) in the filtrate processing accounts emissions for 28.84%, corresponding to 323.38 kg $CO_{2\ eq.}$/ $t_{ORP.}$

As the **Climate change** impact category presents the CV slightly over 20% (21.99%), a further investigation has required, according to the analysis approach applied so far. As reported in Table C3. the negative emissions accounted by CC (-1301.61 kg$CO_{2\ eq.}$/t_{ORP}) find the main contributions by *carbon dioxide fossil* saving and *methane fossil saving*, respectively -1221.58 (-94%) and -272.02 kg$CO_{2\ eq.}$/t_{ORP} (-21%). On the other hand *carbon dioxide from land transformation*, *dinitrogen monoxide* and *methane biogenic* generate little positive emissions in air compartment which account for 190.30 kg$CO_{2\ eq.}$/t_{ORP} (15%).

The investigation of the background unit processes, as depicted in Figure 36 reveals the major responsible of positives are electricity voltage transformation from high to medium voltage (68.60%), high voltage electricity production from hard coal (29.80%), and more marginally high voltage electricity production from oil, combined cycle power plant from natural gas, and high voltage electricity production, from oil. Clearly, all these processes refer to the specific electricity country mix considered for Spain.

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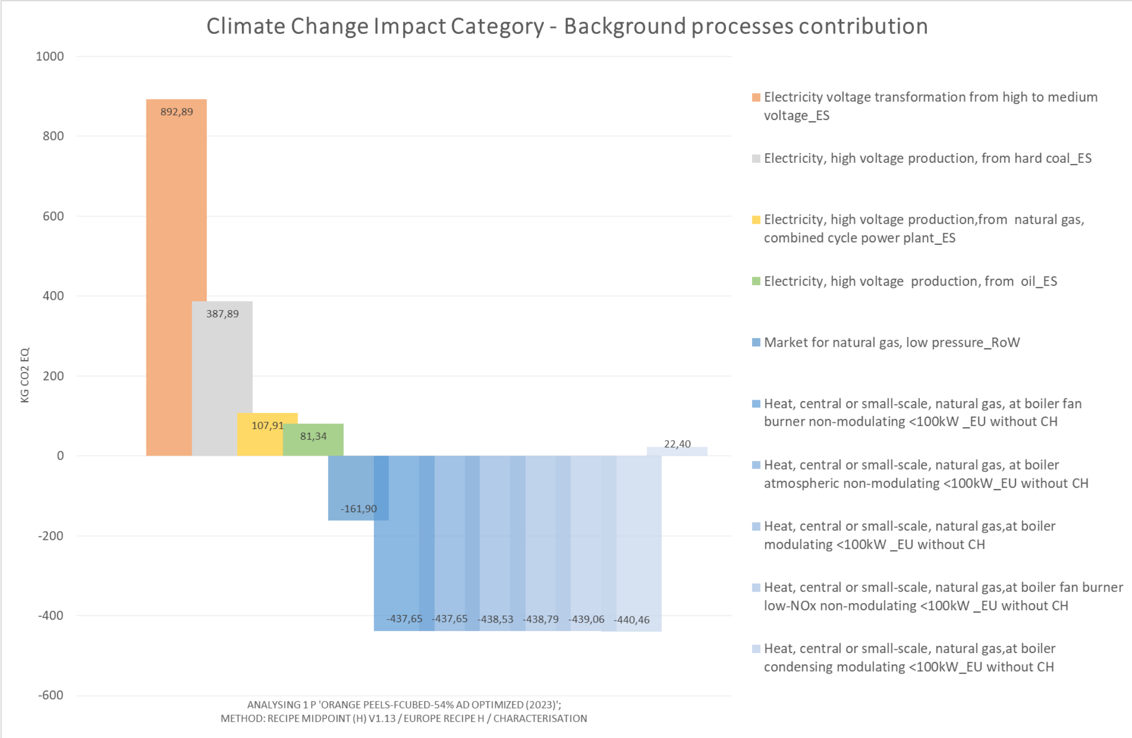

Figure 36 -Background unit processes contribution to the CC impact category for the F-CUBED Production System in the ORP case study

6.1.4.2 Terrestrial Acidification Impact category

Terrestrial acidification impact category for ORP case study accounts for 13.45 kg $SO_{2\ eq.}$/ t_{ORP}. As displayed in Figure 37. TA has its major contributions from electricity voltage transformation (MV) both from biogas (53.31%) and from pellets (36.25%) respectively releasing 7.17 and 4.88 kg $SO_{2\ eq.}$/ t_{ORP}. Therefore, over 89% of the overall emissions are due to these two processes.

For this impact category and others that show the same impact behaviour, concentrated mainly in the electricity voltage transformation, the reason has to be referred to the considerable influence of the electricity country mix composition. Indeed, since Spain is assumed as plant location for ORP case study, the electric grid mix is mainly based on fossil fuels (carbon intensity of electricity in Italy is 0.277 kg $CO_{2\ eq.}$/kWh).

In the ORP case study the heat recovery (scenario 54%), as avoided product from Technosphere in the electricity production by heat and power co-generation unit from pellets, isn't sufficient to compensate the emissions of SO_{2eq}.

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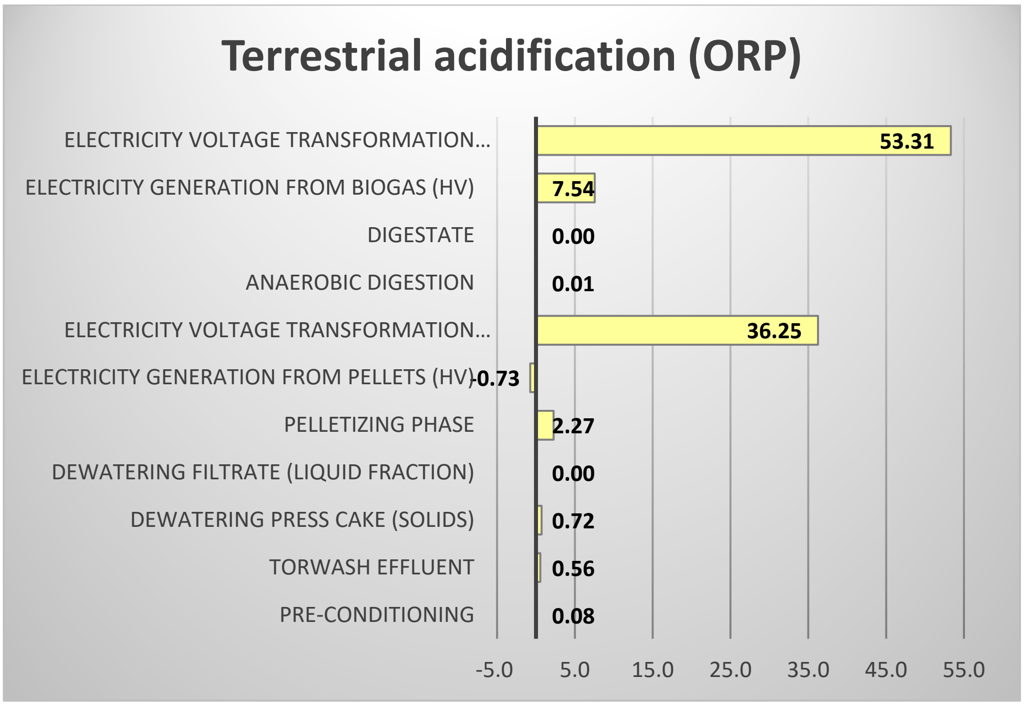

Figure 37 - Distribution of the TA impact category in the processes of the F-CUBED Production System for the ORP case study

The main stream processes, which include the novel Torwash treatment, give a very little contribution of 3.55% and 0.477 kg $SO_{2\ eq.}$/ t_{ORP}. Indeed at a glance, it is clear that the contributions to the TA impact category are concentrated in the upper middle part of the chart (Fig. 35) in charge to downstream processes and electricity voltage transformation (MV) from biogas.

6.1.4.3 Particulate Matter Formation Impact category

Particulate matter formation impact category for ORP case study accounts for 4.59 kg PM10 $_{eq.}$/ t_{ORP}. As displayed in Figure 38 PMF, similarly to TA, has its major contributions from electricity voltage transformation (MV) both from biogas (51.32%) and from pellets (39.44%) respectively releasing 2.53 and 1.81 kg PM10 $_{eq.}$/ t_{ORP}. Therefore, about 91% of the overall impact is due to these two processes. The main processes stream, which include the novel Torwash treatment, contribute with 4.93% and 0.226 kg PM10 $_{eq.}$/ t_{ORP}.

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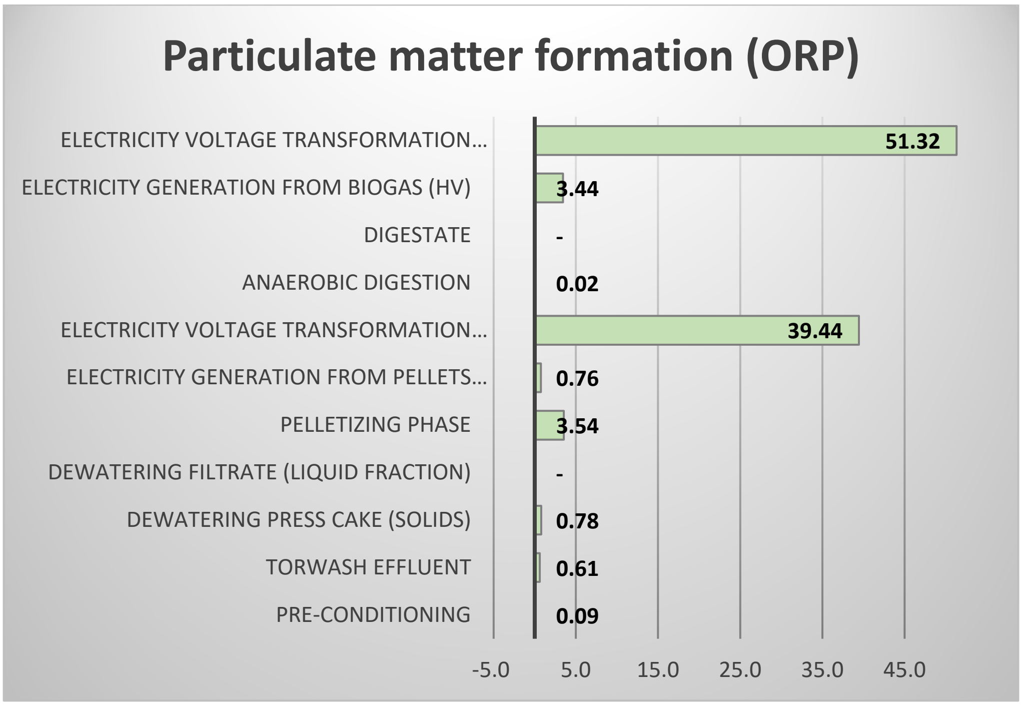

Figure 38 - Distribution of the PMF impact category in the processes of the F-CUBED Production System for the ORP case study

In ORP the pre-treatment processes, comminution and dilution, give a negligible contribution to the PMF impact category, accounting for 0.09% (0.004 kg PM10 $_{eq.}$/ t_{ORP}) when combined. Even for PMF, carbon intensity of the electricity country mix and the heat recovery share are responsible of the different impact category behaviour with respect to the OP case study.

6.1.4.4 ***Fossil Depletion*** *Impact category*

Fossil Depletion impact category for ORP case study accounts for -627.43 kg oil $_{eq.}$/ $t_{ORP.}$ As displayed in Figure 39. FD has its major contributions in downstream processes, particularly from electricity generation (HV) both from pellets (-52.06 %) releasing -326.62 kg oil $_{eq.}$/ t_{ORP} and from biogas (-36.17%; - 226.93 kg oil $_{eq.}$/ t_{ORP}); these two processes account for about -88%, corresponding to an overall avoided depletion of -553.54 kg oil $_{eq.}$/ t_{ORP}, when combined. The main processes stream contributes with slightly positive emissions for 3.43% (21.54 kg oil $_{eq.}$/ t_{ORP}).

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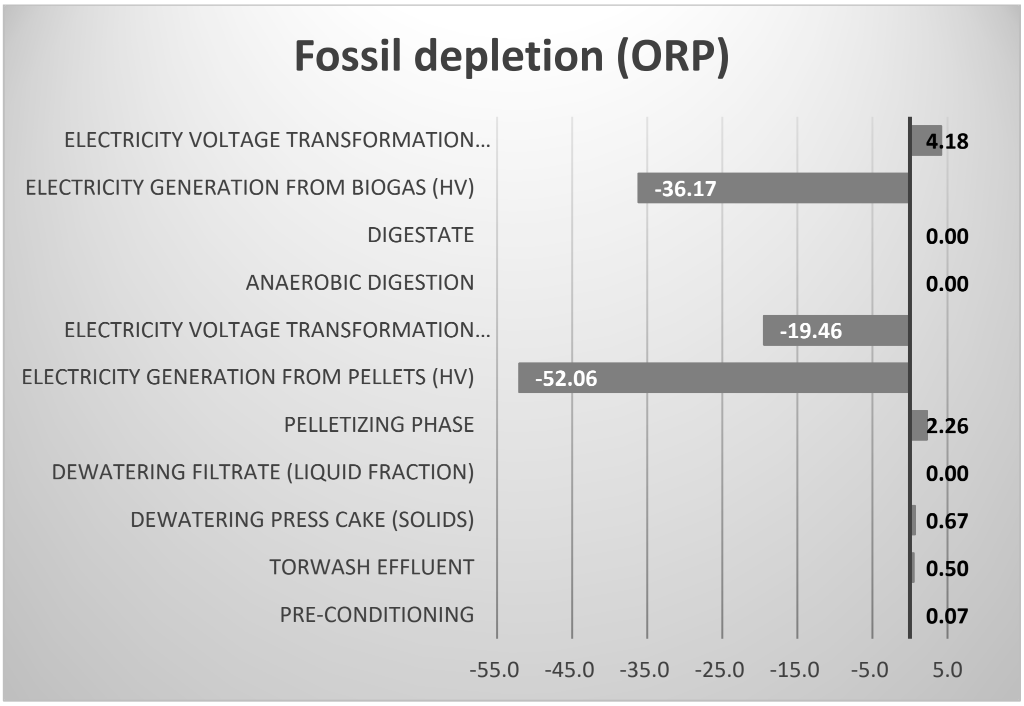

Figure 39 - Distribution of the FD impact category in the processes of the F-CUBED Production System for the ORP case study

In ORP case study the pre-treatment processes, comminution and dilution, give a negligible contribution to the FD impact category, accounting for over 0.07% (0.463 kg oil $_{eq.}$/ t_{ORP}) when combined. To note that secondary filtrate processing accounts for overall negative emissions of about -31.99%, corresponding to -196.45 kg oil $_{eq.}$/ t_{ADp} as avoided product from Technosphere by heat recovery and by the nutrient recovery from digestate utilization.

6.1.4.5 Further analysis of the Impact categories for F-CUBED Production System in the Orange Peels Case Study

Impact categories of relevance for LCA study of the F-CUBED Production System that show high value of the CV, require deepening investigation. Indeed for them, the standard deviation is relatively large relative to the mean due to high variability between the data, indicating a low reliability of the impact assessment results. In the Orange Peels case study, the impact categories with minor reliability for F-CUBED PS are Freshwater eutrophication (FEUT), Freshwater ecotoxicity (FETX) and Human toxicity (HTX). In these categories substance inventory and background unit process are investigate to analyse their distribution and contribution to the impacts generated. The results of the deepening analysis are reported in Table C3 (Appendix C).

FEUT Impact category (CV 74.95%)

Freshwater eutrophication impact category for ORP case study accounts for overall 1.31 kg P $_{eq.}$/ t_{ORP}. As displayed in Figure 40. FEUT has its major contributions from secondary filtrate processing by AD which is responsible of about 75.34% of the overall emissions.

Nevertheless AD process itself accounts a negligible contribution (0.02%) compared to electricity voltage transformation (MV) and electricity generation from biogas: 51.28% and 24.04% respectively, releasing

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0.671 and 0.315 kg P $_{eq.}$/ t_{ORP}. On the other hand the main stream processes, which include the novel TORWASH treatment, provide a small contribute of 2.73% (0.036 kg P $_{eq}$/ t_{ORP}).

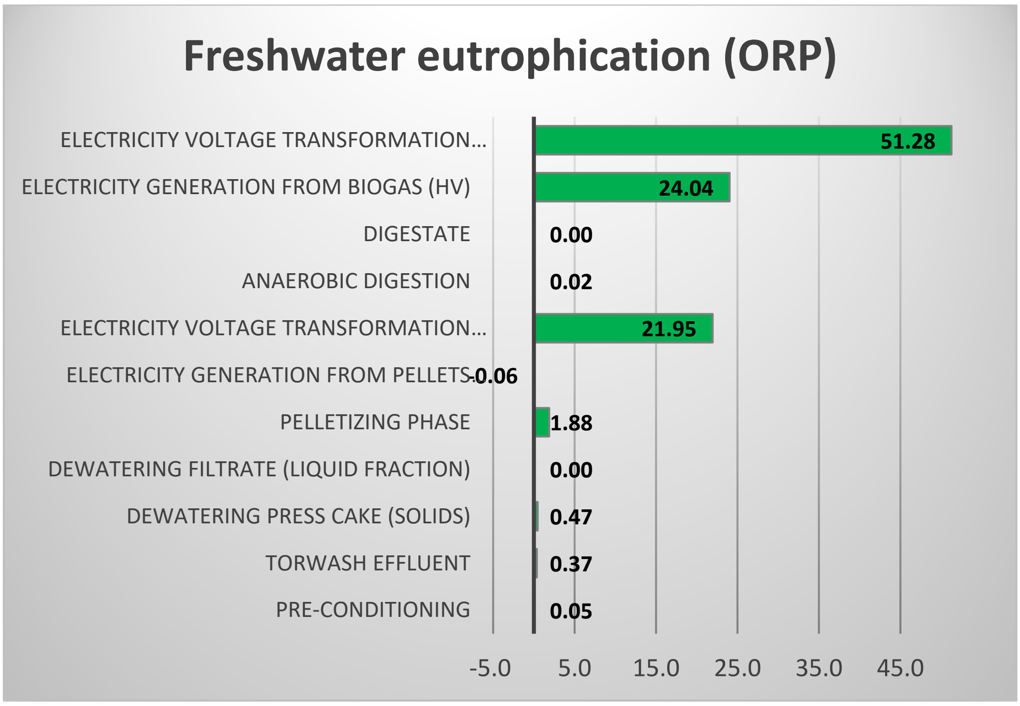

Figure 40 - Distribution of the FEUT impact category in the processes of the F-CUBED Production System for the ORP case study

The Table C3 shows that **Freshwater eutrophication** impact category concerns the chemical molecules of Phosphate and Phosphorus, that provide the overall contribution of 1.31 kg P $_{eq.}$/t $_{ORP}$, generating respectively 98% of the impact in water compartment and 2% in soil compartment.

Further analysis of the background data processes indicate that emissions are mostly originated by to the treatment of digester sludge by municipal incineration (48.6% and 0.637 kg P $_{eq.}$/ t $_{ORP}$), electricity voltage transformation from high to medium voltage for Spain (27.2% and 0.357 kg P $_{eq.}$/ t $_{ORP}$) and treatment of spoil from hard coal mining, in surface landfill (18.3% and 0.24 kg P $_{eq.}$/ t $_{ORP}$).

These processes aren't related to the specific novel technology, but rather to the electricity grid mix for Spain and they could be improved with available data for building up a tailor made LCA model for the energy production unit from bio-pellets and biogas.

HTX Impact category (CV 35.54%)

HTX impact category for ORP case study accounts for overall 656.11 kg 1,4-DB $_{eq.}$/ t_{ORP}. As displayed in Figure 41. HTX has its major contributions from electricity voltage transformation (MV) both from biogas (51.83%) and from pellets (36.21%) releasing 340.03 and 237.56 kg 1,4-DB $_{eq.}$/ t_{ORP} respectively. Therefore, about 88 % of the overall emissions are due to these two processes. The main stream processes, which include the novel Torwash treatment, provide a contribute of 5.19 % and 34.06 kg 1,4-DB $_{eq.}$/ t_{ORP} to the HTX overall impact.

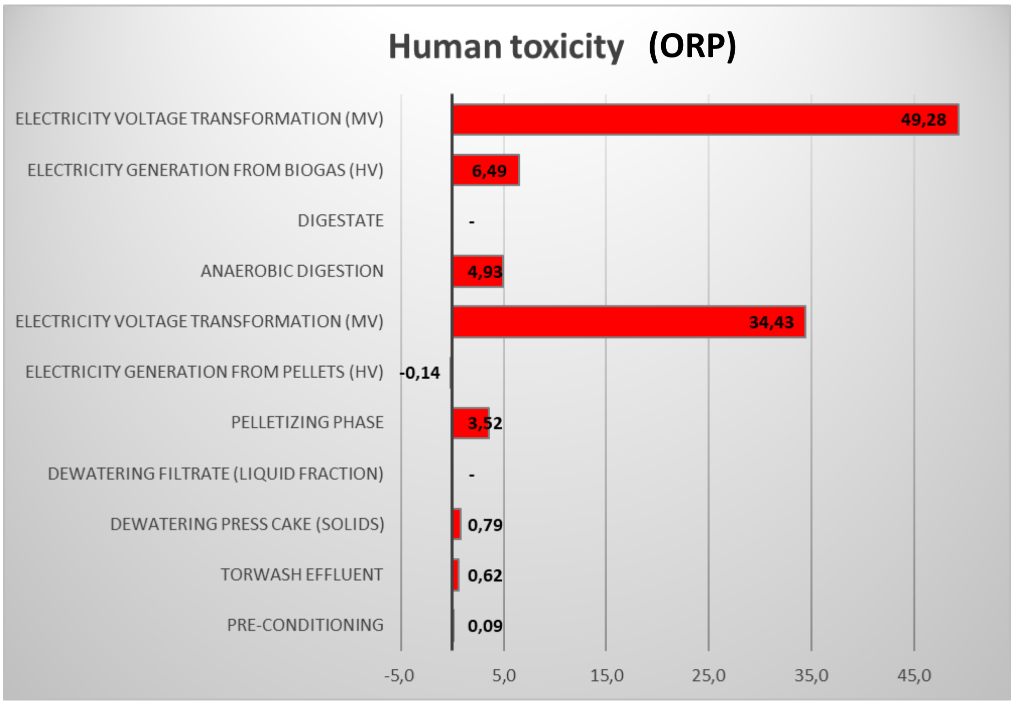

Figure 41 - Distribution of the HTX impact category in the processes of the F-CUBED Production System for the ORP case study

HTX concerns chemical elements such as Arsenic, Lead, Mercury, in air compartment and Arsenic, Barium, Manganese, Molybdenum, Selenium in water compartment. Respectively they account for 50.28 and 530.98 kg 1,4-DB$_{eq.}$/ t$_{ORP}$. It demonstrates that the water compartment is the most vulnerable to the HTX impact category for F-CUBED PS in ORP case study.

Further analysis of the background data processed indicate that additional contributions to the overall HTX impact, beyond electricity voltage transformation to MV (45%; 295 kg 1,4-DB$_{eq}$/ t$_{ORP}$), refer to the treatment of digester sludge by municipal incineration (19.2%; 126 kg 1,4-DB$_{eq}$/ t$_{ORP}$) and treatment of spoil from hard coal mining, in surface landfill (21.0% and 138 kg 1,4-DB $_{eq}$/ t $_{ORP}$).

Therefore the phases of the F-CUBED PS responsible of the more consistent emissions of 1,4-DB $_{eq.}$ aren't related to the specific technology, but rather to the electricity grid mix of the specific country and they could be improved with a tailor made LCA modelling.

FETX Impact category (CV 72.30%)

Freshwater ecotoxicity impact category accounts for overall 29.11 kg 1,4-DB $_{eq.}$/ t$_{ORP}$. As displayed in Figure 42 FETX has its major contributions from secondary filtrate processing by AD which is responsible of about 99% of the overall emissions; electricity voltage transformation (MV) and electricity generation from biogas (70.23% and 28.65% respectively releasing 20.45 and 8.34 kg 1,4-DB $_{eq.}$/ t$_{ORP}$) in this productive phase, while AD itself has a negligible contribution of 0.02%. On the contrary the main stream processes, which include the novel Torwash treatment, provide a contribute of 7.39 % (2.15 kg 1,4-DB $_{eq.}$/ t$_{ORP}$) to the FETX overall impact.

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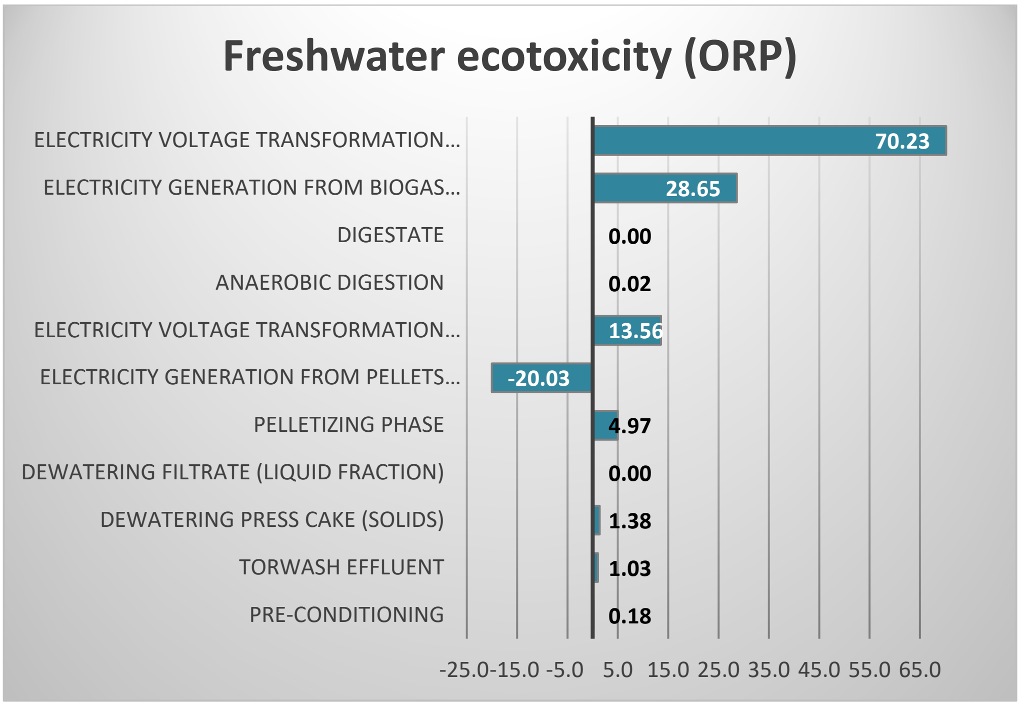

Figure 42- Distribution of the FETX impact category in the processes of the F-CUBED Production System for the ORP case study

Freshwater ecotoxicity impact category concerns chemical elements such as Beryllium, Bromine, Cobalt, Copper, Manganese, Nickel, Silver, Vanadium, Zinc, in water compartment. Here they account for 28.87 kg 1,4-DB $_{eq.}$/ t_{ORP}.

As illustrated in the following table (Tab.23), also for FETX impact category, the UPRs responsible of the more consistent emissions of 1,4-DB $_{eq.}$ aren't related to the specific technology but to electricity grid mix of the specific country, such as: treatment of digester sludge, municipal incineration, electricity voltage transformation from high to medium voltage and treatment of spoil from hard coal mining, in surface landfill.

Table 23 - Background UPR involved in the Freshwater ecotoxicity impact category

Process	Unit	Value
Total of all processes	kg 1,4-DB eq	29.11
Remaining processes	kg 1,4-DB eq	1.43
Treatment of digester sludge, municipal incineration_GLO	kg 1,4-DB eq	22.94
Electricity voltage transformation from high to medium voltage_ES	kg 1,4-DB eq	12.10
High pressure natural gas production_US	kg 1,4-DB eq	- 4.42
Natural gas, unprocessed, at extraction_GLO	kg 1,4-DB eq	-5.07
Treatment of scrap copper, municipal incineration_EU without CH	kg 1,4-DB eq	-1.19
Treatment of scrap copper , municipal incineration_RoW	kg 1,4-DB eq	1.25
Treatment of spoil from hard coal mining, in surface landfill_GLO	kg 1,4-DB eq	3.38
Treatment of sulfidic tailings, from copper mine operation, tailings impoundment_CN	kg 1,4-DB eq	-1.31

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6.2 Comparison between F-CUBED Production System and Reference Cases

In the present section the F-CUBED Production System and Reference Case are compared accordingly to the results of the LCIA of each biogenic residues stream obtained using the ReCiPe impact assessment method (Huijbregts, et al., 2017).

The impact categories considered in the comparison have to satisfy two necessary and sufficient conditions: 1) reliability, evaluated by sensitivity analysis and 2) relevance for the gaols and scopes of the specific LCA. Therefore the analysis of the impact categories which are characterized by inconsistent data and/or not significant is avoided. The comparison is reported in Table 24 where F-CUBED data and RC data for the three case studies are reported. The values of the impact categories are referred to the functional unit (kWh of dispatchable electricity).

In the following section the data are discussed for any single biogenic residue stream and a further comparison with Electricity country mix impacts is provided to put in evidence how the electricity impact intensity of the different country can affect the final outcomes from the sustainability point of view (Fig.43).

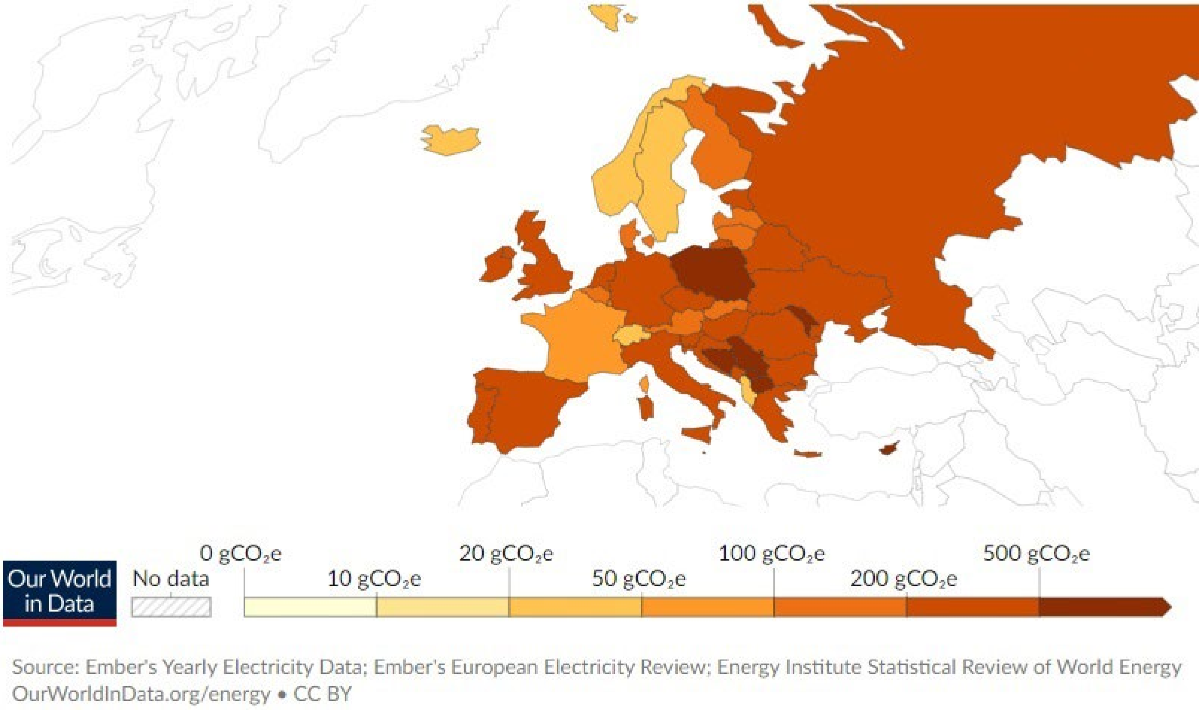

Figure 43 - Carbon Intensity of Electricity (g CO2 eq/kWh) in Europe, 2022

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Table 24 - LCIA results for the F-CUBED Production System s and the Reference case

Impact category	Unit	P. & P. Bio-sludge		Olive Pomace		Orange Peels	
		FCUBED	RC	FCUBED	RC	FCUBED	RC
Climate change	kg CO2 eq/ kWh_e	1.13E+00	3.33E+00	-6.29E-01	-1.68E-01	-2.50E-01	6.64E-02
Ozone depletion	kg CFC-11 eq/ kWh_e	3.09E-07	1.05E-06	-3.15E-08	9.88E-09	-9.36E-10	2.98E-08
Terrestrial acidification	kg SO2 eq/ kWh_e	1.28E-02	2.18E-02	1.45E-03	-2.49E-03	2.58E-03	1.61E-03
Freshwater eutrophication	kg P eq/ kWh_e	1.83E-02	1.65E-01	1.69E-04	1.01E-03	2.51E-04	4.38E-04
Human toxicity	kg 1,4-DB eq/ kWh_e	9.23E-01	2.56E+00	7.28E-02	-8.54E-02	1.26E-01	8.60E-02
Photochemical oxidant formation	kg NMVOC/ kWh_e	6.85E-03	1.12E-02	4.92E-04	-6.61E-04	1.20E-03	9.26E-04
Particulate matter formation	kg PM10 eq/ kWh_e	4.99E-03	8.72E-03	4.50E-04	-1.12E-03	8.80E-04	4.79E-04
Terrestrial ecotoxicity	kg 1,4-DB eq/ kWh_e	-1.36E-02	8.55E-04	6.11E-05	-2.26E-02	1.18E-04	-4.98E-03
Freshwater ecotoxicity	kg 1,4-DB eq/ kWh_e	1.05E-01	2.97E-01	-1.10E-03	-2.96E-02	5.58E-03	6.16E-04
Agricultural land occupation	m^2a/ kWh_e	4.02E+00	1.36E+00	7.76E-01	-8.81E-02	5.93E-01	3.40E-02
Natural land transformation	m^2/ kWh_e	5.74E-04	6.04E-04	-6.03E-05	-1.92E-04	-4.30E-06	-1.93E-05
Water depletion	m^3/ kWh_e	9.19E-02	3.42E-01	1.24E-02	-1.53E-02	1.44E-02	-3.27E-04
Metal depletion	kg Fe eq/ kWh_e	2.43E-01	7.05E-01	-2.99E-03	-1.48E-01	8.96E-03	-2.04E-02
Fossil depletion	kg oil eq/ kWh_e	2.80E-01	1.09E+00	-2.42E-01	-5.40E-02	-1.20E-01	1.87E-02

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6.2.1 Pulp & Paper Bio-sludge

In this section the comparison between F-CUBED Production System and Reference Case for Pulp & Paper Bio-sludge case study is described. Table 25 reports the result of the LCIA for F-CUBED PS, RC and Sweden Electricity Country Mix in the different impact categories: bold font refers to the impact category with highest reliability (CV≤20%), while the others present a lower reliability, with CV comprises from values over 20% up to 100%. The impact category showing inconsistent value are excluded and indicated in red characters in Table.

