ADVANCES IN »
HYDROTHERMAL CONVERSION OF INDUSTRIAL BIOGENIC RESIDUES INTO INTERMEDIATE BIOENERGY CARRIERS

RESULTS FROM THE **F-CUBED PROJECT**

F-CUBED

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 884226.

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Life Cycle Assessment and Socio-Economic Impact of the F-CUBED Production System

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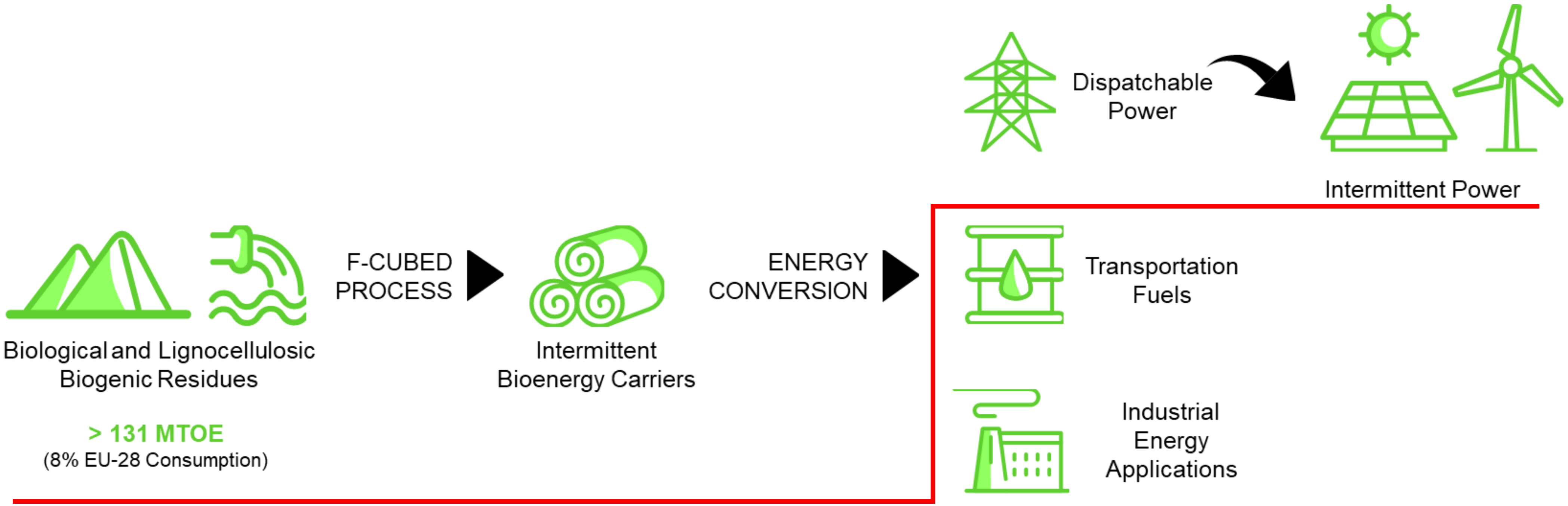
SPECIFIC OBJECTIVES

Attributional life cycle assessment to investigate environmental aspects (E-LCA) and Socio-economic aspects (S-LCA) of the F-CUBE Production System

THE **F-CUBED** Production System



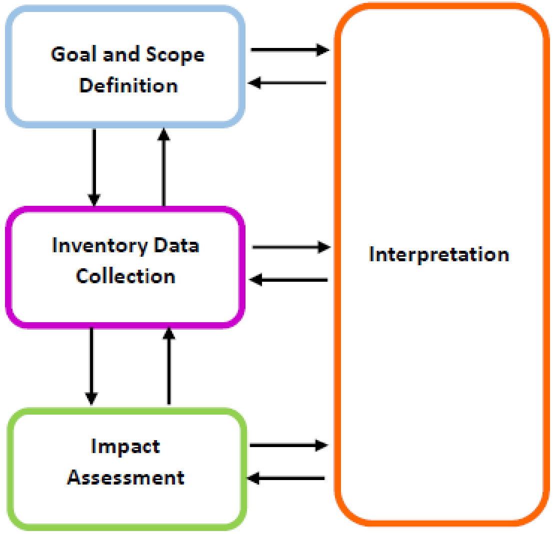
ENVIRONMENTAL LIFE CYCLE ASSESSMENT in F-CUBED

E-LCA Methodology

Main points

It has been follows the criteria stated in International Organization of Standardization (ISO) through ISO:14040:2021 – Principles and Framework and ISO:14044:2021 – Requirements and Guidelines.

The LCA 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.

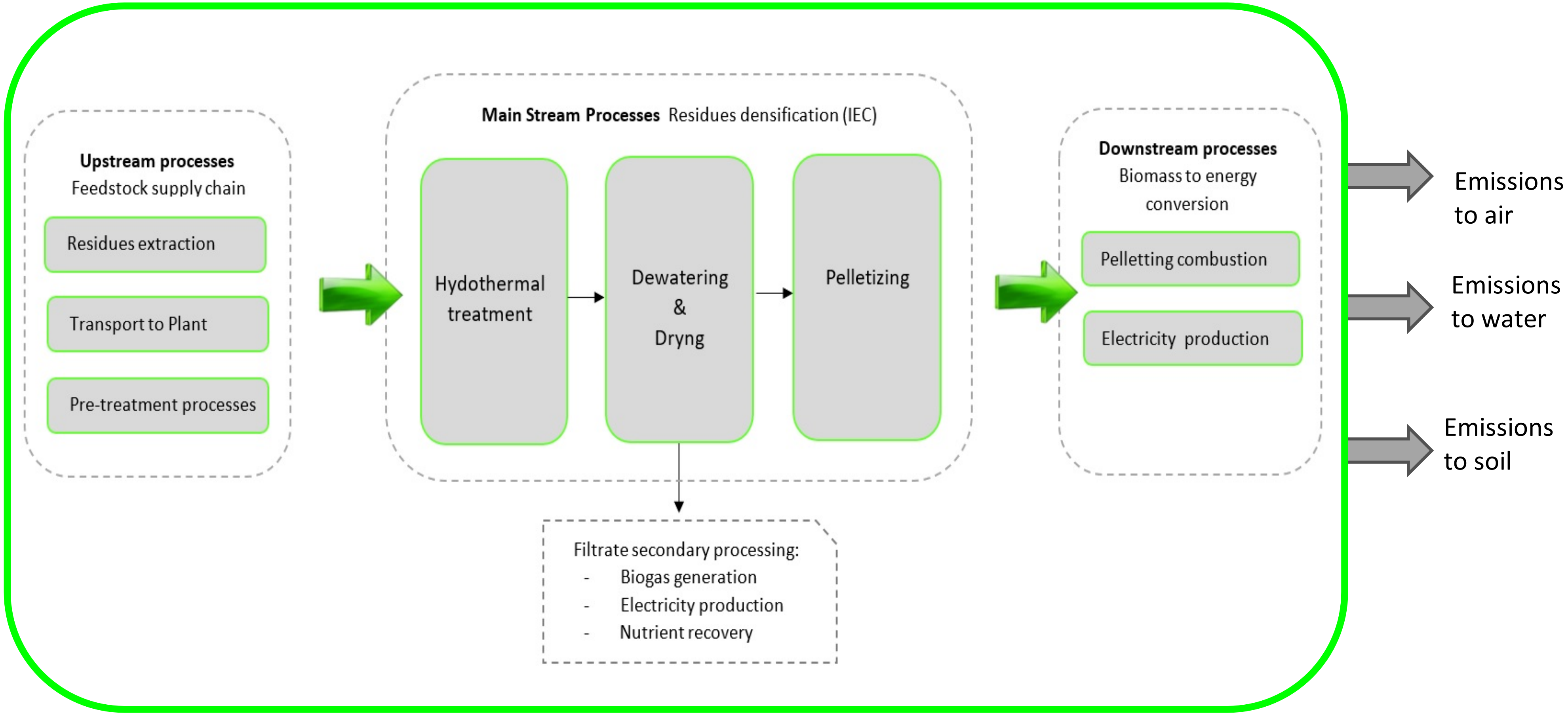


FUNCTIONAL UNIT

- is a quantified description of the performance of the production system to which all outputs and inputs to/from the system are referred: **1 kWh_{el}**
- to facilitate comparative assessment of the processes, the results have been also referred to the overall process, considering the amount (wb) of biogenic residues treated: **1 ton of residue**

E-LCA Methodology

SYSTEM BOUNDARIES



E-LCA Methodology

Life Cycle Inventory

input and output data flows of the parameters affecting environmental performances of the production system

6 E-LCA models, over 1700 data collected and iteratively reviewed

Life Cycle Impact Assessment

Impact assessment method is the **ReCiPe** , one of the most used LCIA method for LCA in bioenergy production systems (Hosseinzadeh, et al., 2021).

The ReCiPe impact assessment method is here applied based on **Hierarchist perspectives**, at midpoint level. Midpoint characterization methods lead to accurate results and reduce the uncertainty. ReCiPe2016 produces **18 midpoint indicators**.
The latest version of the ReCiPe 2016 report has been applied, which is updated to 2018.

LCA software tools used is SimaPro 9.1 which incorporates access to Ecoinvent 3 (r.8) databases

E-LCA Methodology

Life Cycle Impact Assessment

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

First selection of the Impact categories: 18 → 14

E-LCA Methodology

Sensitivity Analysis

In LCA, uncertainty exists as a result of incompleteness of the model, using inputs or methods that imperfectly capture the characteristics of the product system.

In the present work, the method used for parameter uncertainty analysis is Monte Carlo simulation, carried out in two subsequent steps:
1) sensitivity analysis of the LCA model inherently to the unit processes of Ecoinvent data base; 2) a second analysis to measure 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 on the basis of the Coefficient of Variation and its behaviour in the two subsequent sensitivity analysis

It results in the **RELIABILITY** of the **IC** for the **specific biogenic residue stream**

E-LCA Case Studies

F-CUBED Production Systems and Reference Cases of the biogenic residue streams 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 waste water streams from this mill are sent to the waste water 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.

