INTEGRATION OF SCALE-UP AND LCA TO OPTIMIZE THE ENVIRONMENTAL LOAD AND ENERGY CONSUMPTION OF GRINDING PROCESSES BY INTRODUCING NEW EMISSION FACTORS

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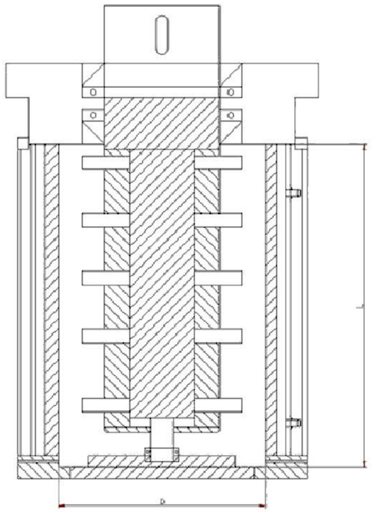
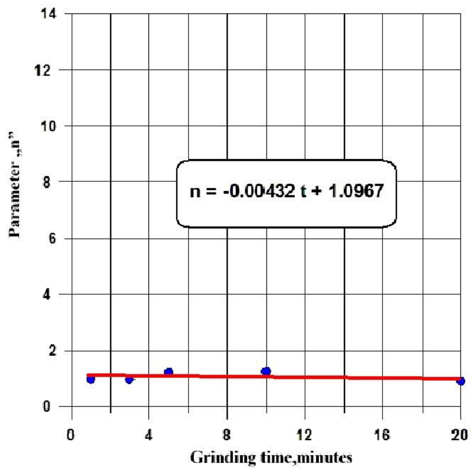
THE CCUV4 WORKSHOP IN LODZ
31. MAY 2023

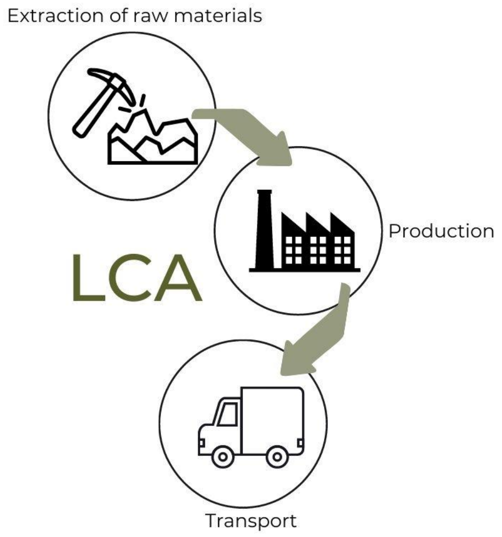


$$F(\xi) = 1 - \exp\left[-\left(\frac{\xi}{4{,}252}\right)^{1{,}098}\right]$$

$$x_{50} = \frac{7{,}38}{W_r^{0{,}19}}$$

$$A = f\left(\frac{w_k}{d_k}, \frac{D_m}{d_k}, \frac{d_g}{d_k}, c_m, \varphi_m\right)$$





