Supplementary Material B

This Supplementary reports the contribution analysis of the impact categories most relevant to the environmental impacts associated with the F-CUBED production system beyond the climate change impact category, for each biogenic residue case study.

B1. Pulp and Paper Bio-sludge Case Study

For the PPB scenario, the reliable impact categories beyond climate change are particulate matter formation (CV 12.0%) and terrestrial acidification (CV 12.1%).

1. Terrestrial acidification impact category

The terrestrial acidification impact category for the PPB case study accounts for 0.202 kg $SO_{2eq.}/t_{ADp}$. As displayed in Figure S1, the TA impact category for the 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 $SO_{2\ eq.}/t_{ADp}$.

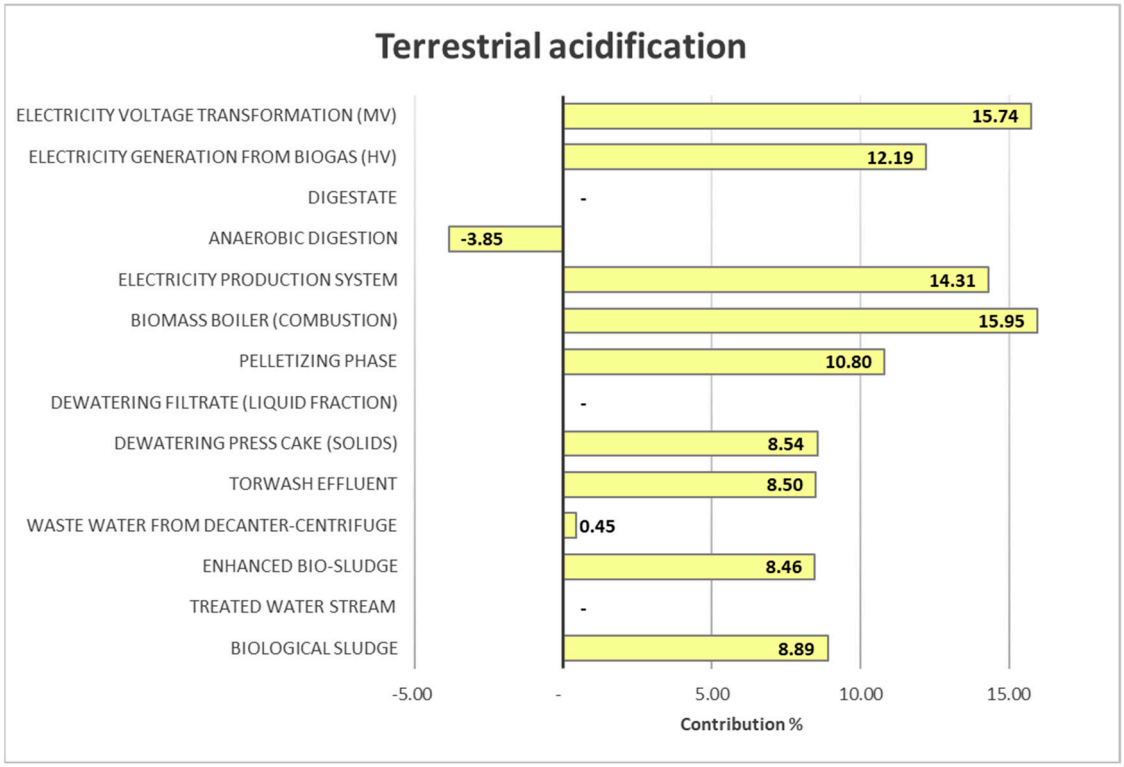

Figure S1. Distribution of the TA impact category in the processes of the F-CUBED production system for the PPB case study.

Also, the upstream pretreatment processes, WWT, and improvement 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 (Figure S1), regarding downstream processes and anaerobic digestion. Nevertheless, the AD process is in countertrend showing a negative emissions share of −3.85% (−0.0078 kg $SO_{2\ eq.}/t_{ADp}$).

2. Particulate matter formation impact category

The particulate matter formation impact category for the PPB case study accounts for 0.0789 kg $PM10_{\ eq.}/t_{ADp}$.