E-LCA Results

Data visualizations per type of residue

- Impact category breakdown by production processes of F-CUBED Production System (Table and Chart)
- Reliability of the impact categories by sensitivity analysis
- Relevant impact categories for LCA study case study
- Details on the Climate change impact category
- Details on other Impact categories
- Comparison F-CUBED Production System and Reference Case (Table and Chart)
- Final notes
- Carbon Footprint
- Main achievements from the case study

E-LCA Results - PPB

Pulp & Paper Bio-sludge – F-CUBED Production System

			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

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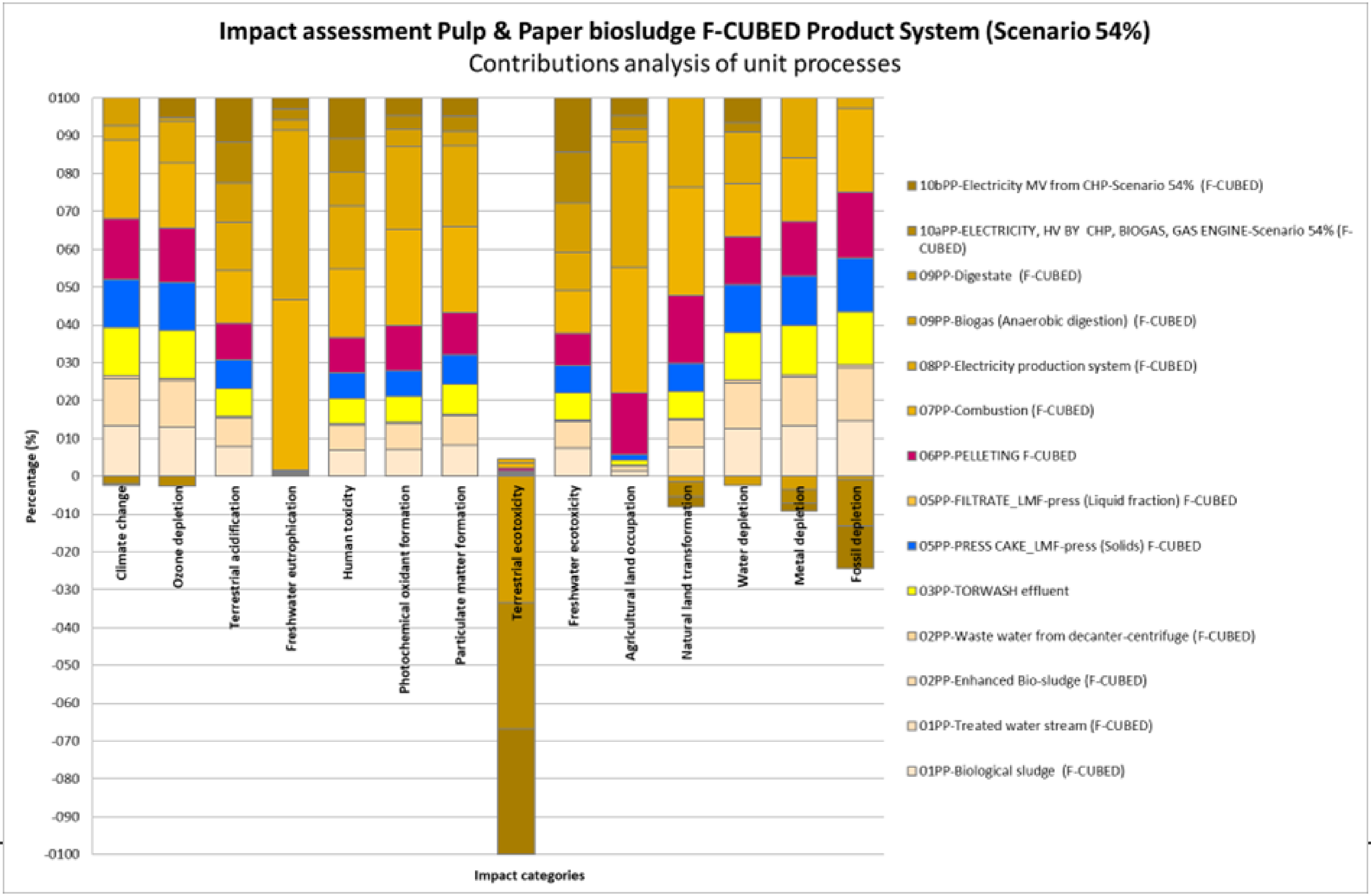
E-LCA Results - PPB

Pulp & Paper Bio-sludge – F-CUBED Production System



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Reliability of the impact categories by sensitivity analysis

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] esteemed [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

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

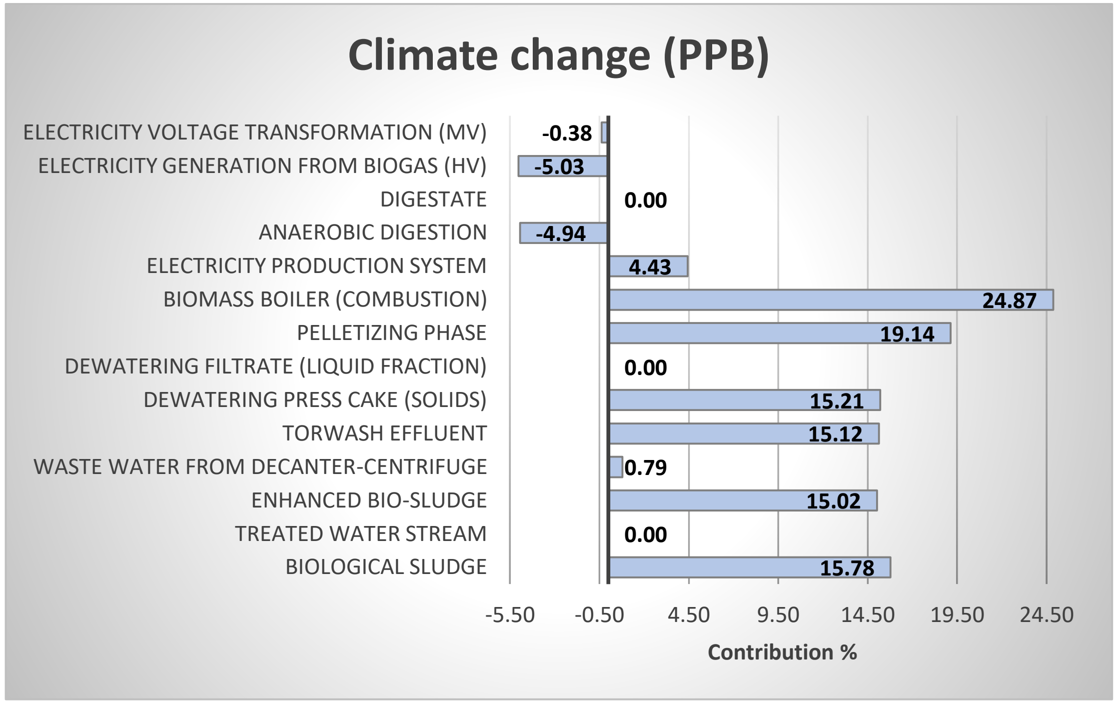
E-LCA Results - PPB

Relevant impact categories for LCA study the PPB case study

Impact category	Unit	Value	CV (%)
Climate change	kg CO_2 eq./ t_{ADp}	1,79E+01	19,1
Ozone depletion	kg CFC-11 eq./ t_{ADp}	4,88E-06	23,0
Terrestrial acidification	kg SO_2 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

E-LCA Results - PPB

Climate change impact category accounts for 17,91 kg CO2 eq/ tADp.



Largest contributions combustion of the pellets in the biomass boiler (24,87%) and pelletizing phase (19,14%), releasing 4,45 and 3,43 kg CO2 eq./ tADp respectively.

Novel hydrothermal treatment: TORWASH treatment, 15,12%; 2,71 kg CO2 eq./ tADp

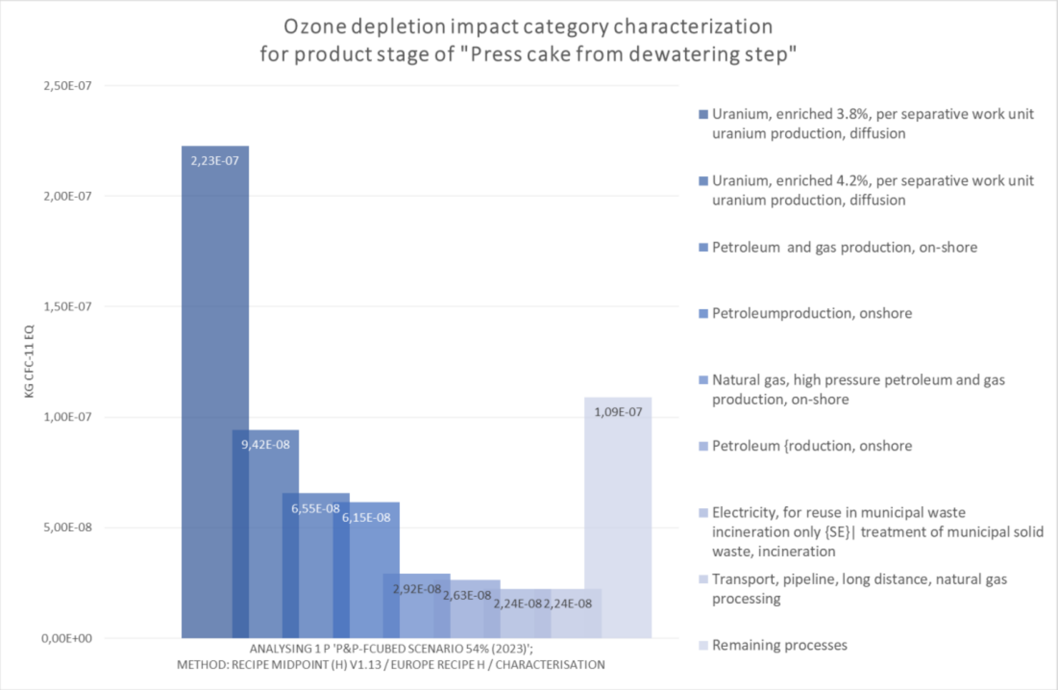
Upstream pre-treatment processes: WWT and improvement of the bio-sludge with decanter-centrifuge, give a significant contribution of 31,59% (5,66 kg CO2 eq./ tADp) when combined.

Secondary filtrate processing: account for negative emissions of -10,35%, corresponding to -1,85 kg CO2 eq./ tADp of GHG emissions savings to the atmosphere as avoided product from Technosphere by heat recovery (scenario 54%).

E-LCA Results - PPB

Ozone depletion impact category accounts for 4,88^10^{-6} kg CFC-11 eq/ tADp.

OD impact category is shifted from the reliable to unreliable category when the foreground data are included in uncertainty calculation and the **main stream processes** of the F-CUBED Production System are the largest contributors (41,83%).