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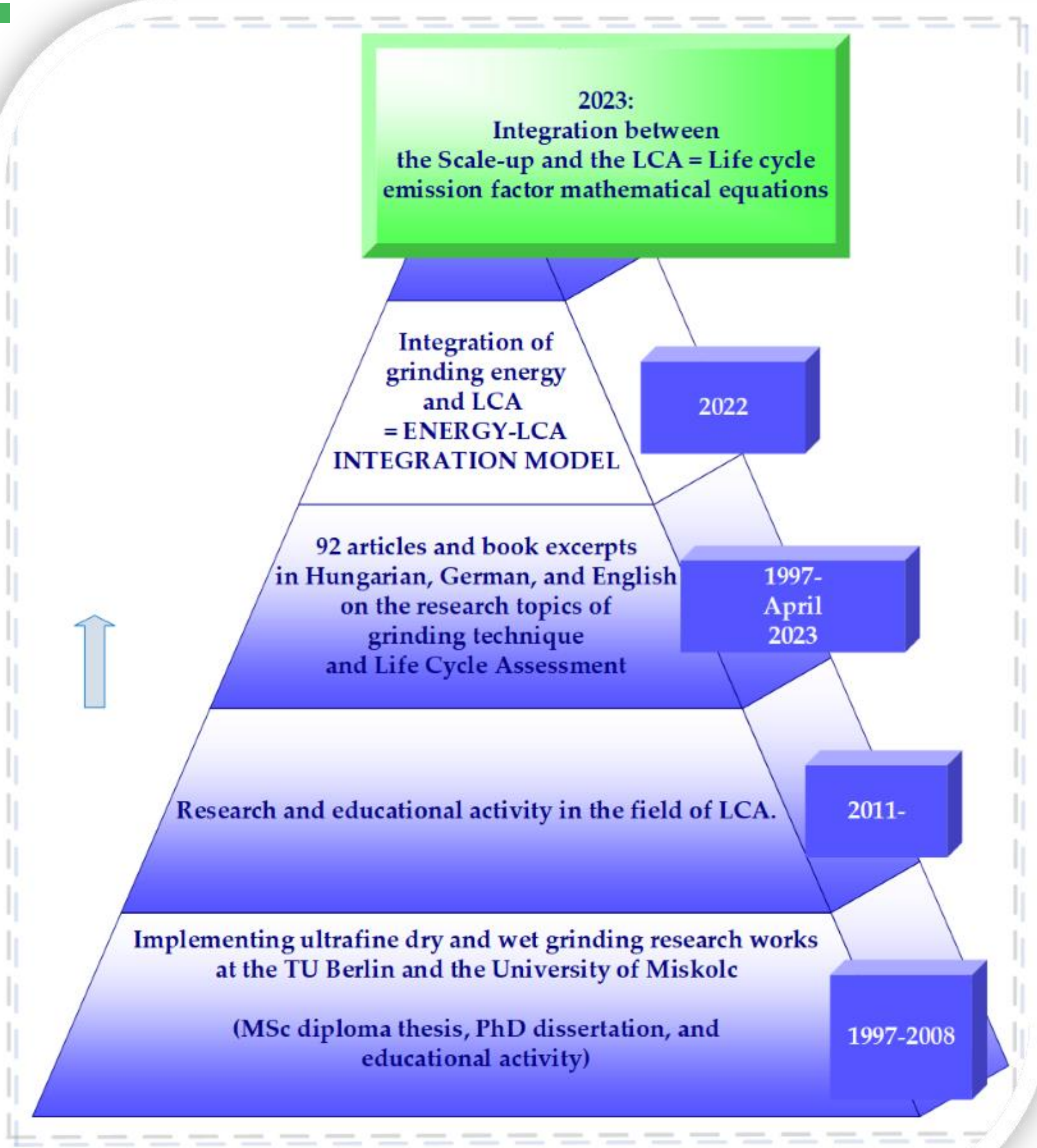
Visegrad Fund
The project is supported by The International Visegrad Fund, project ID22120032.

RESEARCH GOALS

- Determination of the main grinding parameters for limestone and pumice dry grinding in a Bond-mill.
- Description of empirical particle size distribution functions and specific energy consumption for wet grinding.
- Mathematical description of the relationships between grinding fineness, grinding time, and specific grinding work.
- Life Cycle Assessment for wet grindings using GaBi software.
- Scale-up setup for wet grinding with dimensional analysis.
- Development of Energy-LCA and Scale-Up-LCA integration methodologies.
- Mathematical description of the Energy-LCA (for wet limestone grinding) and the Scale-Up-LCA integration models (for wet pumice grinding).