As displayed in Figure S2, the largest contributions to PMF impact category come from combustion of the pellets in the biomass boiler (24.33%) and the 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$_{ADp.}$

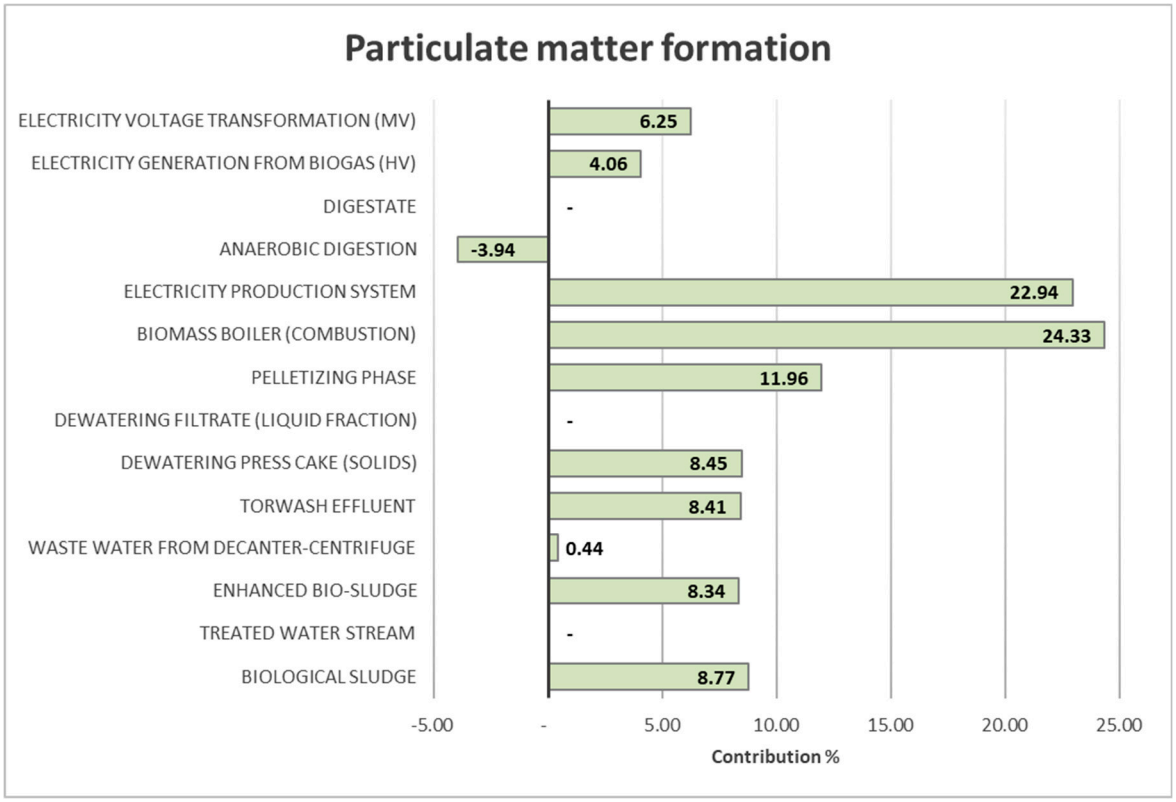

Figure S2. Distribution of the PMF impact category in the processes of the F-CUBED production system for the PPB case study.

In the PPB case study, the upstream pretreatment processes, WWT and improvement of the bio-sludge with decanter-centrifuge also 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$_{ADp}$).

B2. Olive Pomace Case Study

For the OP scenario, the reliable impact categories beyond climate change are fossil depletion (CV 13.18%), terrestrial acidification (CV 17.68%), and particulate matter formation (CV 17.69%).

3. Terrestrial acidification impact category

The terrestrial acidification impact category for the OP case study accounts for 2.99 kg $SO_{2\ eq.}$/t$_{OP}$.

As displayed in Figure S3, 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 for their behaviour must be due to the considerable influence of the electricity country mix composition. Indeed, since Italy is assumed as plant location for the 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 for by the heat and power cogeneration unit, because it assumes a heat recovery scenario of 80%, as an 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}.

