# Supplementary Material

Paper: Cradle-to-gate life cycle assessment of beneficiated phosphate rock production in Tunisia, submitted to Sustainability Management Forum

Authors: Roukaya Issaoui, Christine Rösch, Jörg Woidasky, Mario Schmidt,Tobias Viere

E-mail: Roukaya.issaoui@kit.partner.edu

## 1 Detailed description of the phosphate rock mining and beneficiation

### 1.1 Process "Mining operations phosphate rock."

- Extraction

Two options are available to remove the overburden and the intermediate layers, depending on the layer's geophysical properties. The first option is blast hole drilling using a rotary driller. Then the overburden is stripped by  exavator and bulldozera 15 m high bench[1]. The second option is blasting the overburden using the ANFO[2] explosives. Blasting the overburden is only economically feasible when the overburden is very thick, or the intermediate layers' thickness is above 2 m.

- Crushing and screening

The extracted phosphate rock[3] is transported to the crushing facility by truck. At first, the rocks are sorted by a static sieve with a 400 mm opening mesh size to remove the oversized rocks (> 400 mm). The oversized rocks are backfilled, and the rest is crushed in a jaw crusher to a size of 0-120 mm and sieved through a vibrating sieve of 60 mm opening mesh. The 0-60 mm size rocks undergo a second crushing, and then they are sieved through a vibrating sieve of 40 mm opening mesh to reach the size of 0-40 mm. The 0-40 mm sorted rocks are transported by a conveyor belt or truck, then stocked next to the washing plant.

1 A bench may be defined as a ledge that forms a single level of operation above which mineral or waste materials are mined back to a bench face. The mineral or waste is removed in successive layers, each of which is a bench[135]. http://www.mine-engineer.com/mining/open_pit.htm

2 ANFO : **A**mmonium **N**itrate **F**uel **O**il. It is composed of 94% ammonium nitrate ($NH_4NO_3$) and 6% fuel oil. These explosives belong to the family of nitrated explosives

3 It refers to the layers of phosphate rock before to undergoes any mechanical transformation to remove the non-phosphate rock

## 1.2 Process "Wet beneficiation phosphate rock."

- Scrubbing, screening, and classification

The crude phosphate rock (24% $P_2O_5$) is mixed with water in the rotating scrubber in 2:1 ratio. Then it undergoes attrition and disintegration to transform into a pulp which is poured on a vibrating screen of 2 mm mesh with jets of pressurized water. The pulp containing materials < 2 mm, is pumped into hydro-cyclones to separate the particles at 71 µm. The hydro-cyclone separates 71 µm – 2 mm underflow fraction. The overflow fraction (size <71 µm) is treated in a decantation tank in the wastewater treatment plant for dewatering.

- Filtration

The 71 µm - 2 mm-sized phosphate fraction is conveyed on a filtering belt to reduce the product's water content to 15%. The product coming out on the filter belt is the beneficiated phosphate rock, which is the final marketable product to be sent to the chemical plant or the drying unit. The beneficiated phosphate rock is concentrated at 29% $P_2O_5$.

# 2 Life Cycle Inventory

## 2.1 Input table of the unit process 'mining operations' and 'wet beneficiation"

Table 1: Inputs of the production 1 kg $P_2O_5$ of open-pit mining and wet beneficiation in Tunisia

| Input | Unit | Total | Mining | Beneficiation |
|---|---|---|---|---|
| **Infrastructure** | | | | |
| **Occupation mineral extraction site (industrial area)** | **m²*a** | 1.02E-03 | 1.02E-03 | |
| **Transformation, to mineral extraction site (from desert)** | **m²** | 1.70E-01 | 1.70E-01 | |
| **Occupation, construction building , (5year)** | **m²** | 4.61E-05 | 4.61E-05 | |
| **Occupation for office and maintenance lifetime 20 years** | **m²** | 1.15E-05 | 1.15E-05 | |
| **Buildings crushing, steel** | **m²** | 1.70E-05 | 1.70E-05 | |
| **Building beneficiation plant** | **m²** | 9.43E-06 | | 9.43E-06 |
| **Occupation, construction site** | **m²*a** | 2.12E-06 | | 2.12E-06 |
| **Occupation, industrial site** | **m²*a** | 5.30E-07 | | 5.30E-07 |
| **Water recycling Plant** | **item** | 9.97E-10 | | 9.97E-10 |
| **Conveyor belt (9km, 25 lifetime; 1000t/h, 3500h/year)** | **m** | 5.37E-06 | 4.29E-07 | 4.94E-06 |
| ***Machine*** | | | | |
| **Blasthole Drills** | **kg** | 5.89E-06 | 5.89E-06 | |
| **Hydraulic excavator** | **Item** | 4.42E-10 | 4.42E-10 | |
| **Bulldozer** | **kg** | 3.89E-05 | 3.89E-05 | |