RESEARCH HISTORY

Visegrad Fund

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DRY GRINDING OF LIMESTONE IN A LABORATORY BOND-MILL

$$W_{iB} = \frac{4.9}{{x_{max}}^{0.23} \cdot G^{0.82}\left(\frac{1}{\sqrt{x_{80}}} - \frac{1}{\sqrt{X_{80}}}\right)}$$

$$HGI = 13 + 6.93 \cdot m_H$$

$$W_{iB^H} = \frac{435}{HGI^{0.82}}$$

- During Bond grinding, the median particle size of the ground limestone is 65 µm.
- The **Bond Work Index (W_{iB})** is 14.45 kWh/t.
- During the **Hardgrove Grindability Index (HGI)** determination:
  - The 50–50 g limestone samples from the 0.63–1.25 mm and 50–100 µm particle size fractions were ground for rpm.
  - The ground material was sieved through 0.071 mm.
  - Using the standard Hardgrove formula, the calculated value of the HGI is 73.74.
- The **Bond Operating Index (W_{iB^H})** was estimated based on the HGI, 12.79 kWh/t.

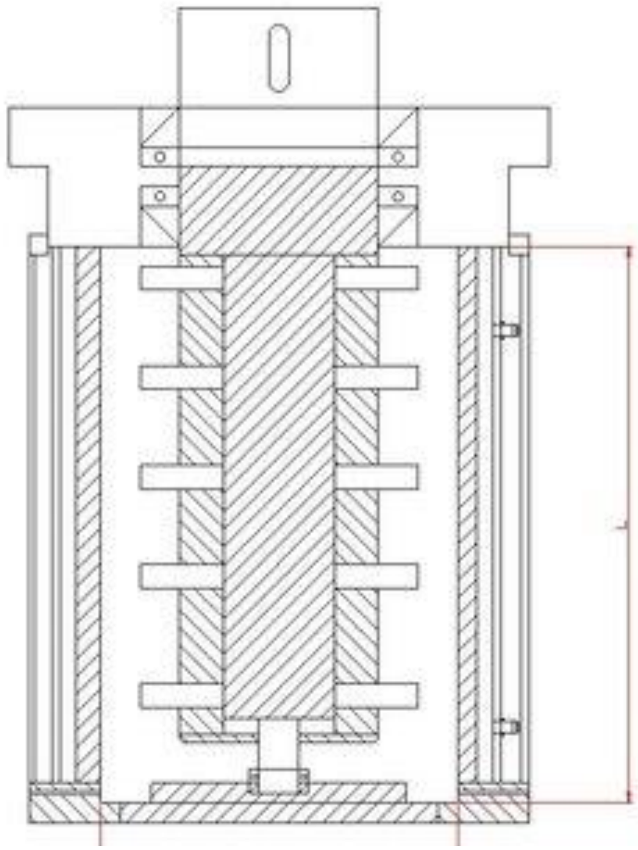
DRY GRINDING OF PUMICE IN A LABORATORY BOND-MILL

During Bond grinding, the median particle size of the ground pumice is 70.5 μm.

Grinding parameters	Value
Bond Work Index Wi_B, $kWh \cdot t^{-1}$	8.69
Hardgrove Grindability Index HGI, -	114.21
Bond Operating Index Wi_B^H, $kWh \cdot t^{-1}$	8.94