Only Agricultural land occupation has been included although it is not priority impact category for PPB case study because it is assumed that F-CUBED system and the TORWASH technology are add-on to the existing processes and replaces the current scenarios in the existing facility. It is also assumed that the required typical utilities are present onsite (Dijkstra, et al. 2023).

Table 25 – Comparison of the LCIA results of F-CUBED, RC and Electricity Country Mix (Sweden)

Impact category	Unit	FCUBED PS	RC	ECM
Climate change	**kg CO_2 eq./ kWh_{el}**	**1.13E+00**	**3.33E+00**	**4.50E-02**
Ozone depletion	kg CFC-11 eq./ kWh_{el}	3.09E-07	1.05E-06	4.29E-08
Terrestrial acidification	**kg SO_2 eq./ kWh_{el}**	**1.28E-02**	**2.18E-02**	**1.55E-04**
Freshwater eutrophication	kg P eq./ kWh_{el}	1.83E-02	1.65E-01	2.30E-05
Human toxicity	kg 1,4-DB eq./ kWh_{el}	9.23E-01	2.56E+00	2.86E-02
Photochemical oxidant formation	**kg NMVOC/ kWh_{el}**	**6.85E-03**	**1.12E-02**	**1.42E-04**
Particulate matter formation	**kg PM10 eq./ kWh_{el}**	**4.99E-03**	**8.72E-03**	**8.19E-05**
Freshwater ecotoxicity	kg 1,4-DB eq./ kWh_{el}	1.05E-01	2.97E-01	1.66E-03
Water depletion	m^3/ kWh_{el}	9.19E-02	3.42E-01	6.31E-03
Fossil depletion	**kg oil eq./ kWh_{el}**	**2.80E-01**	**1.09E+00**	**9.19E-03**
Agricultural land occupation	m2a/ kWh_{el}	4.02E+00	1.36E+00	7.16E-02

In PPB case study, all the impact indicators have lower value for F-CUBED PS ranging from -41.44% of TA to -74.37% of FD. Unique impact category in countertrend is ALO that has an increasing of the value of +195%. As before mentioned, it is assumed that F-CUBED technology (TORWASH and Membrane Filter Press) are integrated in existing facilities, due to the challenges (and environmental impact) of transporting wet residue. Therefore ALO impact has to be attributed mainly to the occupation and transformation of a certain area of land by the phases like drying and pelletization which offer locational flexibility, suggesting the potential for a hub-based infrastructure, and to pellet energy conversion and biogas generation units, into electricity and voltage transformation.

On the contrary the F-CUBED Production System have, in general, worsen results respect the impacts attributable to Sweden electricity country mix. The main reason of this refers to the low impact intensity of Sweden electricity country mix itself. Sweden is one of the global leaders in decarbonization, with renewable energy sources – including hydropower, wind and solar together with nuclear, – representing more than 90 percent of the country's electricity mix, as described by the Figure 44. Indeed, the share of renewable energies in electricity generation in Sweden grew from 57.25% in 2000 to 68.38% in 2022 (Statista 2022). Hydro and nuclear power are the main sources of electricity generation in Sweden in 2021. accounting for 43% and 31% shares of the country's supply, respectively.

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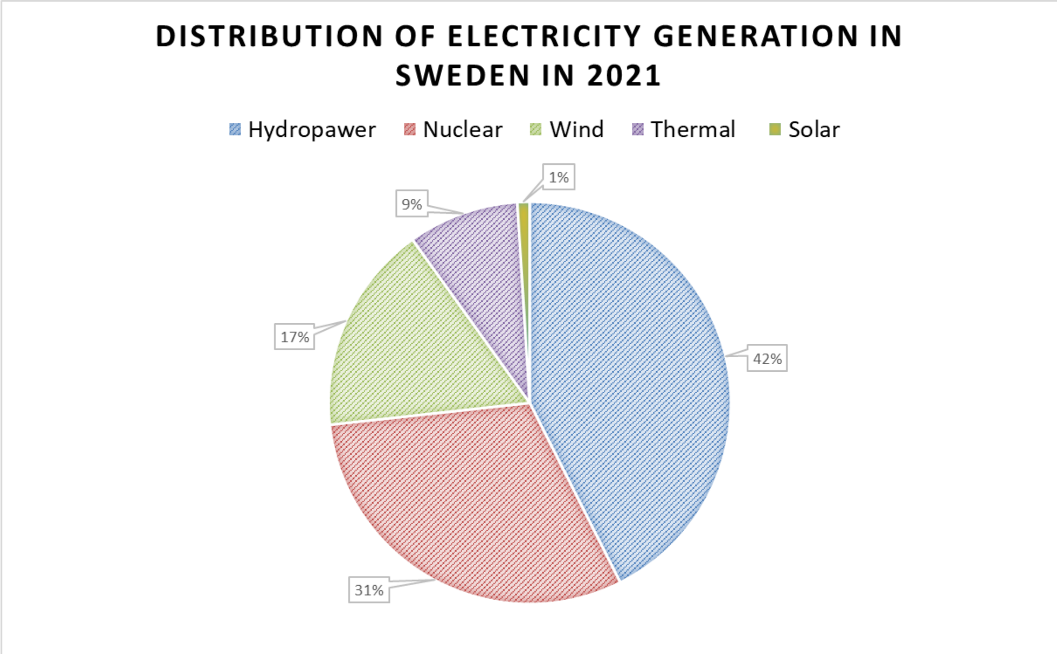

Figure 44- Source of electricity generation in Sweden - Data 2021 (Source: Statista Research Department, Aug 6. 2023)

Moreover Sweden's electricity production from photovoltaics increased by nearly 50-fold in the last decade, surpassing 1.000 gigawatt hours in 2021. despite its currently small share of the electricity matrix. Likewise, Sweden's wind power supply also saw significant growth during that time. The country's renewable energy capacity registered continual growth for more than a decade, reaching 34.6 GW in 2021 (Statista 2022).

The results reported in Table 26 are further depicted in the following Figure 45.

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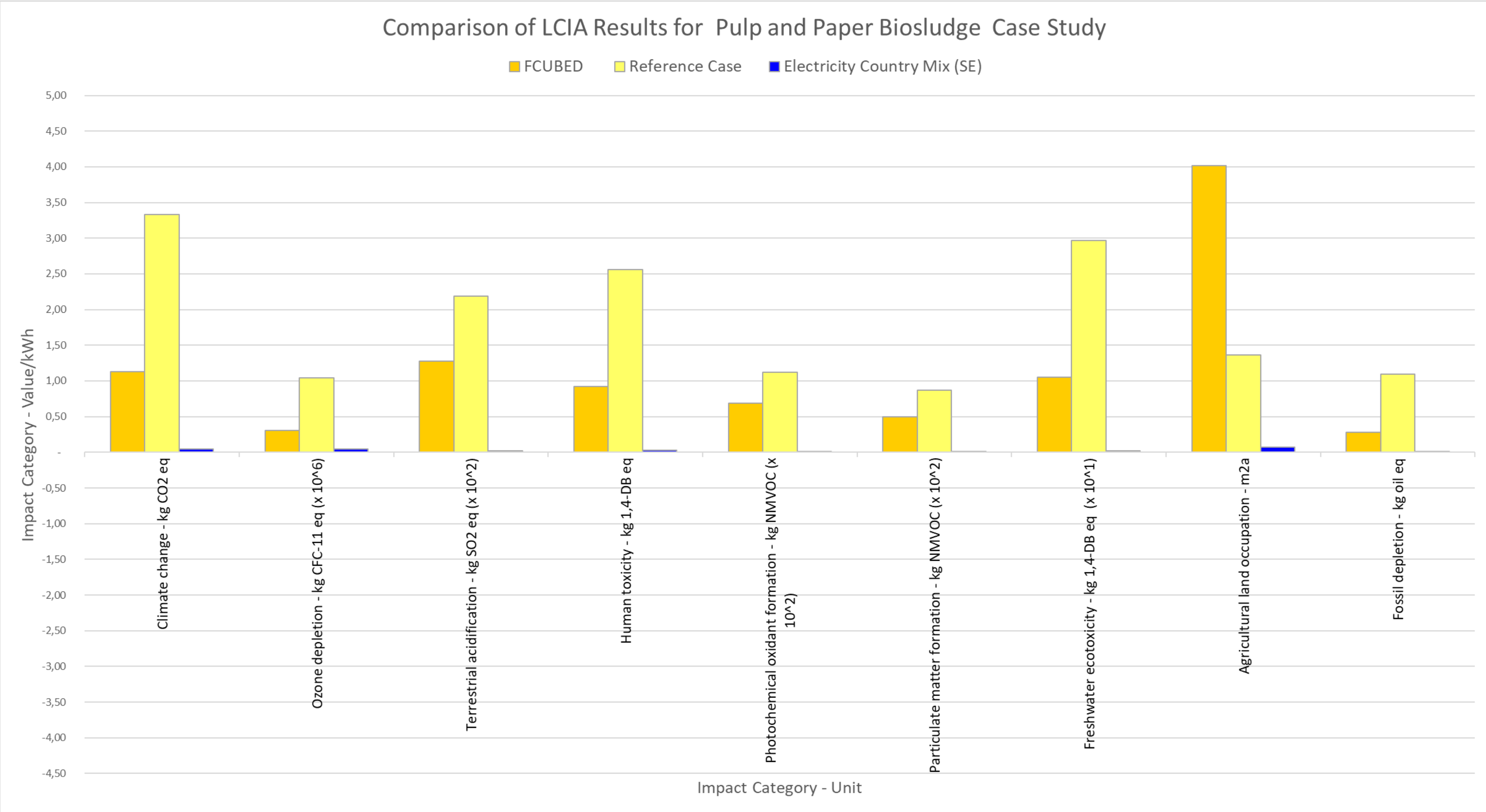

Figure 45 - Comparison of LCIA Results for Pulp & Paper Bio-sludge Case Studies: F-CUBED Production System, Reference case, Electricity Country Mix (Sweden)

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6.2.2 Virgin Olive Pomace

In this section the comparison between F-CUBED Production System and Reference Case for Virgin Olive Pomace case study is described.

Table 26 reports the result of the LCIA for F-CUBED, RC and Electricity Country Mix of Italy in the different impact categories: bold font refers to the impact category with highest reliability (CV≤20%), while the others present a lower reliability, with CV comprises from values > 20% up to 100%. The impact category showing inconsistent value or non-significant for goal and scope of the present LCA are excluded and indicated in red character in Table.

Table 26 – Comparison of LCIA results of F-CUBED, RC and Italy's Electricity Country Mix for Olive Pomace Case Study

Impact category	Unit	FCUBED PS	RC	ECM
Climate change	**kg CO2 eq./ kWh_{el}**	**-6.29E-01**	**-1.68E-01**	**3.72E-01**
Ozone depletion	kg CFC-11 eq./ kWh_{el}	-3.15E-08	9.88E-09	5.81E-08
Terrestrial acidification	**kg SO2 eq./ kWh_{el}**	**1.45E-03**	**-2.49E-03**	**1.66E-03**
Freshwater eutrophication	kg P eq./ kWh_{el}	1.69E-04	1.01E-03	1.27E-04
Human toxicity	kg 1,4-DB eq./ kWh_{el}	7.28E-02	-8.54E-02	8.75E-02
Photochemical oxidant formation	kg NMVOC/ kWh_{el}	4.92E-04	-6.61E-04	1.01E-03
Particulate matter formation	**kg PM10 eq./ kWh_{el}**	**4.50E-04**	**-1.12E-03**	**5.16E-04**
Freshwater ecotoxicity	kg 1,4-DB eq./ kWh_{el}	-1.10E-03	-2.96E-02	4.08E-03
Water depletion	m^3/ kWh_{el}	1.24E-02	-1.53E-02	9.14E-03
Fossil depletion	**kg oil eq./ kWh_{el}**	**-2.42E-01**	**-5.40E-02**	**1.36E-01**

In the OP case study, F-CUBED process, with respect to the RC, presents lower impacts only for 3 Impact categories: CC, FEUT and FD. While considering the comparison with ECM the number increase to 6 of 7 and only FEUT shows lower value of ECM in respect of the F-CUBED.

Regarding CC and FD impact categories F-CUBED PS shows more performative values respect RC, with improvement from 2.5 to 3.5 times (274% and 348% respectively).

In the FEUT domain, F-CUBED PS presents lower impact (-83%) with respect to the RC but higher than the ECM. The highest impact of RC can be explained referring to the large amount of digestate to be treated which implies direct emissions from landfarming applications and burden for spreading process.

On the contrary, for TA, HTX, POF and PMF F-CUBED PS shows opposite behaviour: 1.5-2.0 times higher value with respect to the RC (158%, 185%, 174%, 140%, respectively) but lower in respect of ECM. This latter result can be explained by the relatively small share of renewable energies in electricity generation for Italy which accounted 38.1% in 2020. Indeed the Italian country mix presents high impacts intensity, with particular regards to the carbon intensity which results of 0.372 kg $CO_{2\ eq.}$/kWh (Our World in Data 2022).

Therefore, in OP case study it is possible to conclude that the impact indicators in which the F-CUBED Production System provides a significant favourable impact affect areas of protection and are crucial for global climate change, fossil depletion and freshwater eutrophication.

The results for OP case study are further depicted in the following chart (Fig. 46)

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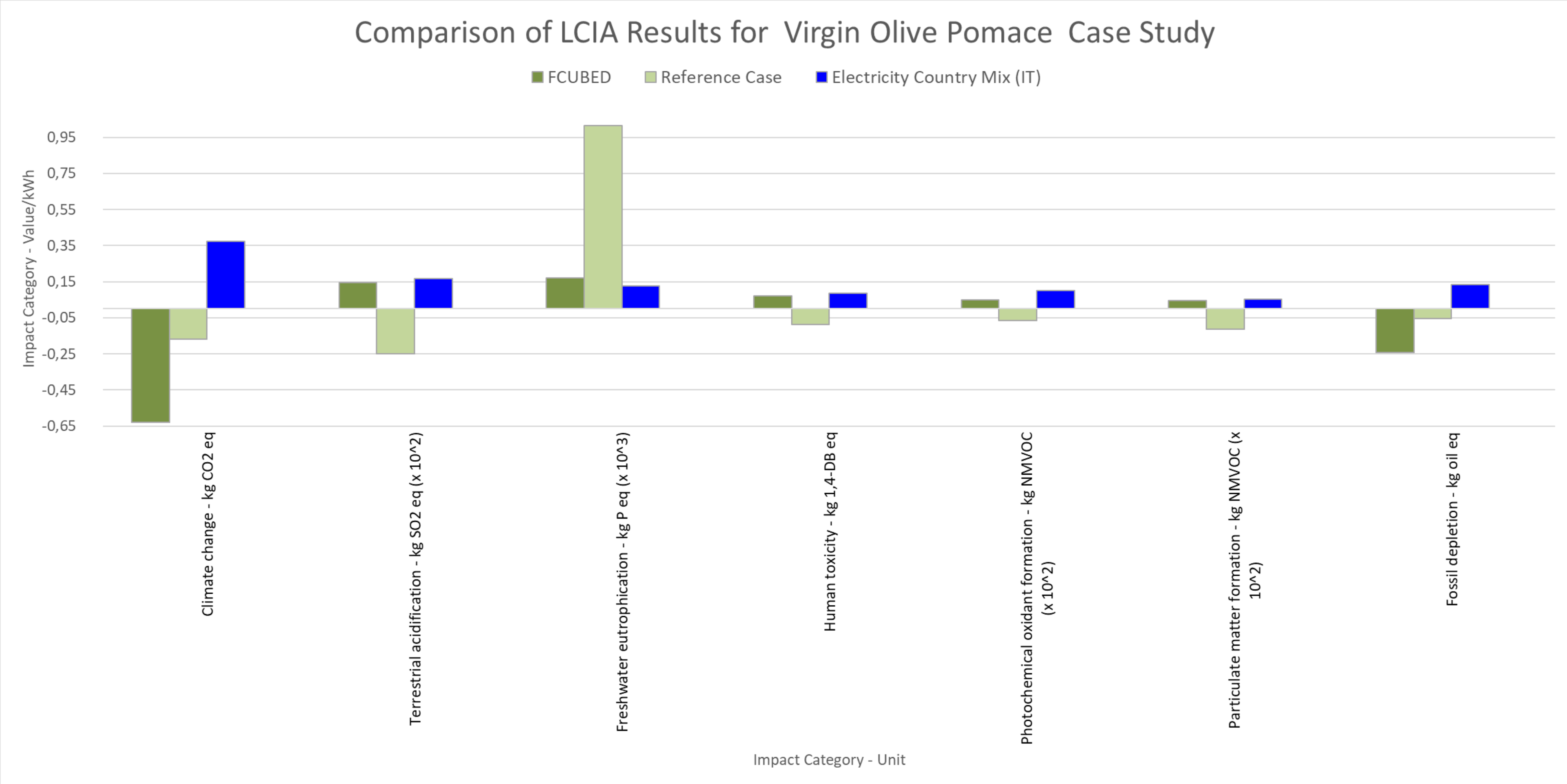

Figure 46- Comparison of LCIA Results for Olive Pomace Case Studies: F-CUBED Production System, Reference case, Electricity Country Mix (Italy)

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6.2.3 Fruit & Vegetable (Orange Peels)

In this section the comparison between F-CUBED Production System and Reference Case for Orange Peels case study is described.

Table 27 reports the result of the LCIA for F-CUBED, RC and Electricity Country Mix of Spain in the different impact categories: bold font refers to the impact category with highest reliability (CV≤20%), while the others present a lower reliability, with CV comprises from values > 20% up to 100%. The impact category showing inconsistent value or non-significant for goal and scope of the present LCA are excluded and indicated in red characters.

Table 27 – Comparison of the LCIA results of F-CUBED, RC and Italy's Electricity Country Mix for Orange Peels Case Study

Impact category	Unit	FCUBED PS	RC	ECM
Climate change	**kg CO2 eq./ kWh_{el}**	**-2.50E-01**	**6.64E-02**	**2.17E-01**
Ozone depletion	kg CFC-11 eq./ kWh_{el}	-9.36E-10	2.98E-08	4.59E-08
Terrestrial acidification	**kg SO2 eq./ kWh_{el}**	**2.58E-03**	**1.61E-03**	**2.12E-03**
Freshwater eutrophication	kg P eq./ kWh_{el}	2.51E-04	4.38E-04	1.23E-04
Human toxicity	kg 1,4-DB eq./ kWh_{el}	1.26E-01	8.60E-02	1.02E-01
Photochemical oxidant formation	**kg NMVOC/ kWh_{el}**	**1.20E-03**	**9.26E-04**	**1.23E-03**
Particulate matter formation	**kg PM10 eq./ kWh_{el}**	**8.80E-04**	**4.79E-04**	**7.56E-04**
Freshwater ecotoxicity	kg 1,4-DB eq./ kWh_{el}	5.58E-03	6.16E-04	4.17E-03
Water depletion	m^3/ kWh_{el}	1.44E-02	-3.27E-04	3.26E-03
Fossil depletion	**kg oil eq./ kWh_{el}**	**-1.20E-01**	**1.87E-02**	**8.72E-02**

In the ORP case study, similarly to OP, F-CUBED PS, with respect to the RC, presents lower impacts only for 3 Impact categories: CC, FEUT and FD. But on the contrary the number doesn't increase when F-CUBED PS is compared to ECM for Spain: only for FEUT, F-CUBED PS worsens its performance whilst it enhances for POF.

The reason lies in the share of renewables (including non-renewable waste) in the national electricity mix that in Spain accounts for 42.2% in 2022. This contributes also to explain the difference in results between Olive Pomace and Orange Peels scenarios. Indeed, Spain's electricity country mix presents minor impacts intensity, with respect to Italy with particular regards to the carbon intensity which results of 0.217 kg $CO_{2\,eq}$./kWh (Our World in Data 2022).

Regarding CC and FD impact categories F-CUBED PS shows more performative values respect both RC and ECM. Particularly the improvement with respect to the RC is consistent and vary between 4.5 and 7.5 times (476% and 742% respectively).
In the FEUT domain, F-CUBED PS presents lower impact (-43%) in respect of the RC but higher than the ECM. The highest impact of RC can be explained referring to the large amount of digestate to be treated which implies direct emissions from landfarming applications and burden for spreading process.
On the contrary, for TA, HTX, POF and PMF F-CUBED PS shows opposite behaviour: from 0.5 up to 8 times higher value with respect to the RC (60%, 46%, 30%, 84%, 807% respectively) but lower with respect to the ECM, with the exception of POF.

Therefore, also for Orange Peels case study, it is possible to underline that the impact indicators in which the F-CUBED Production System provides a significant favourable impact affect areas of protection and are crucial for global climate change, fossil depletion and freshwater eutrophication.
These results for ORP case study are further depicted in the following chart (Fig. 47)

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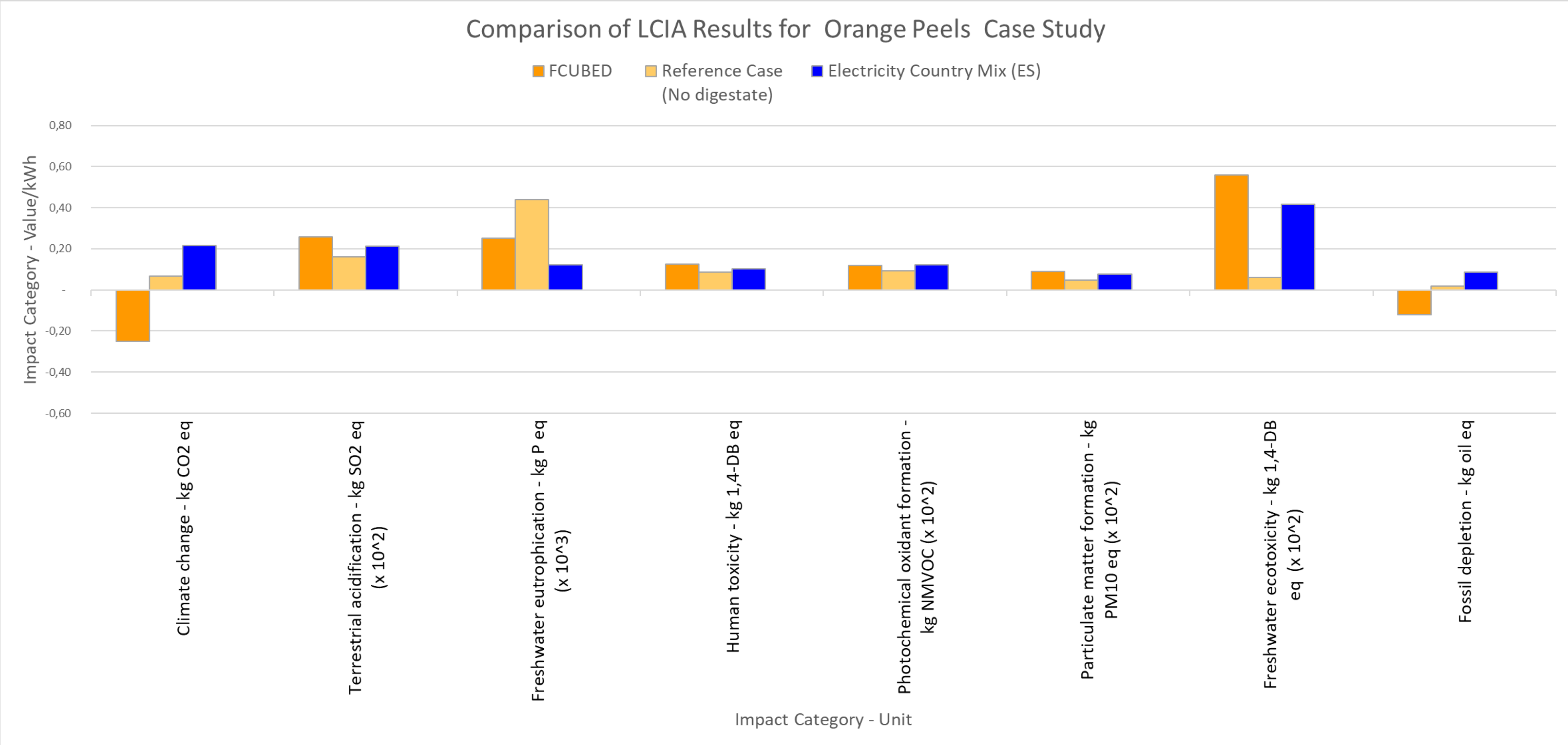

Figure 47 - Comparison of LCIA Results for Orange Peels Case Studies: F-CUBED Production System, Reference case, Electricity Country Mix (Spain)

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6.3. Detailed comments, discussion and significative issues on Climate Change Impact Category

6.3.1 Climate Change Impact Category

For the Climate Change impact category, characterization factor at midpoint level is the widely used Global Warming Potential (GWP) which expresses the amount of additional radiative forcing integrated over time caused by emissions of 1kg of GHG (W y $m^{-2}kg^{-1}$) relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of CO2.

The various GHGs have widely different atmospheric lifetimes, resulting in time-horizon-dependent characterization factors: in the present study the value choices in the modelling of the effect of GHGs is considered relate to Hierarchist category, with time horizon 100 years. Moreover in the study climate carbon feedbacks for non-CO2 GHGs have been included to provides a more consistent midpoint Carbon Footprint.

The GWPs for 100 years are directly provided by the impact assessment method ReCiPe 2016 (updating January 2018), as reported in Table 28.

Table 28 - Characterization factors of Global Warming Potential (100 years)

Impact Indicator Potential	**Unit**	**Characterization factors**		
		CO_2	**CH_4**	**N_2O**
GWP_{100}	kg CO_{2eq}/kg GHG	1	36	298

The damage modelling for CC impact category is subdivided into several steps: emissions of a greenhouse gas (kg) will lead to an increased atmospheric concentration of greenhouse gases (ppb) which, in turn, will increase the radiative forcing capacity (w/m2), leading to an increase in the global mean temperature (°C). Increased temperature ultimately results in damage to human health and to terrestrial and freshwater ecosystems. Concerning the relative risk of health due to an increase in global temperature, it lies in the increased risk of diseases (malnutrition, malaria and diarrhea) and increased flood risk that will lead to additional damage to human health in Disability-Adjusted Life Years (DALY) at end-point. To be noted that not every region in the world is affected in equal measure by all of these effects. For these reasons, results interpretation has to take into account the differences between Scandinavia and Mediterranean Countries.
Damage to terrestrial ecosystems consists in a biodiversity loss, represented by the increase in potentially disappeared fraction of species due to an increase in global temperature or effect factor.

The effect factor is taken from the review by Urban (2015), who reports a predicted extinction of 2.8% at current temperatures (0.8 °C above pre-industrial levels) and an extinction of 15.7% following a business-as-usual scenario (4.3 °C temperature increase above pre-industrial levels). Damage to freshwater ecosystems consists in a biodiversity loss, represented by the potentially disappeared fraction of fish species in river basin due to a change in temperature. Detailed results of the impact category Climate change for functional unit are reported in Table 29 to Table 33. for each F-CUBED Production System.

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6.3.2 Pulp & Paper Bio-sludge

As reported in Table 29. the overall electricity generation from 1 ton of Air Dried Pulp is 15.82 and 5.56 kWh for F-CUBED and RC cases, respectively, representing an improvement of 10.26 kWh for F-CUBED (185%) relevant to the reference case. This production is associated with the carbon footprints of 17.90 and 18.50 kg $CO_{2\ eq}/t_{ADp}$, corresponding to 1.13 and 3.33 kg $CO_{2\ eq}$/kWh, respectively and to an improvement relative to the RC of emissions saving of -2.20 kg $CO_{2\ eq}$/kWh (-66%).

These carbon emissions are positive and consist of emissions in the air compartment (atmosphere); nonetheless, considering the saving emissions related to the avoided treatment and disposal of the pulp & paper bio-sludge, the impact on climate change becomes negative and accounts for -4.56 and – 2.36 kg $CO_{2\ eq}$/kWh, respectively for the F-CUBED and RC processes. These final values result even more sustainable with respect to the Sweden Electricity Country Mix, which presents a carbon intensity of 45 g/kWh (2022) (Our World in Data 2022) [Fig.48]

Table 29 - Performance of the Pulp & Paper F-CUBED Production System in term of Carbon Footprint and comparison with the Reference Case

Indicator	Unit	RC	F-CUBED PS	F-CUBED PS Improvement	
Electricity production	kWh/t_{ADp}	5.56	4.56		
AD electricity production	kWh/t_{ADp}	0.00	11.26		
Total electricity production	kWh/t_{ADp}	5.56	15.82	10.26	185%
Carbon Footprint - process	kg $CO_{2\ eq}/t_{ADp}$	18.50	17.91		
Carbon Footprint - F.U. (1)	**kg$CO_{2\ eq}$/kWh**	**3.33**	**1.13**	-2.20	66%
Avoided treatment & disposal of sludge from pulp and paper production	kg$CO_{2\ eq}$/kWh	5.69	5.69		
Carbon Footprint - F.U. (2)	**kg$CO_{2\ eq}$/kWh**	**-2.36**	**-4.56**	-2.19	93%

In any case, in this case study, to calculate the final carbon footprint the further emissions needed to cover the electricity production gap between F-CUBED and RC was not taken into account because in the Smurfit Kappa plant the overall need of electricity is covered by the internal Energy Production System and the carbon footprint for the functional unit would not change.

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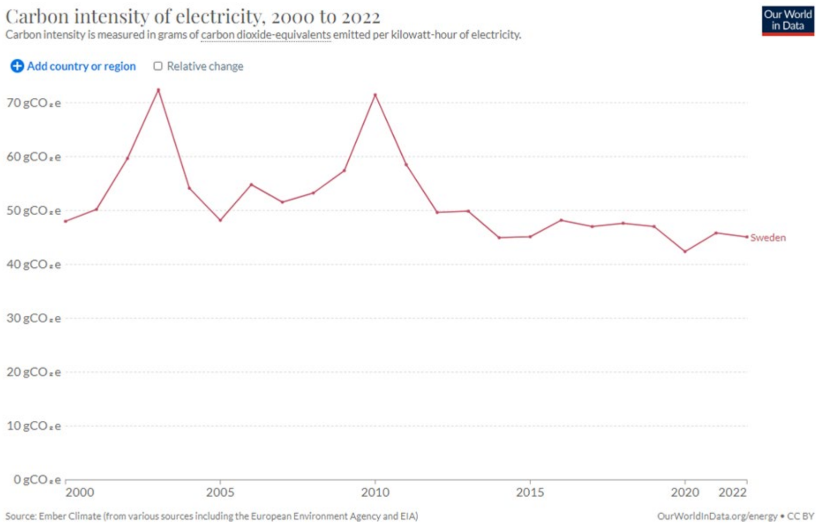

Figure 48 - Carbon Intensity of the Sweden Country Mix (Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy OurWorldInData.org/energy CC BY)

6.3.3 Virgin Olive Pomace

As reported in Table 30. the electricity generation from 1 ton of Virgin Olive Pomace is 2.064.31 kWh and 270.07 kWh for the F-CUBED and Reference Case, respectively. This represents an improvement of 1.794.24 kWh for the F-CUBED process (664%) relative to the reference case. This production is associated with carbon footprints of -1.299.00 and -1.014.83 kg $CO_{2\ eq}/t_{OP}$.