| | | | | |
|---|---|---|---|---|
| **Dumper** | **kg** | 1.50E-04 | 1.50E-04 | |
| **Truck** | **Item** | 4.42E-10 | 4.42E-10 | |
| **Filtering belt** | **m** | 1.13E-05 | | 1.13E-05 |
| **Equipment; scrubber, hydrocylone, screening** | **kg** | 1.15E-04 | | 1.15E-04 |
| **Maintenance for Machinery** | **Item** | 2.80E-09 | 2.80E-09 | |
| ***Movement of soil*** | | | | |
| **Phosphorus, as P (18% in Apatite, 11% in crude ore, in ground)** | **kg P** | 4.58E-01 | 4.58E-01 | |
| **Fluorine,4.5% in Apatite, 2,4% in crude ore, in ground** | **kg F** | 1.00E-01 | 1.00E-01 | |
| **Operating Resources** | | | | |
| **Explosive ANFO** | **kg** | 9.04E-03 | 9.04E-03 | |
| **Explosive N30** | **kg** | 1.65E-04 | 1.65E-04 | |
| ***Total explosive*** | ***kg*** | ***9.20E-03*** | ***9.20E-03*** | |
| **Diesel (used in machinery, 45.6 MJ per kg diesel)** | **MJ** | 7.37E-01 | 7.25E-01 | 1.26E-02 |
| **Electricity (Industrial , Medium voltage)** | **KWh** | 4.00E-02 | 6.89E-04 | 3.93E-02 |
| ***Total energy*** | ***MJ*** | ***8.81E-01*** | ***7.27E-01*** | ***1.54E-01*** |
| **Lubricant oil** | **kg** | 7.79E-04 | 7.17E-04 | 6.22E-05 |
| **Industrial Water** | **$m^3$** | 1.17E-02 | | 1.17E-02 |
| **Flocculant: Semifloc** | **kg** | 2.52E-04 | | 2.52E-04 |
| **Transport** | | | | |
| **Transport of Barren rock (with dumper)** | **kg-km** | 3.53E+00 | 3.53E+00 | |
| **Transport of crude phosphate (with truck)** | **kg-km** | 1.50E+02 | 1.50E+02 | |
| **Transport equipment, road** | **kg-km** | 2.13E-01 | 2.13E-01 | |
| **Transport equipment, freight ship** | **kg-km** | 2.13E+00 | 2.13E+00 | |
| **Transport Explosives, road** | **kg-km** | 5.52E-01 | 5.52E-01 | |
| **Transport of beneficiated rock, road** | **kg-km** | 5.99E+00 | | 5.99E+00 |
| **Transport of waste, road** | **kg-km** | 1.17E+01 | | 1.17E+01 |

## 2.2 Output of the unit process 'Blasting'of Phosphate rock in Tunisia

Table 2: Outputs of the process "Blasting phosphate-TN."

| Output | Unit | Per kg crude PR | Per kg P2O5 |
|---|---|---|---|
| Carbon Monoxide CO | kg | 1.07E-02 | 4.46E-02 |
| Nitrogen Oxides $NO_x$ | kg | 5.73E-02 | 2.39E-01 |
| **Total Suspended Particles TSP** | **kg** | **2.55E-04** | **1.06E-03** |
| PM < 10µm | kg | 1.34E-04 | 5.58E-04 |
| PM < 2.5 µm | kg | 1.32E-04 | 5.49E-04 |
| **$^{238}U$** | kbq | 1.02E-04 | 4.26E-04 |
| **$^{232}Th$** | kbq | 7.67E-06 | 3.19E-05 |
| **$^{226}Ra$** | kbq | 8.29E-05 | 3.45E-04 |
| **$^{40}K$** | kbq | 3.95E-09 | 1.65E-08 |
| **Cd** | kg | 9.39E-09 | 3.91E-08 |