The Uranium enriched in U235 and its compounds; plutonium and its compounds; alloys, dispersions, ceramic products are responsible of this impact.
They refer to the **electricity consumption** and **background UPR** nested in the specific **electricity country mix for Sweden**

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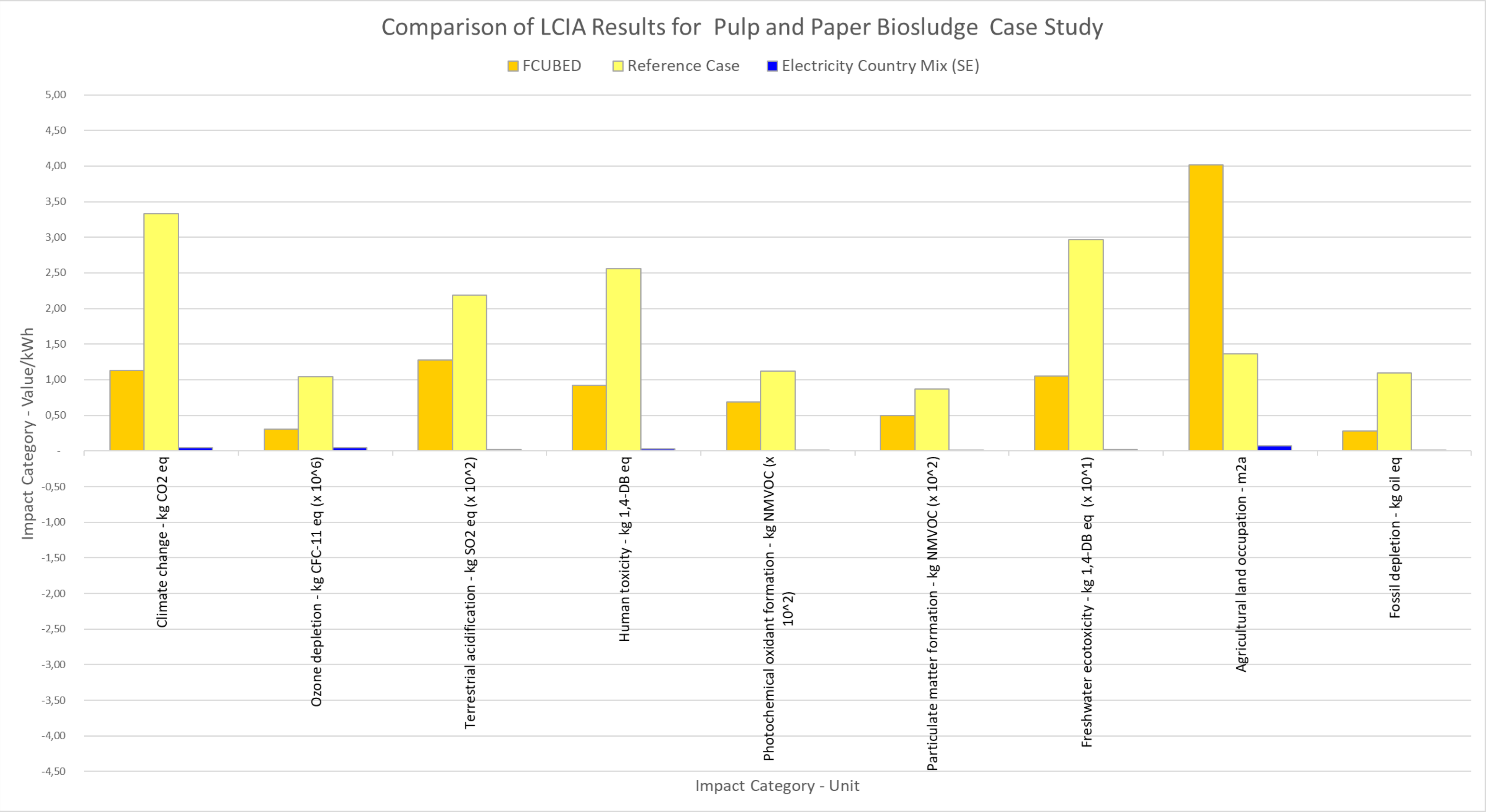
Comparison F-CUBED Production System and Reference Case

Impact category	Unit	FCUBED PS	RC	ECM
Climate change	**kg CO2 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 SO2 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

Reliable | To deepen | Unreliable

E-LCA Results - PPB

Comparison F-CUBED Production System and Reference Case



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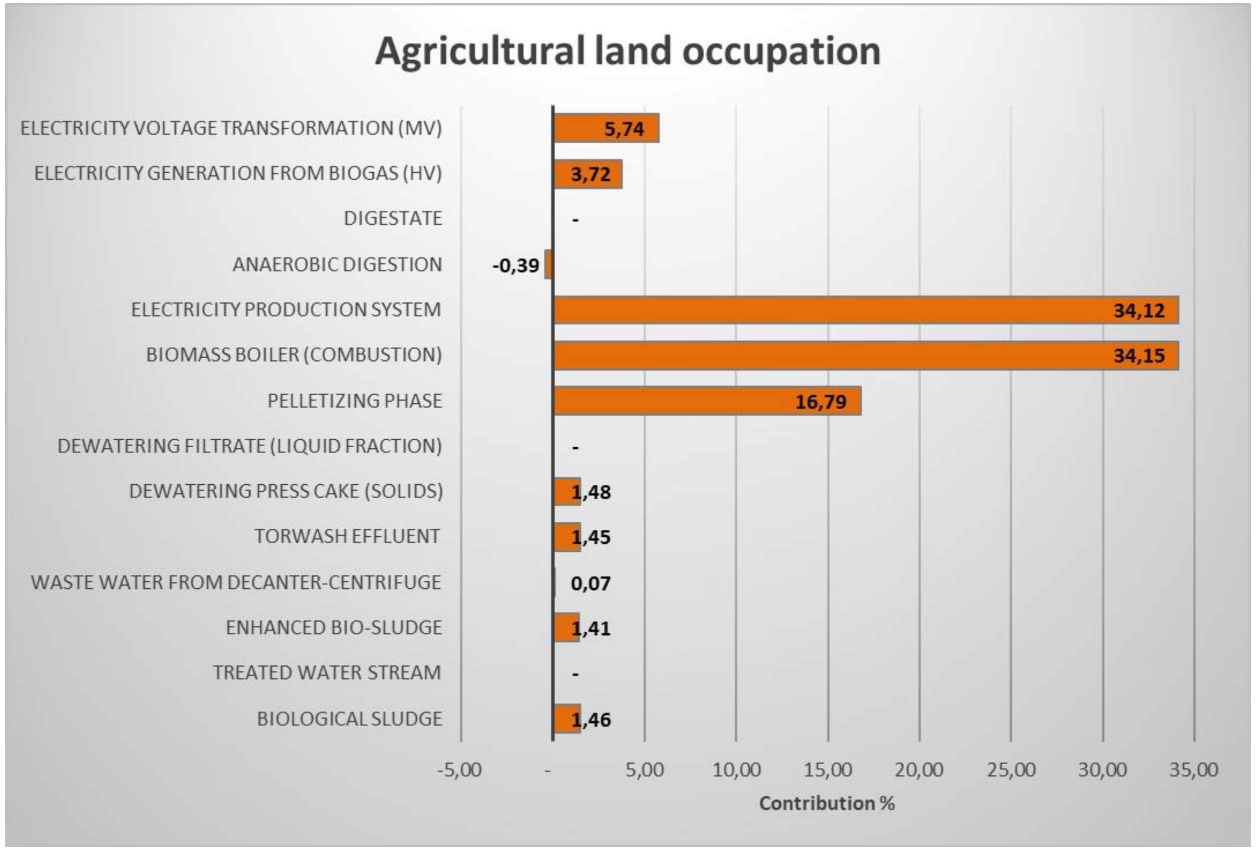
Agricultural land occupation impact category

ALO impact could 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 units, into electricity



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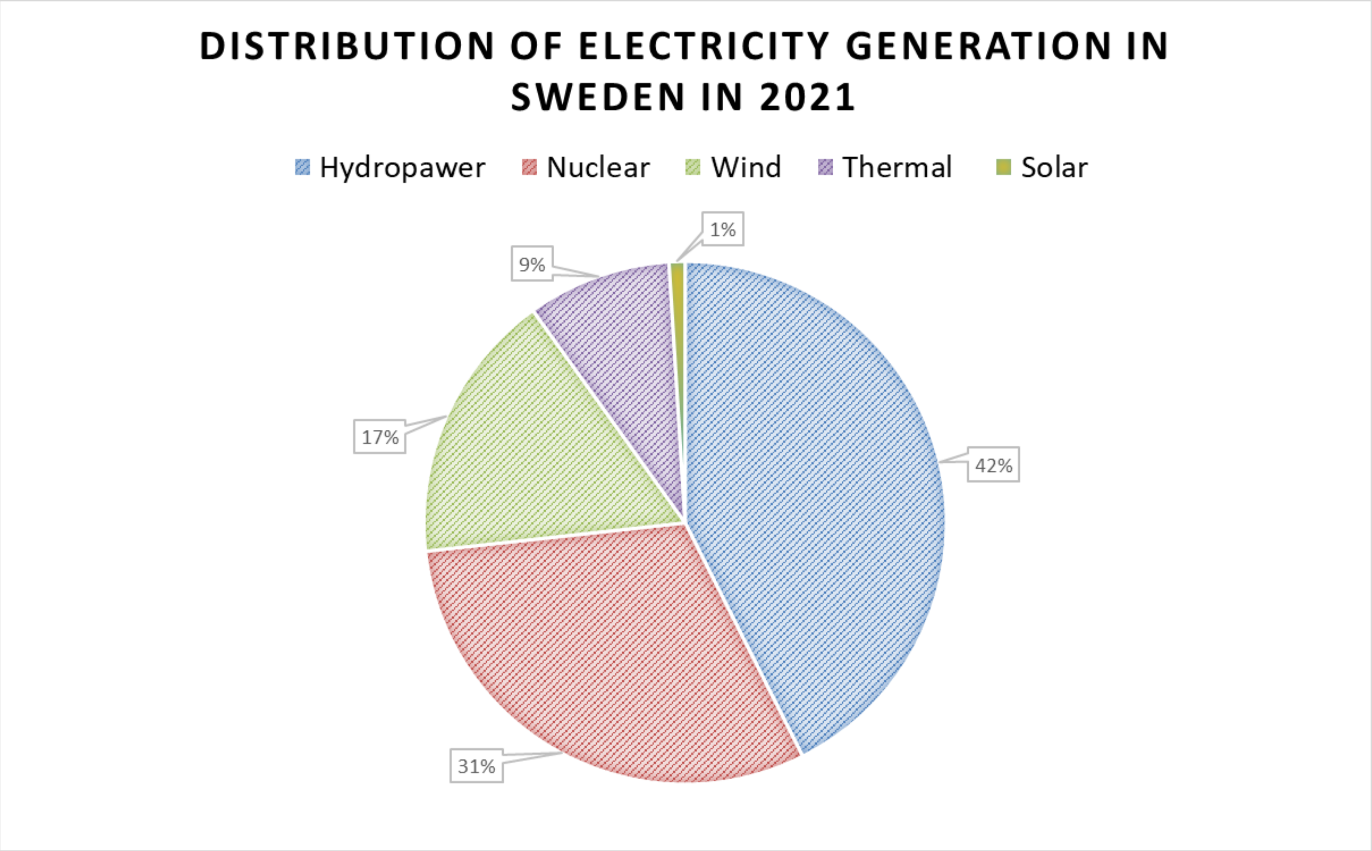
E-LCA Results - PPB

Electricity Country Mix - Sweden

The **impacts** attributable to Sweden electricity country mix is **very small**. 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** representing more than **90% of the country's electricity mix.**

Hydro and nuclear power are the main sources of electricity generation in Sweden in 2021, accounting for 42% and 31% shares of the country's supply, respectively.