To make the two production systems comparable it is necessary to take into account the equivalent electricity generation and adding to the final value of carbon footprint the further emissions needed to cover the electricity production gap between F-CUBED and RC with electricity country mix available at a national level. In this case study the Italian country mix (Fig.49) accounts for a carbon intensity of 0.372 $kgCO_{2\ eq}/kWh$ (Our World in Data 2022). The carbon cost of the gap is therefore 667.46 $kgCO_{2\ eq.}$ This translates in the final value for RC's carbon footprint of -347.38 kg $CO_{2\ eq}/t_{OP}$ and in the F-CUBED improvement with respect to the RC, consisting in the emissions saving of 941.72 kg $CO_{2\ eq}/t_{OP}$.

In conclusion F-CUBED Production System and Reference Case show carbon footprints of -0.63 and -0.17 kg $CO_{2\ eq}/kWh$ respectively. This means that the F-CUBED Production System provide emissions saving of 0.46 kg $CO_{2\ eq}/kWh$, corresponding to the improvement of 274% respect to the RC.

Table 30 - Performance of the Olive Pomace F-CUBED Production System in term of Carbon Footprint and comparison with the Reference Case

Indicator	Unit	RC	F-CUBED PS	F-CUBED Improvement	
Electricity production	kWh/t_{OP}	0.00	1.599.76		
AD electricity production	kWh/t_{OP}	270.07	467.11		
Total electricity production	kWh/t_{OP}	270.07	2.066.87	1.796.80	665%
Carbon Footprint - process	**kg $CO_{2\ eq}/t_{OP}$**	-1.014.83	-1.299.00		
Production GAP from Power Grid	kWh/t_{OP}	1.796.80	0.00		
Carbon intensity of electricity country mix_IT	kg $CO_{2\ eq}/kWh$	0.372			

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Carbon footprint cost of the gap	kg $CO_{2\ eq}$/ t_{OP}	668.41			
Carbon Footprint - process final	kg $CO_{2\ eq}$/ t_{OP}	-346.43	-1.299.00	-952.58	275%
Carbon Footprint - F.U.	**kg $CO_{2\ eq}$/kWh**	-0.17	-0.63	-0.46	275%
Carbon intensity improvement respect National Country Mix	kg $CO_{2\ eq}$/kWh	-0.540	-1.001	-0.46	85%

Finally with respect to the electricity dispatchable from the electric grid as National Country Mix (Italy) both F-CUBED and RC provide emissions saving (-0.540 and – 1.001 kg $CO_{2\ eq}$/kWh, respectively).

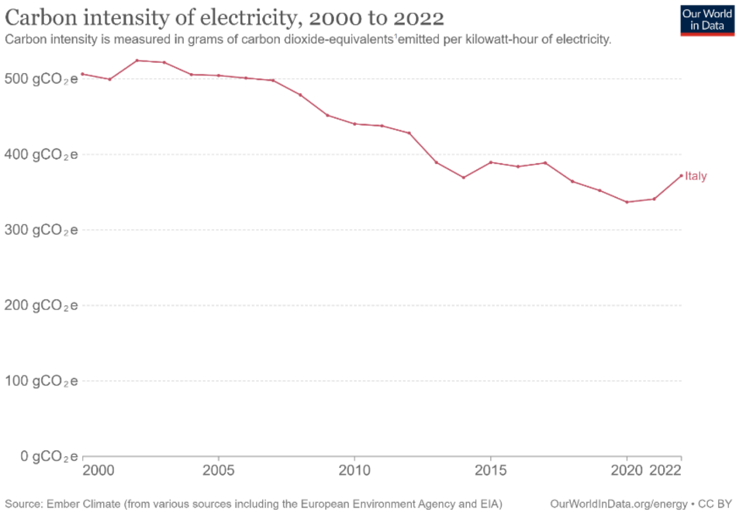

Figure 49 - Carbon Intensity of the Italian Country Mix (Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy OurWorldInData.org/energy CC BY

6.3.4 Orange Peels

As reported in Table 31. the electricity generation from 1 ton of Orange Peels is 5.213.75 and 1.163.01 kWh for the F-CUBED and RC cases, respectively. This difference of 4.050.74 kWh between the two cases corresponds to more than 3 times improvement (348%) for F-CUBED process. This production is associated with carbon footprints of -1.257.05 and -532.63 kg $CO_{2\ eq}$/t ORP.

To make the two production systems comparable it is necessary to take into account the equivalent electricity generation and adding to the final value of carbon footprint the further emissions needed to cover the electricity production gap between F-CUBED and RC with electricity country mix available at a national level. In this case study the Spanish country mix (Fig.50) accounts for a carbon intensity of 0.217 kg$CO_{2\ eq}$/kWh (2022) (Our World in Data 2022). The carbon cost of the gap is therefore 879.01 kg$CO_{2\ eq.}$ This translates in the final value for RC's carbon footprint of 346.38 kg $CO_{2\ eq}$/t ORP and in the F-CUBED improvement with respect to the RC consisting in the emissions saving of 1647.98 kg $CO_{2\ eq}$/tOP.

In conclusion F-CUBED Production System and Reference Case show carbon footprints of -0.25 and 0.07 kg $CO_{2\ eq}$/kWh respectively. This means that the F-CUBED Production System provide emissions saving of 0.32 kg $CO_{2\ eq}$/kWh, corresponding to the improvement of almost 5 times (476%) with respect to the RC.

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Table 31 - Performance of the Orange Peels F-CUBED Production System in term of Carbon Footprint and comparison with the Reference Case

Indicator	Unit	RC	F-CUBED PS	F-CUBED Improvement	
Electricity production Main Stream	kWh/t_{ORP}	0.00	2.326.47		
AD electricity production	kWh/t_{ORP}	1.163.01	2.887.28		
Total electricity production	kWh/t_{ORP}	1.163.01	5.213.75	4.050.74	348%
Carbon Footprint - process	**$kg\ CO_{2\ eq}/t_{ORP}$**	-532.63	-1.301.61		
Production GAP from Power Grid	kWh/t_{ORP}	4.050.74	0.00		
Carbon intensity of electricity country mix_ES	$kg\ CO_{2eq}/kWh$	0.217			
Carbon footprint cost of the gap	$kg\ CO_{2\ eq}/t_{ORP}$	879.01			
Carbon Footprint - process final	$kg\ CO_{2\ eq}/t_{ORP}$	346.38	-1.301.61	-1.647.98	
Carbon Footprint - F.U.	**$kg\ CO_{2eq}/kWh$**	0.07	-0.25	-0.32	476%
Carbon intensity improvement respect National Country Mix	$kg\ CO_{2eq}/kWh$	-0.151	-0.467		

Finally with respect to the electricity dispatchable from the electric grid as National Country Mix (Spain) both F-CUBED and RC provide emissions saving (-0.15 and – 0.47 kg $CO_{2\ eq}$/kWh, respectively).

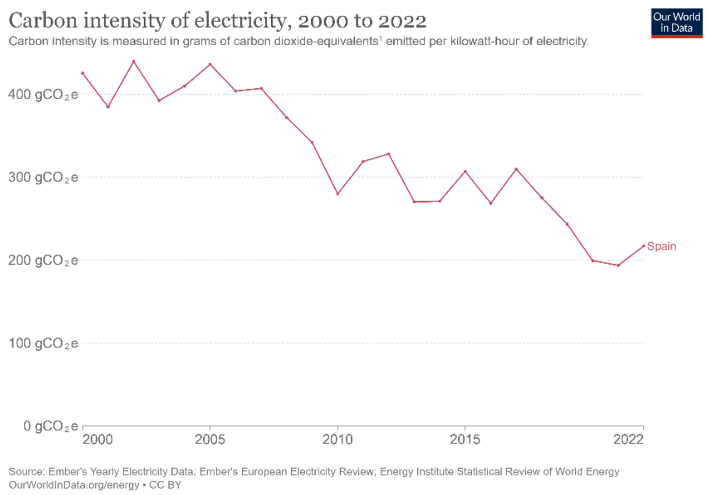

Figure 50 - Carbon Intensity of the Spanish Country Mix (Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy OurWorldInData.org/energy CC BY)

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6.4 Pellets environmental performances in the framework of RED II Methodology

The RED II methodology has been applied to the F-CUBED Production System for the three different biogenic residue streams: pulp & paper bio-sludge, olive pomace, orange peels.

The Annex VI point B of the RED II describes the calculation of the GHGs emissions concerning the production and use of biomass fuels before conversion into electricity, heating and cooling; particularly, the equation used is:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u + e_{sca} + e_{ccs} + e_{ccr}$$

Where:
E = total emissions from the production of the fuel before energy conversion;
e_{ec} = emissions from the extraction or cultivation of raw materials;
e_l = annualised emissions from carbon stock changes caused by land-use change;
e_p = emissions from processing;
e_{td} = emissions from transport and distribution;
e_u = emissions from the fuel in use;
e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;
e_{ccs} = emissions savings from CO2 capture and geological storage;
e_{ccr} = emissions savings from CO2 capture and replacement.

The RED II approach excludes the emissions from the manufacture of machinery and equipment.

For the electricity or mechanical energy coming from energy installations delivering useful heat together with electricity and/or mechanical energy, the emissions calculated have to be referred to the efficiency of the conversion plant as reported in the following equation:

$$EC_{el} = \frac{E}{\eta_{el}} \left(\frac{C_{el}\,\eta_{el}}{C_{el}\,\eta_{el} + C_h\,\eta_h}\right)$$

where:
$EC_{h,el}$ = total greenhouse gas emissions from the final energy commodity, in this case electricity;
E = total greenhouse gas emissions of the fuel before end-conversion;
η_{el} = the electrical efficiency, defined as the annual electricity produced divided by the annual energy input, based on its energy content;
η_h = the heat efficiency, defined as the annual useful heat output divided by the annual energy input, based on its energy content;
C_{el} = fraction of exergy in the electricity, and/or mechanical energy, set to 100 % (C_{el} = 1);
C_h = Carnot efficiency (fraction of exergy in the useful heat) set to 0.3546 for a temperature of 150°C.

The implementation of this approach in the F-CUBED project has been carried out considering for each case study: the emissions due to the pre-treatment and conditioning of the residual biomasses (e_{ec}); the emissions due to the Torwash process, the dewatering phase and the pelleting plant (e_p); the emissions originated from the transport phases of the biomasses and intermediate materials (e_{td}); the emissions for the energy conversion phase (e_u) where the produced pellets are used for generating power and heat.

For accounting all these emissions SimaPro modelling has been used, therefore the following assumptions have to be highlighted:

1. the calculation includes the emissions from the manufacture of machinery and equipment;

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2. the allocation of the emissions between pellets and biogas production has been done using the estimated LHV of the pellets and considering the nominal amount of energy generated by each fuel (e.g. for pulp & paper bio-sludge 95.49 MJ/t_{ADp} for the pellets and 8.37 MJ/t_{ADp} for the biogas);
3. no emissions have been allocated to wastes/residues, but the emissions due to the residual biomass conditioning are included, without considering the benefits due to the avoided waste treatments and disposal;
4. for biomass fuels used for the production of electricity, the fossil fuel comparator has been set to 183 g CO_{2eq}/MJ electricity, which can be different in respect of the specific carbon intensity of the electricity country mixes.

Considering the limitations above listed the obtained results are precautionary, showing savings lower than the expected ones that could be obtained with more detailed modelling and actual values

The emissions calculated for the pellets production are equal to 0.668. 0.175 and 0.219 kg CO2eq/t of residual biomass for pulp & paper bio-sludge, olive pomace, orange peels respectively. These emissions account for savings of -49%, -89% and -91%, respectively as reported in Table 32.

Table 32 – Greenhouse gas emissions savings calculated with the methodology indicated in the Annex VI of the Directive (EU) 2018/2001 for biomass fuels

Parameter description	Symbols	Units	Values		
			PPB	OP	ORP
Total greenhouse gas emissions share of pellect for the electricity generation in the F-CUBED Production Systems		g CO2eq/kg pellets	609,66	152,82	102,20
Low Heating Value of F-CUBED biopellets		MJ/kg	18,20	26,30	22,20
Total greenhouse gas emissions of the pellets before end-conversion	E	gCO2 eq/MJ pellet	33,50	5,81	4,60
Carnot efficiency (fraction of exergy in the useful heat)	C_h	%	0,35	0,35	0,35
Fraction of exergy in the electricity, and/or mechanical energy	C_{el}	%	1,00	1,00	1,00
Heat efficiency	η_h	%	0,53	0,41	0,41
Electrical efficiency	η_{el}	%	0,17	0,14	0,14
Total greenhouse gas emissions from the final energy commodity (electricity)	$EC_{h,el}$	gCO2eq/MJ	93,17	20,86	16,52
Fossil fuel comparator	$EC_{F(el)}$	gCO2eq/MJ	183,00	183,00	183,00
GHG emission saving		%	-49%	-89%	-91%

To have a comparison term, it is useful to consider the default values of GHG emissions saving for Electricity production, provided from DIRECTIVE (EU) 2018/2001 (RED II) (European Commission 2018), for Wood briquettes or pellets from forest residues, referred to the biomass fuel production system belonging to the Case 2a[5], that range between 45% and 59%. While taking in consideration cereals straw pellets these values vary between 64% and 87%.

In conclusion the GHG emissions saving potential of the electricity generated with the biopellet produced by the F-CUBED Production System seems to be in compliance with or overcome the default value stated by RED II.

[5] Case 2a refers to processes in which a woodchips boiler, fed with pre-dried chips, is used to provide process heat. Electricity for the pellet mill is supplied from the grid.

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Nevertheless, for claiming the respect of sustainability criteria for biomass fuels foreseen in the RED II, F-CUBED pellets must fulfil the sustainability and the greenhouse gas emissions saving criteria laid down in Sections 10 of the 29 of the RED II, stating that the GHG emissions saving must be at least 70 % for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025. and 80 % for installations starting operation from 1 January 2026.

In this perspective only the bio-pellets referring to the OP and ORP case studies could be claimed sustainable and suitable to take into account a) the energy from biomass fuels for the purposes contributing towards the Union target set in Article 3 and the renewable energy shares of Member States; b) measuring compliance with renewable energy obligations; c) eligibility for financial support for the consumption of biofuels, bioliquids and biomass fuels.

6.5 – Analysis of the LCA results on annual basis

Starting from the results of LCIA for functional unit, and considering the annual production of biogenic residues and the electricity which can be generated by the F-CUBED Production System, the annual balance of the avoided impact of the more representative indicators are reported in Table 33.

Table 33 - Reductions or removals of GHG emissions and other relevant Impact Category Potentials

Scenario for biogenic residue	Unit	Paper biosludge	Olive Pomace	Orange Peels
Ton feedstock per year	t/y	650.000,00	9.600,00	2.300,00
KWh per ton feedsytock	kWh/t	14,87	2.064,31	5.213,65
Dispatchable electricity	MWh/y	9.665,50	19.817,38	11.991,40
Saving per F.U.				
Climate change	kgCO2 eq/kWh	- 2,2000	- 0,4600	- 0,3200
Freshwater eutrophication	kg SO2 eq./ kWhe	- 0,1463	- 0,0008	- 0,0002
Terrestrial acidification	kg P eq./ kWhe	- 0,0090	0,0039	0,0010
Fossil depletion	kg oil eq./ kWh_e	- 0,8128	- 0,1879	- 0,1391
Saving per ton of residue				
Climate change	kg CO2eq/t feed	- 32,71	- 949,58	- 1.668,37
Freshwater eutrophication	kg P eq. /t feed	- 2,17	- 0,85	- 0,78
Terrestrial acidification	kg SO2 eq. /t feed.	- 0,13	3,96	4,07
Fossil depletion	kg oil eq. /t feed	- 12,09	- 189,17	- 584,51
Yearly saving				
Climate change	t CO2eq /y	- 21.264,10	- 9.115,99	- 3.837,25
Freshwater eutrophication	t P eq. /y	- 1.413,69	- 8,17	- 1,80
Terrestrial acidification	t SO2 eq. /y	- 87,47	38,04	9,35
Fossil depletion	t oil eq. /y	- 7.855,87	- 1.816,05	- 1.344,36

These data put in evidence that the more efficient scenario for the production of dispatchable electricity is OP case study, in respect off PPB and ORP ones. Indeed the amount of Electricity potentially yearly produced by the F-CUBED case for OP is 2 times more productive than the PPB and 1.5 times than ORP.
This relates to the energy efficiency of feedstock and the yearly number of residues available. E.g. for ORP case, although kWh produced per ton of residues is the highest (5,213.65 $kWh/t_{res.}$) the amount of biomass yearly available doesn't reach 2,500 t/y.

The savings are determined on the base of the difference between the emissions of the F-CUBED Production System and those of the Reference Case considered the asset of business as usual practice.
PPB case study shows the highest savings per functional unit demonstrating that, as for economics (Dijkstra, et al. 2023), the best environmental benefits are found for the paper sludge scenario where bio-sludge is processed.

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This is replicable for all the impact categories more relevant for the bioenergy sector and the F-CUBED Production System such as Climate change, Freshwater eutrophication, Terrestrial acidification and Fossil depletion.

Other considerations have to be done for the environmental efficiency of feedstock, where there isn't a linear behaviour of the residues in every impact category. Indeed for Climate change and Fossil depletion impact categories, the OP case presents the highest value of the three (- 1668.37 kg CO_{2eq}/t_{feed} and – 584.51 kg oil $_{eq}/t_{feed}$), whilst for Freshwater eutrophication and Terrestrial acidification PPB case study shows the best results in term of feedstock environmental performance (-2.17 kg P_{eq} /t $_{feed}$ and -0.13 kg SO_{2eq} /t $_{feed}$).

In conclusion if we consider the yearly saving of each case study, PPB shows the best environmental performances, with avoided emissions of carbon dioxide of -21.264 t CO_{2eq}/y, of phosphorous of -1.414 t P_{eq}/y and oil equivalent of – 7.856 t oil_{eq}/y.

The emission savings for OP and ORP case studies, could translate in a potential complementary income for the residue producer, referring to the voluntary market of certified carbon credits. Carbon credits are quantifiable, independently verified reductions in emissions from validated climate action projects which lessen, eliminate, or steer clear of greenhouse gas (GHG) emissions.
Projects must follow a strict set of requirements in order to pass review by a panel of experts referring to voluntary carbon market standard leaders like Verra or Gold Standard as well as certification by independent organizations. This is particularly important for OP case study since practical realities such as the seasonal production of olive pomace and the concentrated operational hours are inherent challenges in sustaining operations.

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7. Conclusions (Part A, E-LCA)

In the framework of the WP5 of the F-CUBED Project, an attributional LCA was carried out to describe the environmental performances of the F-CUBED Production System and its sub-systems, aiming to quantify the environmental impacts related to all relevant resources, energy and materials as inputs and output within the defined system boundaries.

According to the importance of the LCI phase for the direct correlation with the correctness of the LCA results, the data quality control has been permanently conducted through an iterative process. Mostly, the data coming from the modelling of the system process has been considered sensitive data because the technology in the study is at pilot scale and not yet developed at industrial scale.
In conclusion, the overall dataset of the described systems is considered to be high and representative in terms of technology coverage and resource supply chain.

In the LCIA phase the life cycle inventories for the investigated three case studies (scenarios for pulp & paper bio-sludge, virgin olive pomace and orange peels), have been converted into a number of harmonized impact scores by ReCiPe impact assessment method based on Hierarchist perspectives, at midpoint level.

To reduce the complexity of the LCA study, including the multitude of impact categories of ReCiPe method, impact category selection has been performed to identify the highlights of the LCIA results through the LCIA impact categories of relevant significate for the bioenergy sector and F.CUBED Production System, maintaining the accuracy of LCA analysis. Therefore, 10 out of 18. impact categories have been prioritized, according to the different compartments of action. For the air compartment: Climate change, Ozone depletion and Photochemical oxidant formation; for soil compartment: Terrestrial acidification; for water compartment: Freshwater eutrophication and Freshwater ecotoxicity; as resource depletion: Water depletion and Fossil depletion; with specific focus on human health: Human toxicity and Particulate matter formation.

Reliability of this categorisation was also ensured through a sensitivity analysis, as parameter uncertainty analysis, carried out by Monte Carlo simulation. Every impact category has been described by statistical indicators: media, median, standard deviation, coefficient of variation, limits of the 95% confidence interval, standard error of the mean. The reliable impact categories have a coefficient of variation (CV%) ≤ 20%, on the contrary impact categories with CV > 20% up to 100% were classified as unreliable. The latter required deepening investigation and have been interpreted with caution. Indeed for them, the standard deviation is relatively large relative to the mean with high variability between the data, indicating a low reliability of the impact assessment results. Finally, the impact category value associated with CV > 100% have been classified as inconsistent and ignored in the LCIA.

The cross-check of impact category selection and sensitivity analysis lead to the following conclusions.
In Pulp & Paper Bio-sludge case study three impact categories are reliable for F-CUBED Production System based on their coefficients of variation[6] (%): PMF (12.0%), TA (12.1%) and CC (19.1%).
On the contrary, six categories are classified as unreliable: POF (22.7%), OD (23%) FD (24%), ALO (27.5%) HTX (37.8%) FETX (39.3%) and the inconsistent impact categories are two: FEUT (528%) and WD (2.924.6%).
In Olive Pomace case study four impact categories guarantee reliability: FD (13.18%), CC (15.41%), TA (17.68%) and PMF (17.69%).
On the contrary, three categories are classified as unreliable: POF (41.71%), FEUT (87.20%), HTX (96.14%) and the inconsistent are OD (-121.65%), FETX (-535.53%), WD (1.664.99%).
In Fruit & Vegetable (Orange Peels) case study, five impact categories guarantee reliability: TA (6.5%), PMF (6.77%), POF (12.42%), FD (17.09%) and CC (-21.99%).
On the contrary, three categories are classified as unreliable: HTX (34.54%), FETX (72.30%), FEUT (74.95%) and the inconsistent are OD (539.54%) and WD (3.038.20%).

[6] In brackets the value of Coefficient of Variation (CV%)

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These results make clear that to describe the environmental performances of the F-CUBED Production System applied to the selected biogenic residue streams, the most important impact categories are CC, PMF and TA, which show the highest reliability in every case study and are representative of air compartment (atmospheric emissions), human health and soil compartment, respectively.

Secondarily, it is necessary to refer to FTXT and FEUT which attain to and are relevant impact indicators for the specific impact of the wet residues in the water compartment, and HTX which gives a specific focus on human health, although its CV range between unreliable value of 35%-96%.
Finally the impact categories representative and reliable for single biogenic residue stream are FD in Olive Pomace case study, POF in Orange peels and ALO in Pulp & Paper case study.

The results of LCIA provide insights into the environmental impacts of the F-CUBED Production System on the respective biogenic residues sectors. The comments for reliable impact categories highlight positive environmental outcomes useful to draw conclusions about the environmental performance of the hydrothermal treatment of these biogenic residues, while those for unreliable categories suggest the need for more robust data or further investigation.

The Climate change impact category provides the following result, for each case study (kg CO2 eq./t residue): Pulp & Paper Bio-sludge, 17.9; Virgin Olive Pomace, -1.290 (negative value due to GHG saving); Orange Peels, -1.300 (negative value due to GHG saving). The hydrothermal treatment of pulp and paper bio-sludge, olive pomace, and orange peels all result in a significant reduction in carbon emissions with respect to the respective reference cases . This is especially notable for olive pomace and orange peels, where the process is effectively providing a GHG saving from the atmosphere, contributing to a negative carbon footprint. This outcome aligns well with climate change mitigation goals of the F-CUBED Project.

Particulate Matter Formation impact category provides the following reliable result, for every case study (kg PM10 eq./t residue): Pulp & Paper Bio-sludge, 0.0789 ; Virgin Olive Pomace, 0.929 ; Orange Peels, 4.59
While all three cases have low impacts on particulate matter formation, it's worth noting that olive pomace and orange peels show slightly higher impacts. This suggests that measures to control particulate emissions might be beneficial for these residues during treatment.

Terrestrial Acidification impact category provides the following result, for each case study (kg SO2 eq./t residue): Pulp & Paper Bio-sludge, 0.202 ; Virgin Olive Pomace, 2.99 ; Orange Peels, 13.5 pulp & paper bio-sludge has the lowest impact on terrestrial acidification, while olive pomace and orange peels have higher impacts. This indicates that the latter two residues might require additional mitigation measures to reduce their acidification potential during treatment.

Freshwater Eutrophication impact category provides the following result, for each case study (kg P eq./t residue): Pulp & Paper Bio-sludge, 0.289 ; Virgin Olive Pomace, 0.349; Orange Peels, 1.31
All three cases have relatively low impacts on freshwater eutrophication, suggesting that the hydrothermal treatment does not exacerbate nutrient pollution in aquatic ecosystems. This is a theoretically positive outcome, as eutrophication can lead to harmful algal blooms and oxygen depletion in water bodies. On the other hand FEUT has, according to the CV score, an inconsistent value for PPB case study and unreliable values for OP and ORP ones. This means that the treatment of the residues could need additional optimization to minimize their eutrophication effects on aquatic life.

Freshwater Ecotoxicity impact category provides the following result, for each case study kg 1,4-DB eq./t residue): Pulp & Paper Bio-sludge, 1.67 ; Virgin Olive Pomace, -2.26 (negative value indicating savings in chemical elements such as Copper, Manganese, Nickel, Vanadium, Zinc, etc.); Orange Peels, 29.1.
Virgin olive pomace shows a lower impact on freshwater ecotoxicity, while pulp & paper bio-sludge and orange peels have higher impacts. However, as FETX has an inconsistent value for OP case study and unreliable for PPB and ORP ones, the treatment of the residues may need additional steps to minimize their ecotoxic effects on aquatic life.

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Fossil Depletion Freshwater Ecotoxicity impact category provides the following result, for each case study (kg oil eq./t residue): Pulp & Paper Bio-sludge, 4.43; Olive Pomace, -499 (negative value indicating a savings in fossil resource); Orange Peels, -627. OP and ORP cases show a reliable reduction in fossil resource use due to the hydrothermal treatment process. This is a positive outcome, indicating a move toward more sustainable resource utilization.

Human Toxicity impact category provides the following result, for each case study kg 1,4-DB eq./t residue): Pulp & Paper Bio-sludge, 14.6; Virgin Olive Pomace, 150; Orange Peels, 656. The F-CUBED treatment in PPB case study has the lowest impact on human toxicity, while OP and ORP show higher impacts. Although this value is unreliable for every case study, it indicates that need careful management during treatment of the residues to reduce the toxicity related to the presence in the residues of chemical elements such as Antimony, Arsenic, Lead, Mercury, Vanadium, in air compartment and Arsenic, Barium, Lead, Manganese, Molybdenum, Zinc, in water compartment, or released from the treatment in downstream processes or secondary processing. Photochemical Oxidant Formation for Orange peels is 6.27 kg NMVOC/t residue. For Pulp & Paper Bio-sludge, 0.108 and Virgin Olive Pomace, 1.02.

All three cases have relatively low impacts on photochemical oxidant formation, indicating that the hydrothermal treatment does not significantly contribute to the formation of ground-level ozone due to the reaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx) in the presence of sunlight, which is harmful to human health and the environment. These is particularly true for OP case study where the impact category presents high reliability, on the contrary for the latter case studies this category is unreliable This means that the treatment of the residues could need additional optimization to minimize respiratory distress in humans, and negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors.

Agricultural Land Occupation impact category provides the following result, for each case study (m^2a/t residue): Pulp & Paper Bio-sludge, 63.6; Virgin Olive Pomace, 1.600; Orange Peels, 3.090. Although this category is not of primary importance for the specific objectives of the F-CUBED Production System LCA the results have to be explained because F-CUBED technology (TORWASH and Membrane Filter Press), core part of the main stream processes, is assumed to be integrated in existing facilities, due to the challenges (and environmental impact) of transporting wet residue. This means, as consequence, that the impact has to be attributed mainly to the occupation and transformation of a certain area of land by the stages like drying and pelletization which offer locational flexibility, suggesting the potential for a hub-based infrastructure, and to pellet energy conversion and biogas generation units, into electricity and voltage transformation. In PPB case study, ALO provides an overall impact of 63.58 m^2a/ t_{ADp}, mostly in charge of occupation forest intensive, unit process (88%). The downstream processes of the F-CUBED Production System are the largest contributors (43.41 m^2a/ t_{ADp}), but also Main Stream Processes contribute with 12.53 m^2a/ t_{ADp} (about 20%).

In summary, the environmental perspective on these LCA results shows that the hydrothermal treatment of these biogenic residues can have several positive environmental impacts, such as carbon sequestration and reduced fossil resource use. However, there are variations in the environmental performance of the three residues, suggesting that specific mitigation strategies may be needed for certain environmental categories. Additionally, water use and land occupation should be carefully managed to minimize their environmental footprint.

Comparison between the F-CUBED Production System and Reference Cases have been carried out.
The results show that in PPB case study the F-CUBED Production System in all impact categories considered is more performative than Reference case. On the contrary OP and ORP case studies report better values only for three impact categories: CC, FD and FEUT.
A further comparison with Electricity country mix impacts have been conducted to put in evidence how the electricity impact intensity of the different countries can affect the final outcomes, taking into particular

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account the differences in carbon intensity for Sweden, Italy and Spain. In the PPB case study Sweden ECM has a very little carbon intensity of the country mix. However, the overall Energy Production System of the case study is very energy efficient. On the contrary OP case study relates to ECM of Italy which have a relatively high carbon intensity; this makes the electricity produced by F-CUBED process more environmentally friendly than ECM. Finally for the ORP case study F-CUBED perform from environmental point of view better than Spain ECM only for three impact categories (CC, POF and FD) of eight. In fact the carbon intensity of the ECM of Spain has a value between those of Sweden and Italy.

This analysis highlights as Climate change are affecting Europe in various forms, depending on the different regions. It can lead to biodiversity loss, forest fires, decreasing crop yields and higher temperatures. It can also affect people's health. Extreme weather and climate-related hazards such as heat waves, floods and droughts will become more frequent and intense in many regions with different pattern in North and Mediterranean Europe. Therefore, minimising the risks from global climate change requires targeted actions to adapt to the impacts of climate change, in addition to actions to reduce greenhouse gas emissions. Adaptation must be tailored to the specific circumstances in different regions and cities of Europe.

This point is well taken into account from F-CUBED Production System. Finally, it has to be highlighted that the obtained results for the F-Cubed Production System for different residual biogenic streams should not be compared because the biomasses do not characterise alternative scenarios but site-specific solutions considering the locally developed industrial sectors. Particularly, because the residual biomasses are chosen based on their territorial availability; indeed, the environmental performances of the different streams are influenced by their physical-chemical characteristics and by the optimisation of the production systems producing them. For instance the olive pomace and the orange peels have better environmental performances per ton of treated biomass than the pulp and paper bio-sludge. On the other hand the annual savings for the CO2eq of the pulp and paper bio-sludge are higher than those of the olive pomace and the orange peels, because of the higher flow rate and hypothesised plant size.

This significant amount of CO_{2eq} savings implies interesting economic revenues able to promote the F-Cubed Production System adoption through the potential generation of certified carbon credits to be valorised in the voluntary carbon market. By purchasing carbon credits from verified activities that promote community development, conservation of ecosystems, or put in place effective technologies to lower or remove emissions from the atmosphere, companies, institutions and individual persons can make up for their unavoidable emissions. This point should be deepened in the further steps for the scaling up of the F-CUBED technology.

According to the aim of the project, the F-Cubed Production System aims to upgrade different biogenic streams with high moisture content: the Torwash treatment enables the optimisation of the recovery of the dry matter content of the residual biomasses, producing dispatchable energy carriers (i.e. pellets). Moreover, the overall results show the benefits related to the use of renewable sources for energetic purposes, reaching savings of more than 50% for the CO_{2eq} and the fossil depletion indicators, with significant benefits for the climate change contrast and the national energy security. Considering the high potential impacts of the streams on the water compartment, the F-Cubed Production System highlights also a significant reduction of the freshwater eutrophication with respect to the reference cases. No reductions of Terrestrial Acidification have been observed for the F-Cubed Production System because of the hydrogen sulfide (H_2S) emissions produced during the Torwash treatment phase and the biogas cleaning.

In conclusion, the novel technology promoted by F-CUBED Production System, also in compliance with the goals of the EU's Circular Economy Action Plan, improves energy efficiency of bioenergy product and produces cleaner energy with respect to the Reference Cases, providing a concrete help to the EU to achieve its climate goals and reduce its dependency on energy imports. This is in line with the recent (March 2023)

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Parliament and Council deal to boost renewable energy increasing the share of renewables in the EU's final energy consumption to 42.5% by 2030. whilst individual countries should aim for 45%.
Therefore the F-CUBED Production System contributes to justify the production and use of bioenergy and represents a recommendable strategy to further increase the environmental sustainability.

About future aims of the work on E-LCA and recommendation, as TORWASH technology and some of the findings from this research are still in the preliminary development stages, there is room for improvement and optimization in the process models, which directly relate to the need to deepen and refine the LCA study with regard to the optimal solutions for conversion of biomass and biogas into energy.
The optimization of these aspects would increase the environmental performances of the F-CUBED Production System, which has been provided so far according to a conservative approach, and will give useful insights for its scaling up.