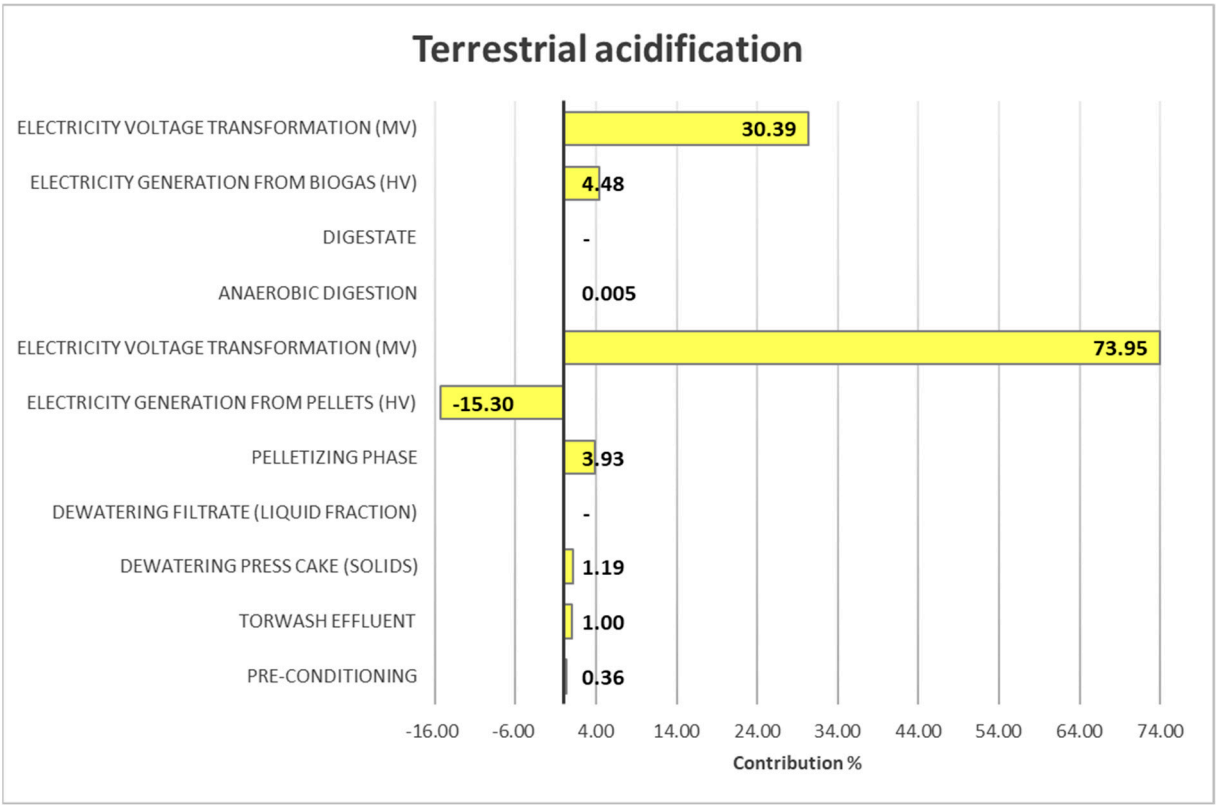

Figure S3. Distribution of the TA impact category in the processes of the F-CUBED production system for the OP case study.

In OP, the pretreatment 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 (Figure S3) due 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 for negative emissions of −15.30%, corresponding to −0.457 kg CO2 eq./t_{OP} of GHG emissions into the atmosphere as avoided products from Technosphere via heat recovery (scenario 80%), and AD provides practically no contribution to the impact (1.4×10^{-4} kg $SO_{2\ eq.}$/t_{OP}).

4. Particulate matter formation impact category

The particulate matter formation impact category for OP case study accounts for 0.93 kg $PM10_{\ eq.}$/t_{OP}.

As displayed in the Figure S4, the 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 process stream, which includes the novel TORWASH® treatment, contributes with 8.78% and 0.0815 kg $PM10_{\ eq.}$/t_{OP}.