E-LCA Results - PPB

Carbon Footprint of the F-CUBED Production System

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%

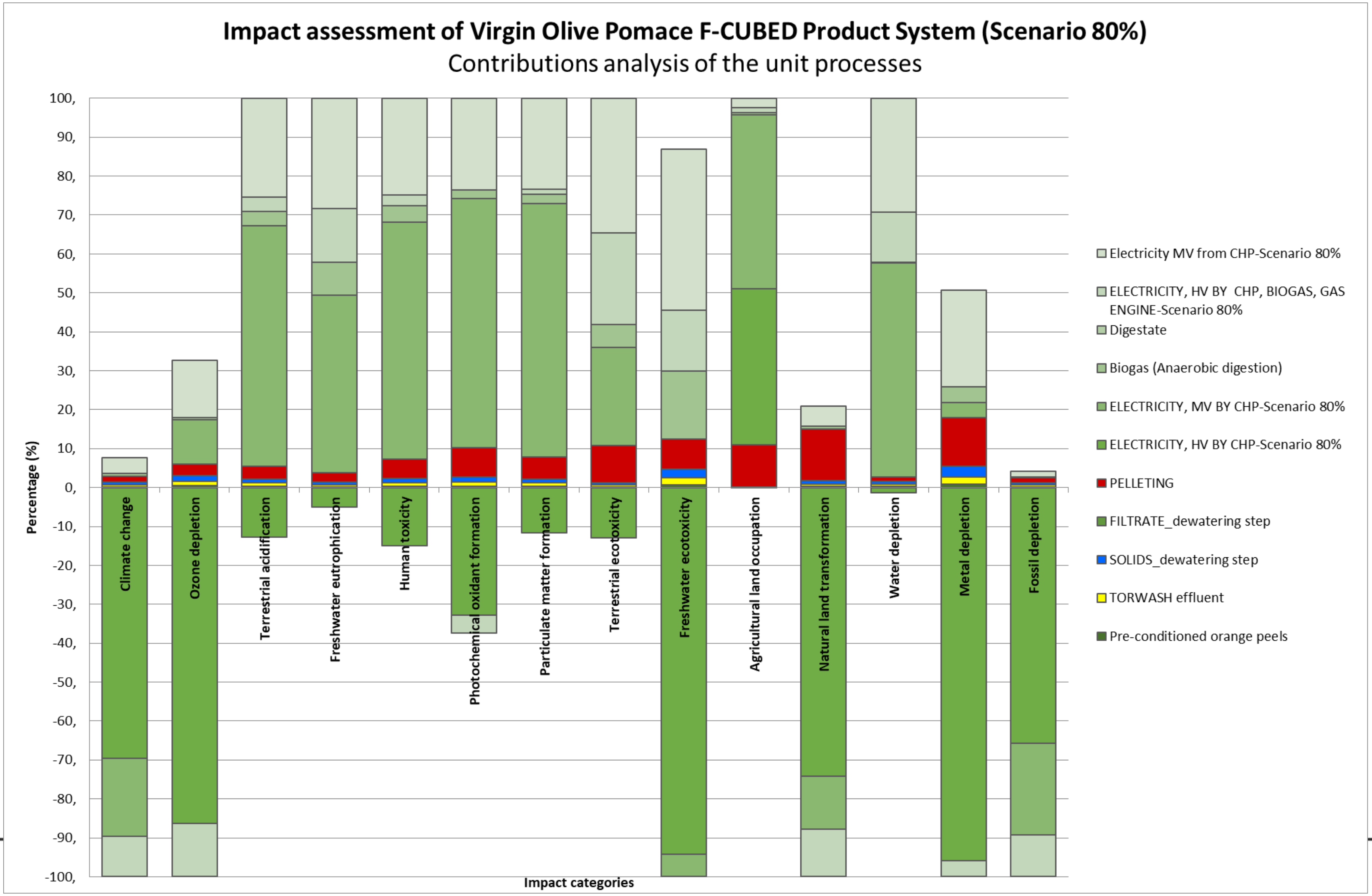
E-LCA Results - PPB

Main achievements from the case study

- The **electricity generation** from 1 ton of Pulp & Paper Bio-sludge is **15,82 kWh and 5,56 kWh** for the F-CUBED and RC cases, respectively. This difference of 10,26 kWh between the two cases corresponds **to 1,8 times improvement (185%)** for F-CUBED process.
- This production is associated with **carbon footprints** **17,90 and 18,50 kg CO2 eq/tADp**, for ton of residue, and of **1,13 and 3,33 kg CO2 eq/kWh** for FU.
- F-CUBED Production System provide **emissions saving** of **2,20 kg CO2 eq/kWh**, corresponding to the **improvement of almost 0,7 times (66%)** with respect to the RC.
- If considering in the calculation 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 CO2 eq/kWhfor** the F-CUBED and RC processes, respectively .

E-LCA Results - OP

Olive Pomace – F-CUBED Production System



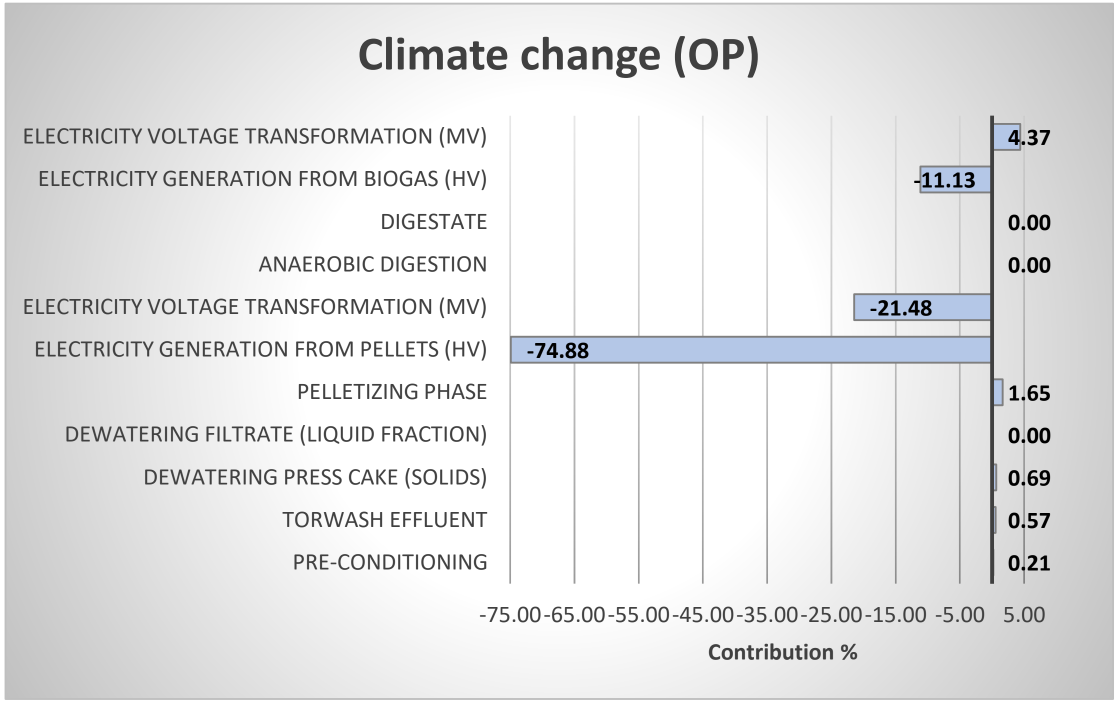
E-LCA Results - OP

Relevant impact categories for LCA study the PPB case study

Impact category	Unit	Value	CV (%)
Climate change	kg CO_2 eq./ t_{OP}.	-1,29E+03	-15,41
Ozone depletion	kg CFC-11 eq./ t_{OP}	-6,50E-05	121,65
Terrestrial acidification	kg SO_2 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

E-LCA Results - OP

Climate change impact category accounts for -1299,00 kg $CO_{2\ eq}$/ tOP.



Largest contributions electricity generation from pellets (HV) (-74,88 %) releasing -972,69 kg CO2 eq./ tOP and electricity voltage transformation (MV) (21,48%; - 279,02 kg CO2 eq./ tOP); these two processes account for -96,36%, and -1251,71kg CO2 eq./ tOP, when combined.