7.1 Limitations of the study

Stating the limitations of the study is essential for appropriate conclusions and recommendations to be made, which can influence decision-making and avoid both unrealistic and misleading LCA results. As limitations of the present LCA study, the following items are excluded from the system boundaries:

- Construction and decommissioning of the plants;
- Repair and maintenance activities;
- Construction of the infrastructure (i.e., roads, railways), as well as construction of the means of transportation (i.e., truck, trains, ship);
- Installation of unloading facilities;
- Human activities associated with labour tasks;
- Low-frequency, high magnitude, non-predictable events (i.e., fugitive, accidental releases).

Moreover, it has to be highlighted that a specific amount of tap water has been considered as input even if no dilution is carried out in the TORWASH phase. This amount of water is a mass balance correction due to the illusory increasing of the effluent flow which is calculated starting from the reduced dry matter content after the treatment. In fact during the TORWASH treatment the solids contained in the pomace change their chemical characteristics shifting also from suspended to diluted ones: these chemical variations have not been detailed in the LCA model; therefore the correction of the mass balance has been carried out.

Some considerations about the secondary processes have to be done. Particularly the F-CUBED system provides the nutrients recovery during the digestion phase and even the production of struvite. Data for struvite production have not been considered reliable because they are from laboratory scale experiments, however the possibility of digestate reuse has been carefully taken into account.

The anaerobic reactor has been hypothesised with a smaller scale if compared with that of the similar plants used for municipal or agricultural biowastes; moreover the inlet biomasses are controlled and characterised by high homogeneity (i.e. the biomass typologies are always the same and from the same plants) and reduced variations of physicochemical parameters (e.g. limited changes of suspended/diluted solids, heavy metals, BOD, COD, etc.). Based on these assumptions the digestate can be considered as a high quality soil improvement with a certain quantity of nutrients that can be easily reused by crops.

The inventory for the anaerobic digestion has been based on the proxy UPR contained in the Ecoinvent database describing a commercial plant for biogas production through the anaerobic digestion of manure scaled by the digestate production input value (foreground data) for the specific biogenic residue stream.

Finally, in F-CUBED Production Systems case study of Virgin Olive Pomace and Orange Peels wastes, Polyphenols and Limonene are presents in substrates, respectively. These compounds are well known as an antimicrobial agent, which limit and depress the biogas production when digesting the substrates. In this work, pre-treatment of the Virgin Olive Pomace and Orange Peels to remove Polyphenols and Limonene aren't considered.

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Part B – Social Life Cycle Assessment

8. Introduction to Social Life Cycle Assessment (S-LCA)

F-CUBED Project gives a crucial relevance to the analysis of the environmental impacts and socio-economic assessment of the F-CUBED novel technology and production system. According to the objective of the Task 5.5. Part B of the Deliverable 5.2 aims to evaluate socio-economic impacts with particular attention to the potential improvement of social conditions and of the overall socio-economic performance provided by F-CUBED Production System for relevant stakeholders involved in the life cycle of the system.

According to Benoît Norris and Norris (2015) S-LCA and the modular social hotspots database (SHDB) provide the necessary elements to conduct an assessment of supply chain due diligence. Therefore, a S-LCA has been conducted to forecast and preliminary evaluate the future potential social impacts (negative as risk or positive as benefit) for the full-scale applications of the actual TRL5 F-CUBED technology. The SHDB database has been used to set up the models of the F-CUBED supply chain for the analysis of the socio-economic aspect of the cradle-to-gate life cycle of the F-CUBED products (pellets, electricity and heat).

9. S-LCA Methodology

Social Life Cycle Assessment (S-LCA) is a methodology to assess the social impacts of products and services across their life cycle e.g. from extraction of raw material to the dispatch of the products, in the case of the system scope "cradle-to-gate". Moreover S-LCA offers a systematic assessment framework that combines quantitative as well as qualitative data.

S-LCA Methodology applied to F-CUBED Production System is based on 2020 UNEP Guidelines for Social Life Cycle Assessment for Products and Organizations (Benoît Norris, Traverso, et al. 2020). Similarly to the E-LCA, 2020 UNEP Guidelines suggests to develop the four phases according to the definitions provided by the International Organization of Standardization (ISO) through ISO 14040:2021 – Principles and Framework (ISO 2022) and ISO 14044:2021 – Requirements and Guidelines (ISO 2023): 1) Goal and scope definition; 2) Inventory phase, 3) Impact assessment (LCIA), and 4) Interpretation of the results. Therefore the LCA methodology, described in the Chapter 2. matches for many aspects with the S-LCA methodology applied in the Part B of the present Deliverable. The purpose, the object, as well as the methodological phases have been subjected to further optimizing reiterations, as set out in the Guidelines procedures. Moreover the novel nature of Project Scenario could imply new iterative assumptions in further steps of the research.

9.1 Goal and scope definition

The S-LCA study aims to define the social impact of F-CUBED Production System for the three selected biogenic residue streams in term of benefits and eventual potential risks for relevant stakeholders involved in the life cycle of the system. The results will contribute to the technology development evaluation (actual TRL5) in social term, to support the sustainability design of the Project forecasting potential Hotspots of the products, emissions and waste.

In compliance to the purpose stated above, the life cycle stages taken into account in the assessment will be assumed as general macro-processes belonging to the main economic sectors for the specific EU countries of the biogenic residues streams productive sites i.e. Sweden, Italy and Spain. This approach allows to unify in a single study the three stream flows Scenarios of residues treatment (pulp & paper bio-sludge, olive pomace and orange peels) and social context (different EU State Members).

9.1.1 Functional Unit And System Boundaries

The functional unit (FU) used for the S-LCA analysis is the same as defined for the E-LCA. It is based on physical attribute (1kWh of dispatchable electricity) that is, in the S-LCA, translated into economic value form using prices. Therefore the definition of the FU and the system boundaries are reported in Sections 3.1.1 and 3.1.2.

Due to the complexity of the whole production system starting from the different agroforestry supply chains in the different geographic areas, due to the developing phase that technology is still in and the multiple outputs which induce further complexity, for the sake of simplicity, the System Boundaries considered in the S-LCA study include the processes from the residues extraction in the industry to the production of the pellets up to the heat/electricity generation. Figure 50 generically outlines, from socio-economic perspective, all the different feedstocks scenarios with a generic biogenic residues input indication. The whole process avoids the field production of biomass, the transport of the biomass to an industrial plant where residues are generated, and start from the point of the extraction of the residue itself, feedstock of the F-CUBED Production System, where they are processed and then dispatchable final products (pellet, heat or electricity) to the end-users.

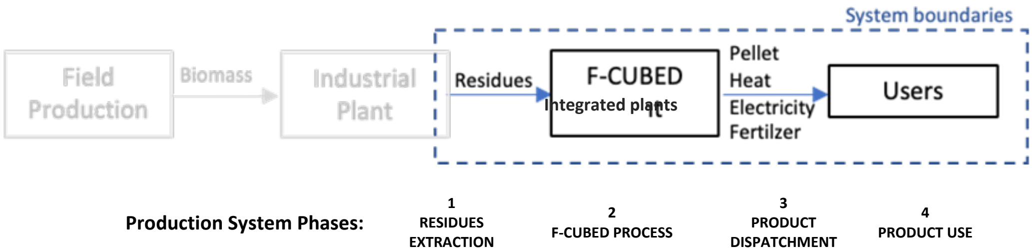

Figure 51 – Scheme of the F-CUBED Production System

This simplification allows to focus more specifically on socio-economic impacts, avoiding the wide factors of influence and variability that would be introduce considering also the upstream biomass production. As it is displayed in Figure 51 the analysis of the socio-economic aspects emphasises the processes and nodes of the production system that can better translated in economic and social indicators. The F-CUBED Production System scheme allowed to apply a process-based-model approach, i.e. a product system subdivided into processes, for arranging the inventory data collection.

9.2 Inventory phase (S-LCI)

The life cycle inventory based on a quantitative approach, consists of the inventory of all flows of the F-CUBED Production System normalized per functional unit. The approach of the data collection conducted in the E-LCA, reported in the Part A of the present study can be considered valuable also for the S-LCA. During the Social Life Cycle Inventory (S-LCI), data collection has been carried out for information about the activity variables (e.g. worker-hours) and for the social flows (indicators) which link with the socio-economic system through the activity variable.

For modelling the background dataset, a database and software have been used i.e. Social Hotspot Database and SimaPro. This dataset has been then integrated and enhanced by modelling the foreground system to cover the complete F-CUBED production system. Beyond the process-based-model approach, the F-CUBED Production System has also been divided into “sectors” related by economic flows from a specified currency (USD 2011). These two approaches therefore have been combined as hybrid approaches (Suh and Huppes 2005). The economic value of all the inputs has been converted from euro, pounds or sake to USD 2011. as the current version of SHDB is based on USD 2011.

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In Social Life Cycle Assessment (SLCA), databases like the SHDB (Social Hotspots Database) often use a specific reference year and currency for consistency and comparability of data. The choice of using USD 2011 as a reference year and currency is typically based on several considerations, such as base year, inflation and currency fluctuations, methodological consistency and comparability. A reference year is chosen as a baseline for data collection and comparison. By selecting a specific year, in this case, 2011. it is possible to capture a snapshot of socioeconomic conditions that can serve as a consistent reference point for evaluating changes over time.

On the other hand using a constant currency like USD 2011 helps to eliminate the effects of inflation and currency fluctuations, which can distort the analysis of social impacts over time. Inflation and exchange rate changes can make it difficult to compare data from different years directly. Finally standardizing on a single reference year and currency ensures methodological consistency across different datasets and studies that use the SHDB. This consistency is crucial for making meaningful comparisons between different products, processes, or projects. In fact, S-LCA aims to provide a basis for comparing the social impacts of different activities or products. By using a common reference year and currency, researchers and practitioners can better compare results and draw meaningful conclusions about the social performance of various options. The collected data are related to the life cycle stages as defined in the production system. Site-specific and quantitative data have been used on the basis of the requirements resulting from the definition of the Goal & Scope phase. In the S-LCI phase the SHDB provides contextual data on the usual social situation in a country and economic sector/industry. This information has been used as background data.

9.2.1 Prioritizing Data Collection

Prioritization and estimation of the relative importance of all unit processes in the F-CUBED Production System are relevant to guide social data collection and allocation of efforts.
In the present study prioritizing data collection of the studied system has been carried out by:

1) the literature review or web search that identifies key social issues not to miss in the S-LCA;
2) the most active or intensive activities/unit processes;
3) Identification of the hotspots in the product's life cycle.

Secondary and primary data for the stakeholders and impact subcategories have been collected for the economic sectors and sites related to the value chain.

A first analysis has been conducted using a database and software to identify the social hotspots of the product system and specific social issues significant and consistent with the system investigated.
Social hotspots are unit processes located in a region (e.g. country) where a situation occurs that may be considered a problem, a risk, or an opportunity, in relation to a social issue that is considered to be threatening social well-being or that may contribute to its further development (Benoît Norris, et al. 2020).
This generic analysis formed the core of the S-LCA study and were complemented with other data sources for some of the processes (foreground or background) and made more specific over time in an iterative fashion.
The **social issues** considered are those covered by the impact subcategories, as well as some other related issues also made available in the different tools and databases.
Secondary data has been also considered for each of the impact categories and subcategories selected by the identification of corresponding social inventory indicators that provide the most direct evidence of a social condition, e.g. salary, number of accidents at workplace (Muthu 2015).

In the present S-LCA study, SHDB databases was the source of indicators for which secondary, quantitative and site-specific data are available. This database conduct hotspot assessments and S-LCAs of products using SimaPro software. Social Hotspots Database (SHDB) is devoted to social and socio-economic risks and impacts and it is directly adapted to the needs of S-LCA (developed in compliance with UNEP 2020 Guidelines). According to Bennema, Norris and Benoit Norris (2022), the SHDB is a modular system, which includes the following three data components:

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1. Information on the trade flows between the economic sectors of each country or region of the world. The Multiregional Input-Output model (MRIO) provides information on supply chain composition and location according to trade data.
2. Information on the labour intensity (worker hours) associated with each country or region by a dollar of output.
3. Information on social risks and opportunities by country and economic sector.
It contains data for 26 subcategories using over 160 qualitative, quantitative, and semi-quantitative indicators on social risks, opportunities, and positive impacts, and covers ca. 13.000 country-specific industry sectors in 244 countries based on the GTAP Input/Output database.
The social hotspot database enables users to calculate social life cycle inventory results for a product system. The social life cycle inventory data reports the quantity of work-hours, at each level of risk in relation to each risk indicator, for each country-specific sector in the system. These data can be aggregated over the country-specific sectors to obtain total work-hours at each level of risk for each indicator, for the product system as a whole.

Primary data have been gathered through direct contact with organizations and companies through questionnaires and survey, interviews or assisted questionnaire compilation with affected stakeholders (e.g. workers, local inhabitants, other target groups). The selected target groups were located in one of the specific countries of interest for the S-LCA (Sweden, Italy and Spain) and distributed among the categories of stakeholder interested and potentially affected by the development of the novel production system implemented with F-CUBED project.

The data collection of primary data conducted by these methods allowed to provide "evidence-based" data for a double purpose: 1) refining the first hotspots assessment using generic data and by SHDB and identifying data gaps; 2) to verify the risk and be able to analyse impacts, focusing on the most important subcategories and indicators.

9.2.2 Stakeholders Engagement And Survey Activity

A substantial body of research on socio-economics and social science advises enhancing data collection by survey methods to mitigate systemic mistakes brought on by the informational context of the assessment. Therefore survey research, questionnaires and interview as methods, and survey methodology as a discipline, make important contributions to empirical social science (Couper 2017).

In determining level(s) of engagement, CA.RE. FOR. Engineering as owner of the engagement, has defined the nature of the relationship to develop with the stakeholders. Indeed the engagement takes place at more than one level (Fig. 52).

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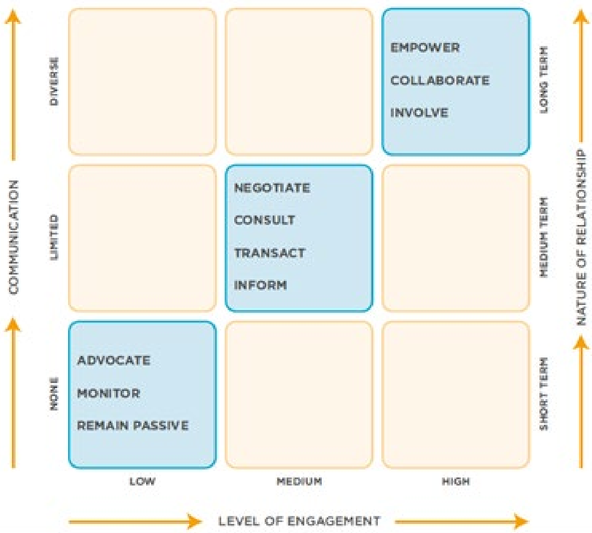

Figure 52 - Different levels and approaches to engagements (Misser, et al. 2015)

The survey planned in Task 5.5. aimed at contributing to the study of the social aspects linked to the effects of the F-CUBED Production System once introduced at local level. In particular, it needed to understand in which way the novel production system could affect on different types of stakeholder's categories for what concerned their overall standard of living, social aspects, quality of work and of life. This goal has been pursued taking into account a set of social performance indicators (impact sub-categories) outlined in the UNEP Guidelines, in order to render this assessment comparable with other biomass conversion technology benchmarks.

The method of engagement has been chosen to best meet the needs, capacity and expectations of the relevant stakeholders. More than one tool (questionnaire, phone call, interview by web platform, etc.) may be selected for any given engagement and different solutions may be used concurrently or sequentially.

9.2.2.1 Questionnaire Structure

The tool used to perform the survey was a questionnaire with the following layout:

-a 1.5-page introductory section briefly describing the F-CUBED project, the survey objectives and the questionnaire content;

-a 1st section ("system phase of interest") where respondents were requested to indicate in which product system phase they were placed (e.g., residues production, product use, etc) with respect to the F-CUBED Production System;

-a 2nd section where it was asked which stakeholder category, foreseen by the UNEP Guidelines, were more likely to be affected by the introduction of the technology (including six options ranging from Workers to Children);

-a 3rd section specifically devoted to the estimate of the social impacts: it required respondents to assess, for a set of distinct impact sub-categories, the likely type of impact (positive, negative, or zero/not significant) and its rating (1 to 4. from low to high). The set of impact categories changed between the different stakeholder category, with Workers (11) and Local Community (9) being the ones with the largest set of categories, and Children the one listing the smallest number (4);

-the 4th section ended the questionnaire asking the respondents to accept some privacy-related conditions concerning the use of the gathered information.

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9.2.3 Allocation Criteria

About allocation approach, it is possible refer to the criteria reported in Section 3.1.4 of the Part A (E-LCA).

9.3 Impact assessment (S-LCIA)

In the present research on the Social Life Cycle Assessment of the F-CUBED Production System, in compliance with ISO 14040 (ISO 2022), the **social life cycle impact assessment (S-LCIA)** is defined as the phase of S-LCA, used to quantify, comprehend, and assess the potential social consequences of a product system over the course of the product's life cycle. it can be used to estimate future potential social impacts connected to an emerging or non-existent system. Potential social impact is defined as the likelihood that a social impact will occur as a result of both the consumption of the product and the actions/behaviours of organizations connected to its life cycle (Benoît Norris, et al. 2020).

Impact indicator, in the same way of the impact category potential in E-LCA, reflects the extent of the social impact and belongs to a certain impact (sub)category. The impact category potential, related to a certain characterization factor, in S-LCA are represented by worker hours, related to labour hour intensity factors[7]. These factors allow, used together with the social risk level characterizations, to express social risks and opportunities in terms of work hours, by sector and country (Benoît Norris and Norris 2015). The utilization of a S-LCA databases, such as SHDB, automatizes a great number of steps related to the S-LCIA phase, and the steps of Reference Scale (RS) S-LCIA are intended all performed during an S-LCA database analysis (Benoît Norris, et al. 2020).

By the SHDB model development the LCI's quantitative data are collected in the raw form, to be characterized through the LCIA. Consequently SHDB calculates the number of worker-hours required for each unit process in the supply chain to satisfy a specific final demand (the output of the system in the form of a final good or service). The sociosphere flows are calculated as worker hours per US dollar (USD 2011) of process input, given a risk indicator. The results are expressed in **medium risk hour equivalent**, reflecting the probability of a danger or an opportunity to occur. Finally SHDB execute the risk characterization through a weighting procedure that represent the **relative probability** of an adverse situation to occur with respect to medium risk level which assume the value of 1 (more detailed explanation follows below and in Section 9.3.2).

9.3.1 Impact Assessment Method

SHDB Includes four impact assessment methods, Social Hotspot 2022 Category Method was used in the present S-LCA. It refers to the Reference Scale Assessment (formerly Type I or RS S-LCIA) and aims to assess social performance or social risk. This method includes characterization of different risk levels within each subcategory, followed by a damage assessment step that aggregates subcategory results to the category level. In this method, each subcategory within a category carries equal weight in determining the final category-level risk, and these weights are set so that category-level results are not influenced by having more or fewer subcategories.

This social life cycle impact assessment method allowed to aggregate work-hours at different levels of risk, within a detailed set of social risk subcategories (up to 30), or within a smaller set of 5 broad social risk categories (damage categories) which have been considered in our data collection. In each case, this "characterization step" multiplies the worker-hours at a given risk level by a factor that reflects the relative probability of occurrence of the adverse working condition or community condition, for that indicator. These probability levels are expressed relative to the likelihood of the adverse condition occurring when the risk is level is medium. Low risk indicates roughly 1 tenth the likelihood of occurrence as medium risk, so the

[7] Labour intensity data in SHDB have been developed by converting GTAP data on wage payments into estimates of worker hours.

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characterization factor for low risk is 0.1 **medium risk-hour equivalent.** Very high risk indicates a roughly 10 times higher likelihood of occurrence than 1 medium risk, so its characterization factor is 10 medium risk-hour equivalents per very high risk-hour. And high risk indicates roughly half the likelihood of very high risk, or 5 times the likelihood as medium risk, so its characterization factor is 5 medium risk-hour equivalents per high risk-hour.

Using these characterization factors enables the user to: (1) determine a total quantity of risk (in medium risk-hour equivalents) for each indicator, and (2) identify which country-specific sectors and which social inventory flows contribute how much of the total risk for each indicator, pointing to hot spots for each indicator.

An ordinal scale with 1 to 4 performance reference points (PRPs, from "low risk" to "very high risk") serves as the reference scale for impact assessment in the current investigation. PRPs are thresholds, targets, or objectives context-dependent that establish various social risk or performance levels and enable estimation of the scope and importance of potential social consequences related to target groups in the product system. These criteria translate in the Mrh factors of the SHDB Impact Assessment method, as outlined in Table 34.

Table 34 SHDB Impact Assessment method: Mrh factors

Scale level	Colour	Description	**Value** (mrheq)
4		*Very High risk*	10
3		*High risk*	5
2		*Medium risk*	1
1		*Low risk*	0.1

When appropriate inventory indicator data is compared to these levels, it is possible to determine whether the obtained data points to a poor or strong performance.

9.3.2 Aggregation And Weighting

During the impact assessment phase, there are several opportunities for aggregation and weighting to take place. For example, social subcategory outcomes can be aggregated into impact categories to generate a set of stakeholder-level performances and allows to synthetise complicated phenomena, particularly in S-LCIA, in order to gain a deeper understanding and for the dissemination of findings. Because the location dependent component of the results is significant, the aggregation has been done with great care to prevent misinterpretation and loss of context of the results. As a consequence, when the supply chain was globally. it is avoided.

To exhibit expressions of performance at the impact indicator/subcategory level, weighting is necessary. The attribution of each indicator's relative importance (or contribution) to the performance of a particular impact subcategory is, in fact, represented by weights. In SHDB database weighting reflects the proportionate probability of an unfavourable scenario after taking into account the risk determination. Relationships between relative probabilities and the medium risk hour (mrh) level are expressed (Bennema, Norris and Benoit Norris 2022).

9.4 Interpretation of the results.

Social Life Cycle Interpretation is the final phase of an S-LCA by which the findings of the S-LCIA phase are checked and discussed in depth to form the basis for conclusions and recommendations in accordance with the Goal and Scope definition.

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10. Results

In the present chapter the results of the Social Life Cycle Assessment (S-LCA) of F-CUBED Production System applied to the three investigated biogenic residue streams are presented and discussed.

10.1 LCI Results

Firstly the SHDB model has been built on the basis of the existing environmental LCA by the identification of the unit processes representative of the F-CUBED Production System using the most relevant country specific sectors (CSS) available in SHDB. As explained in Section 9.1.1. the whole production system avoids the field production of biomass, the transport of the biomass to an industrial plant where residues are generated, and start from the point of the extraction of the residue. Therefore, as listed in Table 35. the production processes included in the Social life cycle inventory phase (S-LCI) are: the pre-treatment of the residues, the TORWASH hydrothermal treatment and dewatering step, the solid matter processing in bio-pellets and the dispatchable final products (pellet, heat and/or electricity) ready to the end-users. The exercise developed in the LCI phase is to find out how much of each input (in USD 2011) from each relevant CSS, is used to produce F-CUBED products in the three investigated case studies.

Table 35 - Input production processes selected for the S-LCA and the respective sector of economy

Input Process	Sub-process	Sector of the Economy
Pre-conditioning		Specific industrial sector generating the residues
TORWASH treatment and Dewatering step		Other machinery and equipment manufacturing (except transport and electronic equipment)
Bio-pellets production		Lumber and wood products production
Electricity production (PELLETS)	Electricity production	Electricity production
	Avoided heat production	Gas extraction
Electricity production (BIOGAS)	Electricity production	Electricity production
	Avoided heat production	Gas extraction

Some of the unit processes of the inventory phase have been designed as Social Hotspot (SH) processes from SHDB, for the specific country (Sweden, Italy or Spain) related to the specific biogenic residue stream (Pulp & Paper Bio-sludge, Olive Pomace or Orange Peels). According to the UNEP Guidelines (Benoît Norris, et al. 2020), SH process, describes a unit process or a phase of the life cycle of a product that has a significant potential social or environmental impact and contributes substantially to the total impacts of an impact category. In the present S-LCA any Social Hotspots is associated with a geographical location. The use of SH processes contributes to reduce the risk of data lack in the inventory phase, for instance because a product or its indicator and respective weighting are missing, and increases the completeness of the LCA datasets.

10.1.1 S-LCI of the F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

In the present section the S-LCI phase of Pulp & Paper Bio-sludge case study is described. Primary data provided by E-LCA was used as the starting point to carry out the S-LCA. Specifically, it provided the data describing the supply chain composition, identifying all the F-CUBED production system phases required to produce the dispatchable electricity starting from the wet biogenic residue stream of pulp & paper bio-sludge.

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The country corresponds to the site of industrial partner involved in the TORWASH pilot plant testing, specifically Smurfit Kappa in Sweden, and the economic sectors refer to the specific industrial sector of the paper products, machinery and equipment, wood pellets and electricity generation.
The social LCI datasets used are listed in Table 36.

Table 36 - Social LCI datasets for the country-specific economic sectors linked to the Pulp & Paper Bio-sludge Case Study

Process	Co-Products	Economic sector	Values	Units
Feedstock pretreatment	Enhanced Bio-sludge	Paper products, publishing (ppp)/SWE U	-0,186	USD 2011
TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Sweden	0,403	USD 2011
Biopellets production	Biopellets	Lumber and wood products production in Sweden	0,550	USD 2011
Electricity production (PELLETS)	Avoided heat production	Gas extraction in Sweden	8,378	USD 2011
	Dispatchable Electricity	Electricity production in Sweden	1,214	USD 2011
Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Sweden	2,150	USD 2011
	Electricity production	Electricity production in Sweden	1,028	USD 2011

The table of the data collection (Table 37) and the description of the assumptions complete the description of the social inventory phase for Pulp & Paper Bio-sludge case study. The unit-processes indicated as output of the production system are derived, as before mentioned, from the LCI of the environmental life cycle assessment, while the unit-processes indicated as input of the production system are derived from the sources, outlined in the following table (Tab. 5). For the unit USD 2011. the exchange rate applied is 1.33 €/$ (January 2011).

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Table 37 – Social Life Cycle Inventory of F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

	Process	Co-products	SH Unit process - Input data	Values	Units	Output data	Values	Units
UPSTREAM	Feedstock pretreatment	Enhanced Bio-sludge	Paper products, publishing (ppp)/SWE U	-0,18614474	USD 2011	Biosludge (wb) DM 3,5%	32,9	kg/tADp
			Biosludge (db)	1,1515	kg/tADp			
			disposal cost for Landfilling of sewage sludge in Sweden	-0,215	€/kg			
MAIN STREAM	TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Sweden	0,403	USD 2011	kg solids from Main Stream processis	11,41	kg/tADp
			Substitution values of solids	0,047	€/kg			
	Biopellets production	Biopellets production	Lumber and wood products production in Sweden	0,55	USD 2011	Biopellets	5,25	kg/tADp
			Substitution values of pellets (bulk)	0,139	€/kg			
DOWNSTREAM	Electricity production (PELLETS)	Avoided heat production	Gas extraction in Sweden	8,38	USD 2011	Electricity from PELLETS	1	p
			Avoided heat scenario 54%	41	kWh/tADp			
			price of thermal kWh	23,43	p/kWh			
			current exchange rate pound - €/£	1,16	€/£			
		Dispatchable Electricity	Electricity production value in Sweden	1,21	USD 2011			
			Electricity production	13,3	kWh/tADp			
			prices per kWh of electricity	144,5	öre/kWh			
			current exchange rate SEK- €/öre	0,00084	€/öre			
FILTRATE PROCESSING	Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Sweden	2,15	USD 2011	Electricity from BIOGAS	1	p
			Avoided heat scenario 54%	10,52	kWh/tADp			
			price of thermal kWh in Sweden	23,43	p/kWh_{th}			
			current exchange rate pound - €/$	1,16	€/£			
		Dispatchable Electricity	Electricity production value in Sweden	1,03	USD 2011			
			Electricity production	11,26	kWh/tADp			
			prices per kWh of electricity in Sweden	144,5	öre/kWh			
			current exchange rate SEK- €/öre	0,00084	€/öre			

For the sake of clarity, in Table 38 the production processes and unit processes are listed together with the Sector of Economy and the Sources used for prices or value of surrogacy. The Sector of Economy are entailed country-specific. The value of surrogacy allows the estimation of value through the cost of a surrogate, that is, of a good able to provide a similar level of utility to the consumer or to carry out the same function within the production cycle (Bonfanti, et al. 2018).

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Table 38 – F-CUBED Production processes provided by SHDB for the Pulp & Paper Bio-sludge Case Study and respective sources

Process	Co-products	Sector of the Economy	Data Source
Pre-conditioning	Enhanced Bio-sludge	Paper products, publishing (ppp)/SWE U	SHDB and EU-COMMISSION STAFF WORKING DOCUMENT EVALUATION SWD(2023) 158 final (European Commission 2023)
TORWASH treatment and Dewatering step	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment)_SE	Wood fuel and peat prices for heating plants, nominal prices, 192 SEK/MWh (2021); in Energy in Sweden Facts and Figures 2022: Statistics based on the energy balances of the Swedish Energy Agency (Swedish Energy Agency 2022)
Bio-pellets production	Bio-pellets	Lumber and wood products production_SE	Price of wood pellets for European Industrial Wood Pellets from Argus, Biomass Market, Dec. 2022 (Argus 2023)
Electricity production (PELLETS)	Dispatchable Electricity	Electricity production_SE	Electricity price for households, taxes and network price not included: Energy in Sweden Facts and Figures 2022: Statistics based on the energy balances of the Swedish Energy Agency (Swedish Energy Agency 2022)
	Avoided heat production	Gas extraction_SE	UNDERFLOOR HEATING -01/02/2022 (The underfloor heating store 2022)
Electricity production (BIOGAS)	Dispatchable Electricity	Electricity production_SE	Electricity price for households, taxes and network price not included: Energy in Sweden Facts and Figures 2022: Statistics based on the energy balances of the Swedish Energy Agency (Swedish Energy Agency 2022)
	Avoided heat production	Gas extraction_SE	UNDERFLOOR HEATING - 01/02/2022 (The underfloor heating store 2022)

The price of wood chips and densified wood fuels price were derived by Energy Statistics based on the energy balances of the Swedish Energy Agency in Sweden Facts and Figures 2022 (Swedish Energy Agency 2022). They are in 2021. 192 and 324 SEK/MWh$_{th}$, respectively, as also displayed in Figure 53. Conversion of SEK/MWh$_{th}$ in €/t is based on LHV of 2.91 and 5.12 MWh/t for wood chips and pellets, respectively, and the exchange rate of 0.084€/SEK.

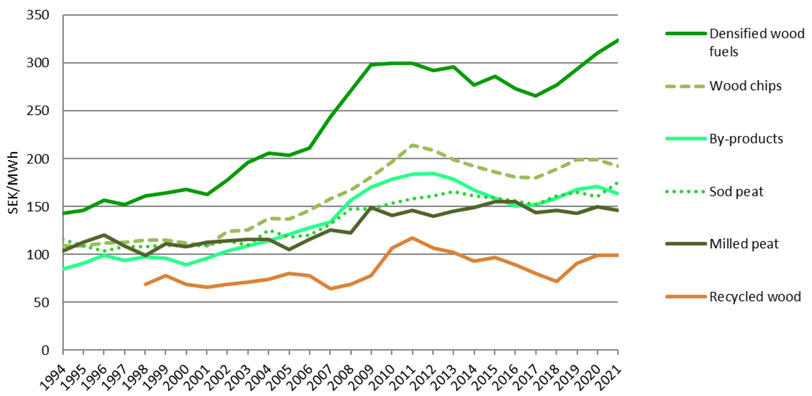

Figure 53 - Wood fuel and peat prices for heating plants, nominal prices in SEK/MWh (Swedish Energy Agency 2022)

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10.1.1.1 List of assumption for the Pulp & Paper Bo-sludge Case Study

- For the pulp & paper sludge the disposal, within defined safety parameters to the landfill, has defined as conventional route of application. An avoided cost has been introduced.
- The economic value of solids, produced by TORWASH technology and dewatering step, has been referred to the value of the wood chips as a substitutable good.
- The economic value of bio-pellets, produced with the F-CUBED solids, has been referred to the value of the wood pellets as a substitutable good.

The value of surrogacy allows the estimation of value through the cost of a surrogate, that is, of a good able to provide a similar level of utility to the consumer or to carry out the same function within the production cycle (Bonfanti, et al. 2018).

10.1.2 S-LCI of the F-CUBED Production System for Olive Pomace Case Study

In the present section the LCI phase of Olive Pomace case study is described. Primary data provided by E-LCA was used as the starting point to carry out the S-LCA. Specifically, it provided the data describing the supply chain composition, identifying all the F-CUBED production system phases required to produce the dispatchable electricity starting from the wet biogenic residue stream of olive pomace. The country corresponds to the site of industrial partner involved in the TORWASH pilot plant testing, specifically an APPO mill, Frantoio Oleario Chimienti in Italy, and the economic sectors refer to the specific industrial sector of the vegetable oil production in Italy, machinery and equipment, wood pellets and electricity generation. The social LCI datasets used are listed in Table 39.