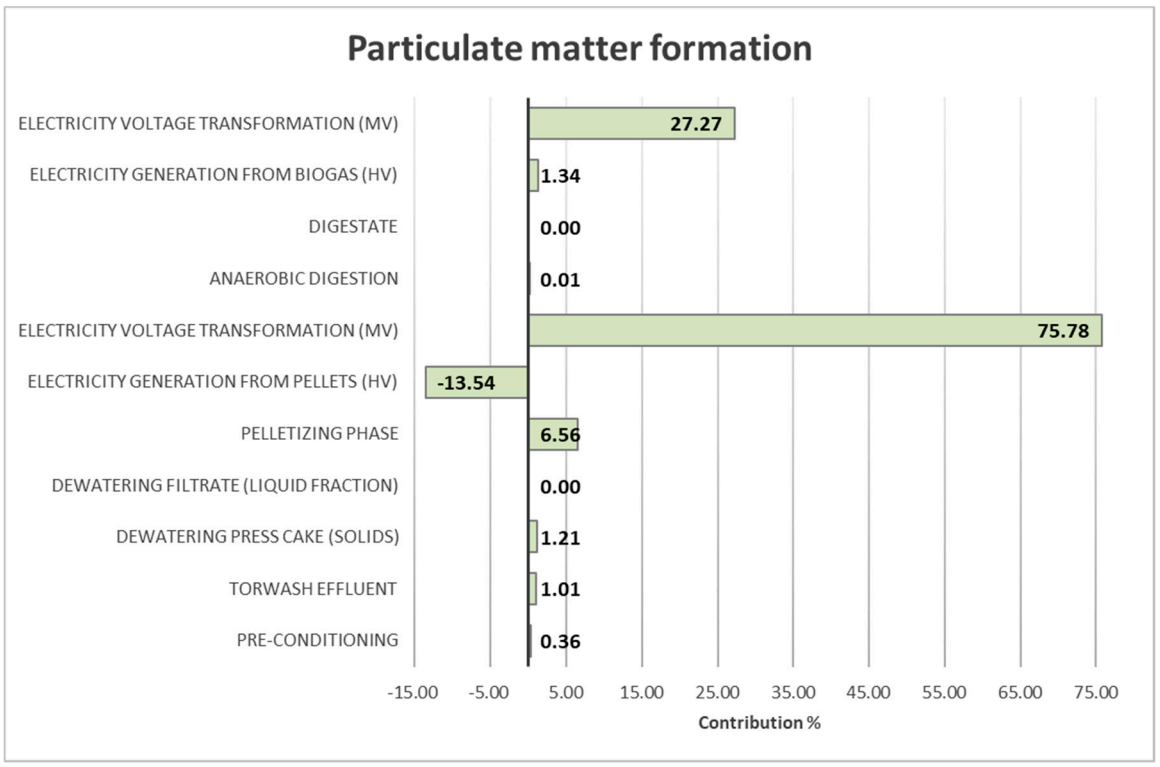

Figure S4. Distribution of the PMF impact category in the processes of the F-CUBED production system for the OP case study.

In the OP case study, the upstream pretreatment 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.

It is noteworthy that, similarly to TA, electricity generation from pellets (HV) accounts for negative emissions of −0.126 kg PM10 $_{eq.}$/t$_{OP}$ (−13.54%) as avoided products from Technosphere via the heat recovery scenario (80%).

5. Fossil depletion impact category

The fossil depletion impact category for the OP case study accounts for −499.24 kg oil $_{eq.}$/t$_{OP}$.

As displayed in Figure S5, 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 a savings of −464.43 kg oil $_{eq.}$/t$_{OP}$ when combined.

The main process stream contributes with slightly positive emissions at 2.39% (11.92 kg oil $_{eq.}$/t$_{OP}$).

