BC Industrial Hub 4Circularity

Impact quantification of the sustainability measures in the Basque Hub

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Hub Configuration

The major manufacturing and production industries in the Basque Hub are: *Petronor (Oil & E-fuels)*, *Smurfit Kappa (Paper Industry)*, *Sidenor (Steel Manufacturing)*, and *Calcinor (Lime Production)*. The companies are located in the province of Basque Country, Spain.

Petronor's oil processing plant is located at the town of Muskiz (population: ≈ 7.500) and the e-fuels plant at the Port of Bilbao (PoB). There is a distance of 6.35 km between the two plants, facilitating potential synergies between the plants, as is the case.

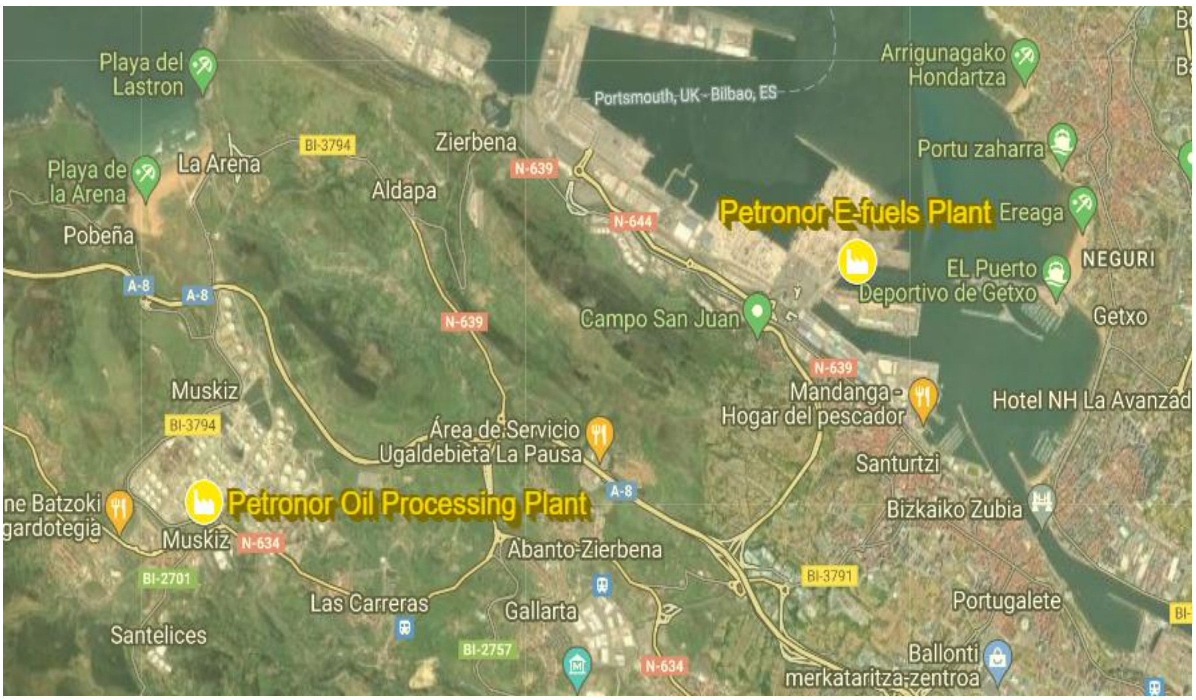

Figure 1: Petronor's Oil & E-fuels Plants // Source: Google Maps

Smurfit Kappa Nervion is the paper processing and producing company of the Basque Hub. Smurfit Kappa is located at the outskirts of the town of Durango (population: ≈ 30.000), 18.4 km away from the outskirts of the city of Bilbao (population: ≈ 346.000). Petronor's oil and e-fuel plants are located 39.5 and 34.9 km away, respectively. The exact location of Smurfit Kappa can be observed in Figure 2, along with its proximity to the town of Durango. According to the data provided by *Technalia* (responsible for the R&D aspect of the Basque Hub), Smurfit Kappa has a number of assets present in the wider Basque Country, so the quantification of impacts is performed collectively.