Table 39 - Social LCI datasets for the country-specific economic sectors linked to the Olive Pomace Case Study

Process	Co-products	Economic sector	Values	Units
Feedstock pretreatment	Olive pomace destoned & diluited	Vegetable oils and fats (vol)/ITA U	1,51	USD 2011
TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Italy	5,211	USD 2011
Biopellets production	Biopellets	Lumber and wood products production in Italy	35,05	USD 2011
Electricity production (PELLETS)	Avoided heat production	Gas extraction in Italy	506,68	USD 2011
	Electricity production	Electricity production value in Italy	281,50	USD 2011
Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Italy	84,31	USD 2011
	Electricity production	Electricity production value in Italy	82,18	USD 2011

The table of the data collection (Table 40) and the description of the assumptions complete the description of the social inventory phase for Olive Pomace case study. The unit-processes indicated as output of the production system are derived, as before mentioned, from the LCI of the environmental life cycle assessment, while the unit-processes indicated as input of the production system are derived from the sources, outlined in the following table (Tab. 41).

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For the unit USD 2011. the exchange rate applied is 1.33 €/$ (January 2011).

Table 40 - Social Life Cycle Inventory of F-CUBED Production System for Olive Pomace Case Study

	Process	Sub-process	SH Unit process - Input	Values	Units	Unit process - Output	Values	Units
UPSTREAM	Feedstock pretreatment	Olive pomace destoned & diluited	Vegetable oils and fats (vol)/ITA U	1,51	USD 2011	Olive pomace preconditioned	2013,5	kg/tOP
			Resdiue's value	0,001	€/kg			
MAIN STREAM	TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Italy	5,211	USD 2011	kg solids from Main Stream processis	198	kg/tOP
			Substitution values of solids	0,035	€/kg			
	Biopellets production	Biopellets	Lumber and wood products production in Italy	35,05	USD 2011	Biopellets	126	kg/tOP
			Substitution values of pellets (bulk)	0,37	€/kg			
DOWNSTREAM	Electricity production (PELLETS)	Avoided heat production	Gas extraction in Italy	506,68	USD 2011	Electricity from PELLETS	1	p
			Avoided heat scenario 80%	3860	kWh/tADp			
			price of thermal kWh - Italy	15,05	p/kWh			
			current exchange rate pound - €/£	1,16	€/£			
		Electricity production	Electricity production value in Italy	281,50	USD 2011			
			Electricity production	1600	kWh/tOP			
			prices per kWh of electricity - Italy	0,234	€/kWh			
FILTRATE PROCESSING	Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Italy	84,31	USD 2011	Electricity from BIOGAS	1	p
			Avoided heat scenario 80%	642,27	kWh/tOP			
			price of thermal kWh - Italy	15,05	p/kWh			
			current exchange rate pound - €/SEK	1,16	€/£			
		Electricity production	Electricity production value in Italy	82,18	USD 2011			
			Electricity production	467,11	kWh/tOP			
			prices per kWh of electricity - Italy	0,234	€/kWh			

For the sake of clarity, in Table 41 the production processes and unit processes are listed together with the Sector of Economy and the Sources used for prices or value of surrogacy. The sector of the economy is implicitly considered country-specific.

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Table 41 – F-CUBED Production processes provided by SHDB for the Olive Pomace Case Study and respective sources

Process	Sub-process	Sector of the Economy	Data Source
Pre-conditioning	Olive pomace destoned & diluted	Vegetable oils and fats (vol)/ITA U	SHDB and authors expertise in the sector
TORWASH treatment and Dewatering step	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment)_IT	Authors expertise in the sector: average price of wood chips M50. 35€/t
Bio-pellets production	Bio-pellets	Lumber and wood products production_IT	Price of wood pellets for European Industrial Wood Pellets from Argus, Biomass Market, Dec. 2022 (Argus 2023)
In the sector	Electricity production	Electricity production_IT	Sorgenia 01/09/2023
	Avoided heat production	Gas extraction_IT	UNDERFLOOR HEATING -01/02/2022 (The underfloor heating store 2022)
Electricity production	Electricity production	Electricity production_ITA	Sorgenia 01/09/2023 (Sorgenia 2023)
(BIOGAS)	Avoided heat production	Gas extraction_ITA	UNDERFLOOR HEATING - 01/02/2022 (The underfloor heating store 2022)

10.1.2.1 List of assumption for the Olive Pomace Case Study

- The economic value of residue, produced by the two-phase olive oil extraction system that generates wet pomace, has been referred to the value of the olive pomace in Italy as derived from Authors' expertise.
- The economic value of solids, produced by TORWASH technology and dewatering step, has been referred to the value of the wood chips as a substitutable good.
- The economic value of bio-pellets, produced with the F-CUBED solids, has been referred to the value of the wood pellets as a substitutable good.

10.1.3 S-LCI of the F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study

In the present section the LCI phase of Orange Peels case study is described. Primary data provided by E-LCA was used as the starting point to carry out the S-LCA. Specifically, it provided the data describing the supply chain composition, identifying all the F-CUBED production system phases required to produce the dispatchable electricity starting from the wet biogenic residue stream of orange peels.

The country corresponds to the site of industrial partner involved in the TORWASH pilot plant testing, specifically Delafruit industry in Spain, and the economic sectors refer to the specific industrial sector of the vegetables, fruits, nuts growing in Spain, machinery and equipment, wood pellets and electricity generation. The social LCI datasets used are listed in Table 42.

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Table 42 - Social LCI datasets for the country-specific economic sectors linked to the Orange Peels Case Study

Process	Co-products	Economic sector	Values	Units
Feedstock pretreatment	Orange peels grinded and diluited	Vegetables, fruit, nuts (v_f)/ESP U	33,67	USD 2011
TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Spain	25,05	USD 2011
Biopellets production	Biopellets	Lumber and wood products production in Spain	36,06	USD 2011
Electricity production (PELLETS)	Avoided heat production	Gas extraction in Spain	1.033,33	USD 2011
	Electricity production	Electricity production value in Spain	398,82	USD 2011
Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Spain	732,76	USD 2011
	Electricity production	Electricity production value in Spain	494,96	USD 2011

The table of the data collection (Table 43) and the list of the assumptions complete the description of the social inventory phase for Orange Peels case study. The unit-processes indicated as output of the production system are derived, as before mentioned, from the LCI of the environmental life cycle assessment, while the unit-processes indicated as input of the production system are derived from the sources, outlined in the following table (Tab. 44). For the unit USD 2011. the exchange rate applied is 1.33 €/$ (January 2011).

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Table 43 - Social Life Cycle Inventory of F-CUBED Production System for Fruit & Vegetable (Orange Peels) Case Study

	Process	Sub-process	SH Unit process - Input	Values	Units	Unit process - Output	Values	Units
UPSTREAM	Feedstock pretreatment	Orange peels grinded and diluited	Vegetables, fruit, nuts (v_f)/ESP U	33,67	USD 2011	Orange peels preconditioned	5180	kg/tORP
			Resdiue's value	0,0065	$/kg			
MAIN STREAM	TORWASH pretreatment	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment) in Spain	25,053	USD 2011	kg solids from Main Stream processis	476	kg/tORP
			Substitution values of solids	0,07	€/kg			
	Biopellets production	Biopellets	Lumber and wood products production in Spain	36,06	USD 2011	Biopellets	217	kg/tORP
			Substitution values of pellets (bulk)	0,221	€/kg			
DOWNSTREAM	Electricity production (PELLETS)	Avoided heat production	Gas extraction in Spain	1.033,33	USD 2011	Electricity from PELLETS	1	p
			Avoided heat scenario 54%	3.799,78	kWh/tORP			
			price of thermal kWh - Spain	31,18	p/kWh			
			current exchange rate pound - €/£	1,16	€/£			
		Electricity production	Electricity production value in Spain	398,82	USD 2011			
			Electricity production	2.326,47	kWh/tORP			
			prices per kWh of electricity - Spain	0,228	€/kWh			
FILTRATE PROCESSING	Electricity production (BIOGAS)	Avoided heat production	Gas extraction in Spain	732,76	USD 2011	Electricity from BIOGAS	1	p
			Avoided heat scenario 54%	2.694,50	kWh/tORP			
			price of thermal kWh - Spain	31,18	p/kWh			
			current exchange rate pound - €/SEK	1,16	€/£			
		Electricity production	Electricity production value in Spain	494,96	USD 2011			
			Electricity production	2.887,28	kWh/tORP			
			prices per kWh of electricity - Spain	0,228	€/kWh			

For the sake of clarity, in Table 44 the production processes and unit processes are listed together with the Sector of Economy and the Sources used for prices or value of surrogacy. The Sector of Economy are entailed country-specific.

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Table 44 – F-CUBED Production processes provided by SHDB for the Olive Pomace Case Study and respective sources

Process	Sub-process	Sector of the Economy	Data Source
Pre-conditioning	Orange peels grinded and diluted	Vegetables, fruit, nuts /ESP U	Mackliff L.G., 2021. Master Thesis; http://dspace.utb.edu.ec/handle/49000/9311 (Mackliff 2021)
TORWASH treatment and Dewatering step	Solids produced	Other machinery and equipment manufacturing (except transport and electronic equipment)_ESP	Average price of wood chips P45/G50. 70 €/t, from Astillas, precio según tamaño de grano y coste de producción, 2017. Font: Oficina Técnica Municipal de Prevención de Incendios (Rodríguez 2019)
Bio-pellets production	Bio-pellets	Lumber and wood products production_ESP	Pellets, precio según el tipo de suministro, 2017. Source: AVEBIOM in (Rodríguez 2019)
Electricity production	Electricity production	Electricity production_ESP	Sorgenia 01/09/2023
(PELLETS)	Avoided heat production	Gas extraction_ESP	UNDERFLOOR HEATING -01/02/2022 (The underfloor heating store 2022)
Electricity production	Electricity production	Electricity production_ESP	Sorgenia 01/09/2023 (Sorgenia 2023)
(BIOGAS)	Avoided heat production	Gas extraction_ESP	UNDERFLOOR HEATING - 01/02/2022 (The underfloor heating store 2022)

10.1.3.1 List of assumption for the Orange Peels Case Study

- The economic value of residue, produced by the orange processing for the orange juice production, has been referred to the value of the orange peels used as feed in Ecuador. It is however understood that the reference supply chain for the extraction of the residue is national, and take place in Spain.
- The economic value of solids, produced by TORWASH technology and dewatering step, has been referred to the value of the wood chips as a substitutable good.
- The economic value of bio-pellets, produced with the F-CUBED solids, has been referred to the value of the wood pellets as a substitutable good.

10.2 Results of the survey on socio-economic aspects

10.2.1 Sample of Interviewed Stakeholders and Questionnaire Distribution

In order to carry out the survey it has been selected a range of stakeholders in the three countries where the F-CUBED Pilot Plant had been tested: Italy, Spain and Sweden. In detail, initially, a selection of 44 stakeholders potentially useful for the primary data collection was identified. The survey started with 12 stakeholders in Italy, 11 in Spain, and 11 in Sweden; they included also some project partners located in other EU countries.

A first letter inviting the sample members to participate in the survey and answer the questionnaire was sent by email in June, obtaining only minor results. A second round of emails was sent in mid-July, after having slightly simplified the questionnaire layout, and added that the company was available to assist the stakeholders in filling the questionnaire (either by phone or by web call). A third and final reminder was sent by email at the beginning of August. Taking into account that at that point we had collected only 7 answers, we used our network to involve an additional set of stakeholders in the sample, and this led to 12 more questionnaires duly filled, for a total of 19 replies.

For what concerns the geographical origin the resulting questionnaires came from:
-8 from Italian stakeholders;
-4 from stakeholders in The Netherlands;
-2 from Irish stakeholders;
-2 from Spanish stakeholders;
-1 each from, German and Swedish stakeholders.
The mid percentage of survey replies (19 out of 44 sent, equal to 43%) can be presumably explained by the following factors:
-the July-August months are the ones when staff tend to take their holidays, so it was more difficult to reach stakeholders;
-the nature of the survey was quite difficult, because it requested the stakeholders to Figure out a future scenario where to place the introduction of the F-CUBED Production System at industrial scale. This represented a challenging task for many respondents, as social impact assessment is rarely part of their activities;
-the description that we provided in the introductory part of the questionnaire was considered too short by many stakeholders, that requested additional information. It was provided either by telephone and/or email and however they were invited to visit the F-CUBED web-site;
-some stakeholders active at European scale (e.g., associations representing sectors where the technology could be employed) stated that they were not sufficiently informed about their national members' attitude towards it, and preferred not to answer the questionnaire from their umbrella perspective.

However 43% of survey reply, can be considered a statistically significant result.

10.2.2 Survey results

The key survey's results focusing first on which main stakeholders' categories were highlighted as potentially more affected by the implementation of the F-CUBED Production System, and then on the internal analysis of the most important impact sub-categories.

Firstly, Table 45. offers us an overview of the survey's results about the stakeholder's categories, showing that, in general terms, answers were quite scattered across the range of available stakeholders' category. Only the "Children" category received far less attention, but comments to this specific group need a more thoughtful analysis that can be found later on.

Table 45 - Survey's results about the stakeholder's categories (from UNEP Guidelines, 2020)

STAKEHOLDER's CASTEGORY	%
WORKERS	19.7
LOCAL COMMUNITY	20.6
VALUE CHAIN ACTORS	23.2
CONSUMERS	13.9
SOCIETY	18.2
CHILDREN*	4.4

Three stakeholder types were ranked slightly above all the others: "Value chain actors", "Local community", and "Workers". This fits with an intuitive view of which social areas might be more sensitive to the introduction of the F-CUBED technology: all of them can be clearly associated with the novel plants' activities. The fact that "Value chain actors" was ranked in 1st place may be affected by the sample composition, including among the respondents the project partners. To our opinion this element does not represent a significant potential bias, because every partner was instructed to provide objective answers to the survey.

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The following tables (Tab. 46) report details on the impact sub-categories that were highlighted more frequently and more strongly by the survey's respondents. The analysis will examine every stakeholder category, following their ranking place (from the most important to the least important), selecting the four areas that received higher attention for each stakeholder category.

Table 46 - Most important impact sub-categories in Value Chain Actors impact category

VALUE CHAIN ACTORS	
Impact sub-categories	%
Technological advancements	18.3
Market opportunities	16.1
Economic viability	14.4
Employment perspectives	13.9

In the "Value chain actors" category a technological factor comes first, yet all the following threes are related to economic concerns. This is an element that we will find also for other stakeholder types: the economic area seems, in overall terms, very important for the surveyed persons. To note that other sub-categories such as "Fair competition" and "Promoting social responsibility" received little attention.

In the "Local community" category (Tab. 47), two economy-related impact sub-categories are ranked among the most important. Interesting to report, this aspect is balanced by the equal weight of two social-related impact sub-categories, like "Availability of local resources" (meaning improved access to them), and "Air and water quality" (meaning improvement of these qualities). It is remarkable to observe that none of the respondents (that include the representatives of two environmental NGOs) placed a negative impact to this last impact area, usually the one that more worries local residents whenever the project of a new plant is announced (the *Nimby* syndrome).

Table 47 - Most important impact sub-categories in Local Community impact category

LOCAL COMMUNITY	
Impact sub-categories	%
Economic opportunities	14.4
Availability local resources	13.8
Air and water quality	11.9
Local employment	11.9

It may be rather surprising to see that the "Workers" category (Tab. 48) was ranked only at third place in the survey, because they are clearly the subjects more directly affected by the introduction of the new technology. Less surprising is to acknowledge that this is the category where answers tend to be more balanced, because it is also the one with the highest number of options for answering. Once more, we can notice that impact sub-categories closer to the economy sphere tend to receive more attention by the survey's respondents. Other socially-related issues like "Equal opportunity", "Job stability", "Social benefits" were ranked below.

Table 48 - Most important impact sub-categories in Workers impact category

WORKERS	
Impact sub-categories	%
Work conditions	12.4
Career prospects	12.4

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Job satisfaction	12.4
Training requirements	11.1

When asked to comment about more specific, socially-related impact subcategories, as per Society impact category, our sample of respondents shows an overall, positive view of the F-CUBED Production System introduction. The highlighted impact sub-categories (Tab. 49) depict an optimistic vision for that concerns its potential role for facing social challenges and contributing to sustainable development. Equally interesting is to observe that those impact categories closer to an ethic area (such as "Societal values" and "Commitment to sustainability issues") received less attention. This is understandable, because the mere introduction of a new technology can hardly affect people's behaviour regarding their ethic orientation.

Table 49 - Most important impact sub-categories in Society impact category

SOCIETY Impact sub-categories	%
Contribution to sustainable development	23.4
Alignment with societal goals-policies	21.3
Social challenges & energy demands	19.1
Broader social acceptance	19.1

In the "Consumers" category (Tab. 50) was ranked just in 5ht place of importance by the respondents. It can be noticed that the perception of potential improvements that F-CUBED Production System can bring about is high, especially in terms of product reliability. Again, this reply may have been affected by the sample composition, including among the respondents the project partners, and these are clear expectations of the project's impacts. Once more, we tend to dismiss this remark due to the instructions we provided and to the fact that the majority of respondents (61.5%) did not take part in the F-CUBED project.

Table 50 - Most important impact sub-categories in Consumers impact category

CONSUMERS Impact sub-categories	%
Reliability of bioenergy products	23.4
Energy affordability	21.5
Accessibility of bioenergy products	20.6
Perception of Tech. benefits-drawbacks	19.6

Finally, the "Children" stakeholder category deserves a specific analysis, that cannot rely on a single summary table. This was the questionnaire area with the least number of respondents: only 8 considered it important in terms of potential impact, but also the only impact area where two respondents provided a negative reply, indicating a potential, negative impact deriving from the introduction of the new technology and related to the potential health risks. They did so for the same sub-category: "Potential health risks", and this type of answer leads to conclude that this category can be excluded by further analysis at the moment but needs to be definitely included in future social assessment exercises of deepening.

In summary, the survey placed the stakeholder categories ranked highest i.e. "Value chain actors", "Local community" and "Workers" at a minimum distance. These are also the categories that intuitively tend to be more affected by the introduction of new technology plants.

Regarding the internal analysis of every main stakeholder category, the survey results indicate that, in overall terms, economic-related issues tend to be considered more important by the respondents than socially or

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ethic-related ones. This suggest that the new technology is expected to provide clear benefits in this area, while there is more uncertainty about the other two.

10.3 LCIA Results

The Social LCIA has been based on two mains methodological adjustments: 1) Harmonization between the impact categories of SHDB database and UNEP 2020 Guidelines; 2) selection of the SHDB sub-categories most representative and relevant for the F-CUBED Production System.

The SHDB impact assessment method returns information on five main social impact categories: Labor Rights and Decent Work, Health & Safety, Human Rights, Local Community and Governance. This structure is similar to the Social LCA Guidelines (Benoît Norris, Traverso, et al. 2020) but some differences can be found because not all relevant issues included in the Guidelines are present and an adjustment for harmonization is necessary (Benoît Norris and Norris, Chapter 8: The Social Hotspots Database Context of the SHDB 2015).

In the SHDB, impact categories derive from the aggregation of 30 impact sub-categories considered in the S-LCIA. On the other hand, UNEP 2020 S-LCA Guidelines identify, related to the Stakeholder Categories, six impact categories (Human rights, Working Conditions, Health & Safety, Cultural Heritage, Governance, Socio-economic repercussions) and 40 subcategories.

Table 51 report the Social Impact Categories investigated in the S-LCIA and the selected sub-categories on the basis of the results of the survey described in Section 10.2.
An attempt at harmonization between SHDB's and UNEP 2020 Guidelines' sub-categories is also outlined

Table 51 – SHDB Social Categories investigated in the F-CUBED Production System LCIA, selected impact sub-categories and proposed correspondence with the UNEP Guidelines sub-categories.

Social Impact Categories	Sub-categories	SHDB - ID	UNEP 2020 harmonization
Labor rights and decent work	Wage assessment	1A	• Career prospects • Employment Prospects
	Workers in poverty	1C	• Economic opportunities
	Forced Labor	1E	• Work conditions
	Excessive WkTime	1F	• Work conditions
	Social Benefits	1I	• Job satisfaction
	Labor Laws/Convs	1J	• Training requirements
	Unemployment	1L	• Job stability
Health and safety	Occ Tox & Haz	2A	• Children, Health and well-being • Children, Exposure to pollutants or hazardous substances:
Society	Poverty and inequality	3F	• Local employment • Broader Social Acceptance • Social Challenges and Energy Demands
	State of Env Sustainability	3G	• Availability of local resources • Contribution to Sustainable Development
Governance	Legal System	4A	• Market Opportunities • Alignment with Societal Goals and Policies
	Corruption	4B	• Future prospects
Community	Access to Drinking Water	5A	• Air and water quality
	Access to Sanitation	5B	• Alignment with Societal Goals and Policies
	Children out of School	5C	• Children, Health and well-being

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	Access to Hospital Beds	5D	• Alignment with Societal Goals and Policies
	Smallholder v Commercial Farms	5E	• Economic Viability Market Opportunities
	Access to Electricity	5F	• Energy Affordability • Accessibility of Bioenergy Products • Perceptions of Technology and its Benefits or Drawbacks
	Property rights	5G	• Technological Advancements • Reliability of Bioenergy Products

To this list, two more sub-categories have to be included. They are Injuries & Fatalities (2B) because its contribution to the working conditions and labour intensity criteria is always relevant, and Democracy &Freedom of Speech (4C) that becomes relevant in the nowadays geopolitical scenario in which the dependence of energy supply could relate to Country where strict restrictions on freedom of expression and peaceful assembly, in a continuous crackdown on dissent, exist.

10.3.1 S-LCIA of the F-CUBED Production System for Pulp & Paper Bio-sludge Case Study

The social footprint of the F-CUBED Production System has been described by four different data visualizations. Firstly, the social footprint of the F-CUBED Production System was calculated by aggregating the social impacts associated with each country-specific economic sector (CSS), listed in Table 36. into a single score attributed to each Damage Category, expressed in both mrheq and mPt. In this framework a Damage category corresponds to area of protection that is desired to be sustained or protected because it is of recognizable value to society. Table 52 shows the result obtained for the Pulp & Paper Bio-sludge cases study.

Table 52 - Social impacts of the Pulp & Paper Bo-sludge Case Study by impact category

	Damage category	**Social Impact**	
		(mrheq)	(mPt)
1	Labor rights & decent work	-0,103	-102,918
2	Health & safety	-0,180	-179,729
3	Society	-0,061	-60,587
4	Governance	-0,149	-148,950
5	Community	-0,054	-53,883
	Total	**-0,546**	**-546,067**

Minor scores, which are however benefits, are resulted for the categories of Community and Society.
The social impacts were assessed for every economic sector. Table 53 reports the impacts of each social category obtained for each sector involved in the Pulp & Paper Bo-sludge supply chain.

Table 53 - Social impacts of the F-CUBED Production System for Pulp & Paper Bo-sludge Case Study by economic sectors

Economic sector/Production phase	**Unit**	**Labor rights & decent work**	**Health & safety**	**Society**	**Governance**	**Community**
1-Enhanced Biosludge	mrheq	-0,002	-0,003	-0,001	-0,002	-0,001
2-TORWASH & DEWATERING	mrheq	0,005	0,010	0,004	0,006	0,004
3-BIO-PELLETS	mrheq	0,009	0,016	0,006	0,012	0,006
4-Electricity from pellets	mrheq	-0,095	-0,167	-0,057	-0,134	-0,052
5-Electricity from biogas	mrheq	-0,021	-0,036	-0,012	-0,030	-0,010
Total	**mrheq**	**-0,103**	**-0,180**	**-0,061**	**-0,149**	**-0,054**

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In Table 53. it is clearly shown that slight social impact is provided by the production phases of Bio-pellets production and Torwash and dewatering processes.

Likewise Figure 54 displays graphically the contribution by each sector to the total impact in each social category: the Bio-pellets production and the Torwash & Dewatering treatments are the relative major contributors to the social impacts. However, the Bio-pellets production phase, linked to the economic sector of Lumber and wood products production in Sweden, gives a small adverse contribution to social impacts, ranging between 8% and 11%. Even for Torwash & Dewatering treatment, the values drop to 4% and 7%. On the other hand, the Electricity production steps both by bio-pellets and biogas gives benefits to the different Impact categories. In fact, the benefits are determined by the heat recovery from the conversion processes of the bio-pellets and biogas into energy. The results show that the Electricity production in Sweden, related to the bio-pellets energetic conversion, comprises most of the favourable impact for every social category, ranging between -90% and -97% of total social impact depending on the social category.

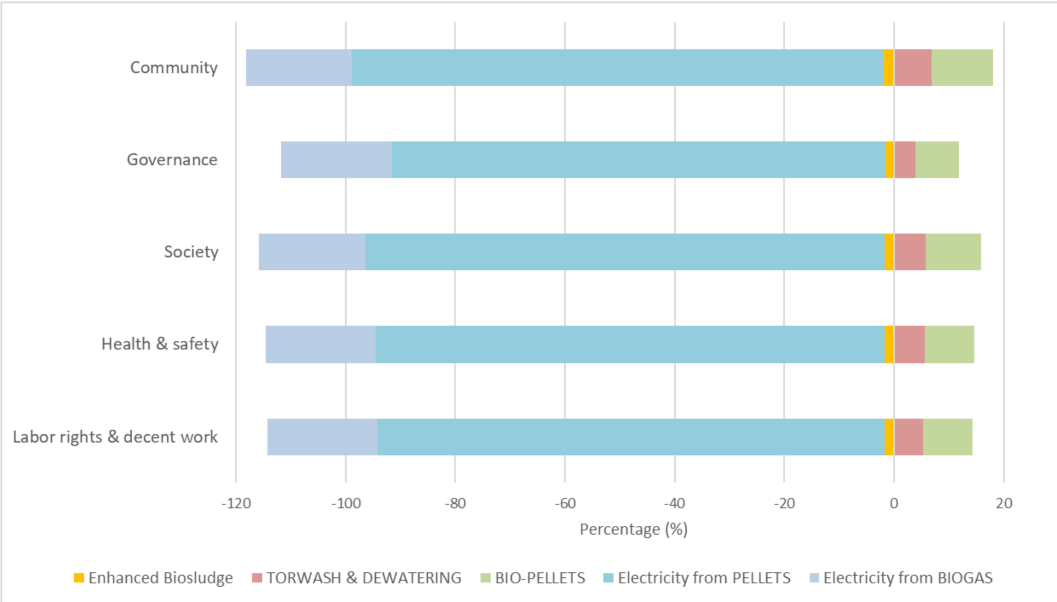

Figure 54 - Contribution of each economic sector to the total social impacts of the Pulp & Paper Bo-sludge Case Study by social impact category.

A more detailed analysis of the social impacts of the Pulp & Paper Bo-sludge Case Study, is provided through the analysis of the sub-categories which make up the before mentioned impact categories. Table 54 shows the impacts sub-category for each economic sector involved in the F-CUBED Production System supply chain for Sweden.

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Table 54 - Contribution analysis of each economic sector to the total social impacts of the Pulp & Paper Bo-sludge Case Study by impact sub-category

Impact sub-category	Unit	Total	1-Enhanced Biosludge	2-TORWASH & DEWATERING	3-BIO-PELLETS	4-Electricity from pellets	5-Electricity from biogas
1A Wage assessment	mrheq	-0,202	-0,003	0,008	0,016	-0,181	-0,042
1C Workers in poverty	mrheq	-0,060	-0,001	0,004	0,007	-0,058	-0,011
1E Forced Labor	mrheq	-0,155	-0,003	0,008	0,014	-0,142	-0,031
1F Excessive WkTime	mrheq	-0,151	-0,003	0,009	0,013	-0,140	-0,031
1I Social Benefits	mrheq	-0,064	-0,001	0,004	0,006	-0,060	-0,013
1J Labor Laws/Convs	mrheq	-0,039	-0,001	0,002	0,003	-0,035	-0,008
1L Unemployment	mrheq	-0,060	-0,001	0,004	0,006	-0,058	-0,011
2A Occ Tox & Haz	mrheq	-0,136	-0,002	0,008	0,014	-0,128	-0,027
2B Injuries & Fatalities	mrheq	-0,224	-0,004	0,012	0,019	-0,206	-0,045
3F Poverty and inequality	mrheq	-0,097	-0,002	0,007	0,009	-0,092	-0,019
3G State of Env Sustainability	mrheq	-0,104	-0,002	0,006	0,011	-0,098	-0,020
4A Legal System	mrheq	-0,149	-0,002	0,006	0,012	-0,134	-0,030
4B Corruption	mrheq	-0,053	-0,001	0,002	0,004	-0,048	-0,011
4C Democracy &Freedom of Speech	mrheq	-0,245	-0,004	0,009	0,020	-0,220	-0,050
5A Access to Drinking Water	mrheq	-0,032	-0,001	0,003	0,005	-0,033	-0,005
5B Access to Sanitation	mrheq	-0,064	-0,001	0,004	0,008	-0,063	-0,012
5C Children out of School	mrheq	-0,075	-0,001	0,004	0,007	-0,070	-0,015
5D Access to Hospital Beds	mrheq	-0,069	-0,001	0,005	0,007	-0,066	-0,014
5E Smallholder v Commercial Farms	mrheq	-0,057	-0,001	0,001	0,006	-0,052	-0,011
5F Access to Electricity	mrheq	-0,018	0,000	0,002	0,002	-0,018	-0,004
5G Property rights	mrheq	-0,062	-0,001	0,006	0,008	-0,062	-0,012

The same data are depicted in Figure 55. that display the contribution analysis of each economic sector by the single sub-categories. In particular the social impact sub-categories which express the most benefits are Democracy &Freedom of Speech (4C), Injuries & Fatalities (2B) and Wage assessment (1A), respectively, for Governance, Health and Safety and Labor rights & decent work impact categories.

On the contrary the production steps referring to Bio-pellets and Torwash & dewatering provide major social risks to the same subcategories 1A, 2B and 4C. However, it should be noted that, on the basis of the characterization factors that describe the severity of a serious situation or opportunity and facilitate data interpretation and visualization of results, the assessed risk level is low for all the selected subcategories and therefore it is considered acceptable. This is reported in Table 55 that outlines the characterized results of the sub-categories responsible of the main social risk in the economic sector of the production phases of the F-CUBED Production System for the treatment of the Pulp & Paper Bo-sludge in Sweden. The thresholds and algorithms used in the characterization models of the SHDB are transparently reported in its documentation and summarized in Section 9.3.

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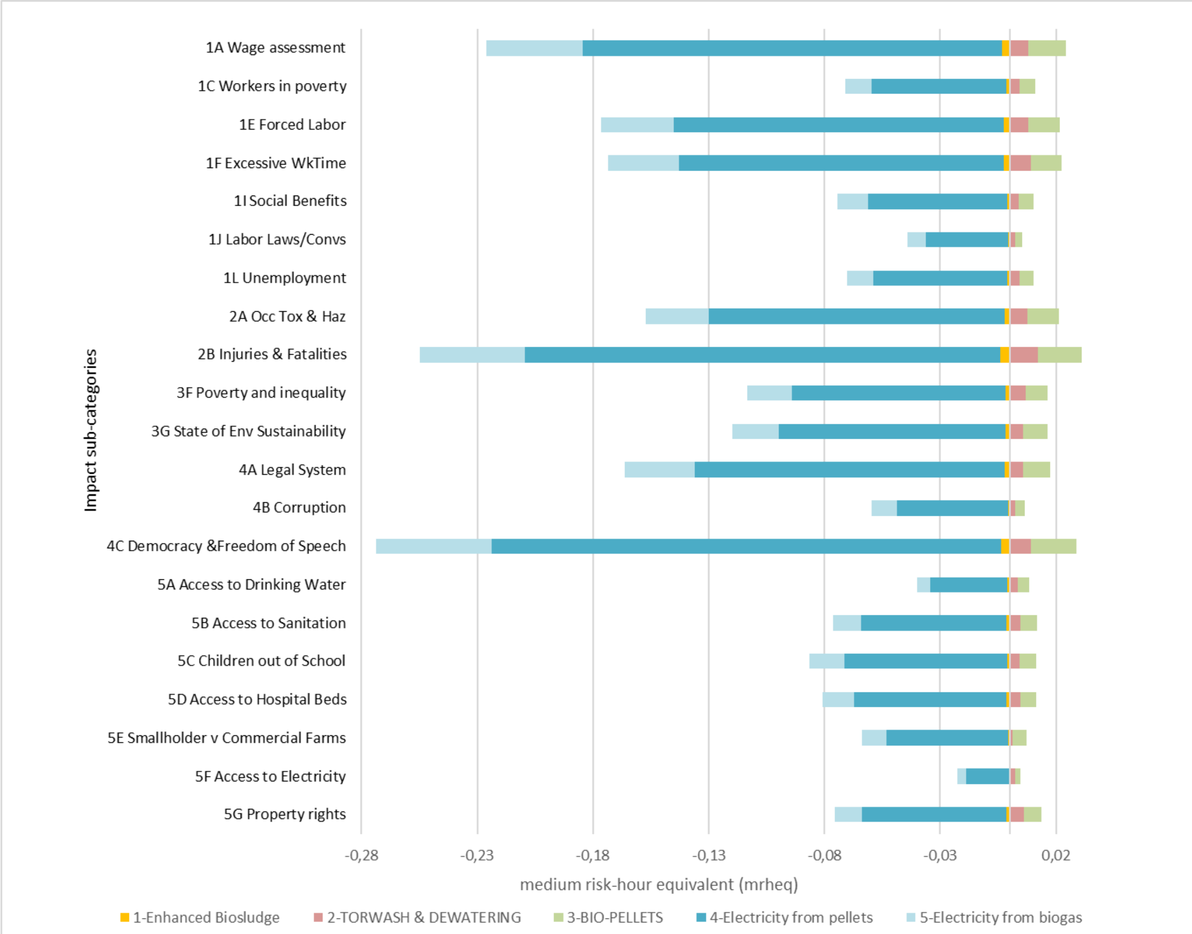

Figure 55 – Contribution analysis of each economic sector, related to the production phases to the total social impacts of F-CUBED Supply Chain by social impact sub-category

Table 55 – Characterization results of the sub-categories mainly affected by social risk from the economic sector of the production phases of the F-CUBED Production System in the treatment of the Pulp & Paper Bo-sludge in Sweden

Impact category	Sub-category	Country-specific economic sector	Country	Risk value	Characterized results (scale values)
Labor rights & decent work	1A Wage assessment	Enhanced Biosludge	Sweden	-0,003	Low Risk
		TORWASH & DEWATERING	Sweden	0,008	Low Risk
		BIO-PELLETS	Sweden	0,016	Low Risk
		Electricity from pellets	Sweden	-0,181	Low Risk
		Electricity from biogas	Sweden	-0,042	Low Risk
Health and Safety	2B Injuries & Fatalities	Enhanced Biosludge	Sweden	-0,004	Low Risk
		TORWASH & DEWATERING	Sweden	0,012	Low Risk
		BIO-PELLETS	Sweden	0,019	Low Risk
		Electricity from pellets	Sweden	-0,206	Low Risk
		Electricity from biogas	Sweden	-0,045	Low Risk
Governance	4C Democracy &Freedom of Speech	Enhanced Biosludge	Sweden	-0,004	Low Risk
		TORWASH & DEWATERING	Sweden	0,009	Low Risk
		BIO-PELLETS	Sweden	0,020	Low Risk
		Electricity from pellets	Sweden	-0,220	Low Risk
		Electricity from biogas	Sweden	-0,050	Low Risk

Finally it is necessary to specify that the residues extraction is inherent to the national supply chain. Indeed the study doesn't take in account the upstream production phases regarding the cultivation of the agricultural and forestry products and respective transportation phase.