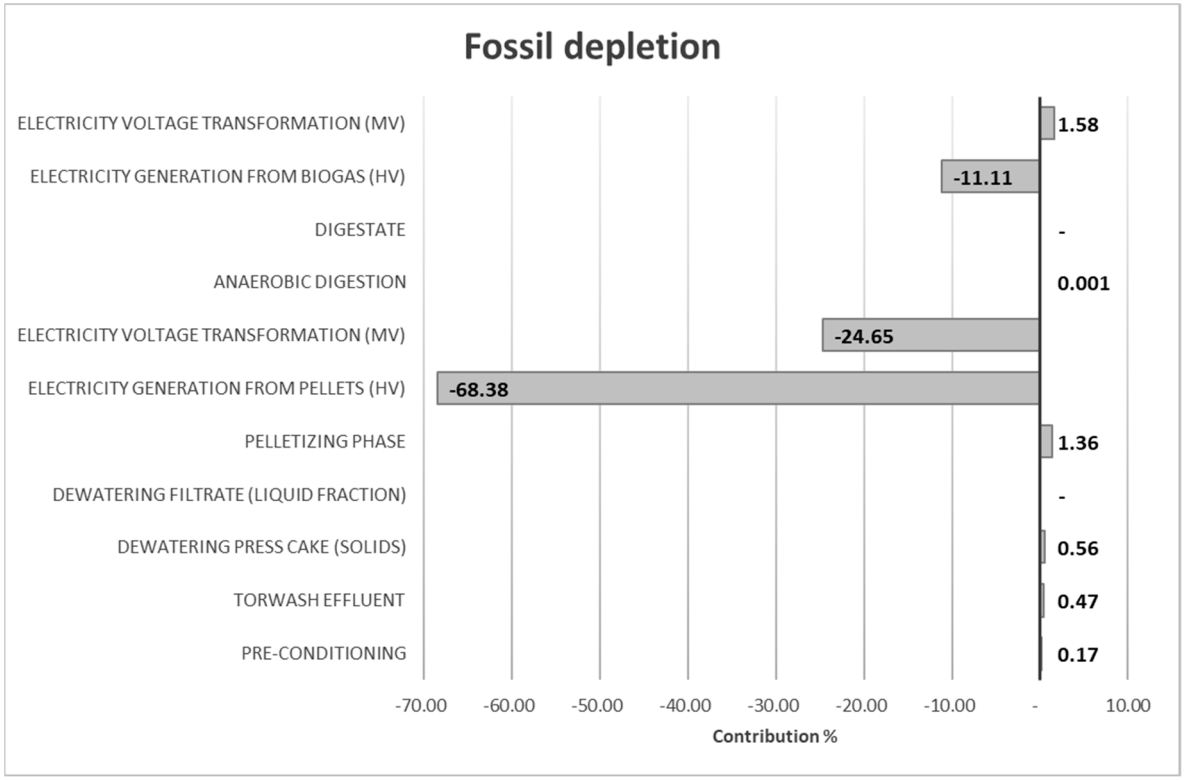

Figure S5. Distribution of the FD impact category in the processes of the F-CUBED production system for the OP case study.

The upstream pretreatment 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.

It is noteworthy that secondary filtrate processing accounts for overall negative emissions of about −11.11%, corresponding to −47.56 kg oil $_{eq.}$/t$_{OP}$ as avoided products from Technosphere via heat recovery and nutrient recovery from digestate utilization.

B3. Orange Peel Case Study

For the ORP scenario, the reliable impact categories beyond climate change are particulate matter formation (CV 6.77%), terrestrial acidification CV 6.50%) and fossil depletion (CV 17.09%). Moreover, as the climate change impact category presents the CV slightly over 20% (21.99%), a further investigation is required, according to the analysis approach applied so far.

6. Terrestrial acidification impact category

The terrestrial acidification impact category for the ORP case study accounts for 13.45 kg $SO_{2\,eq.}$/t$_{ORP}$.

As displayed in Figure S6, 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 behaviour must be due to the considerable influence of the electricity country mix composition. Indeed, since Spain is assumed as the plant location for the 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, heat recovery occurred (scenario 54%) as avoided products from Technosphere in the electricity production via a heat and power

cogeneration unit from pellets, which is not sufficient to compensate the emissions of SO_{2eq}.