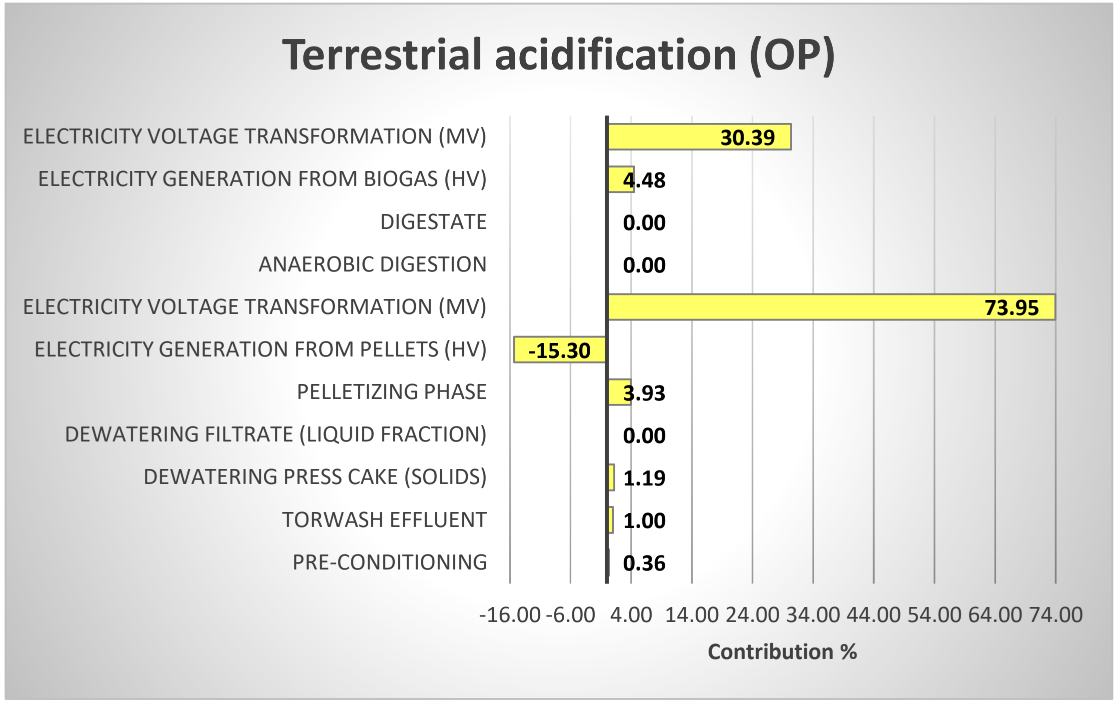
Main stream processes: slightly contribution to CC with +2,91% (37,86 kg CO2 eq./ tOP)

Upstream pre-treatment processes: small contribution accounting for 0,21% (2,67 kg CO2 eq./ tOP) when combined

Secondary filtrate processing: account for negative emissions of -6,76%, corresponding to -87,81 kg CO2 eq./ tOP of GHG emissions savings to the atmosphere as avoided product from Technosphere by heat recovery (scenario 80%).

E-LCA Results - OP

Terrestrial acidification impact category accounts for 2,99 kg $SO_{2\ eq}$/ tOP



Largest contributions: electricity voltage transformation (MV) both from pellets (73,95%) and from biogas (30,29%) respectively releasing 2,210 and 0,908 kg SO2 eq./ tOP.

Main stream processes: contribution of 6,12% and 0,183 kg SO2 eq/ tOP.

Upstream pre-treatment processes: small contribution accounting for 0,36% (0,011 kg SO2 eq/ tOP) when combined.

For this IC 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, in **Italy, the electric grid mix is mainly based on fossil fuels** (carbon intensity of electricity in Italy is 0,372 kg CO2 eq./kWh - 2022). 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.

E-LCA Results - OP

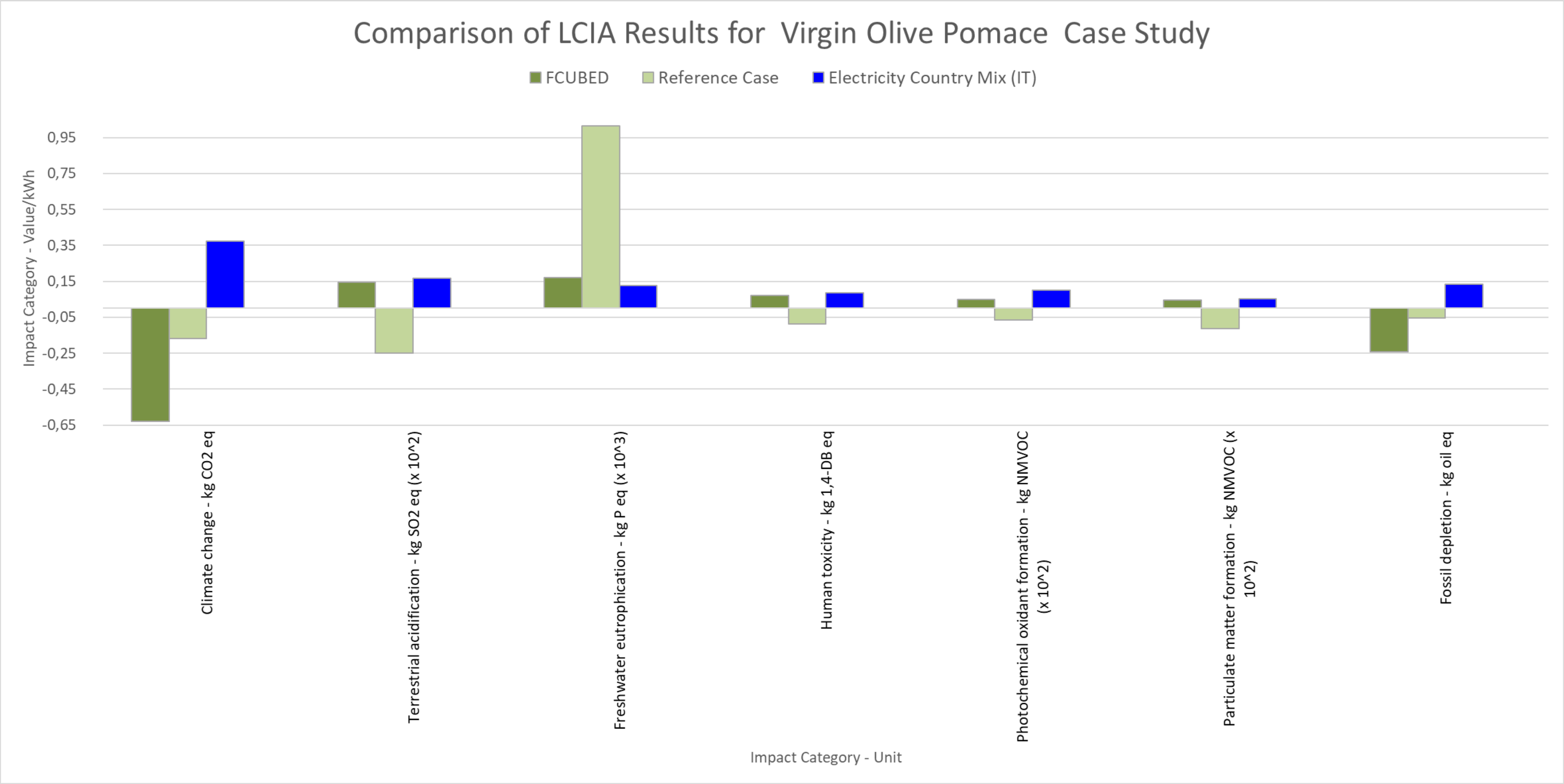
Comparison F-CUBED Production System and Reference Case

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**

Reliable   To deepen   Unreliable

E-LCA Results - OP

Comparison F-CUBED Production System and Reference Case



E-LCA Results - OP

Main results of the comparison

- F-CUBED process presents lower impacts only for 3 Impact Categories: CC, FEUT and FD
- Extending the comparison to the ECM the number increase to 6 of 7;
- For CC and FD, F-CUBED 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 presents lower impact (-83%) with respect to the RC, because the large amount of digestate to be treated in RC which implies direct emissions from landfarming applications and burden for spreading process: 4,86 t/tOP vs 1,059^10^{-6}t/tOP;

F-CUBED Production System provides a **significant favourable impact** affecting areas of protection that are crucial for global climate change, fossil depletion and freshwater eutrophication.

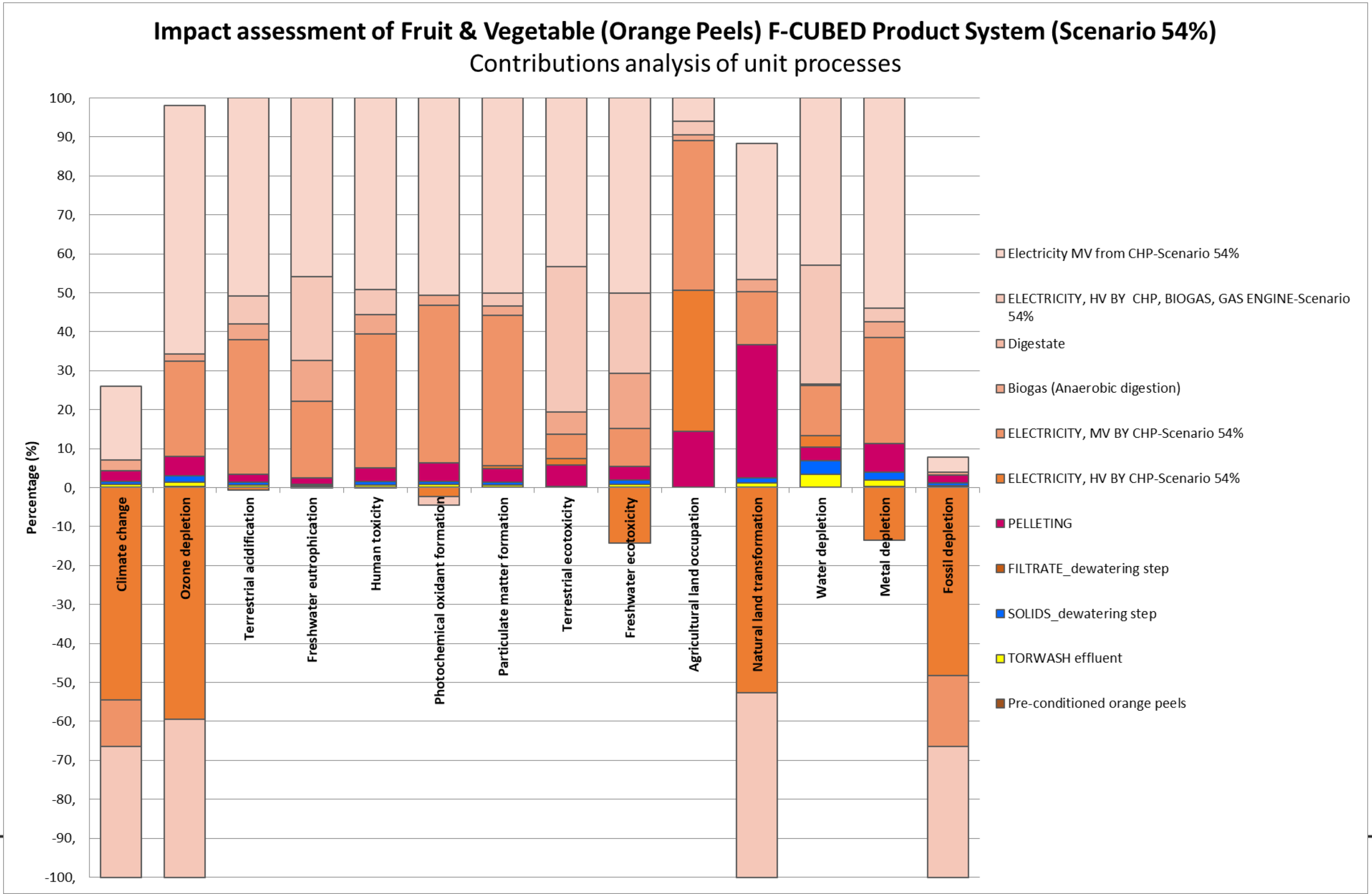
E-LCA Results - OP

Carbon Footprint of the F-CUBED Production System

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			
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%