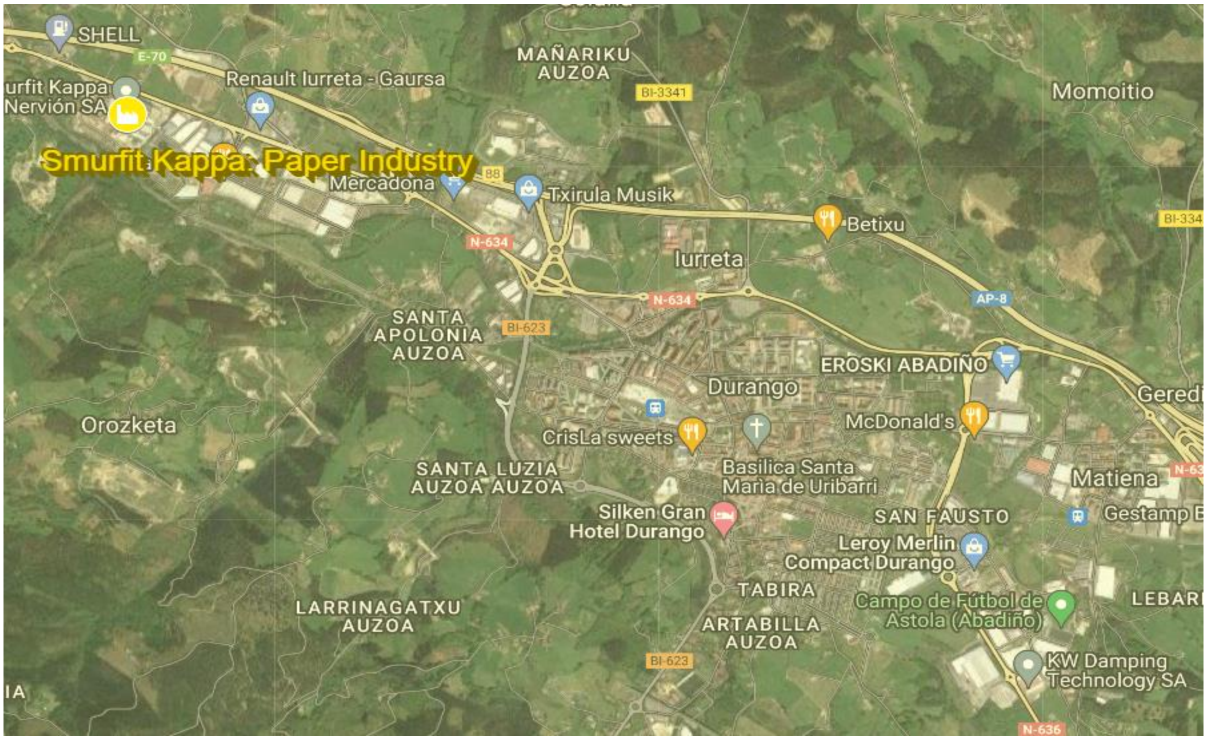

Figure 2: Smurfit Kappa Nervion's plant location // Source: Google Maps

Sidenor is the steel-manufacturing company at the outskirts of Bilbao. It is located 21.3 km away from Petronor's plant at Muskiz and 17.7 km for the plant at the PoB. Durango and Smurfit Kappa's paper producing plant are 21.3 km away.

Figure 3: Sidenor's steel-manufacturing plant // Source: Google Maps

Calcinor is the lime-producing company of the BC Hub. Calcinor's lime quarry is 68.3 km southeast of Sidenor, located almost halfway between the urban centers of Bilbao and Pamplona.

Figure 4: The location of Calcinor's lime quarry // Source: Google Maps

The exact locations of the major companies comprising the Basque Industrial Hub 4Circularity, as well as the hub's boundaries, are observed in Figure 5. The surface area of the hub is 5.815 km² and, by assuming that the major urban centers are Bilbao, Eibar, and Durango, the population number reaches, at least, 405.000 people.

Figure 5: Overview of the companies' locations & the hub's boundaries // Source: Google Maps

In the following table, the distances between the different industries comprising the hub are displayed.

Table 1: Distance between the hub's components

	Petronor - Muskiz	Petronor - PoB	Smurfit Kappa	Sidenor	Calcinor
Petronor - Muskiz		6.35 km	39.5 km	21.3 km	88.9 km
Petronor - PoB	6.35 km		34.9 km	17.7 km	83.8 km
Smurfit Kappa	39.5 km	34.9 km		18.4 km	49.9 km
Sidenor	21.3 km	17.7 km	18.4 km		68.3 km
Calcinor	88.9 km	83.8 km	49.9 km	68.3 km	

Petronor (Oil & E-fuels Production)

1. Green Hydrogen, CCUS & E-fuels

Petronor has the oil processing plant located at the town of Muskiz and the e-fuels plant located at the Port of Bilbao. According to Technalia, the e-fuels plant is expected to have reached an initial capacity of 2.8 Mliters/year by 2025, with potential for scaling-up the capacity in the future.