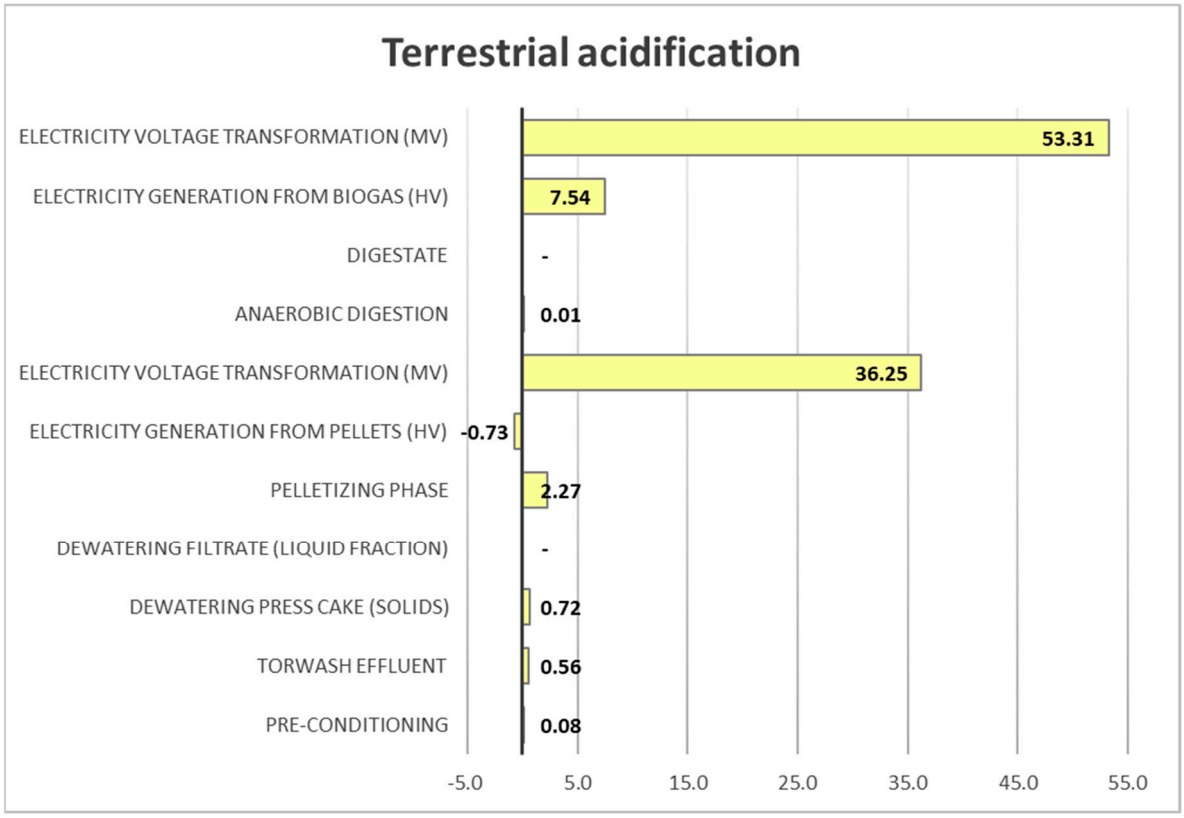

Figure S6. Distribution of the TA impact category in the processes of the F-CUBED production system for the ORP case study.

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 (Figure S6) in relation to downstream processes and electricity voltage transformation (MV) from biogas.

7. Particulate matter formation impact category

The particulate matter formation impact category for the ORP case study accounts for 4.59 kg $PM10_{eq.}$/t_{ORP}.

As displayed in Figure S7, PMF, similarly to that of 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 process stream, which includes the novel TORWASH® treatment, contributes with 4.93% and 0.226 kg $PM10_{eq.}$/t_{ORP}.