E-LCA Results - ORP

Orange Peels – F-CUBED Production System



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E-LCA Results - ORP

Relevant impact categories for LCA study the PPB 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

E-LCA Results - ORP

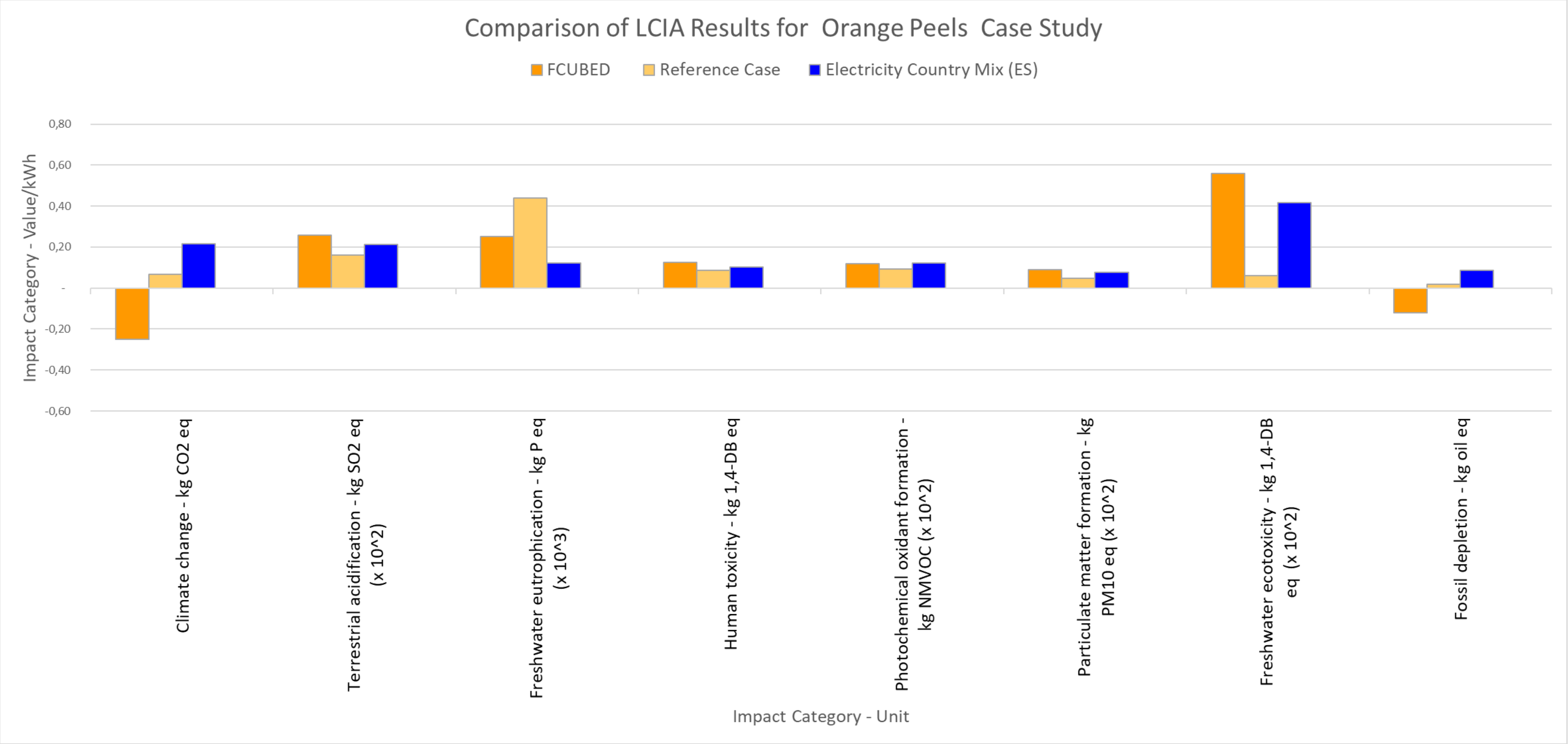
Comparison F-CUBED Production System and Reference Case

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**

Reliable | To deepen | Unreliable

E-LCA Results - ORP

Comparison F-CUBED Production System and Reference Case



E-LCA Results - OP

Main results of the comparison

- F-CUBED process presents lower impacts only for 3 Impact Categories: CC, FEUT and FD but on the contrary the number doesn’t increase extending the comparison to the ECM of Spain;
- For CC and FD, F-CUBED shows more performative values respect RC, with improvement between 4,5 and 7,5 times (476% and 742% respectively);
- In the FEUT domain, F-CUBED presents lower impact (-43%) with respect to the RC, because the large amount of digestate to be treated in RC which implies direct emissions from landfarming applications and burden for spreading process: 2,74 t/tORP vs 4,155^10^{-4}t/tORP;

F-CUBED Production System provides a **significant favourable impact** affecting areas of protection that are crucial for global climate change, fossil depletion and freshwater eutrophication.

E-LCA Results - ORP

Carbon Footprint of the F-CUBED Production System

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		

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Pellets environmental performances as biomass fuel in the framework of RED II Methodology

The **Annex VI, part B, par. 1 a** 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:

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

(Unit: g CO2 eq/MJ of biomass)

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.

In the F-CUBED project has been carried out:

eec = emissions due to the pretreatment and conditioning of the residual biomasses ;
ep = emissions due to the Torwash process, the dewatering phase and the pelleting plant ;
etd = emissions originated from the transport phases of the biomasses and intermediate materials;
eu = emissions for the energy conversion phase where the produced pellets are used for generating power and heat.

Pellets evaluation according to RED II Sustainability Criteria

For the use of biomass fuels in producing **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 (**Annex VI, part B, par. 1 d**) :

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

Unit: g CO2 eq/MJ of final energy commodity

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.

Pellets evaluation according to RED II Sustainability Criteria

The overall emissions calculated for the pellets production from the F-CUBED Production Systems are equal to 0,668, 0,175 and 0,219 kgCO2eq/t of residual biomass for pulp & paper bio-sludges, olive pomace, orange peels respectively.

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%

The emissions savings account for 49%, 89% and 91%, respectively

Pellets evaluation according to RED II Sustainability Criteria

Conclusion

- To have a comparison term, **Wood briquettes or pellets from forest residues**, shaw emissions saving that ranges between 45% and 59%. While taking in consideration **cereals straw** pellets these values vary between 64% and 87%.
- To fulfil the sustainability criteria of the Art. 29 (section 10) of the RED II, 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.
- **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.

E-LCA Results - On Annual Basis

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	-2,20	-0,46	-0,32
Freshwater eutrophication	kg SO2 eq./ kWhe	-0,15	-0,0008	-0,0002
Terrestrial acidification	kg P eq./ kWhe	-0,01	0,0039	0,0010
Fossil depletion	kg oil eq./ kWh_e	-0,81	-0,19	-0,14
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

E-LCA Results - On Annual Basis

Conclusions

- The **more efficient scenario** for the **production of dispatchable electricity** is **OP case study:** this relates to the energy efficiency of feedstock and the yearly number of residues available.
- The **savings** (Handprint) 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.
- The **PPB case study** shows the **highest savings per functional unit** demonstrating that, as for techno-economics (Dijkstra, et al. 2023), the **best environmental benefits** are found where bio-sludge is processed, 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**.
- The GHG emission savings for OP (-9.116 kg CO2 eq/y) and ORP (-3.837 kg CO2 eq/y) case studies, could translate in a **potential complementary income** for the residue producer, referring to the voluntary market of **certified carbon credits.**
- 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**.

SOCIAL
LIFE CYCLE ASSESSMENT
in F-CUBED

S-LCA Methodology

Main points

- Part of the study 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.
- The study deals with the potential socio-economic impacts, **negative as risk or positive as benefit**, for the full-scale applications of the actual TRL5 F-CUBED technology.
- 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).

S-LCA Methodology

Social Life Cycle Inventory phase (S-LCI)

- For modelling the background dataset, Social Hotspot Database and SimaPro have been used .
- The process-based-model approach of SimaPro, has been then integrated and enhanced by the Country Specific economic Sectors (CSS) related to the F-CUBED Production System
- The utilization of a S-LCA databases, such as SHDB, automatizes a great number of steps related to the S-LCIA phase
- Consequently SHDB calculates the number of **worker-hour**s 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 socio-sphere flows are calculated as **worker hours per US dollar** (USD 2011) of process input
- The results are expressed in **medium risk hour equivalent**, reflecting the probability of a danger or an opportunity to occur.
- The risk characterization through a weighting procedure represents the relative probability of an adverse situation to occur with respect to medium risk level which assume the value of 1

Social Life Cycle Impact Assessment (S-LCIA)

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.

Scale level	**Colour**	**Description**	**Value** (mrheq)
4		*Very High risk*	10
3		*High risk*	5
2		*Medium risk*	1
1		*Low risk*	0,1

S-LCA - Stakeholders Engagement

Stakeholders Engagement and Questionnaire Distribution

A selection of 44 stakeholders potentially useful for the primary data collection was identified. A total of 19 replies was collected (43%).

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

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

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

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

SHDB & UNEP Guidelines harmonization

In the SHDB, 5 impact categories derive from the aggregation of 30 impact sub-categories considered in the S-LCIA.

In UNEP 2020 S-LCA Guidelines, there are 6 impact categories (Human rights, Working Conditions, Health & Safety, Cultural Heritage, Governance, Socio-economic repercussions) and 40 subcategories.