The second building block of Petronor is the on-site production of green Hydrogen by the installation of three (3) electrolysers. It is estimated that by 2024 the installed capacity will be 2.5 MW, by 2025 10 MW, and 100 MW by 2027. The company's plan is to capture the CO_2 produced by the operation of the oil processing plant, combine it with the locally-produced green Hydrogen to produce e-fuels, and use these e-fuels to power the oil plant. In that way, the CO2 emissions are neutralized, as they are being recycled between the two plants for energy production, and an internal circularity economy is established.

For the quantification of the impact of the aforementioned approach, some assumptions need to be made. Those are:

- Capacity for e-fuels production in 2025: 2.8 Mliters/year
- Electrolysers Capacity in 2025: 10 MW
- The RES power output will be high enough to allow for the production of the required amounts of green Hydrogen
- The electrolysers will utilize state-of-the-art models (such as Hysata and Sunfire technologies) and will have an average efficiency of 85%.
- Stoichiometric ratio of H_2 to e-fuels: 3:1 (3kg of H_2 for 1kg of e-fuel)

According to the U.S Department of Energy, an electrolyser with η=100% requires approximately 55 kWh/kg (50-60 kWh/kg). So, if we assume an electrolyser with an efficiency of 85% we can deduce that the required energy (in kWh) to produce 1 kg of green hydrogen, using an electrolyser with **η = 0.85** is equal to:

- (55 kWh/kg / 0.85) = **64.70 kWh/kg**

Using these data, it is possible to estimate how much green H_2 must be produced per year for the production of 2.8 Mliters of e-fuel.

- $2.8 * 10^6 * (3:1)$ = **8,400,000 kg of green hydrogen per year** are needed

According to the literature, a typical Fischer-Tropsch reactor (used in the production of synthetic fuels) has a CO_2 conversion rate between 60% and 90%. If we assume an average of 80% we can deduce that (1kg of e-fuel/0.80) = **1.25 kg of CO2** is needed for 1 kg of e-fuel.

Thus, it is possible to make an approximate calculation of the amount of CO2 captured from the oil plant, converted into e-fuel, and utilized (re-used) in the oil plant, in yearly basis.

- $2.8 * 10^6$ (Mliters e-fuel) * 1.25 (kg of CO_2) * (1/0.8) (FT reactor conversion efficiency) = **4,375,000 kg of CO_2** are captured and utilized per year.

According to the *"Greenhouse Gases Equivalencies Calculator"*, the production of **1 barrel (42 gallons) of refined oil results in 432 kg of CO2** emitted in the atmosphere. Assuming that a medium-scale oil process plant produces around **120,000 barrels of refined oil per day**, we can deduce the following:

- 120,000 barrels/day → 43,800,000 barrels/year
- 1 barrel (42 gallons) → 432 kg CO_2 so 43,800,000 * 432 = **18,921,600,000 kg CO_2 per year**
- Calculating the percentage of CO_2 reduction: x = (4,375,000/18,921,600,000) * 100 ⇔ **x ≈ 0.0231%**

2. Biogas & Biocoke

Petronor's plans for production of biogas and biocoke involve the pyrolysis of urban waste. *Technalia's* data estimate an inflow of **10,000 tons (10,000,000 kg/year) of urban waste by 2030** and 100,000 tons by 2050. The expected power output is **4 GW** and 40 GW, respectively. Apart from producing biogas to power the Muskiz oil plant, which is a sustainable alternative to conventional fossil fuels, the generation of biocoke is also of significance, as it can be used as a substitute to the metallurgical coke utilized both by Sidenor for steel manufacturing and Calcinor for producing cement/lime.

To quantify the approximate generation of biogas from the pyrolysis reactor, some assumptions regarding the biogas yield of the process must be made. An average **yield of 60% of biogas** (6 kg of waste for 1 kg of biogas) from the pyrolysis of urban waste is a safe assumption to be made. It is also assumed that the waste inflow is immediately fed into the pyrolysis reactors and there is no need for torrefaction and the associated energy costs. According to the International Energy Agency (IEA), the LHV (heat released during combustion) of 1 kg of biogas is approximately **18.5 MJ** (from 16.7 MJ to 20.8 MJ). Therefore:

- 10,000,000 kg urban waste → (60% biogas yield) → **6,000,000 kg of biogas** produced
- 6,000,000 (biogas yield) * 18,5 (LHV of 1 kg biogas) = **111,000,000 MJ** total power output of biogas

Natural gas is the primary fossil fuel burned in the Petronor oil plant. Thus, the biogas energy output available must be expressed in the equivalent natural gas value. It is known that the energy content of **1 m^3 of natural gas is equal to 38.8 MJ**. So:

- 111,000,000 MJ / 38.3 MJ = **2,898,172 (≈ 2.9 million) m^3 of natural gas** can be replaced by the generated biogas.