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10.3.2 S-LCIA of the F-CUBED Production System for Olive Pomace Case Study

The social footprint of the F-CUBED Production System has been described by different data visualizations. Firstly the social footprint was calculated by aggregating the social impacts associated with each country-specific sector (CSS), listed in Table 39. into a single score attributed to each impact category or Damage Category, expressed in both mrheq and Pt.

In this framework a Damage category corresponds to area of protection that is desired to be sustained or protected because it is of recognizable value to society. Table 56 shows the result obtained for the Olive Pomace cases study.

Table 56 - Social impacts of the Olive Pomace Case Study by impact category

Damage category	Social Impact Indicator Damage assessment (mrheq)	 Single score (Pt)
1 Labor rights & decent work	3,661	3,661
2 Health & safety	5,907	5,907
3 Society	2,933	2,933
4 Governance	4,405	4,405
5 Community	2,589	2,589
Total	**19,496**	**19,496**

The social impacts were assessed also for every economic sector, connected to the production phases. Table 57 shows the impacts of each social category obtained broken down by economic sector involved in the Olive Pomace supply chain, and Figure 56 shows graphically the same contribution.

Table 57 - Social impacts of the F-CUBED Production System for Olive Pomace Case Study by economic sectors

Economic sector/Production phase	Unit	Labor rights & decent work	Health & safety	Society	Governance	Community
1-Preconditioning	mrheq	0,048	0,075	0,036	0,040	0,036
2-TORWASH & DEWATERING	mrheq	0,056	0,091	0,040	0,063	0,036
3-BIO-PELLETS	mrheq	1,710	2,630	1,325	1,941	1,204
4-Electricity from pellets	mrheq	1,339	2,258	1,122	1,718	0,961
5-Electricity from biogas	mrheq	0,509	0,853	0,410	0,642	0,351
Total	**mrheq**	**3,661**	**5,907**	**2,933**	**4,405**	**2,589**

As shown in the histograms of the Figure 56. the Bio-pellets production and the Electricity production steps by bio-pellets in Italy are the major responsible of the social impacts, ranging between 44-47% and 36-39% of total social impact , respectively, depending on the social category. On the other hand the Torwash & Dewatering treatments and Preconditioning steps have small adverse contributions to social impacts, ranging between 1.4%-1.5%. and 0.9-1.4% of total social impact , respectively, depending on the social category.

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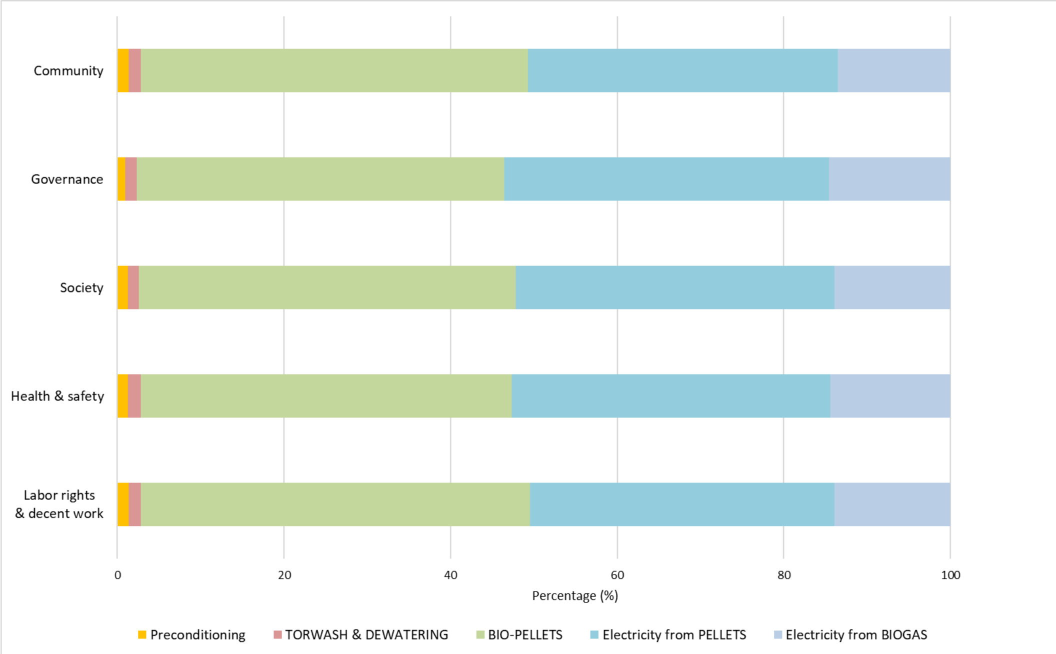

Figure 56 - Contribution of each economic sector to the total social impacts of the Olive Pomace Case Study by social impact category

A more detailed analysis of the social impacts of the Olive Pomace Case Study, is provided through the examination of the sub-categories which make up the before mentioned impact categories.
Table 58 shows the breakdown of each economic sector into the impacts sub-categories in the F-CUBED Production system supply chain for Italy.

Table 58 - Contribution analysis of each economic sector to the total social impacts of the Olive Pomace Case Study by impact sub-category

Impact sub-category	Unit	Total	Preconditioning	TORWASH & DEWATERING	BIO-PELLETS	Electricity from pellets	Electricity from biogas
1A Wage assessment	mrheq	4,316	0,046	0,074	2,379	1,275	0,542
1C Workers in poverty	mrheq	4,478	0,036	0,053	1,855	1,882	0,652
1E Forced Labor	mrheq	5,122	0,087	0,083	2,269	1,937	0,745
1F Excessive WkTime	mrheq	4,681	0,049	0,073	2,197	1,708	0,655
1G Freedom of Assoc	mrheq	4,141	0,076	0,059	1,941	1,510	0,555
1J Labor Laws/Convs	mrheq	0,663	0,008	0,018	0,355	0,187	0,096
1L Unemployment	mrheq	4,125	0,043	0,048	1,728	1,697	0,610
2A Occ Tox & Haz	mrheq	5,665	0,059	0,076	2,614	2,133	0,783
2B Injuries & Fatalities	mrheq	6,149	0,091	0,106	2,646	2,383	0,924
3F Poverty and inequality	mrheq	4,642	0,044	0,062	2,140	1,751	0,646
3G State of Env Sustainability	mrheq	5,185	0,050	0,067	2,318	2,027	0,724
4A Legal System	mrheq	5,012	0,053	0,067	2,143	2,013	0,736
4B Corruption	mrheq	2,457	0,024	0,030	0,989	1,044	0,370
4C Democracy &Freedom of Speech	mrheq	5,747	0,043	0,093	2,693	2,096	0,821
5A Access to Drinking Water	mrheq	1,481	0,026	0,031	0,668	0,542	0,215
5B Access to Sanitation	mrheq	4,009	0,034	0,047	1,703	1,649	0,577
5C Children out of School	mrheq	3,172	0,045	0,047	1,511	1,147	0,422
5D Access to Hospital Beds	mrheq	2,845	0,040	0,046	1,289	1,068	0,402
5E Smallholder v Commercial Farms	mrheq	0,955	0,061	0,018	0,831	0,010	0,035
5F Access to Electricity	mrheq	1,700	0,009	0,016	0,742	0,697	0,236
5G Property rights	mrheq	3,962	0,037	0,051	1,686	1,618	0,571

For an easier reading & interpretation, the same data are depicted in Figure 57. that display the contribution analysis of each economic sector by single sub-category. It clearly shows that the economic sector of Bio-pellets and Electricity production steps by bio-pellets in Italy provide the most adverse contributions to the social risk for the social impact sub-categories i.e., Injuries & Fatalities (2B), Forced Labor (1E), Occupational Toxics and Hazards (2A), State of Environmental Sustainability (3G), for Health & safety, Labor rights & decent work and Society impact categories, respectively.

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The sub-categories 2B, 1E and 2A, refer to the work condition related to the economic sectors, particularly the Lumber and wood products' production in Italy, and they show a coherency with the Italian situation regarding accidents at work and occupational diseases. According to European statistics on accidents at work (ESAW) administrative data collection exercise (Eurostat 2022), Italy shows, as fatal accidents at work in 2019. an incidence rate (per 100.000 persons employed) of 2.1 against the average of 1.7 in EU. Moreover, at national level, the National Institute for Occupational Accident Insurance (INAIL[8]) reports that as of 2022 December 31st, the number of accidents occurred in 2022 was 697.773. an increase of 25.7% compared to 2021. and of 25.9% compared to 2020. At the national level, the data show, in particular, an increase compared to 2021 both of the cases occurred at work (+28.0%) and those in transit, that is, occurred on the return journey between home and work (+11.9%) (INAIL 2023).

About the sub-category 3G, State of Environmental Sustainability, it assesses the potential environmental risks related to supply chains. This subcategory relates to the Environmental Performance Index (EPI) indicator (Bennema, Norris and Benoit Norris 2022) used to rank 180 countries on environmental health and ecosystem vitality and provide a gauge at a national scale of how close countries are to established environmental policy targets. On the contrary it seems strange to find the Democracy &Freedom of Speech (4C) among the most affected subcategories by the social risk from the F-CUBED Production System. Indeed it relates to Freedom of expression which is a fundamental Human Right, as stated in article 19 of the Universal Declaration of Human Rights.

The risks related to this subcategory is determined through the application of three indices: Economist Intelligence Unit's Democracy Index, and the indices produced by The Freedom House and by the IDEA. They evaluate the state of democracy worldwide on the basis of criteria such as electoral process and pluralism, the functioning of government, political participation, political culture and civil liberties (Bennema, Norris and Benoit Norris 2022).

Five attributes of democracy are investigated: Representative government, Fundamental rights, Checks on government, Impartial administration, Participatory engagement. Three groups of countries are accordingly distinguished: Free, Partly free, and Not free. Italy undoubtedly belongs to the first group.
A likely explanation in this view is the European experiences of local communities and energy cooperatives, which demonstrate that energy democracy is the route to resolving a number of socio-economic concerns and addressing climate change (Patrucco 2020).

Cities and local communities around the globe have been reclaiming public services or redesigning them to meet people's needs, realize their rights, and jointly address social and environmental concerns (Kishimoto,, Steinfort and Petitjean 2020). On the contrary, in Italy, although the introduction of the free market in the energy sector, ENEL is still the main producer of electricity detaching all with a share of 37.5% and the third producer of gas with 11%, based on data provided by ARERA (BORSA & FINANZA 2022).

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[8] INAIL is te Italian Focal Point for the institutional system of safety and health at work; INAIL coordinates the national network of the European Agency for Safety and Health at Work.

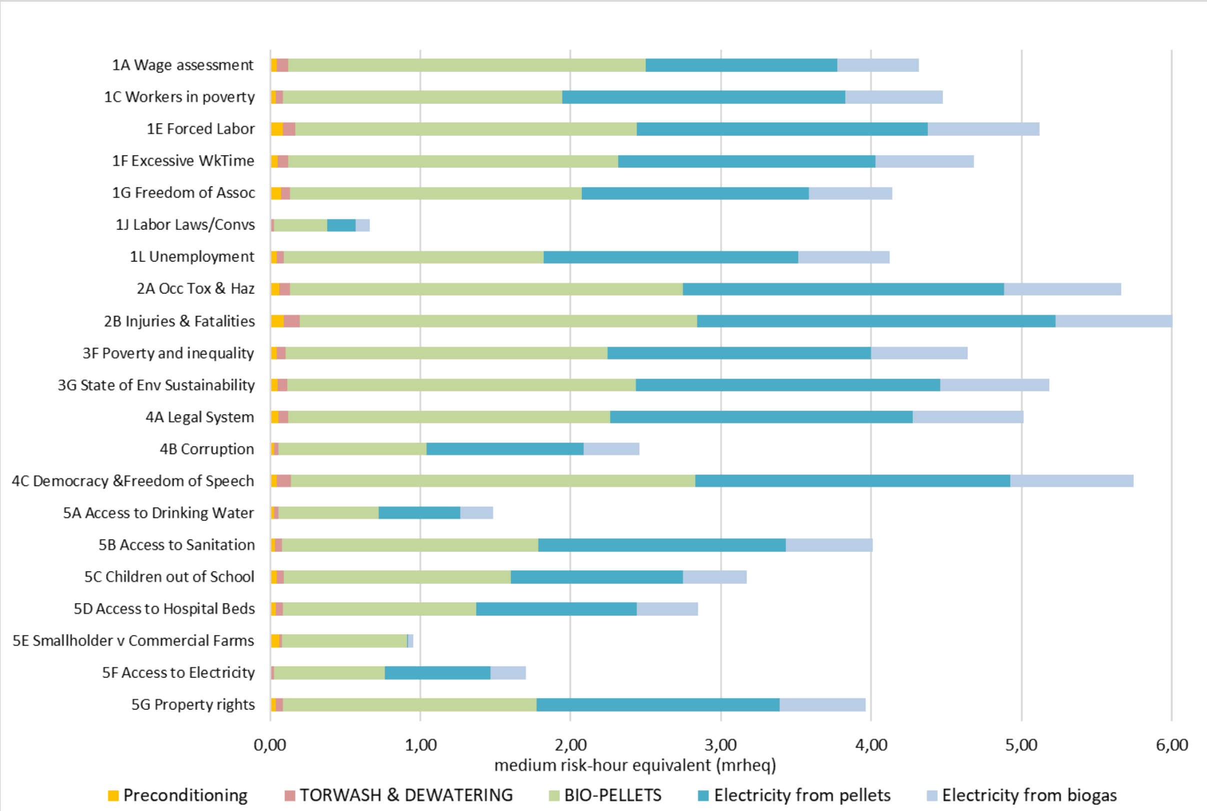

Figure 57 – Contribution analysis of each economic sector, related to the production phases to the total social impacts of F-CUBED Supply Chain in the Olive Pomace Case Study, by social impact sub-category

On the other hand, the production steps referring to Preconditioning and Torwash & dewatering provide a contribution very little to the overall social risk of these case study.

However, it should be noted that, on the basis of the characterization factors that describe the severity of a serious situation or opportunity and facilitate data interpretation and visualization of results, the assessed risk level for the adverse contribution of the Bio-pellet production and Electricity from pellets to the subcategories is medium. This is reported in Table 59 that outlines the characterized results of the sub-categories affected by the main social risk in the economic sector induced by the production phases of the F-CUBED Production System for the treatment of the Olive Pomace in Italy. The thresholds and algorithms criteria used in the characterization models of the SHDB are transparently reported in its documentation and summarized in Section 9.3.

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Table 59 – Characterization results of the sub-categories mainly affected by social risk from the economic sector of the production phases of the F-CUBED Production System in the treatment of the Olive Pomace in Italy

Impact category	Sub-category	Country-specific economic sector	Country	Risk value	Characterized results (scale values)
Labor rights & decent work	1E Forced Labor	Preconditioning	Italy	0,087	Low Risk
		TORWASH & DEWATERING	Italy	0,083	Low Risk
		BIO-PELLETS	Italy	2,269	Medium Risk
		Electricity from pellets	Italy	1,937	Medium Risk
		Electricity from biogas	Italy	0,745	Low Risk
	1J Labor Laws/Convs	Preconditioning	Italy	0,008	Low Risk
		TORWASH & DEWATERING	Italy	0,018	Low Risk
		BIO-PELLETS	Italy	0,355	Low Risk
		Electricity from pellets	Italy	0,187	Low Risk
		Electricity from biogas	Italy	0,096	Low Risk
Health and Safety	2A Occupational Toxics and Hazards	Preconditioning	Italy	0,059	Low Risk
		TORWASH & DEWATERING	Italy	0,076	Low Risk
		BIO-PELLETS	Italy	2,614	Medium Risk
		Electricity from pellets	Italy	2,133	Medium Risk
		Electricity from biogas	Italy	0,783	Low Risk
	2B Injuries & Fatalities	Preconditioning	Italy	0,091	Low Risk
		TORWASH & DEWATERING	Italy	0,106	Low Risk
		BIO-PELLETS	Italy	2,646	Medium Risk
		Electricity from pellets	Italy	2,383	Medium Risk
		Electricity from biogas	Italy	0,924	Low Risk
Society	3G State of Env Sustainability	Preconditioning	Italy	0,050	Low Risk
		TORWASH & DEWATERING	Italy	0,067	Low Risk
		BIO-PELLETS	Italy	2,318	Medium Risk
		Electricity from pellets	Italy	2,027	Medium Risk
		Electricity from biogas	Italy	0,724	Low Risk
Governance	4C Democracy &Freedom of Speech	Preconditioning	Italy	0,043	Low Risk
		TORWASH & DEWATERING	Italy	0,093	Low Risk
		BIO-PELLETS	Italy	2,693	Medium Risk
		Electricity from pellets	Italy	2,096	Medium Risk
		Electricity from biogas	Italy	0,821	Low Risk
Community	5E Smallholder vs Commercial Farms	Preconditioning	Italy	0,061	Low Risk
		TORWASH & DEWATERING	Italy	0,018	Low Risk
		BIO-PELLETS	Italy	0,831	Low Risk
		Electricity from pellets	Italy	0,010	Low Risk
		Electricity from biogas	Italy	0,035	Low Risk

The results confirm the same social problems identified in Italian sectors previously analysed: some relevant sub-categories have been already discussed(i.e. 2A, 2B and 4c), but some comments have to be added for the Forced Labor (1E) and Occupational Toxics and Hazards (2A).
The first, according to (Bennema, Norris and Benoit Norris 2022) constitutes a violation of fundamental human rights. It deprives societies of developing skills and human resources and educating children for the future labour market. The ILO Conventions also provides that forced labour shall be punishable as a penal offense (Bennema, Norris and Benoit Norris 2022). Here the occurrence of a medium risk level in the economic sectors of the Bio-pellets production and electricity sector, respectively, requires further investigations and accuracy in monitoring these production steps of the F-CUBED supply chain in Italy. The existence and effective application of a comprehensive anti-trafficking law and criminal accountability are essential elements that have to be looked upon.
The medium risk level in the sub-category 2A is relevant issue. The subcategory of Occupational Toxics and Hazards deals with the exposure of humans to various risks, such as hazardous noise levels, carcinogenic substances, and airborne particles that may cause respiratory or other health diseases.
Therefore it means that these economic sectors of the F-CUBED supply chain in Italy doesn't comply the average level of risk of Europe.

Nevertheless, in the whole picture of the Olive Pomace Case Study, the two subcategories 5E and 1J showing low risk in all the involved economic sectors can be read as opportunities. Particularly the Smallholder vs Commercial Farms impact sub-category results interesting.

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Smallholder farms should be considered a unit within the local economy, community, and agricultural environment, contributing significantly to economic growth, poverty reduction, and the local population's food security when supported with initiative from their local governments and communities. This translates to the potential of the F-CUBED Production System to represent a theoretical alternative technical solution exploitable at mill level (or associates mills) differently from the conventional olive pomace exploitation involving a third party industrial entity as olive pomace mills. Therefore the low risk level reflects likelihood of the existence of smallholders.

Finally it is necessary to specify that the residues extraction is inherent to the national supply chain. Indeed the study doesn't take in account the upstream production phases regarding the cultivation of the agricultural and forestry products and respective transportation phase.

10.3.3 S-LCIA of the F-CUBED Production System for Orange Peels Case Study

The social footprint of the F-CUBED Production System has been described by four different data visualizations. Firstly the social footprint of the F-CUBED Production System was calculated by aggregating the social impacts associated with each country-specific sector (CSS), listed in Table 42. into a single score attributed to each impact category or Damage Category, expressed in both mrheq and Pt. In this framework a Damage category corresponds to area of protection that is desired to be sustained or protected because it is of recognizable value to society. Table 60 shows the result obtained for the Orange Peels cases study.

Table 60 - Social impacts of the Orange Peels Case Study by impact category

Damage category	Social Impact Indicator	
	Damage assessment (mrheq)	Single score (Pt)
1 Labor rights & decent work	-108,217	-108,217
2 Health & safety	-161,077	-161,077
3 Society	-85,303	-85,303
4 Governance	-130,811	-130,811
5 Community	-79,562	-79,562
Total	**-564,970**	**-564,970**

The social impacts were further assessed for every economic sector. Table 61 shows the impacts of each social impact category broken down by economic sector involved in the Orange Peels supply chain, and Figure 58 display graphically the same contribution analysis of economic sectors on impact categories.

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Table 61 - Social impacts of the F-CUBED Production System for Orange Peels Case Study by economic sectors

Economic sector/Production phase	Unit	Labor rights & decent work	Health & safety	Society	Governance	Community
1-Preconditioning	mrheq	0,538	0,894	0,427	0,514	0,427
2-TORWASH & DEWATERING	mrheq	0,267	0,436	0,194	0,305	0,175
3-BIO-PELLETS	mrheq	0,920	1,415	0,713	1,044	0,648
4-Electricity from pellets	mrheq	-66,778	-99,570	-52,594	-80,402	-48,959
5-Electricity from biogas	mrheq	-43,163	-64,253	-34,042	-52,273	-31,854
Total	**mrheq**	**-108,217**	**-161,077**	**-85,303**	**-130,811**	**-79,562**

As shown in the histograms of the Figure 58. the Bio-pellets production and the Preconditioning phase, related to the economic sector of Lumber and wood products' production in Spain and to the Vegetables, fruits, nuts growing in Spain, both provide small adverse contribution to the impact categories. Indeed their values are of the order of magnitude of 0.8% and 0.5% of the total social impact. Even TORWASH and dewatering treatments can be considered negligible. On the other hand the Electricity production steps both by bio-pellets and biogas, referring to the Electricity generation in Spain economic sector, give social benefits to the different impact categories. Indeed, the benefits are determined by the heat recovery from the conversion processes of the bio-pellets and biogas into energy.

The results show that the Electricity production in Spain, related to the bio-pellets energetic conversion, comprises most of the favourable impact for every social category, of the order of magnitude of -62% and -40% of total social impact, respectively. The percentage contributions of the economic sectors on the impact categories do not differ to much each other, even if Health & Safety and Governance Impact categories receive the highest benefits. The performance of the latter is consistent with the current geopolitical situation. In fact it contributes to generating energy independence from countries that show a lack of democracy, and introduces a benefit and an opportunity in term of social impacts towards Governance impact category.

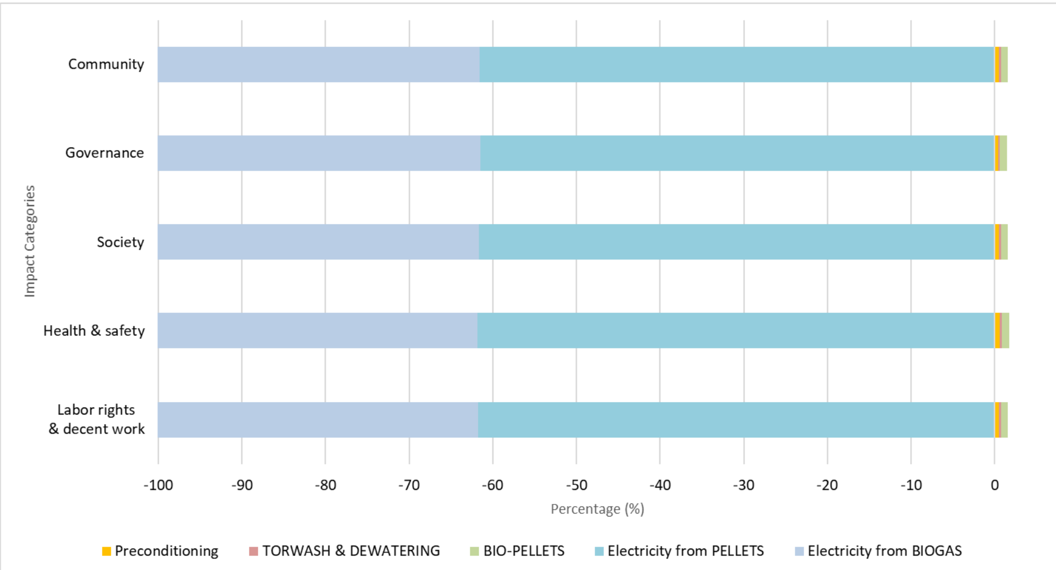

Figure 58 - Contribution of each economic sector to the total social impacts of the Orange Peels Case Study by social impact category

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A more detailed analysis of the social impacts of the Orange Peels Case Study, is provided through the examination of the sub-categories which make up the before mentioned impact categories. Table 62 shows the breakdown of each economic sector into the impacts sub-categories in the F-CUBED Production system supply chain for Spain.

Table 62 - Contribution analysis of each economic sector to the total social impacts of the Orange Peels Case Study by impact sub-category

Impact sub-category	Unit	Total	Preconditioning	TORWASH & DEWATERING	BIO-PELLETS	Electricity from pellets	Electricity from biogas
1A Wage assessment	mrheq	-128,981	0,639	0,357	1,280	-80,179	-51,077
1C Workers in poverty	mrheq	-154,812	0,639	0,253	0,998	-94,677	-62,024
1E Forced Labor	mrheq	-155,865	0,789	0,399	1,221	-96,192	-62,083
1F Excessive WkTime	mrheq	-149,980	0,516	0,352	1,182	-92,048	-59,982
1I Social Benefits	mrheq	-18,567	0,280	0,153	0,485	-12,292	-7,193
1J Labor Laws/Convs	mrheq	-21,892	0,092	0,088	0,191	-13,599	-8,663
1L Unemployment	mrheq	-145,715	0,735	0,232	0,930	-89,343	-58,268
2A Occ Tox & Haz	mrheq	-156,115	0,890	0,364	1,406	-96,188	-62,588
2B Injuries & Fatalities	mrheq	-166,040	0,898	0,508	1,424	-102,953	-65,917
3F Poverty and inequality	mrheq	-148,193	0,621	0,296	1,151	-90,988	-59,274
3G State of Env Sustainability	mrheq	-154,280	0,652	0,320	1,247	-94,748	-61,750
4A Legal System	mrheq	-150,366	0,552	0,323	1,153	-92,226	-60,167
4B Corruption	mrheq	-81,214	0,367	0,144	0,532	-49,767	-32,489
4C Democracy &Freedom of Speech	mrheq	-160,855	0,624	0,447	1,449	-99,213	-64,163
5A Access to Drinking Water	mrheq	-23,008	0,362	0,148	0,359	-14,783	-9,094
5B Access to Sanitation	mrheq	-140,005	0,515	0,224	0,916	-85,396	-56,264
5C Children out of School	mrheq	-91,019	0,504	0,225	0,813	-56,329	-36,231
5D Access to Hospital Beds	mrheq	-87,493	0,601	0,220	0,693	-54,017	-34,991
5E Smallholder v Commercial Farms	mrheq	-1,101	0,242	0,086	0,447	-1,480	-0,396
5F Access to Electricity	mrheq	-69,430	0,230	0,076	0,399	-42,360	-27,776
5G Property rights	mrheq	-144,880	0,538	0,245	0,907	-88,346	-58,224

For an easier reading & interpretation, the same data are depicted in Figure 59. that display the contribution analysis of each economic sector by single sub-category. At a glance, Electricity generation in Spain from bio-pellets and biogas provide relevant favourable impacts for the most of the impact sub-categories. Only for Social Benefits (1I), Labor Laws & Conventions (1J), Access to Drinking Water (5A), the benefits are smaller. Finally, for Smallholder vs. Commercial Farms (5E) impact category the influence of F-CUBED Production System is practically negligible.

In particular the social impact sub-categories which receive the most benefits from the F-CUBED Production System are Democracy &Freedom of Speech (4C), Injuries & Fatalities (2B), Forced Labor (1E), Workers in poverty (1C) and Occupational Toxicity and Hazards (2A). In other words, the Impact category that receive benefits form the development of the F-CUBED Production System in Spain are Governance, Health and Safety and Labor rights & decent work impact categories. On the other hand Community impact category shows less favourable contribution.

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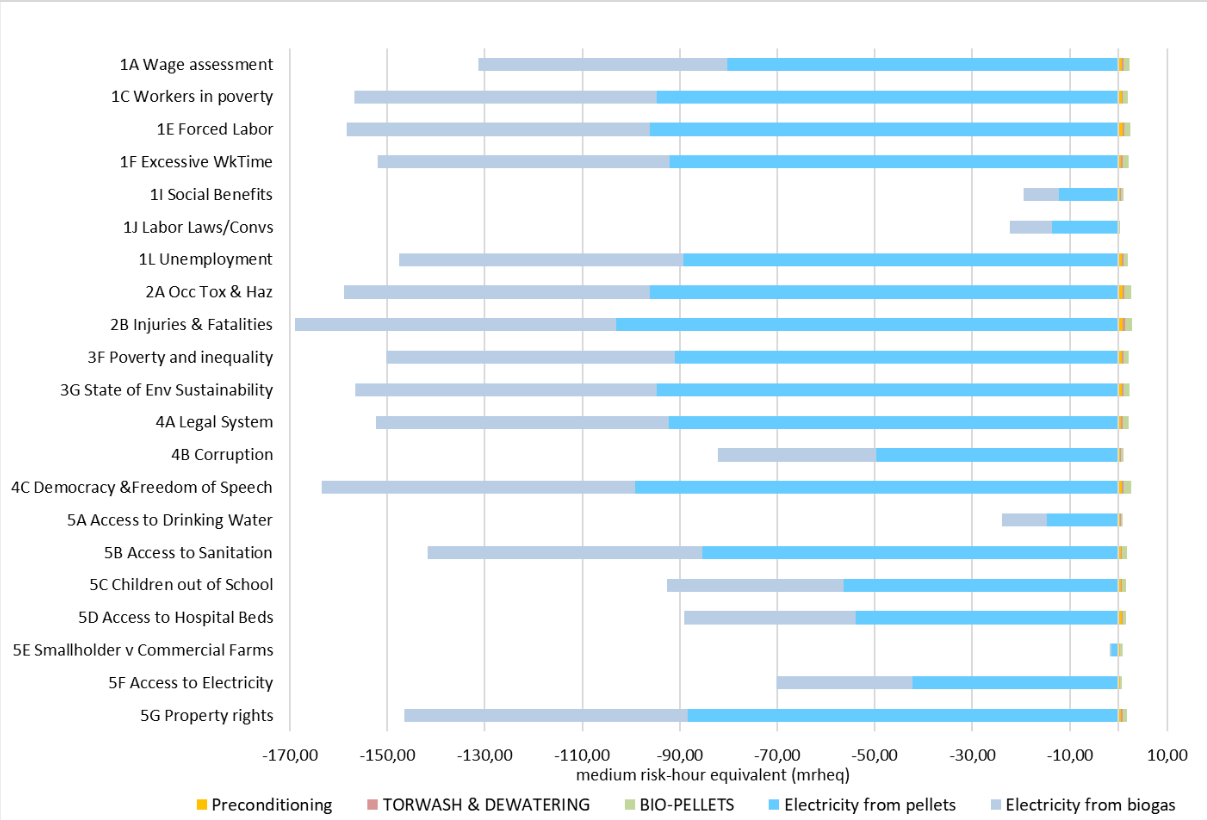

Figure 59 – Contribution analysis of each economic sector, related to the production phases to the total social impacts of F-CUBED Supply Chain in the Orange Peels Case Study, by social impact sub-category

However, focusing mainly on those economic sectors that have an adverse influence on the impact categories, it should be noted that, on the basis of the characterization factors which describe the severity of a serious situation or opportunity and facilitate data interpretation and visualization of results, the assessed risk level for the Preconditioning, Torwash & dewatering treatment and Biopellet production results in negligible contribution for the first and very small for the second, while about the Bio-pellets production it is convenient a more detailed analysis as reported in Table 63 . Table 63 outlines the characterized results of the sub-categories responsible of the main social risk in the economic sector of the production phases of the F-CUBED Production System for the treatment of the Orange Peels in Spain. The thresholds and algorithms criteria used in the characterization models of the SHDB are transparently reported in its documentation and summarized in Section 9.3.