SHDB Social Impact Categories	Sub-categories	SHDB - ID	UNEP 2020 harmonization
Labor rights and decent work	Wage assessment	1A	1. Career prospects 2. Employment Prospects
	Workers in poverty	1C	3. Economic opportunities
	Forced Labor	1E	4. Work conditions
	Excessive WkTime	1F	5. Work conditions
	Social Benefits	1I	6. Job satisfaction
	Labor Laws/Convs	1J	7. Training requirements
	Unemployment	1L	8. Job stability
Health and safety	Occ Tox & Haz	2A	9. Children, Health and well-being 10. Children, Exposure to pollutants or hazardous substances:
Society	Poverty and inequality	3F	11. Local employment 12. Broader Social Acceptance 13. Social Challenges and Energy Demands
	State of Env Sustainability	3G	14. Availability of local resources 15. Contribution to Sustainable Development
Governance	Legal System	4A	16. Market Opportunities 17. Alignment with Societal Goals and Policies
	Corruption	4B	18. Future prospects
Community	Access to Drinking Water	5A	19. Air and water quality
	Access to Sanitation	5B	20. Alignment with Societal Goals and Policies
	Children out of School	5C	21. Children, Health and well-being
	Access to Hospital Beds	5D	22. Alignment with Societal Goals and Policies
	Smallholder v Commercial Farms	5E	23. Economic Viability Market Opportunities
	Access to Electricity	5F	24. Energy Affordability 25. Accessibility of Bioenergy Products 26. Perceptions of Technology and its Benefits or Drawbacks
	Property rights	5G	27. Technological Advancements 28. Reliability of Bioenergy Product

S-LCA Results

Data visualizations per type of residue

- Datasets for the country-specific economic sectors
- Social impacts (mrheq) as single score attributed to each Damage Category
- Social impacts by economic sectors of the F-CUBED Production (Table & Chart)
- Contribution analysis of each economic sector by impact sub-category (Table & Chart)
- Characterized results of the sub-categories mainly affected by social risk
- Main achievements from the case study

S-LCA Results - PPB

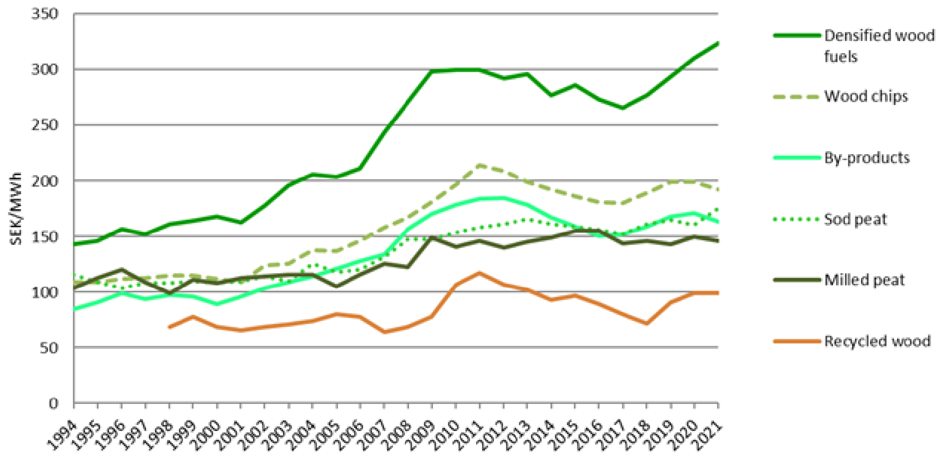
Datasets for the country-specific economic sectors linked to the Pulp & Paper Bio-sludge Case Study

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

For the unit USD 2011, the exchange rate applied is 1,33 €/$ (January 2011).

S-LCA Results - PPB

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



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

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)
Biopellets production	Biopellets	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)

S-LCIA of the F-CUBED Production System – Damage categories

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, into a single score attributed to each Damage Category, expressed in both mrheq and mPt.

	Damage category	Social Impact (mrheq)	Social Impact (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**

S-LCA Results - PPB

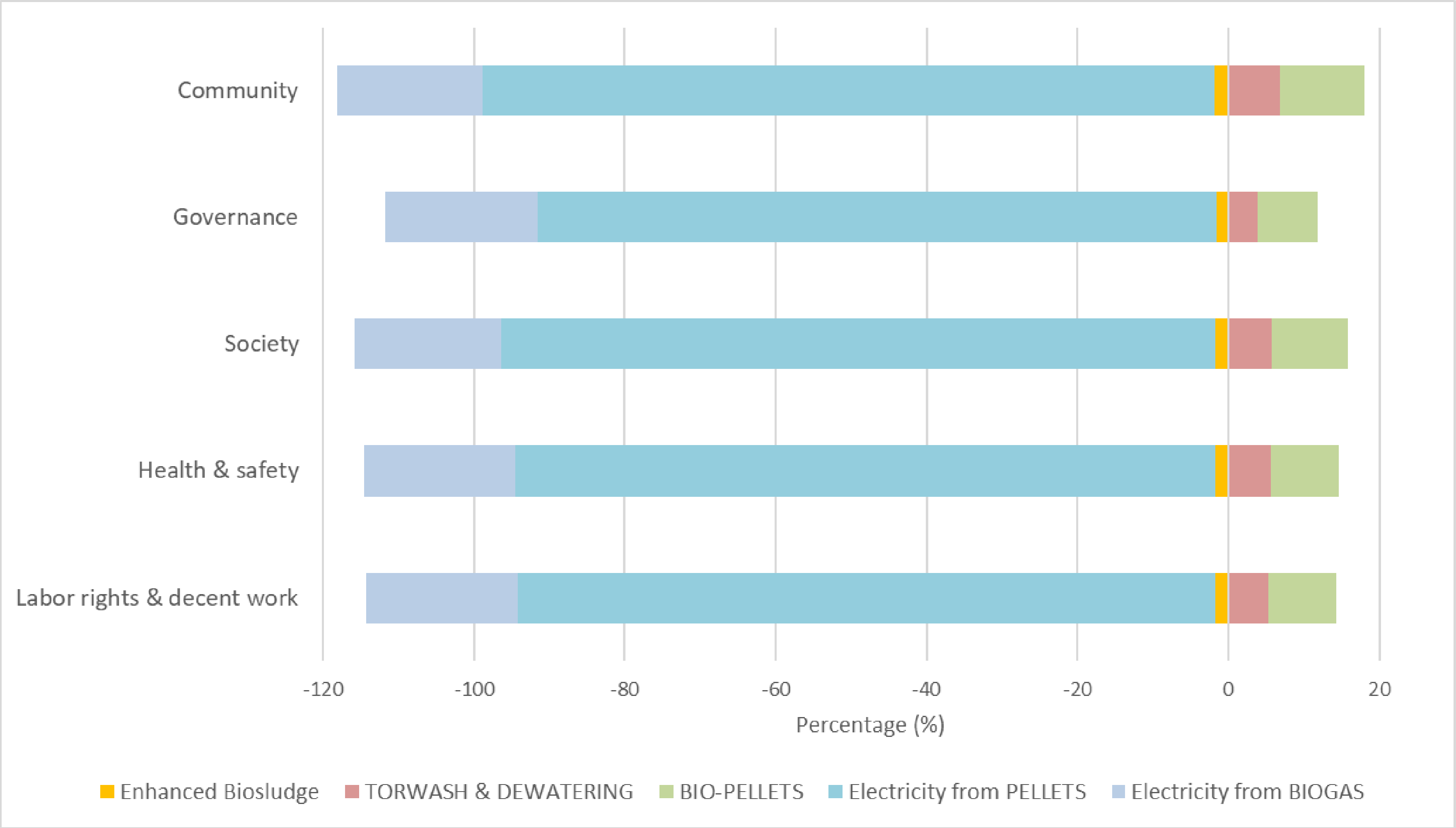
Social impacts of the F-CUBED Production by economic sectors

Slight social impact is provided by the production phases of Biopellets production and Torwash and dewatering processes.

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**

S-LCA Results - PPB

Social impacts of the F-CUBED Production by economic sectors



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S-LCA Results - PPB

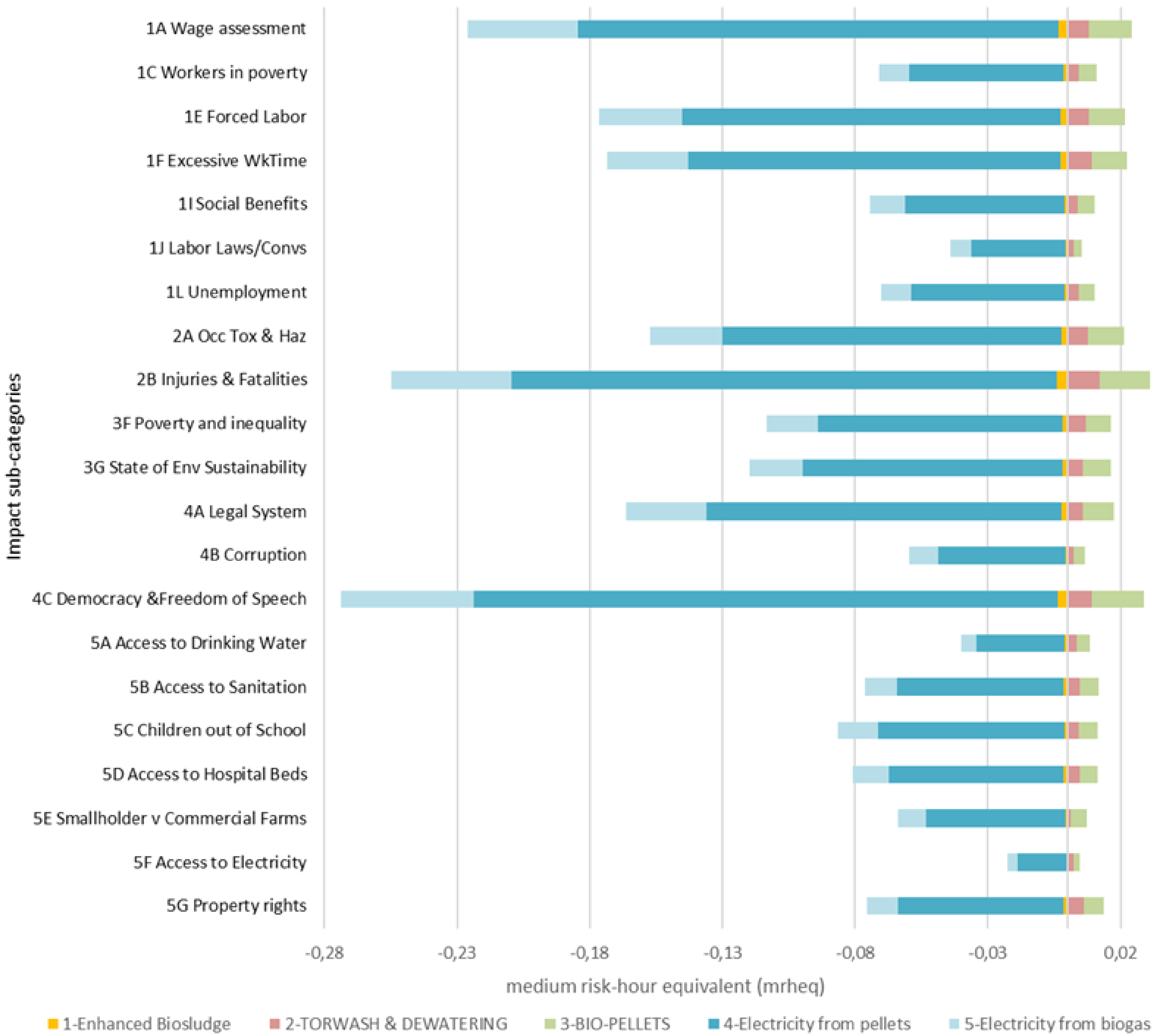
Contribution analysis of each economic sector to the total social impacts by impact sub-category

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

S-LCA Results - PPB

The most benefits are **Democracy &Freedom of Speech** (4C), **Injuries & Fatalities** (2B) and **Wage assessment** (1A).