According to the literature, the combustion of 1 cubic meter of natural gas results in 1.9 kg CO_2 being released in the atmosphere. Therefore, the benefits of the partial-replacement of NG by sustainable biogas are quantified as follows:

- 2,898,172 m^3 NG * 1.9 kg CO_2 = **5,506,527 kg of CO2** emissions are avoided. The oil plant generates **18,921,600,000 kg CO_2 per year**, so percentage-wise the reduction is:

  y = (5,506,527/18,921,600,000) * 100 ⇔ **y = 0.0292 % CO2** emissions reduction.

→ Check the percentage-wise reduction after I get the NG inflow of Petronor

Biocoke is also included among the products of Petronor's processing of the urban waste. Through a process known as *carbonization*, the urban waste is heated in the absence of air and the volatile elements removed. The resulting solid residue is the biocoke yield. Assuming a scenario where the entirety of the 10,000,000 kg of urban waste are carbonized, and the biocoke yield is 30% (according to the literature the yield ranges between 20% and 50%), we can deduce the following:

- 10,000,000 kg urban waste * 0.3 biocoke yield = **3,000,000 kg biocoke** (or 3,000 metric tons) that can be used as an agent for facilitating the reduction of metal oxides into metals.

Smurfit Kappa (Paper Industry)

In the case of Smurfit Kappa, the quantification of the de-carbonization measures and sustainability-related data is performed collectively, with Smurfit Kappa Nervion as the focal point, as the company has at least ten of its assets located both within the hub's boundaries and the wider Basque Country. Currently, the company's presence in the Hub can be described in numbers as follows:

- Paper production: 1,383,000 tons/year (1.383 ktons/year)

- CO_2 emissions: 462000 tons/year (462 ktons/year)
- Energy Consumption: 3,172 GWh/year (biomass 32%, natural gas 36%, electricity 32%)

1. Bioethanol through paper waste

According to the information provided by Technalia, Smurfit Kappa produces between 415,000 to 1,383,000 m^3 of paper sludge per year (0.3 to 1 m^3 of PS/ton paper). It is assumed that the production of paper sludge in the Basque Hub is **≈900,000 cubic meters/year**. The paper sludge by-product can be subjected to a process known as *enzymatic hydrolysis* to produce bioethanol, a biofuel derived from the reduction and fermentation of cellulose into simple sugars.

According to the available literature, most case studies utilize paper sludge with cellulose content between 14% and 35%. Therefore, an average **25% of cellulose per cubic meter of paper sludge** will be assumed.

- 900,000 * (25/100) = **225,000 cubic meters of cellulose per year**.

Assuming that the cellulose feedstock is subjected to the acidic pretreatment process, the **conversion rate of cellulose to sugars is 92%**.

- 225,000 * (92/100) = **207,000 cubic meters of glucose per year**.

According to the available literature, the conversion rate of glucose to ethanol through the process of enzymatic hydrolysis is approximately 95%.

- 207,000 * (95/100) = **196,650 cubic meters of bioethanol** produced annually.

The energy content of **pure ethanol (LHV) is 26.7 MJ/liter**. Assuming that the produced bioethanol is 90% pure, the LHV value drops to (26.7 * 0.9) = **24.03 MJ/liter**. After converting the yearly bioethanol production units from cubic meters to liters (**196,650,000 liters of bioethanol**), it is possible to estimate the total LHV of the production:

- 196,650,000 * 24.03 = **4,725,499,500 MJ** total energy content.

According to the U.S Energy Information Agency, the energy content of **1 m^3 NG is equal to 38.4 MJ**. Therefore, the produced bioethanol replaces the following amount of natural gas:

- 4,725,499,500 MJ / 38.4 MJ per m^3 = **123,059,883 m^3 NG**.

According to the literature, the emissions of burning 1 m^3 of NG are equal to 0.5 kg CO_2. Therefore, CO2 emissions from the BC Hub are reduced by:

- 123,059,883 * 0.5 = **61,529,942 kg CO_2**

The bioethanol fuel can be utilized either in the paper production plant or in some other industrial process taking place in the BC Hub. The data regarding the annual CO_2

emissions from Smurfit Kappa are available (462 ktons of CO_2), so the percentage-wise quantification of the CO_2 reductions due to the use of bioethanol can be estimated:

- φ = (61,529,942 kg CO2 / 462,000,000 kg CO_2) * 100 ⇔ **φ = 13.31% reduction of CO2 emissions** from Smurfit Kappa's paper plant.