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Table 63 – Characterization results of the economic sector of the production phases of the F-CUBED Production System responsible of the main risk in the social sub-categories for the treatment of the Olive Pomace in Italy

Impact sub-category	Unit	Total	Preconditioning	Characterized results	TORWASH & DEWATERING	Characterized results	BIO-PELLETS	Characterized results
1A Wage assessment	mrheq	-128,981	0,639	Low Risk	0,357	Low Risk	1,280	Medium Risk
1C Workers in poverty	mrheq	-154,812	0,639	Low Risk	0,253	Low Risk	0,998	Low Risk
1E Forced Labor	mrheq	-155,865	0,789	Low Risk	0,399	Low Risk	1,221	Medium Risk
1F Excessive WkTime	mrheq	-149,980	0,516	Low Risk	0,352	Low Risk	1,182	Medium Risk
1I Social Benefits	mrheq	-18,567	0,280	Low Risk	0,153	Low Risk	0,485	Low Risk
1J Labor Laws/Convs	mrheq	-21,892	0,092	Low Risk	0,088	Low Risk	0,191	Low Risk
1L Unemployment	mrheq	-145,715	0,735	Low Risk	0,232	Low Risk	0,930	Low Risk
2A Occ Tox & Haz	mrheq	-156,115	0,890	Low Risk	0,364	Low Risk	1,406	Medium Risk
2B Injuries & Fatalities	mrheq	-166,040	0,898	Low Risk	0,508	Low Risk	1,424	Medium Risk
3F Poverty and inequality	mrheq	-148,193	0,621	Low Risk	0,296	Low Risk	1,151	Medium Risk
3G State of Env Sustainability	mrheq	-154,280	0,652	Low Risk	0,320	Low Risk	1,247	Medium Risk
4A Legal System	mrheq	-150,366	0,552	Low Risk	0,323	Low Risk	1,153	Medium Risk
4B Corruption	mrheq	-81,214	0,367	Low Risk	0,144	Low Risk	0,532	Low Risk
4C Democracy &Freedom of Speech	mrheq	-160,855	0,624	Low Risk	0,447	Low Risk	1,449	Medium Risk
5A Access to Drinking Water	mrheq	-23,008	0,362	Low Risk	0,148	Low Risk	0,359	Low Risk
5B Access to Sanitation	mrheq	-140,005	0,515	Low Risk	0,224	Low Risk	0,916	Low Risk
5C Children out of School	mrheq	-91,019	0,504	Low Risk	0,225	Low Risk	0,813	Low Risk
5D Access to Hospital Beds	mrheq	-87,493	0,601	Low Risk	0,220	Low Risk	0,693	Low Risk
5E Smallholder v Commercial Farms	mrheq	-1,101	0,242	Low Risk	0,086	Low Risk	0,447	Low Risk
5F Access to Electricity	mrheq	-69,430	0,230	Low Risk	0,076	Low Risk	0,399	Low Risk
5G Property rights	mrheq	-144,880	0,538	Low Risk	0,245	Low Risk	0,907	Low Risk

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There is evidence from Figure 59. that all the social impact sub-categories are affected, although with different magnitude, by favourable influence on the overall social risks from the development of the F-CUBED Production System in the Orange Peels Case Study in Spain. Indeed, as outlined in Table 62 and 63 the values range from -1.1 to -166.0 mrheq for all the sub-categories. Nevertheless the economic sector of Lumber and wood products production which include and represent the production phase of Biopellet generation, contributes with medium risk level to the overall social risk for some sub-categories, i.e. 1A, 1E and 1F in the Labour rights & decent work impact category, 2A and 2B, in the Health & safety category, 3F e 3G in the Society category and 4A and 4C in the Governance impact category. Finally it is necessary to specify that the residues extraction is inherent to the national supply chain. Indeed the study doesn't take in account the upstream production phases regarding the cultivation of the agricultural and forestry products and respective transportation phase.

11. Conclusion Part B (S-LCA)

Performing a Social Life Cycle Assessment (SLCA) for a novel concept like F-CUBED Production System, which focuses on bioenergy production using a novel hydrothermal treatment, is a comprehensive task that requires a systematic approach.

SHDB characterization models assign a risk (or opportunity) level to the dataset and make possible to identify target areas in the investigated supply chains to verify or improve social conditions.
By the characterization factors, the severity of the presence of a serious situation or opportunity has been described to facilitate data interpretation and visualization of results.

Three case study have been investigated in three different EU countries, i.e. Sweden, Italy and Spain, as explained in Section 2. of Part A of the present work. The social footprint of the F-CUBED Production System has been described for each country, by four different data visualizations.

Firstly the social footprint was calculated aggregating the social impacts associated with each country-specific economic sector (Social Hotspot unit process) by impact category. Secondarily the social impact categories were assessed identifying the contribution to the overall social risk of each economic sector representing every production step of the supply chain of a specific biogenic residue stream and country.
Finally, in order to facilitate data interpretation, a more detailed analysis of the social impacts of the Case Studies, was carried out through the breakdown of the sub-categories which make up the before mentioned impact categories and the contribution analysis of each economic sector to the total social impacts by impact sub-category, on the basis of the characterization factors that describe the severity of a serious situation or opportunity/benefits.

In Sweden and Spain the treatment of the respective residues, Pulp & Paper Bio-sludge and Orange Peels, provides large benefits and small risk, with the exception for economic sector of Bio-pellets production and Electricity generation in Spain, where the risk level has been classified as medium for both.
On the contrary Olive Pomace case Study in Italy shows prevailing of adverse contribution to social risks for the most of the impact sub-categories. However also in this case study the social risk doesn't overcome the threshold of medium level.

In Sweden, the social impacts related to the implementation of F-CUBED Production System for the Pulp & paper Case Study, is concentrated in the Bio-pellets production and the Torwash & Dewatering treatments. However, the Bio-pellets production phase, linked to the economic sector of Lumber and wood products' production in Sweden, gives a small adverse contribution to social impacts, ranging between 8% and 11%. Even for Torwash & Dewatering treatment, the values drop to 4% and 7%.
Moreover, on the basis of the characterization factors, the assessed risk level is low for all the selected subcategories and therefore it is considered acceptable.

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On the other hand the Electricity production steps both by bio-pellets and biogas give large benefits to the different Impact categories. In fact, the benefits are determined by the heat recovery from the conversion processes of the bio-pellets and biogas into energy. The results show that the Electricity production in Sweden, related to the bio-pellets energetic conversion, comprises most of the favourable impact for every social category, ranging between -90% and -97% of total social impact depending on the social category.

The social impact sub-categories which receive the most benefits are Democracy &Freedom of Speech (4C), Injuries & Fatalities (2B) and Wage assessment (1A), respectively, for Governance, Health and Safety and Labor rights & decent work impact categories, respectively. The relevance of Governance is coherent with the current geopolitical situation, in which Europe and Russia are in fact in a situation of energy interdependence. Russia needs to export gas to the EU to access European markets, while Europe needs to import it in order to meet its needs. Therefore reduce the interdependence with a country which is interpreted as an antonym with respect to democracy means introduce a benefit and an opportunity in term of social impacts towards Governance impact category .

In summary, the implementation of the F-CUBED Production System in Sweden can have positive impacts in these subcategories. Nevertheless, since the impact categories of Governance (subcategories of Democracy & Freedom of Speech), Health and safety at Work (Injuries and Fatalities), and Working conditions (Wage Assessments) are already valuable in the context of Sweden and high standards exists in these areas, the potential benefits of the F-CUBED production system would reinforce rather than introducing these benefits. Therefore, the implementation of the F-CUBED production system should focus on maintaining and building upon Sweden's already strong foundations in these social and labour-related topics.

For Olive Pomace Case Study, the Bio-pellets production and the Electricity production steps by bio-pellets in Italy, provide the most adverse contributions ranging between 44-47% and 36-39% of total social impact , receptively, depending on the social category. On the other hand the Torwash & Dewatering treatments and Preconditioning steps have small adverse contributions to social impacts, ranging between 1.4%-1.5%. and 0.9-1.4%, respectively, depending on the social category. Particularly, Bio-pellets production and the Electricity production steps by bio-pellets in Italy show medium risk level for the social impact sub-categories Injuries & Fatalities (2B), Forced Labor (1E), Occupational Toxics and Hazards (2A), State of Environmental Sustainability (3G) and , Democracy &Freedom of Speech (4C) in the Health & safety, Labor rights & decent work and Society impact categories, respectively. Nevertheless, in the whole picture of the Olive Pomace Case Study, the two subcategories 5E and 1J showing low risk in all the involved economic sectors can be read as opportunities, particularly the Smallholder vs Commercial Farms impact sub-category results interesting.

This Italian scenario, apparently unfavourable with respect to the others, can be explained considering that the economic sector Vegetable oil production in Italy can be classified as primary activity close to the agriculture sector rather than a specific industrial process. Moreover the small sized of the olive mill plant imply higher social risks e.g. in Health and safety, Working condition and Wage assessment and a limited implementation of residue recovery in the framework of circular economy criteria. Therefore the introduction of the F-CUBED Production System should introduce a valuable contribution to the improvement of the actual scenario and the comparison between the conventional practices with the circular economy models may determine benefits reducing significantly the social impacts.

For Orange Peels Case Study in Spain, the Bio-pellets production and the Preconditioning phase, connected to the economic sector of Lumber and wood products production in Spain and to the Vegetables, fruits, nuts growing in Spain, respectively, provide relatively small adverse contribution to the social impacts. Indeed their values have a magnitude of 0.8% and 0.5% of total social impact. Even TORWASH and dewatering treatment can be considered negligible.

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On the other hand the Electricity production steps both by bio-pellets and biogas, referring to the Electricity generation in Spain, give large social benefits to the different Impact categories. Indeed the benefits are determined by the heat recovery from the conversion processes of the bio-pellets and biogas into energy.
Deepening analysis show that the economic sector of Lumber and wood products production which include and represent the production phase of Biopellet generation, provides contributions to the overall social risk at medium level, i.e. for sub-categories 1A, 1E and 1F in the Labour rights & decent work impact category, for the sub-categories 2A and 2B, in the Health & safety category, 3F e 3G in the Society category and 4A and 4C in the Governance impact category. This should be taken in proper consideration and could require mitigation measures.

In summary, the implementation of the F-CUBED production system in Spain can lead to various benefits in the impact categories of Governance (subcategories of Democracy & Freedom of Speech), Health & safety (Injuries and Fatalities), and Labor rights & decent work. These benefits include promoting democratic values, enhancing worker safety, and respecting labour rights, all of which can contribute to the F-CUBED production system sustainability, ethical standing, and long-term success in the Spanish context.
Moreover, when considering Spain's specific socio-economic situation, the potential benefits of the F-CUBED production system remain significant. Job creation, adherence to labour laws, and economic diversification can align with Spain's social and economic goals.

This approach, and specifically the identification of the economic sectors that contributed with medium risk level to the overall social risk of the country where F-CUBED Production System has been implemented, allows to foreseen and propose mitigation measures for each sector.
Indeed specific mitigation and improvement measures in the context of the Social Life Cycle Assessment (SLCA) for F-CUBED Production System should be taken for each of the sub-categories affected by social risk at a medium level. These measures should be tailored to the specific risk level and context of the country where the F-CUBED Production System is being developed and should be implemented in collaboration with relevant stakeholders, including workers, local communities, and government authorities. Regular monitoring and reporting on the progress of these measures are essential to ensure continuous improvement and mitigate social risks effectively.

The specific measures and actions in principle should be aimed at reducing the social risks associated with the sectors themselves. They include i.e. Labor standards and regulations enforcement, Capacity-building programs for workers, Engagement with local communities, Supply chain transparency initiatives, Collaboration with NGOs or governmental bodies.

According to the Social LCA iterative approach, further investigation and continuously assess and update the measures and actions as the F-CUBED Production System progresses, will make available new information to track the effectiveness of the proposed measures over the time. This will ensure that the social risks associated with the medium-risk sectors are continually assessed and mitigated.

In conclusion the information provided with the S-LCA can help supply chain stakeholders of the F-CUBED Production System to improve their management of social responsibility issues and create incentives to collaborate and drive progress.

Finally in the Part B of the present report, regarding the S-LCA, an attempt to integrate the SHDB methodology with the UNEP Guidelines was made in order to refine and tailor the analysis to the F-CUBED Production System. For these purposes the Stakeholders engagements have provided a consistent validation of the methodological choices that have been done in the development of the Social Life Cycle Assessment both in the selection of the most relevant sub-categories to analyse and in the interpretation of the final results.
It is significant to note that an overwhelming majority of respondents expects a positive impact by the introduction of the F-CUBED technology, on almost every possible social ground. Repeating a similar survey

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in the future, with a more comprehensive description of the novel technology, and with a better and easier guide to its compilation by respondents might provide even clearer results.

11.1 Limitation of the Study of S-LCA

The current version of SHDB is based on USD 2011 and it's possible to adjust or convert the data to different years or currencies when conducting specific SLCA studies. For this purpose should be necessary a deflator expressing the change in prices over the period of time for the products entailed in the F-CUBED Production System to 'deflate' (price adjust) a measure of value changes for the same period, thus removing the price increases or decreases. This adjustment has not been executed in the present study, also because, it should be done carefully and transparently to maintain the integrity of the analysis and ensure that any conversions or adjustments are properly justified and documented.

The data collection could be refined by sensitivity analysis on inventory data, conducted through Monte Carlo simulation. We omitted this phase in favour of the selection of the country-specific economic sectors in the S-LCA

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APPENDIXES

Appendix A – Life cycle inventory of the Reference cases

Appendix B – Contribution analysis of the impact assessment for Reference Cases

Appendix C –Analysis of the substances and process distribution in the single impact categories

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Appendix A – Life cycle inventory of the Reference cases

A1 Pulp & Paper Bio-sludge Case Study

Table 64 (A1)- Life Cycle Inventory of Reference Case for Pulp & Paper Bio-sludge Case Study

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
UPSTREAM	**Waste Water Treaatment**	**Land Use Change**	Forest land transormation	8,46E-03	m2	Foreground	Biological sludge (3,5%, DM)	Product	9,89E-02	t wb/tADp	Foreground
			Occupation, industrial area	1,55E-04	m2a	Foreground	Treated water stream	Product	1,79E+01	t/tADp	Background
		WWT	Waste water from idustrial process	1,80E+01	t/tADp	Background					
			Urea (46%)	5,69E-01	kg/tADp	Foreground					
			Phosphoric acid (85%)	1,72E-01	kg/tADp	Foreground					
			Building construction	1,55E-04	m2/tADp	Foreground					
			Pipeline long distance	1,26E-07	km/tADp	Foreground					
		Electricity/heat	Electricity, medium voltage, Sweden country-mix	8,00E+00	kWh/tADp	Background					
	Concentrated biosludge	**Biogenic residues (Mixed sludge, DM 2,39%)**	Biological sludge (3,5%, DM)	9,89E-02	t wb/tADp	Foreground	Concentrated mixed sludge (DM 8%) - after gravity table	Product	1,08E-01	t wb/tADp	Foreground
			Fiber sludge stream (DM 1,65%)	3,15E-01	t wb/tADp	Foreground					
		Gravity table	Steel, low-alloyed	9,05E-05	kg/tADp	Background					
		Electricity/heat	Electricity, medium voltage, Sweden country-mix	3,31E+00	kWh/tADp	Background					
MAIN STREAM	**Dewatering**	**Concentrated sludge**	Concentrated mixed sludge (DM 8%) - after gravity table	1,08E-01	t wb/tADp	Foreground	SOLIDS (30% DM) - after screw press	Product	2,74E-02	t wb/tADp	Foreground
		Chiemicals	Iron sulfate (40%)	6,54E-01	kg db/tADp	Foreground	Waste water in output from wire screw press	Product	8,08E-02	t wb/tADp	Calculated
			Polyacrylamide	3,85E-02	kg db/tADp	Foreground					
		Screw press	Steel, low-alloyed	7,96E-05	kg/tADp	Background					
			Electricity, medium voltage, Sweden country-mix	1,08E+00	kWh/tADp	Background					
	Biomass boiler Kyaerner BFB "Hybex" [132MW, 50kg/s (Smurfit Kappa Pitea, Technical Presentation, 2016)]	Feedstock to biomass boiler	SOLIDS (30% DM) - after screw press	2,74E-02	t wb/tADp	Foreground	Energy-Heat-Steam (Available thermal power)	Product	1,00E+02	MJ/tADp	Calculated
		Acid neutralizer	Sodium hydroxide in 50% solution state	5,55E-01	kg/t ADp	Background	NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to Air	3,76E-05	kg/tADp	Background
		NOx removal	Ammonia, liquid	1,71E-02	kg/t ADp	Background	Particulates, > 10 um	Emission to Air	4,14E-05	kg/tADp	Background
		Flou Gas Cleaning	Water, deionised	4,25E-01	t /tADp	Background	Water	Emission to Air	2,96E-03	m3/tADP	Background
		Biomass boiler	Steel, low-alloyed	3,92E-05	kg/t ADp	Calculated	Water	Emission to Water	2,67E-03	m3/tADP	Background
		Electricity/heat	Electricity, medium voltage, Sweden country-mix	4,22E+00	kWh/tADp	Background	Ash from paper production sludge	Waste to treatment	6,85E-03	t/tADp	Background
	Electric power production by Steam Turbine	**Energy-Heat-Steam**	Energy-Heat-Steam (Available thermal power)	1,00E+02	MJ/tADp	Calculated	Electric power production	Product	5,56E+00	kWh/tADp	Background
		Steam Turbine	Steel, low-alloyed	8,46E-04	kg/t ADp	Background	Heat, central or small-scale, natural gas	Product	5,17E+00	kWh/tADp	Background

A2 Virgin Olive Pomace Case Study

Table 65 (A2) - Life Cycle Inventory of Reference Case for Virgin Olive Pomace Case Study

	Process	Sub-process	Unit process - Input	Values	Units	Type of source	Unit process - Output	Sub-process	Values	Units	Type of source
UPSTREAM	Preconditioning	**Biogenic residue**	Virgin olive pomace (ar, DM 19,36%)	1,00E+00	t OP	Foreground	Pre-conditioned olive pomace (destoned and diluited) DM 3,26%	Product	3,55E+00	t wb/tOP	Calculated
		Destoning	Steel, low-alloyed	6,94E-03	kg/tOP	Background	Olive's stones recovered	Product	8,05E-02	t wb/tOP	Background
		Diluition	Tap water	2,63E+00	kg/Top	Background					
		Electricity/heat	Electricity, medium voltage, Italy country-mix	6,34E+00	kWh/top	Background/Foreground					
MAIN STREAM	Anaerobic digestion	**Feedstock**	Pre-conditioned olive pomace (destoned and diluited) DM 3,26%	3,55E+00	twb/tOP	Calculated	Biogas from anaerobic digestion	Products	1,07E+01	Nm3/tOP	Background
		Biogas production process	Biogas anaerobic digestion of manure	1,07E+01	Nmc/tOP	Background	Digestate	Products	4,87E+03	kg/tOP	Background
		Landfarming	Treatment of refinery sludge by landfarming	4,87E+03	kg/tOP	Background					
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	1,61E-04	kgFe2O3/tOP	Calculated					
			Silica sand	6,05E-05	kgSiO2/tOP	Calculated					
			Oxygen, liquid	4,84E-05	kgO2/tOP	Calculated					
DOWNSTREAM	Electricity production from biogas	**Feedstock**	Biogas from anaerobic digestion	1,07E+01	m3/tOP	Background	Electricity, HV by heat and power co-generation, biogas, gas engine-100%	Product	2,72E+02	kWh el/tOP	Background
		Gas engine	Electricity, high voltage (IT) heat and power co-generation, biogas, gas engine/m3 BIOGAS	1,07E+01	m3/tOP	Background	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	4,67E+02	kWh th/tOP	Background
								Avoided product - Scenario 80%	3,73E+02	kWh th/tOP	Background
	Transformation from High to Medium Voltage	**Electricity High Voltage**	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	2,72E+02	kWh/tADp	Background	Electricity MV from heat and power co-generation	Product	2,70E+02	kWh/tOP	Background
		Electricity transforation	Electricity voltage transformation from high to medium voltage (IT)	2,72E+02	kWh/tADp	Background					

A3 Fruit & Vegetable (Orange Peels) Case Study

Table 66 (A3) - Life Cycle Inventory of Reference Case for Fruit & Vegetable (Orange Peels) Case Study

	Process	Sub-process	Unit process-Input	Values	Units	Source	Unit process-Output	Sub-process	Values	Units	Source
UPSTREAM	Preconditioning	Biogenic residue	Virgin orange peels (ar, DM 20%)	1,00E+00	t ORP	Foreground	Pre-conditioned orange peels (grinded and diluited) DM 10%	Product	2,00E+00	t wb/tORP	Foreground/Calculated
		Grinding	Steel, low-alloyed	2,89E-02	kg/tORP	Background					
		Diluition	Tap water	1,00E+00	kg/tORP	Calculated					
		Electricity/heat	Electricity, medium voltage, Italy country-mix	3,33E-01	kWh/tORP	Background/Foreground					
MAIN STREAM	Anaerobic digestion	Feedstock	Pre-conditioned orange peels (grinded and diluited) DM 10%	2,00E+00	twb/tORP	Foreground/Calculated	Biogas from anaerobic digestion	Products	5,74E+01	Nm3/tORP	Background
		Biogas production process	Biogas anaerobic digestion of manure /kWh	5,74E+01	Nmc/tORP	Background	Digestate	Products	2,74E+03	kg/tORP	Background
		Landfarming	Treatment of refinery sludge by landfarming	2,74E+03	kg/tOP	Background					
		IRON SPONGE BED technology for H2S Gas Cleaning	Iron pellet	6,78E+00	kgFe2O3/tORP	Calculated					
			Silica sand	2,55E+00	kgSiO2/tORP	Calculated					
			Oxygen, liquid	2,04E+00	kgO2/tORP	Calculated					
DOWNSTREAM	Electricity production from biogas	Feedstock	Biogas from anaerobic digestion	5,74E+01	m3/tOP	Background	Electricity, HV by heat and power co-generation, biogas, gas engine-100%	Product	1,17E+03	kWh el/tOP	Background
		Gas engine	Electricity, high voltage (IT) heat and power co-generation, biogas, gas engine/m3 BIOGAS	5,74E+01	m3/tOP	Background	Heat, central or small-scale, natural gas	Avoided product - Scenario 100%	2,01E+03	kWh th/tOP	Background
								Avoided product - Scenario 54%	1,09E+03	kWh th/tORP	Background
	Transformation from High to Medium Voltage	Electricity High Voltage	ELECTRICITY, HIGH VOLTAGE BY HEAT AND POWER CO-GENERATION, BIOGAS, GAS ENGINE	1,17E+03	kWh/tADp	Background	Electricity MV from heat and power co-generation	Product	1,16E+03	kWh/tADp	Background
		Electricity transforation	Electricity voltage transformation from high to medium voltage (IT)	1,17E+03	kWh/tADp	Background					

Appendix B – Contribution analysis of the impact assessment for Reference Cases

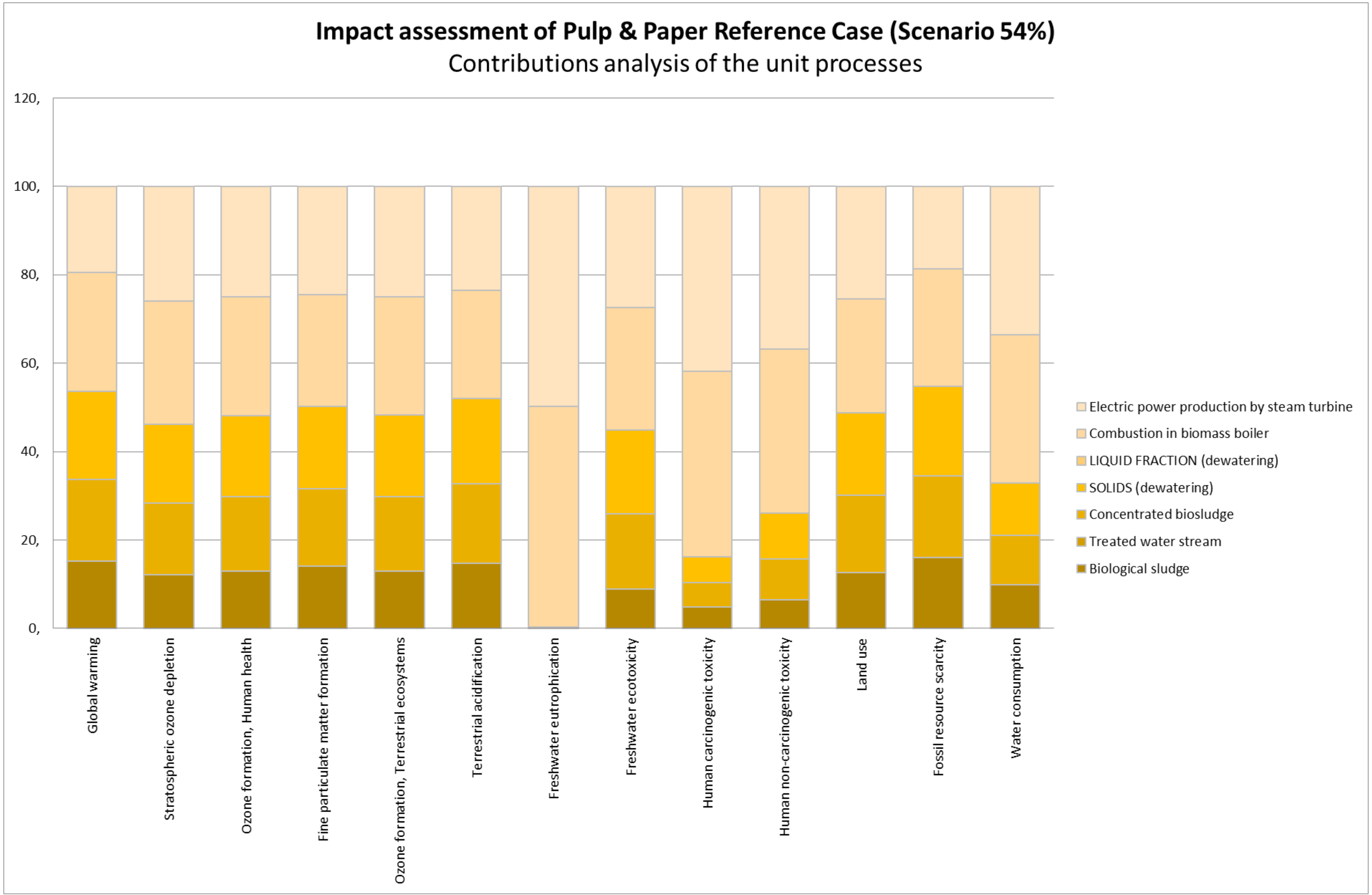

Figure 60 - B1 Pulp & Paper Bio-sludge Case Study

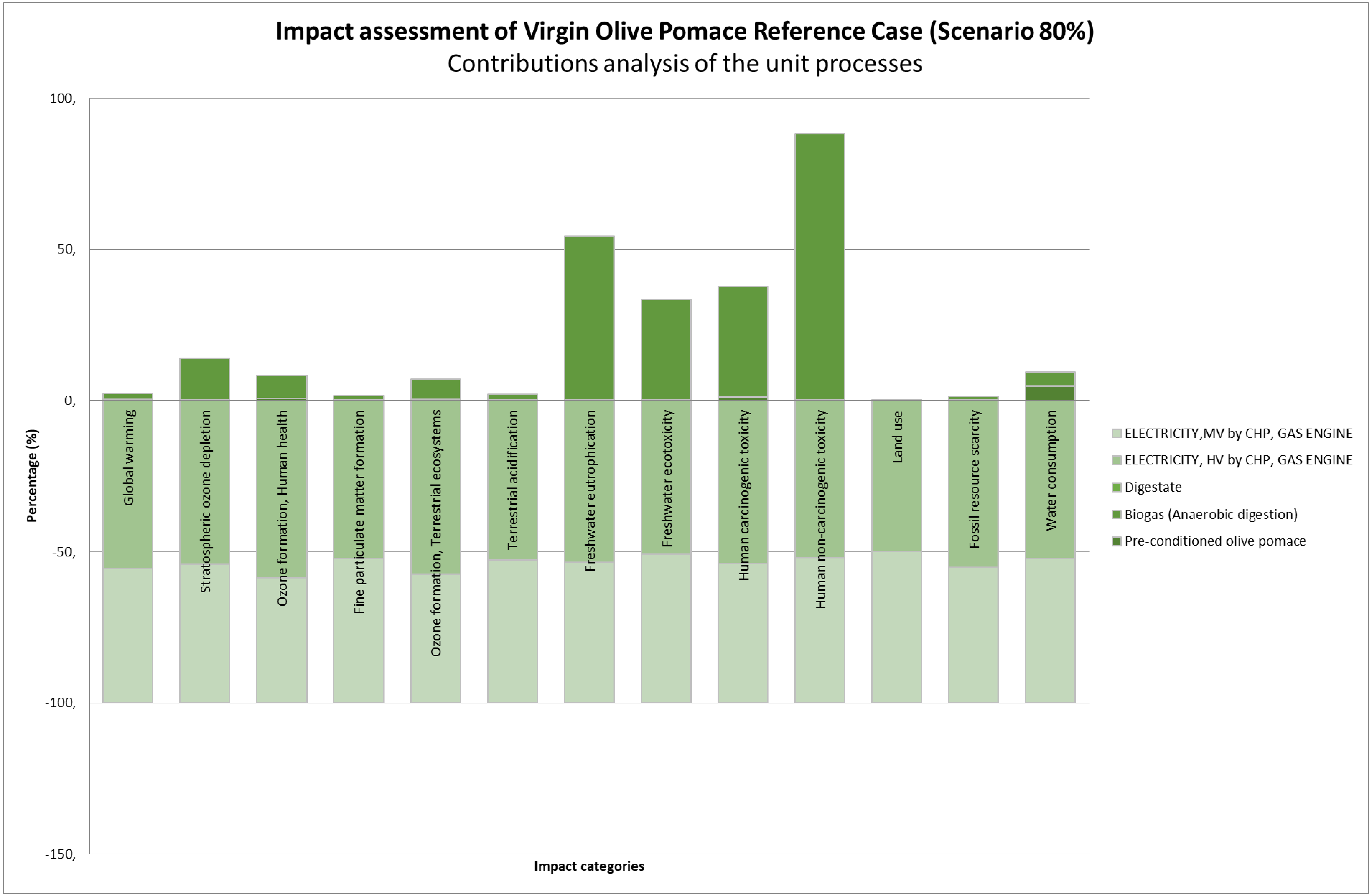

Figure 61 - B2 Virgin Olive Pomace Case Study

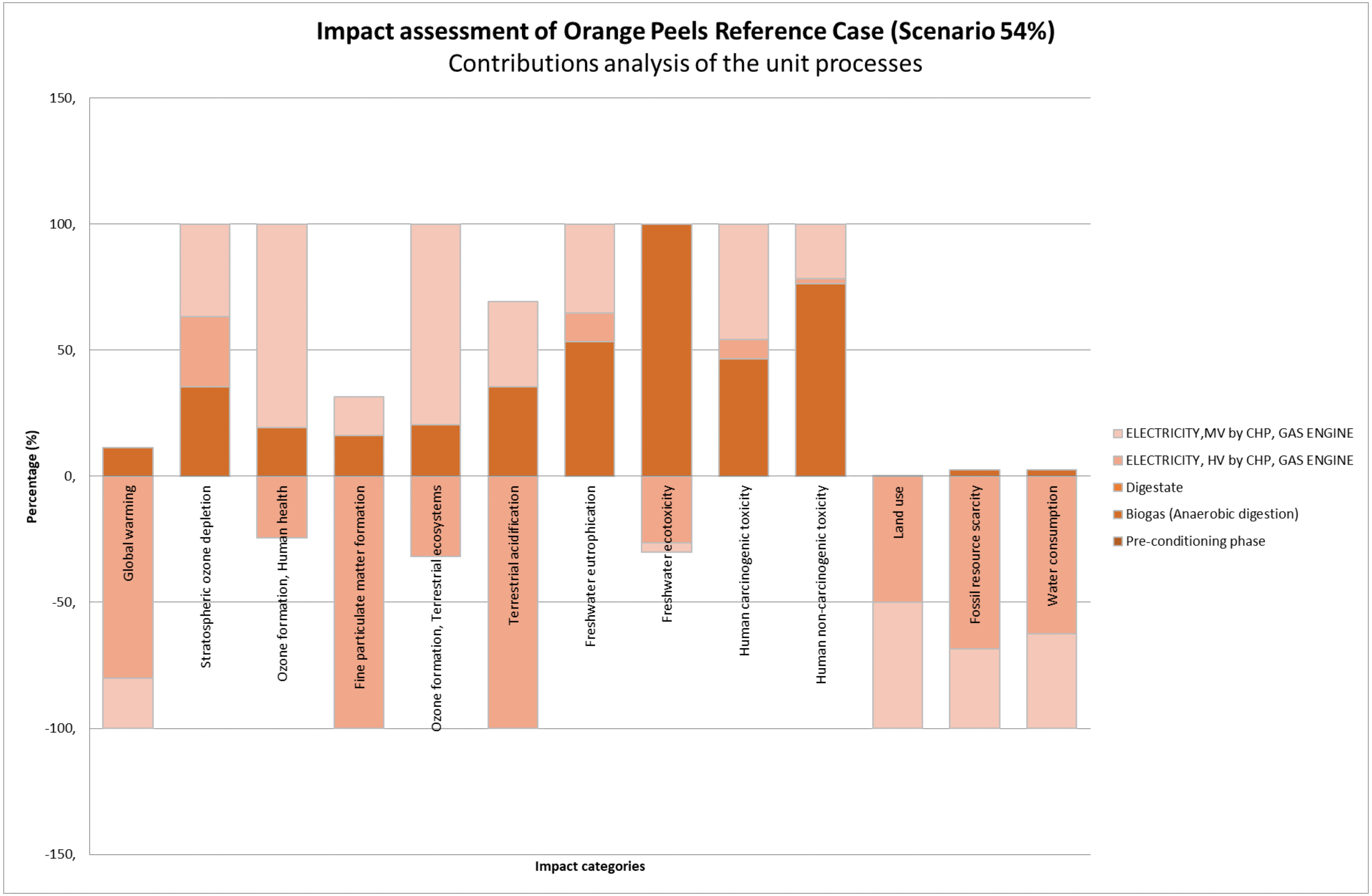

Figure 62 - B3 Fruit & Vegetable (Orange Peels) Case Study

Appendix C – Analysis of the substances and process distribution in the single impact categories