The production steps referring to **Biopellets and Torwash & dewatering** provide major social risks to the same subcategories 1A, 2B and 4C. the assessed risk level is low and therefore it is considered acceptable.



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S-LCA Results - PPB

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

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

S-LCA Results - PPB

Main achievements

- In Sweden, the social impacts is concentrated in the Biopellets production and the Torwash & Dewatering treatments that give however a small adverse contribution, ranging between 4% and 11%.
- On the other hand the Electricity production steps both by biopellets and biogas give **large benefits** to the different Impact categories by the heat recovery from the conversion processes of the biopellets and biogas into energy, **ranging between -90% and -97%** of total social impact depending on the social category.
- In summary, the implementation of the F-CUBED Production System in Sweden can have positive impacts in the impact categories of **Governance (subcategories of Democracy & Freedom of Speech), Health and safety at Work (Injuries and Fatalities), and Working conditions (Wage Assessments).**
- Since they 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.

S-LCA Results - OP

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

For the unit USD 2011, the exchange rate applied is 1,33 €/$ (January 2011).

S-LCIA of the F-CUBED Production System – Damage categories

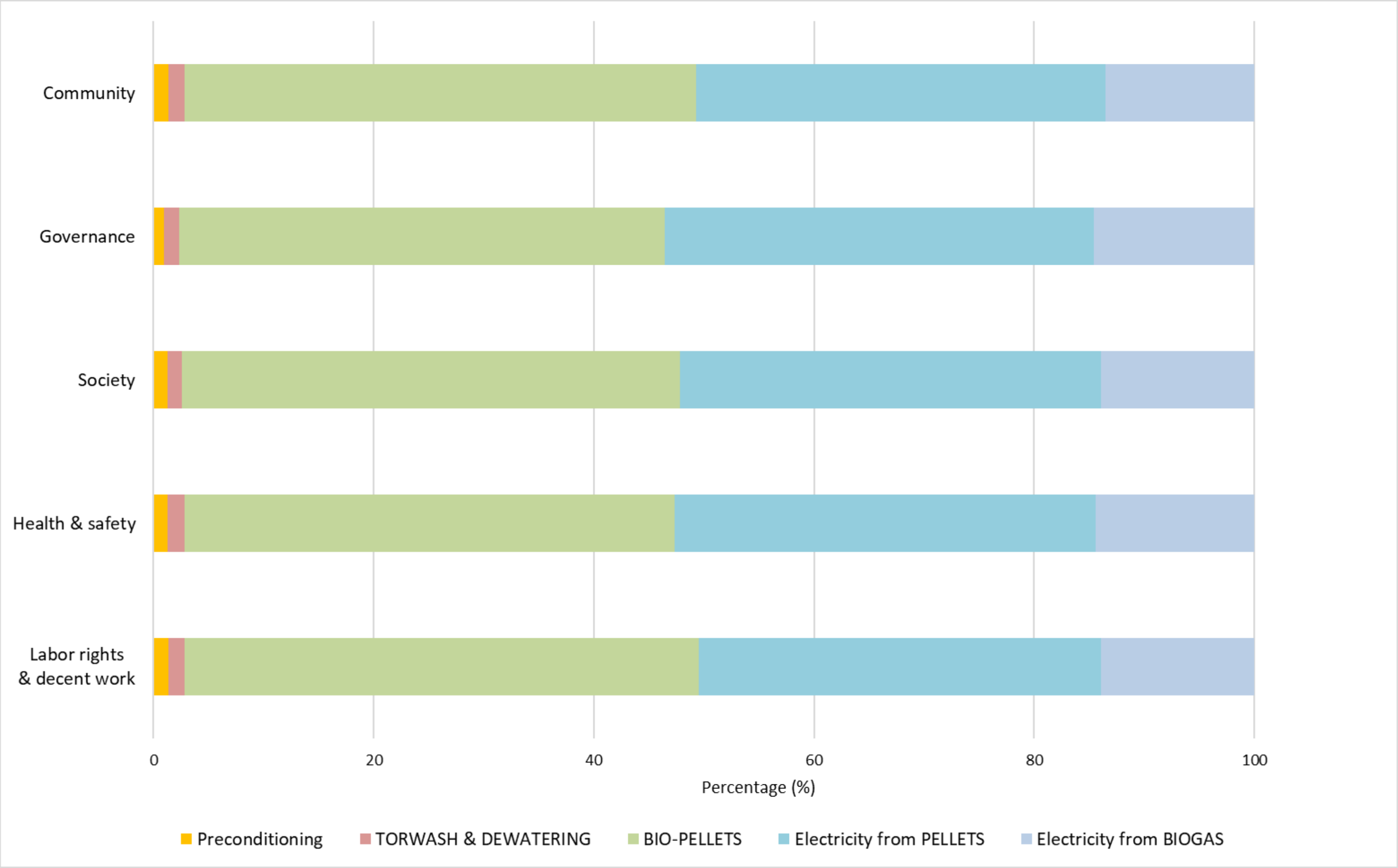
Firstly, the social footprint of the F-CUBED Production System was calculated by aggregating the social impacts associated with each country-specific economic sector (CSS), listed in Table, into a single score attributed to each Damage Category, expressed in both mrheq and mPt.

	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**

S-LCA Results - OP

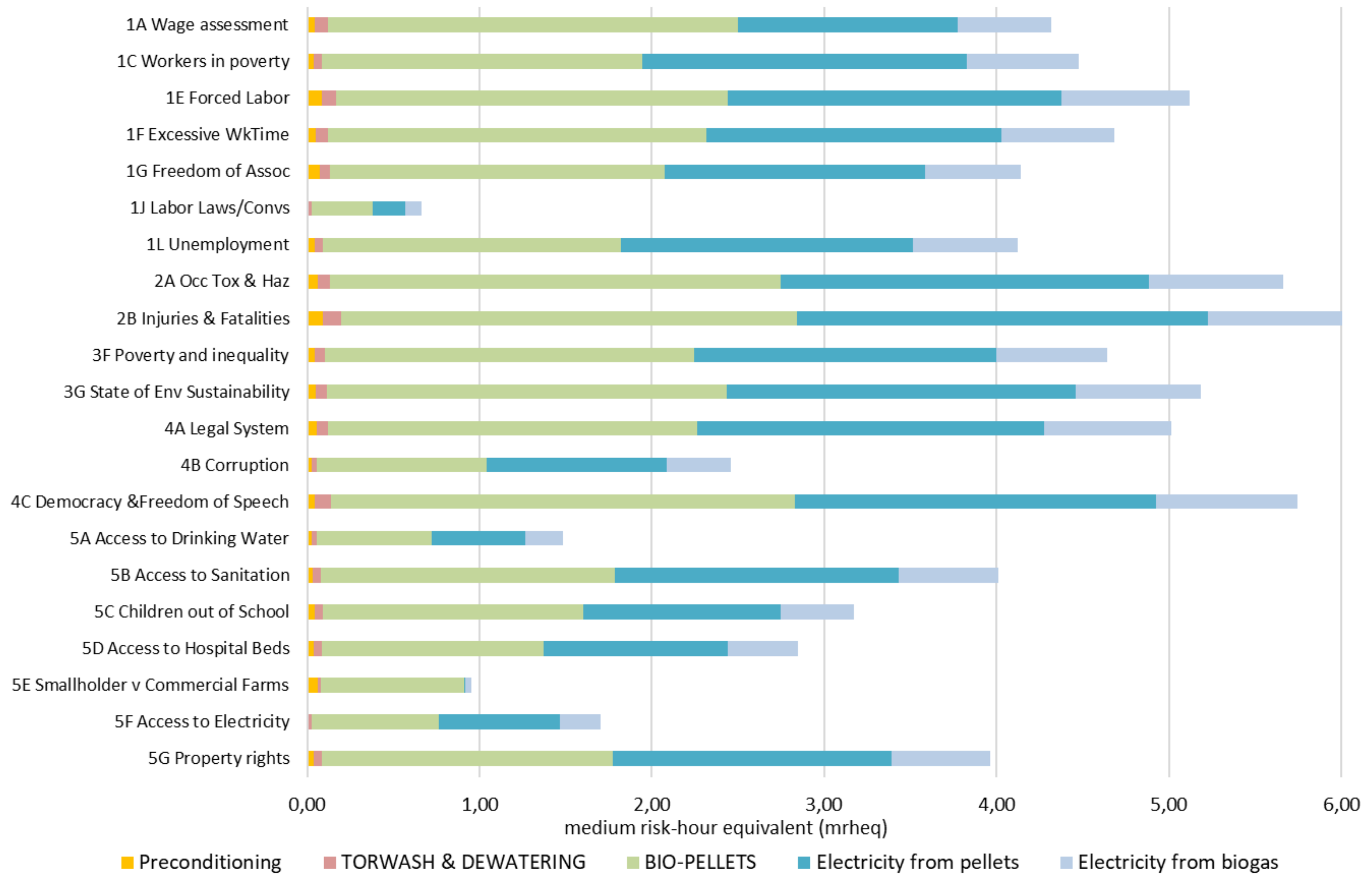
Social impacts of the F-CUBED Production by economic sectors

The **Biopellets production** and the **Electricity production by biopellets** in Italy are the major responsible of the social impacts, ranging between **44-47% and 36-39%**, respectively, depending on the social category.



Contribution analysis of each economic sector to the total social impacts by impact sub-category

The economic sector of **Biopellets and Electricity production by biopellets** 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),**



S-LCA Results - OP

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

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

S-LCA Results - OP

Main achievements

- 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) 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.
- According to the results for **Smallholder farms**, F-CUBED Production System 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.
- 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 in Italy. 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). On the contrary, in Italy, there is **a lack the free market** in the energy sector.

S-LCA Results

General Conclusion

- 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 Biopellets production and Electricity generation in Spain, where the risk level has been classified as medium.
- 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.
- The Italian scenario is apparently unfavourable with respect to the others, and this 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. This translate in 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.

THANK YOU

F-CUBED

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