2. Syngas from paper sludge

Gasification of the side-produced paper sludge is another possible measure for the reduction of materials and energy inflows, and carbon dioxide emissions. The primary product of gasification is synthetic gas (syngas), an e-fuel that can be used to power industrial operation within the Basque Hub.

Assuming that the yearly paper sludge production is equal to 900,000 cubic meters, some estimation regarding the output of syngas can be made. Taking into consideration the literature, paper sludge has **carbon content equal to 34%**. Further assumptions include a **stoichiometric ratio of 1:1** between syngas and carbon and the use of a **gasification reactor with η = 70%**.

- 900,000 m^3 PS * 0.34 = **306,000 m^3 of carbon** (C)
- 306,000 m^3 * 0.70 = **214,200 m^3 (214,200,000 kg) of syngas** are produced

According to the literature, the average LHV of syngas is equal to **3.8 MJ/kg**. Therefore, we can estimate a total energy content of:

- 214,200,000 kg * 3.8 MJ/kg = **813,960,000 MJ total energy content**

It is already known that the LHV of NG is equal to 38.4 MJ/kg and that 1 m^3 of NG releases 0.5 kg CO_2 in the atmosphere. Therefore, the reduction in NG requirements and CO_2 emissions respectively is:

- 813,960,000 MJ / (38.4 MJ/kg) = **21,196,875 kg of NG**
- 21,196,875 kg NG * 0.5 kg CO_2 = **10,598,438 kg of CO_2**

Percentage-wise, the reduction in CO_2 emissions is equal to:

- ψ = (10,598,438 kg CO_2 / 462,000,000 kg CO_2) * 100 ⇔ **ψ = 2.294% reduction of CO2 emissions** as a result of producing and utilizing syngas.

3. Calcium Oxide (Lime) in PS

The significant presence of calcium carbonate ($CaCO_3$) in the paper sludge waste streams of Smurfit Kappa presents another interesting case, as calcium oxide (CaO), or lime, can be extracted from it. Lime is a key ingredient in the production of construction materials, including cement, mortar and stucco. There is the potential for I2I symbiosis with Calcinor.

First is the extraction of calcium carbonate content from the paper sludge. According to the literature, calcium carbonate forms between 50% and 60% of the paper sludge composition, along with some other elements. A conservative estimation of 50% is being made. Further information:

- 900,000 * (50/100) = 450,000 m3 of $CaCO_3$ can be extracted from that amount of paper sludge.

Literature review reveals that the molar masses of $CaCO_3$ and CaO are 100.1 g/mole and 56.1 g/mole, respectively. Therefore, the molar mass ratio between the two elements, for converting $CaCO_3$ to CaO is (56.1/100.1) = 0.560. So, from the available quantity of $CaCO_3$ the following amount of CaO can be extracted:

- 450,000 m^3 * 0.560 = 252,000 cubic meters of CaO (252,000,000 kg).

According to the literature available, the ratio between CaO and cement is 0.65:1. Therefore, it is possible to deduce the following:

- (257,000,000 kg CaO / 0.65) = 387,692,308 kg of cement can be produced by utilizing the CaO available in the paper sludge from Smurfit Kappa.

In the data provided by Technalia, the lime production from Calcinor's quarry is equal to 1000 tons (1,000,000 kg). The calculation of how much limestone needs to be extracted by Calcinor to produce 1,000,000 kg of lime is the following:

- (1,000,000 kg CaO / 56.1) * 100.1 = 1,784,951 kg of limestone.

According to the literature, 600 kg of CO_2 are emitted for the extraction of 1 ton of limestone. By Smurfit Kappa supplying Calcinor with the limestone ($CaCO_3$) produced by paper sludge, significant CO_2 emissions can be achieved, as Calcinor would be able to reduce its CO_2 footprint during the mining process. Specifically:

- 1785 tons of $CaCO_3$ * 600 kg CO_2 = 1,071,000 kg of CO_2 reduction in the yearly emissions of CO_2.

From the total 1,000,000 tons (1,000,000,000 kg) of CO2 emitted yearly from cement-related operations in the Basque Hub, the aforementioned reduction in CO2 represents a percentage of : $\theta = (1{,}071{,}000/1{,}000{,}000{,}000) * 100 \Leftrightarrow \theta = 0.107\%$ reduction in total CO_2 emissions.