Table 67 (C1) - Pulp & Paper Bio-sludge F-CUBED Production System

				Upstream processes				Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
Substances	**Compartment**	**Units**	**Total**	**Biological sludge**	**Treated water stream**	**Enhanced Bio-sludge**	**Waste water from decanter-centrifuge**	**TORWASH effluent**	**Dewatering PRESS CAKE (Solids)**	**Dewatering FILTRATE (Liquid fraction)**	**PELLETIZING phase**	**Biomass boiler (combustion)**	**Electricity production system**	**Anaerobic digestion**	**Digestate**	**ELECTRICITY generation from biogas (HV)**	**ELECTRICITY voltage transformation (MV)**
Ozone depletion																	
Total of all compartments		kg CFC-11 eq	4,88E-06	6,61E-07	-	6,33E-07	3,33E-08	6,45E-07	6,53E-07	-	7,45E-07	8,85E-07	5,60E-07	-8,48E-08	-	-1,74E-07	3,27E-07
Remaining substances		kg CFC-11 eq	1,31E-07	6,76E-08	-	6,44E-08	3,39E-09	6,48E-08	6,52E-08	-	7,61E-08	9,07E-08	-6,81E-08	-1,66E-08	-	-1,14E-07	-1,02E-07
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	2,90E-06	3,27E-07	-	3,15E-07	1,66E-08	3,24E-07	3,32E-07	-	3,54E-07	3,92E-07	3,85E-07	-4,99E-09	-	-3,71E-09	4,59E-07
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	1,52E-06	2,37E-07	-	2,25E-07	1,18E-08	2,26E-07	2,27E-07	-	2,80E-07	3,61E-07	2,04E-07	-6,00E-08	-	-1,05E-07	-9,08E-08
Methane, dichlorodifluoro-, CFC-12	Air	kg CFC-11 eq	1,73E-07	2,28E-08	-	2,19E-08	1,15E-09	2,25E-08	2,30E-08	-	2,64E-08	3,05E-08	2,91E-08	-1,55E-09	-	-1,68E-09	-1,13E-09
Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	1,67E-07	7,20E-09	-	6,86E-09	3,61E-10	6,92E-09	6,94E-09	-	8,04E-09	9,89E-09	9,50E-09	-1,66E-09	-	5,08E-08	6,21E-08
Process contribution (%)				13,54%	0,00%	12,97%	0,68%	13,20%	13,38%	0,00%	15,25%	18,12%	11,46%	-1,74%	0,00%	-3,55%	6,69%
Sum					27,19%				41,83%			29,58%			1,40%		
Human toxicity																	
Total of all compartments		kg 1,4-DB eq	1,46E+01	1,12E+00	-	1,07E+00	5,61E-02	1,08E+00	1,09E+00	-	1,50E+00	2,93E+00	2,71E+00	-4,44E-01	-	1,42E+00	2,07E+00
Remaining substances		kg 1,4-DB eq	1,07E+00	1,28E-01	-	1,22E-01	6,42E-03	1,23E-01	1,24E-01	-	1,67E-01	2,53E-01	2,37E-01	-7,78E-02	-	-2,10E-02	5,92E-03
Antimony	Air	kg 1,4-DB eq	2,45E-01	1,18E-02	-	1,12E-02	5,89E-04	1,13E-02	1,13E-02	-	3,94E-02	7,61E-02	7,55E-02	-4,57E-03	-	4,96E-03	7,89E-03
Arsenic	Air	kg 1,4-DB eq	7,72E-01	1,10E-01	-	1,05E-01	5,52E-03	1,06E-01	1,07E-01	-	1,23E-01	1,52E-01	1,40E-01	-4,36E-02	-	-2,82E-02	-3,82E-03
Lead	Air	kg 1,4-DB eq	7,14E-01	8,38E-02	-	7,99E-02	4,20E-03	8,05E-02	8,13E-02	-	1,06E-01	1,78E-01	1,69E-01	-3,44E-02	-	-2,38E-02	-1,10E-02
Manganese	Air	kg 1,4-DB eq	2,28E-01	4,51E-03	-	4,33E-03	2,28E-04	4,44E-03	4,52E-03	-	1,99E-02	9,13E-02	9,11E-02	-4,85E-04	-	1,67E-03	6,09E-03
Mercury	Air	kg 1,4-DB eq	7,58E-01	3,48E-02	-	3,33E-02	1,75E-03	3,40E-02	3,48E-02	-	4,55E-02	7,76E-02	7,12E-02	-5,95E-03	-	1,92E-01	2,39E-01
Vanadium	Air	kg 1,4-DB eq	5,32E-01	8,47E-02	-	8,05E-02	4,24E-03	8,06E-02	8,07E-02	-	8,30E-02	8,61E-02	8,57E-02	-2,00E-02	-	-1,59E-02	-1,77E-02
Arsenic	Water	kg 1,4-DB eq	3,06E+00	1,60E-01	-	1,53E-01	8,04E-03	1,55E-01	1,56E-01	-	1,88E-01	8,33E-01	8,16E-01	-4,89E-02	-	2,59E-01	3,81E-01
Barium	Water	kg 1,4-DB eq	5,21E-01	1,07E-01	-	1,02E-01	5,37E-03	1,03E-01	1,03E-01	-	1,18E-01	1,40E-01	5,74E-02	-4,48E-02	-	-8,76E-02	-8,22E-02
Lead	Water	kg 1,4-DB eq	3,62E-01	3,11E-02	-	2,96E-02	1,56E-03	2,98E-02	3,01E-02	-	3,40E-02	4,16E-02	3,80E-02	-1,63E-02	-	6,29E-02	7,95E-02
Manganese	Water	kg 1,4-DB eq	5,66E+00	3,41E-01	-	3,25E-01	1,71E-02	3,30E-01	3,34E-01	-	5,50E-01	8,54E-01	7,86E-01	-1,39E-01	-	9,54E-01	1,30E+00
Molybdenum	Water	kg 1,4-DB eq	4,47E-01	1,20E-02	-	1,15E-02	6,06E-04	1,17E-02	1,18E-02	-	1,48E-02	1,34E-01	1,33E-01	-4,59E-03	-	5,30E-02	6,91E-02
Zinc	Water	kg 1,4-DB eq	2,38E-01	8,97E-03	-	8,55E-03	4,50E-04	8,62E-03	8,70E-03	-	1,10E-02	1,59E-02	1,47E-02	-4,32E-03	-	7,42E-02	9,07E-02
Process contribution (%)				7,66%	0,00%	7,30%	0,38%	7,38%	7,45%	0,00%	10,28%	20,09%	18,59%	-3,04%	0,00%	9,76%	14,15%
Sum					15,34%				25,11%			38,69%			20,86%		
Freshwater ecotoxicity																	
Total of all compartments		kg 1,4-DB eq	1,67E+00	1,44E-01	-	1,37E-01	7,22E-03	1,39E-01	1,41E-01	-	1,64E-01	2,21E-01	1,93E-01	-6,61E-02	-	2,57E-01	3,32E-01
Remaining substances		kg 1,4-DB eq	6,12E-02	1,15E-02	-	1,09E-02	5,75E-04	1,10E-02	1,10E-02	-	1,29E-02	1,71E-02	5,89E-03	-4,74E-03	-	-8,06E-03	-6,89E-03
Cypermethrin	Soil	kg 1,4-DB eq	-3,47E-02	4,83E-05	-	4,60E-05	2,42E-06	4,62E-05	4,63E-05	-	7,92E-05	1,18E-04	1,16E-04	-1,12E-02	-	-1,09E-02	-1,31E-02
Copper	Water	kg 1,4-DB eq	1,36E+00	1,12E-01	-	1,07E-01	5,63E-03	1,08E-01	1,10E-01	-	1,26E-01	1,62E-01	1,47E-01	-4,40E-02	-	2,33E-01	2,95E-01
Manganese	Water	kg 1,4-DB eq	3,56E-02	2,15E-03	-	2,05E-03	1,08E-04	2,08E-03	2,11E-03	-	3,47E-03	5,38E-03	4,95E-03	-8,73E-04	-	6,01E-03	8,20E-03
Nickel	Water	kg 1,4-DB eq	1,53E-01	1,08E-02	-	1,03E-02	5,40E-04	1,04E-02	1,05E-02	-	1,38E-02	2,69E-02	2,55E-02	-3,97E-03	-	2,06E-02	2,75E-02
Vanadium	Water	kg 1,4-DB eq	4,02E-02	5,33E-03	-	5,07E-03	2,67E-04	5,09E-03	5,11E-03	-	5,47E-03	5,97E-03	5,82E-03	-3,93E-04	-	8,37E-04	1,61E-03
Zinc	Water	kg 1,4-DB eq	4,90E-02	1,80E-03	-	1,72E-03	9,04E-05	1,73E-03	1,75E-03	-	2,24E-03	3,25E-03	3,00E-03	-8,95E-04	-	1,54E-02	1,89E-02
Process contribution (%)				8,62%	0,00%	8,22%	0,43%	8,31%	8,44%	0,00%	9,81%	13,26%	11,55%	-3,96%	0,00%	15,43%	19,89%
Sum					17,27%				26,56%			24,81%			31,36%		
Water depletion																	
Total of all compartments		m3	1,45E+00	1,88E-01	-	1,79E-01	9,43E-03	1,87E-01	1,88E-01	-	1,90E-01	2,06E-01	2,04E-01	-4,91E-02	-	3,64E-02	1,16E-01
Remaining substances		m3	3,09E-01	2,39E-02	-	2,27E-02	1,20E-03	2,37E-02	2,41E-02	-	4,69E-02	7,64E-02	6,86E-02	-1,54E-02	-	1,44E-02	2,25E-02
Water, cooling, unspecified natural origin, RER	Raw	m3	3,68E-01	5,99E-02	-	5,69E-02	3,00E-03	5,71E-02	5,71E-02	-	5,79E-02	5,90E-02	5,87E-02	-1,46E-02	-	-1,24E-02	-1,45E-02
Water, cooling, unspecified natural origin, SE	Raw	m3	1,98E+00	2,33E-01	-	2,25E-01	1,18E-02	2,31E-01	2,36E-01	-	2,37E-01	2,39E-01	2,38E-01	-1,08E-04	-	-2,22E-04	3,29E-01
Water, river, Europe without Switzerland	Raw	m3	2,90E-02	2,20E-04	-	2,11E-04	1,11E-05	5,43E-03	5,43E-03	-	5,52E-03	5,62E-03	5,61E-03	-4,13E-05	-	4,30E-04	5,38E-04
Water, turbine use, unspecified natural origin, SE	Raw	m3	1,00E+03	1,18E+02	-	1,13E+02	5,97E+00	1,17E+02	1,19E+02	-	1,20E+02	1,20E+02	1,20E+02	-5,14E-02	-	-1,17E-01	1,70E+02
Water, RER	Water	m3	-2,34E-01	-3,77E-02	-	-3,59E-02	-1,89E-03	-3,59E-02	-3,60E-02	-	-3,69E-02	-3,81E-02	-3,78E-02	9,30E-03	-	7,78E-03	8,91E-03
Water, SE	Water	m3	-1,01E+03	-1,18E+02	-	-1,14E+02	-5,98E+00	-1,17E+02	-1,20E+02	-	-1,20E+02	-1,21E+02	-1,20E+02	5,15E-02	-	1,17E-01	-1,71E+02
Process contribution (%)				12,91%	0,00%	12,31%	0,65%	12,83%	12,91%	0,00%	13,10%	14,19%	14,02%	-3,37%	0,00%	2,50%	7,95%
Sum					25,87%				38,83%			28,21%			7,08%		
Agricultural land occupation																	
Total of all compartments		m2a	6,36E+01	9,31E-01	-	8,95E-01	4,71E-02	9,20E-01	9,38E-01	-	1,07E+01	2,17E+01	2,17E+01	-2,49E-01	-	2,37E+00	3,65E+00
Remaining substances		m2a	1,01E+00	7,00E-03	-	6,67E-03	3,51E-04	6,73E-03	6,78E-03	-	1,45E-01	3,14E-01	3,13E-01	-1,27E-01	-	1,54E-01	1,86E-01
Occupation, forest, intensive	Raw	m2a	5,78E+01	9,22E-01	-	8,87E-01	4,67E-02	9,11E-01	9,30E-01	-	1,05E+01	2,14E+01	2,14E+01	-5,47E-02	-	4,58E-02	8,67E-01
Occupation, grassland, natural, for livestock grazing	Raw	m2a	1,68E+00	5,88E-04	-	5,64E-04	2,97E-05	5,79E-04	5,89E-04	-	1,63E-03	2,94E-03	2,81E-03	-2,40E-02	-	7,69E-01	9,22E-01
Occupation, pasture, man made	Raw	m2a	3,05E+00	1,22E-03	-	1,17E-03	6,17E-05	1,20E-03	1,22E-03	-	3,14E-03	5,59E-03	5,34E-03	-4,34E-02	-	1,40E+00	1,68E+00
Process contribution (%)				1,46%	0,00%	1,41%	0,07%	1,45%	1,48%	0,00%	16,79%	34,15%	34,12%	-0,39%	0,00%	3,72%	5,74%
Sum					2,95%				19,71%			68,27%			9,07%		

Table 68 (C2) - Virgin Olive Pomace F-CUBED Production System

Substances	Compartment	Units	Total	Pre-conditioning	TORWASH effluent	Dewatering PRESS CAKE (Solids)	Dewatering FILTRATE (Liquid fraction)	PELLETIZING phase	ELECTRICITY generation from pellets (HV)	ELECTRICITY voltage transformation (MV)	Anaerobic digestion	Digestate	ELECTRICITY generation from biogas (HV)	ELECTRICITY voltage transformation (MV)
				Upstream processes	**Main stream processes**				**Downstream processes**		**Filtrate (liquid fraction) processing**			
Ozone depletion														
Total of all compartments		kg CFC-11 eq	-6,50E-05	4,01E-07	1,12E-06	1,33E-06	-	2,97E-06	-8,26E-05	1,09E-05	2,81E-09	-	-1,31E-05	1,40E-05
Remaining substances		kg CFC-11 eq	7,81E-07	5,15E-08	1,44E-07	1,71E-07	-	2,57E-07	-1,10E-06	1,07E-06	7,92E-11	-	-2,23E-07	4,10E-07
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC-11 eq	3,77E-06	1,20E-09	3,35E-09	3,97E-09	-	9,35E-09	1,72E-06	1,97E-06	5,63E-12	-	-1,10E-09	7,15E-08
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	1,28E-05	4,35E-08	1,22E-07	1,44E-07	-	5,55E-07	-1,36E-06	1,04E-05	1,68E-10	-	-2,63E-07	3,14E-06
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	-9,01E-06	2,43E-07	6,81E-07	8,04E-07	-	9,73E-07	-4,14E-05	2,44E-05	9,38E-11	-	-6,91E-06	1,22E-05
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	-7,62E-05	5,83E-08	1,63E-07	1,95E-07	-	1,14E-06	-4,04E-05	-2,77E-05	2,43E-09	-	-6,65E-06	-2,96E-06
Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	2,94E-06	3,56E-09	9,99E-09	1,19E-08	-	3,15E-08	-5,79E-08	8,69E-07	3,53E-11	-	9,02E-07	1,17E-06
Process contribution (%)				-0,62%	-1,73%	-2,05%	0,00%	-4,56%	127,09%	-16,78%	0,00%	0,00%	20,21%	-21,56%
Sum				-0,62%		-8,34%			110,31%			-1,36%		
Freshwater eutrophication														
Total of all compartments		kg P eq	3,49E-01	7,89E-04	2,21E-03	2,64E-03	-	9,86E-03	-2,04E-02	1,84E-01	5,31E-06	-	5,53E-02	1,15E-01
Remaining substances		kg P eq	1,09E-03	1,59E-06	4,48E-06	5,33E-06	-	2,88E-05	2,36E-05	3,15E-04	3,01E-08	-	3,12E-04	3,96E-04
Phosphate	Water	kg P eq	3,32E-01	7,83E-04	2,19E-03	2,62E-03	-	9,23E-03	-2,76E-02	1,76E-01	5,26E-06	-	5,50E-02	1,14E-01
Phosphorus	Soil	kg P eq	1,64E-02	4,91E-06	1,38E-05	1,63E-05	-	6,01E-04	7,18E-03	8,26E-03	1,27E-08	-	-1,08E-05	3,05E-04
Process contribution (%)				0,23%	0,63%	0,75%	0,00%	2,82%	-5,84%	52,75%	0,00%	0,00%	15,82%	32,83%
Sum				0,23%		4,21%			46,91%			48,66%		
Human toxicity														
Total of all compartments		kg 1,4-DB eq	1,50E+02	5,80E-01	1,62E+00	1,96E+00	-	9,33E+00	-2,78E+01	1,13E+02	5,79E-03	-	5,25E+00	4,61E+01
Remaining substances		kg 1,4-DB eq	6,35E+00	5,95E-02	1,65E-01	2,02E-01	-	1,15E+00	-5,32E+00	5,16E+00	1,55E-03	-	9,42E-01	3,99E+00
Antimony	Air	kg 1,4-DB eq	3,16E+00	1,50E-03	4,21E-03	5,44E-03	-	5,01E-01	1,04E+00	1,38E+00	3,40E-05	-	6,35E-02	1,61E-01
Lead	Air	kg 1,4-DB eq	2,74E+00	1,57E-02	4,36E-02	5,38E-02	-	4,94E-01	-3,12E-01	2,08E+00	5,08E-04	-	-1,68E-01	5,28E-01
Manganese	Air	kg 1,4-DB eq	4,85E+00	1,60E-03	4,46E-03	5,33E-03	-	2,80E-01	2,05E+00	2,39E+00	9,78E-06	-	9,32E-03	1,09E-01
Mercury	Air	kg 1,4-DB eq	3,64E+00	9,53E-03	3,16E-02	4,90E-02	-	2,40E-01	-9,62E-01	1,41E+00	1,26E-04	-	1,09E+00	1,78E+00
Vanadium	Air	kg 1,4-DB eq	3,65E+00	1,22E-02	3,41E-02	4,04E-02	-	8,05E-02	2,33E-02	2,65E+00	2,32E-05	-	2,34E-02	7,87E-01
Cadmium	Soil	kg 1,4-DB eq	2,72E+00	1,10E-03	3,09E-03	3,68E-03	-	9,55E-02	1,01E+00	1,27E+00	2,41E-05	-	1,31E-01	2,06E-01
Arsenic	Water	kg 1,4-DB eq	2,47E+01	8,18E-02	2,29E-01	2,74E-01	-	8,42E-01	-3,67E+00	1,75E+01	5,71E-04	-	1,64E+00	7,78E+00
Barium	Water	kg 1,4-DB eq	-4,53E+01	2,33E-02	6,41E-02	7,91E-02	-	3,40E-01	-2,22E+01	-1,79E+01	4,53E-04	-	-3,52E+00	-2,27E+00
Manganese	Water	kg 1,4-DB eq	1,38E+02	3,53E-01	9,86E-01	1,18E+00	-	5,05E+00	1,33E+00	9,24E+01	2,36E-03	-	5,14E+00	3,16E+01
Selenium	Water	kg 1,4-DB eq	5,67E+00	2,07E-02	5,79E-02	6,91E-02	-	2,58E-01	-7,93E-01	4,66E+00	1,33E-04	-	-9,73E-02	1,49E+00
Process contribution (%)			1,80E+01	0,39%	1,08%	1,31%	0,00%	6,21%	-18,49%	75,28%	0,00%	0,00%	3,50%	30,73%
Sum				0,39%		8,60%			56,79%			34,23%		
Photochemical oxidant formation														
Total of all compartments		kg NMVOC	1,02E+00	6,43E-03	1,80E-02	2,16E-02	-	1,26E-01	-5,51E-01	1,07E+00	2,16E-04	-	-7,60E-02	3,96E-01
Remaining substances		kg NMVOC	-2,63E-03	1,15E-04	3,13E-04	3,97E-04	-	4,11E-03	-2,24E-02	4,35E-03	5,60E-06	-	1,37E-03	9,15E-03
Butane	Air	kg NMVOC	-3,28E-02	1,45E-05	4,07E-05	4,82E-05	-	7,24E-05	-1,63E-02	-1,24E-02	1,52E-07	-	-2,70E-03	-1,56E-03
Carbon monoxide, biogenic	Air	kg NMVOC	4,72E-02	1,58E-05	4,43E-05	5,25E-05	-	2,94E-03	1,78E-02	2,16E-02	5,64E-08	-	1,86E-03	2,94E-03
Ethane	Air	kg NMVOC	-4,91E-02	2,84E-05	7,95E-05	9,41E-05	-	1,27E-04	-2,54E-02	-1,78E-02	5,05E-08	-	-4,20E-03	-1,98E-03
Methane, fossil	Air	kg NMVOC	-7,70E-02	6,51E-05	1,82E-04	2,19E-04	-	4,20E-04	-4,31E-02	-2,58E-02	2,38E-07	-	-7,02E-03	-1,98E-03
Nitrogen oxides	Air	kg NMVOC	1,44E+00	4,92E-03	1,38E-02	1,65E-02	-	9,32E-02	-1,39E-01	1,11E+00	1,82E-04	-	-1,31E-02	3,49E-01
NMVOC, non-methane volatile organic compounds, unsp	Air	kg NMVOC	-3,32E-01	6,42E-04	1,79E-03	2,21E-03	-	1,93E-02	-2,41E-01	-8,03E-02	2,52E-05	-	-4,08E-02	5,91E-03
Pentane	Air	kg NMVOC	-1,54E-02	1,76E-05	4,92E-05	5,82E-05	-	6,12E-04	-9,23E-03	-4,56E-03	2,13E-07	-	-1,85E-03	-4,91E-04
Propane	Air	kg NMVOC	-2,88E-02	1,14E-05	3,19E-05	3,78E-05	-	5,44E-05	-1,41E-02	-1,11E-02	8,62E-08	-	-2,33E-03	-1,44E-03
Sulfur dioxide	Air	kg NMVOC	1,07E-01	5,94E-04	1,67E-03	1,98E-03	-	4,41E-03	-4,24E-02	1,05E-01	3,06E-06	-	-3,88E-03	3,90E-02
Toluene	Air	kg NMVOC	-3,64E-02	4,80E-06	1,35E-05	1,61E-05	-	9,92E-04	-1,62E-02	-1,50E-02	6,22E-08	-	-3,33E-03	-2,99E-03
Process contribution (%)				0,63%	1,77%	2,12%	0,00%	12,44%	-54,28%	105,78%	0,02%	0,00%	-7,48%	39,00%
Sum				0,63%		16,33%			51,50%			31,53%		

Table 69 (C3) - Fruit & Vegetable (Orange Peels) F-CUBED Production System

Substances	Compartment	Units	Total	Upstream processes	Main stream processes				Downstream processes		Filtrate (liquid fraction) processing			
				Pre-conditioning	TORWASH effluent	Dewatering PRESS CAKE (Solids)	Dewatering FILTRATE (Liquid fraction)	PELLETIZING phase	ELECTRICITY generation from pellets (HV)	ELECTRICITY voltage transformation (MV)	Anaerobic digestion	Digestate	ELECTRICITY generation from biogas (HV)	ELECTRICITY voltage transformation (MV)
Freshwater eutrophication														
Total of all compartments		kg P eq	1,31E+00	6,94E-04	4,87E-03	6,18E-03	-	2,47E-02	-8,11E-04	2,87E-01	2,05E-04	-	3,15E-01	6,71E-01
Remaining substances		kg P eq	4,29E-03	1,95E-07	1,78E-06	2,30E-06	-	6,25E-05	6,72E-05	1,34E-04	4,43E-07	-	1,97E-03	2,05E-03
Phosphate	Water	kg P eq	1,28E+00	6,92E-04	4,85E-03	6,15E-03	-	2,31E-02	-1,21E-02	2,75E-01	2,04E-04	-	3,13E-01	6,68E-01
Phosphorus	Soil	kg P eq	2,60E-02	2,16E-06	1,48E-05	1,87E-05	-	1,52E-03	1,12E-02	1,21E-02	1,12E-07	-	-2,31E-05	1,16E-03
Process contribution (%)				0,05%	0,37%	0,47%	-	1,88%	-0,06%	21,95%	0,02%	-	24,04%	51,28%
Sum				0,05%		2,73%			21,88%			75,34%		
Human toxicity														
Total of all compartments		kg 1,4-DB eq	6,56E+02	6,03E-01	4,29E+00	5,48E+00	-	2,43E+01	-9,84E-01	2,38E+02	6,19E-02	-	4,48E+01	3,40E+02
Remaining substances		kg 1,4-DB eq	7,49E+01	5,12E-02	3,28E-01	4,31E-01	-	4,38E+00	6,90E+00	2,31E+01	4,19E-03	-	9,78E+00	2,99E+01
Arsenic	Air	kg 1,4-DB eq	1,33E+01	2,62E-02	1,76E-01	2,27E-01	-	9,69E-01	-2,07E+00	5,65E+00	-7,20E-04	-	-6,30E-01	8,93E+00
Lead	Air	kg 1,4-DB eq	1,53E+01	1,97E-02	1,25E-01	1,65E-01	-	1,29E+00	1,21E+00	6,47E+00	-2,67E-04	-	-2,63E-01	6,25E+00
Mercury	Air	kg 1,4-DB eq	2,17E+01	9,12E-03	2,07E-01	2,74E-01	-	7,62E-01	-8,84E-02	3,37E+00	3,86E-03	-	6,46E+00	1,07E+01
Arsenic	Water	kg 1,4-DB eq	1,29E+02	1,11E-01	7,60E-01	9,67E-01	-	2,42E+00	-1,90E+00	4,59E+01	8,69E-03	-	1,05E+01	6,97E+01
Barium	Water	kg 1,4-DB eq	-5,52E+01	2,51E-02	1,44E-01	1,93E-01	-	8,57E-01	-2,12E+01	-1,47E+01	-4,26E-04	-	-1,42E+01	-6,22E+00
Manganese	Water	kg 1,4-DB eq	4,33E+02	3,36E-01	2,37E+00	3,00E+00	-	1,29E+01	1,65E+01	1,57E+02	4,49E-02	-	3,34E+01	2,07E+02
Selenium	Water	kg 1,4-DB eq	2,47E+01	2,52E-02	1,78E-01	2,25E-01	-	7,08E-01	-3,09E-01	1,07E+01	1,65E-03	-	-2,32E-01	1,34E+01
Process contribution (%)				0,09%	0,65%	0,84%	-	3,70%	-0,15%	36,21%	0,01%	-	6,83%	51,83%
Sum				0,09%		5,19%			36,06%			58,66%		
Freshwater ecotoxicity														
Total of all compartments		kg 1,4-DB eq	2,91E+01	5,23E-02	3,01E-01	4,03E-01	-	1,45E+00	-5,83E+00	3,95E+00	5,05E-03	-	8,34E+00	2,04E+01
Remaining substances		kg 1,4-DB eq	2,44E-01	7,08E-04	4,38E-03	5,76E-03	-	3,70E-02	-1,42E-01	8,75E-02	-6,05E-04	-	-1,65E-02	2,67E-01
Beryllium	Water	kg 1,4-DB eq	4,64E-01	6,29E-04	4,09E-03	5,29E-03	-	1,86E-02	-2,57E-02	2,03E-01	2,18E-05	-	-1,23E-02	2,70E-01
Bromine	Water	kg 1,4-DB eq	-7,85E+00	2,04E-04	1,46E-03	1,93E-03	-	1,31E-02	-2,37E+00	-2,28E+00	-3,63E-05	-	-1,66E+00	-1,55E+00
Cobalt	Water	kg 1,4-DB eq	5,55E-01	6,17E-04	3,58E-03	4,74E-03	-	1,77E-02	-1,73E-02	1,77E-01	6,51E-05	-	6,44E-02	3,04E-01
Copper	Water	kg 1,4-DB eq	2,37E+01	3,81E-02	2,10E-01	2,84E-01	-	9,90E-01	-2,86E+00	1,91E+00	4,19E-03	-	8,59E+00	1,45E+01
Manganese	Water	kg 1,4-DB eq	2,73E+00	2,12E-03	1,49E-02	1,89E-02	-	8,13E-02	1,04E-01	9,89E-01	2,83E-04	-	2,10E-01	1,31E+00
Nickel	Water	kg 1,4-DB eq	7,24E+00	7,28E-03	4,51E-02	5,90E-02	-	2,10E-01	-1,53E-01	2,40E+00	8,17E-04	-	7,59E-01	3,91E+00
Silver	Water	kg 1,4-DB eq	-9,00E-01	6,95E-04	3,23E-03	4,64E-03	-	2,22E-02	-3,45E-01	-2,61E-01	-4,72E-05	-	-2,14E-01	-1,11E-01
Vanadium	Water	kg 1,4-DB eq	1,23E+00	1,18E-03	9,07E-03	1,16E-02	-	2,82E-02	-9,25E-03	4,90E-01	5,52E-05	-	3,90E-02	6,57E-01
Zinc	Water	kg 1,4-DB eq	1,74E+00	7,98E-04	5,00E-03	6,55E-03	-	2,88E-02	-1,51E-02	2,40E-01	3,10E-04	-	5,77E-01	8,93E-01
Process contribution (%)				0,18%	1,03%	1,38%	-	4,97%	-20,03%	13,56%	0,02%	-	28,65%	70,23%
Sum				0,18%		7,39%			-6,46%			98,89%		
Climate change														
Total of all compartments		kg CO2 eq	-1,30E+03	1,67E+00	1,13E+01	1,46E+01	-	4,65E+01	-9,26E+02	-2,04E+02	9,20E-02	-	-5,70E+02	3,23E+02
Remaining substances		kg CO2 eq	1,70E+00	1,57E-02	1,05E-01	1,33E-01	-	2,50E-01	-3,10E-02	8,77E-01	3,69E-04	-	-3,88E-01	7,36E-01
Carbon dioxide, fossil	Air	kg CO2 eq	-1,22E+03	1,54E+00	1,04E+01	1,34E+01	-	4,22E+01	-8,24E+02	-1,54E+02	5,96E-02	-	-5,70E+02	2,59E+02
Carbon dioxide, land transformation	Air	kg CO2 eq	2,56E+01	1,51E-02	9,88E-02	1,26E-01	-	3,12E-01	4,07E-01	7,24E+00	-1,21E-04	-	4,48E+00	1,29E+01
Dinitrogen monoxide	Air	kg CO2 eq	1,09E+02	2,02E-02	1,38E-01	1,76E-01	-	1,67E+00	2,01E+00	1,09E+01	1,82E-02	-	4,13E+01	5,23E+01
Methane, biogenic	Air	kg CO2 eq	5,61E+01	2,25E-03	1,61E-02	2,05E-02	-	1,40E-01	1,72E-01	1,17E+00	1,16E-02	-	2,67E+01	2,79E+01
Methane, fossil	Air	kg CO2 eq	-2,72E+02	7,88E-02	5,28E-01	7,06E-01	-	1,97E+00	-1,04E+02	-7,00E+01	2,28E-03	-	-7,17E+01	-2,96E+01
Process contribution (%)				0,13%	0,87%	1,12%	0,00%	3,57%	-71,10%	-15,68%	0,01%	0,00%	-43,75%	24,84%
Sum				0,13%		5,56%			-86,79%			-18,90%		