## 2.3 Output table of the unit process 'mining operations' and 'wet beneficiation'

Table 3: LCI output data for the production of 1 kg $P_2O_5$ from open-pit mining and wet beneficiation in Gafsa-Tunisia

| Output | Unit | Total | Mining | Beneficiation |
|---|---|---|---|---|
| **Emission to air** | | | | |
| **Carbon monoxide** | **kg/kg** | 4.46E-02 | 4.46E-02 | |
| **Nitrogen monoxide** | **kg/kg** | 2.39E-01 | 2.39E-01 | |
| **Cadmium** | **kg/kg** | 1.37E-06 | 1.37E-06 | |
| ***Particulate Matter*** | | | | |
| **Particulates, <10 um** | **kg/kg** | 2.16E-03 | 2.12E-03 | |
| **Particulates, > 2.5 um, and < 10um** | **kg/kg** | 1.13E-02 | 1.07E-02 | |
| **Particulates, < 2.5 um** | **kg/kg** | 2.79E-03 | 1.08E-03 | |
| ***Radioactive*** | | | | |
| **Uranium-238** | **kBq/kg** | 1.49E-02 | 1.49E-02 | |
| **Thorium-232** | **kBq/kg** | 1.12E-03 | 1.12E-03 | |
| **Radium-226** | **kBq/kg** | 1.21E-02 | 1.21E-02 | |
| **K-40** | **kBq/kg** | 2.28E-03 | 2.28E-03 | |
| **Emission to water** | | | | |
| **Fluorine** | **mg/kg** | 3.09E+02 | | 3.09E+02 |
| **Sulfate** | **mg/kg** | 1.69E+04 | | 1.69E+04 |
| **Phosphate PO4** | **mg/kg** | 1.63E+02 | | 1.63E+02 |
| **Nitrate NO3** | **mg/kg** | 1.16E+02 | | 1.16E+02 |
| **Nitrite NO2** | **mg/kg** | 1.00E+02 | | 1.00E+02 |
| **Cd** | **mg/kg** | 6.56E-02 | | 6.56E-02 |
| **Pb** | **mg/kg** | 6.56E-03 | | 6.56E-03 |
| **Zn** | **mg/kg** | 3.48E-01 | | 3.48E-01 |
| **Emission to soil** | | | | |
| **Cd** | **mg/kg** | 2.46E+01 | | 2.46E+01 |
| **lead** | **mg/kg** | 4.15E+00 | | 4.15E+00 |
| **U** | **mg/kg** | 2.86E+01 | | 2.86E+01 |
| **Zn** | **mg/kg** | 2.58E+02 | | 2.58E+02 |
| **U 234** | **kBq/kg** | 4.29E+01 | | 4.29E+01 |
| **U238** | **kBq/kg** | 1.43E+01 | | 1.43E+01 |

## 2.4 Particulate matter emission of the unit process 'mining operations'

Table 4: Particulate matter emission factor g/metric ton of crude phosphate rock according to the EEA calculation model (European Environmental Agency 2019b, 2019a), the composition of Total Suspended Particles (TSP) (%), and Gafsa mining weather conditions

| Process step | Emission Factor g/metric ton | | | Data source |
|---|---|---|---|---|
| | TSP% | PM-10% | PM-2.5% | |
| **Blasting/drilling** | 100% | 53% | 52% | CPG Internal data(Direction of the sector Metlaoui-Kef Schfaier 2017a, 2017b) (Direction of Accounting 2017, 2018)/ US EPA,1998 (U.S. Environmental Protection Agency 1998) |
| | **15** | **8.1** | **8.0** | |
| **Material processing: Dry crushing and grinding without filtering** | 100% | 35% | 5% | CPG Internal data (Direction of the sector Metlaoui-Kef Schfaier 2017a, 2017b) (Direction of Accounting 2017, 2018)/ US EPA,1998 (U.S. Environmental Protection Agency 1998) |
| | **2.1** | **0.77** | **0.09** | |
| **Transportation between sites: transport of crude PR and transport of overburden** | 100% | 29% | 3% | EPA unpaved road (U.S. Environmental Protection Agency) |
| | **6,575** | **1,889** | **191** | |
| **Material handling: trucks and Dumper loading and unloading** | 100% | 47% | 7% | CPG Internal data (Direction of Accounting 2017; Direction of the sector Metlaoui-Kef Schfaier 2017b)/ USEPA,1998 (U.S. Environmental Protection Agency) |
| | **0.71** | **0.33** | **0.051** | |
| **Total Emission factor excluding the blasting/drilling** | 100 | 29% | 3% | |
| | **6,578** | **1,890** | **191** | |