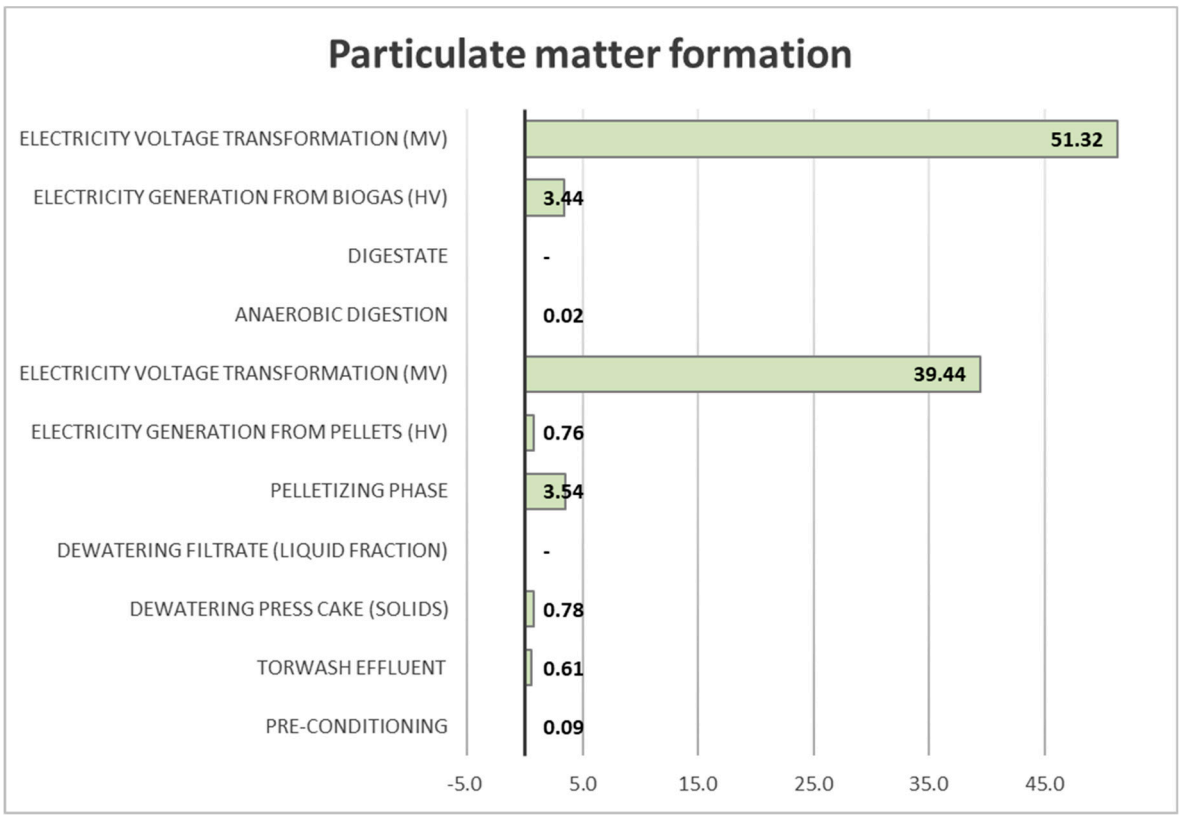

Figure S7. Distribution of the PMF impact category in the processes of the F-CUBED production system for the ORP case study.

In the ORP the pretreatment processes, comminution and dilution, it gives a negligible contribution to the PMF impact category, accounting for 0.09% (0.004 kg $PM10_{eq.}/t_{ORP}$) when combined.

Even for PMF, the carbon intensity of the electricity country mix and the heat recovery share are responsible for the different impact category behaviour with respect to the OP case study.

8. Fossil depletion impact category

The fossil depletion impact category for the ORP case study accounts for −627.43 kg $oil_{eq.}/t_{ORP.}$

As displayed in Figure S8, 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 process stream contributes slightly positive emissions of 3.43% (21.54 kg $oil_{eq.}/t_{ORP}$).

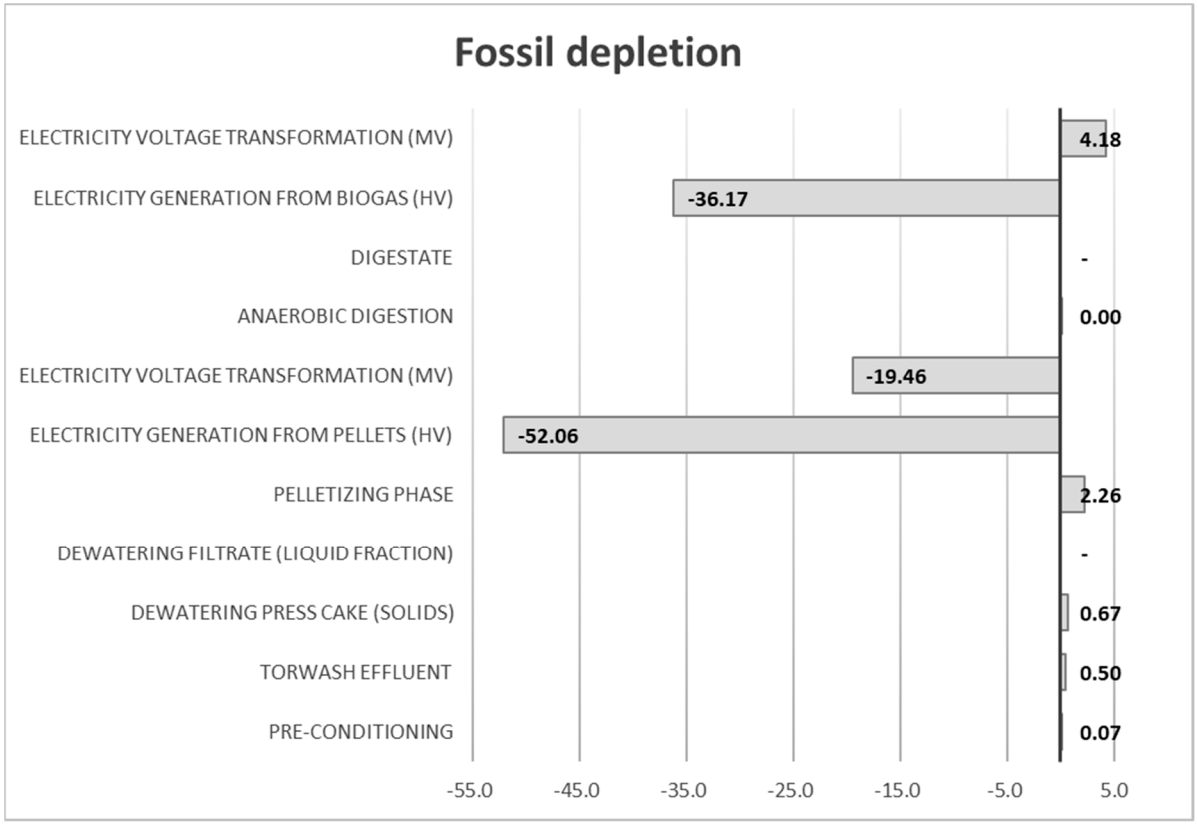

Figure S8. Distribution of the FD impact category in the processes of the F-CUBED production system for the ORP case study.

In the ORP case study, the pretreatment 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.

One must 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 products from Technosphere via heat recovery and nutrient recovery from digestate utilization.

9. Climate change impact category deepening

The negative emissions accounted for by CC (−1301.61 kg$CO_{2\ eq.}$/t_{ORP}) find the main contributions from *carbon dioxide fossil* savings and *methane fossil savings*, 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 few positive emissions in the air compartment, which accounts for 190.30 kg$CO_{2\ eq.}$/t_{ORP} (15%).

The investigation of the background unit processes, as depicted in Figure S9, reveals the major elements responsible for 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 plants from natural gas, and high voltage electricity production, from oil. Clearly, all these processes refer to the specific electricity country mix considered for Spain.

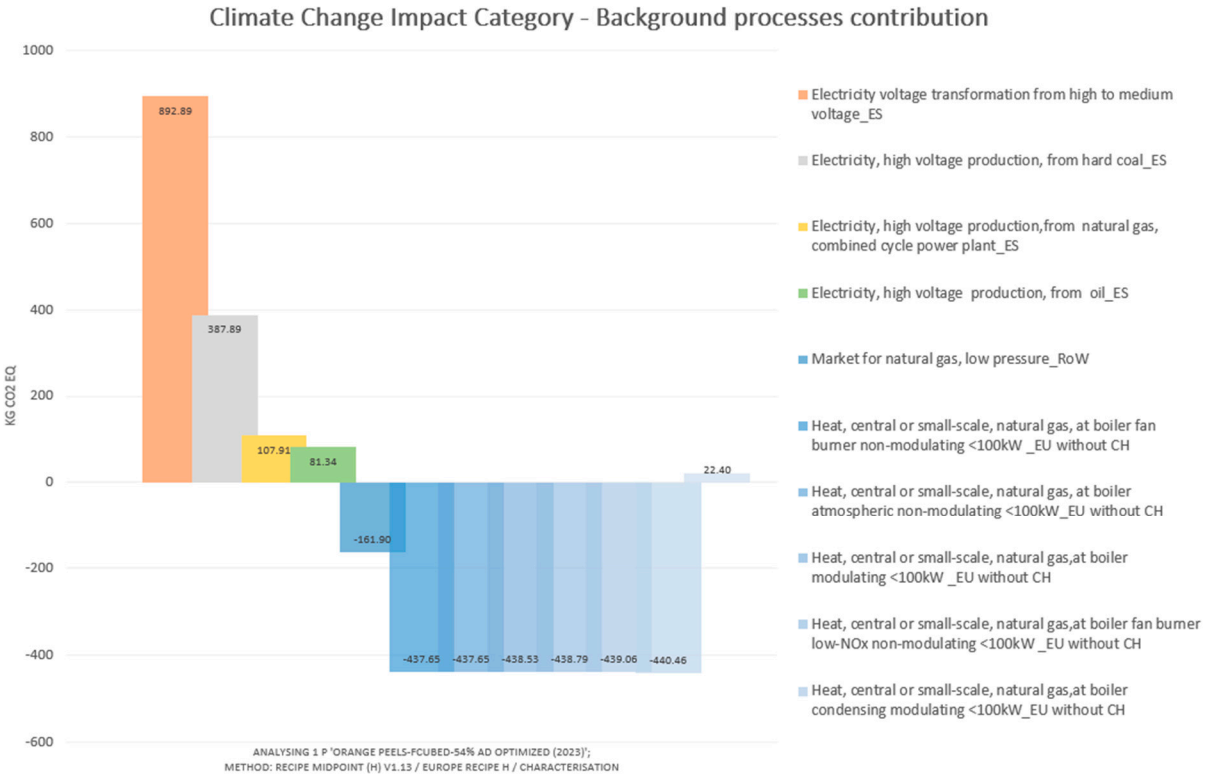

Figure S9. Background unit processes contribution to the CC impact category for the F-CUBED Production System in the ORP case study.