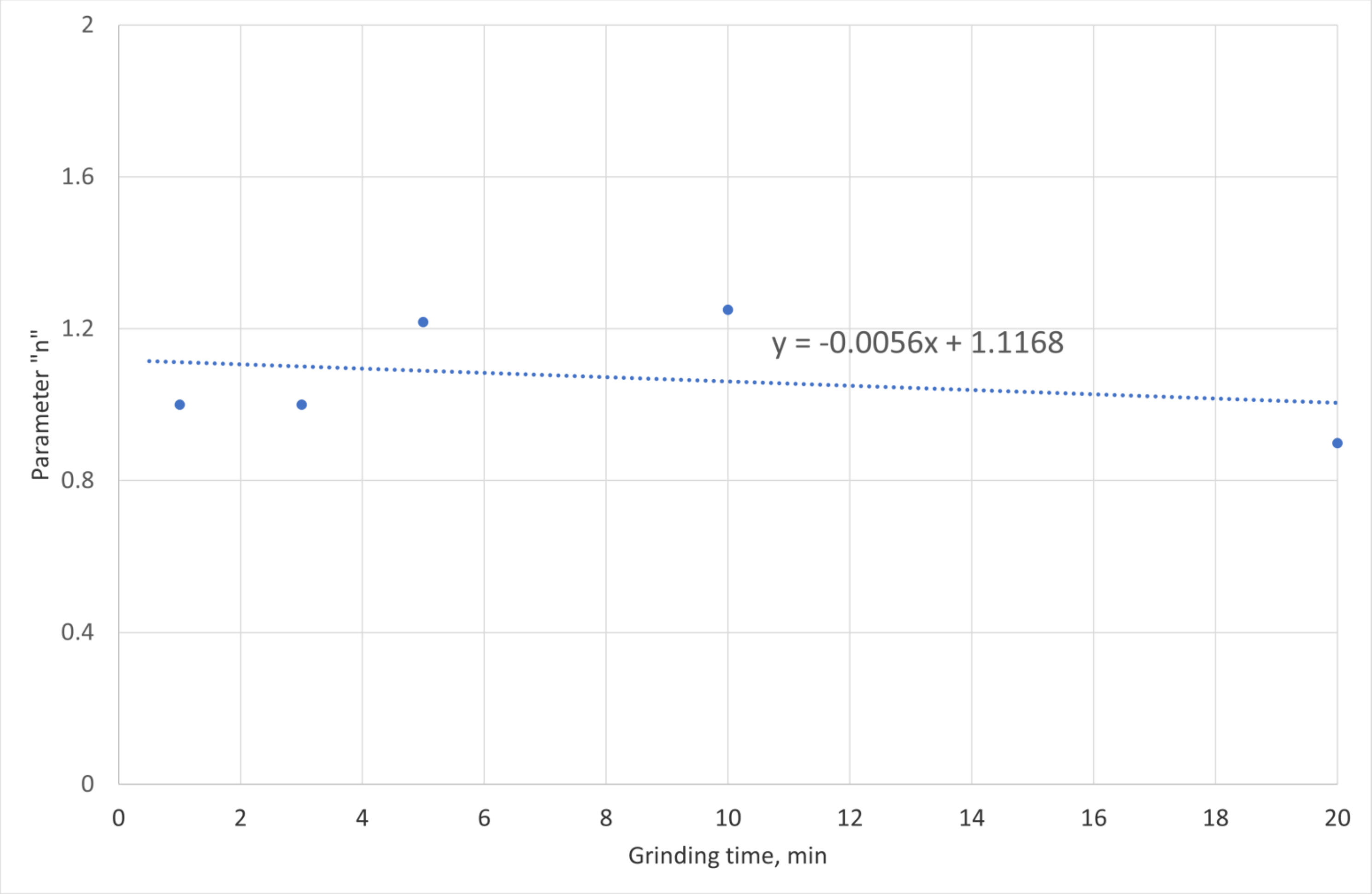
WET GRINDING OF LIMESTONE IN A LABORATORY STIRRED BALL MILL

- After 20 minutes of grinding, the limestone product has a median particle size of 1.76 μm and a maximum particle size of 9.6 μm (at 70% mill filling ratio, 1440 rpm stirrer speed, and 20% solid mass concentration).



Name		Grinding Time (min)			
	1	3	5	10	20
Parameter "*a*", μm	12	6.2	4.435	3.932	4.337
Exponent "*n*", -	1.0	1.0	1.217	1.250	0.899
Relative standard deviation, *RSD*, %			0.002	0.003	0.048
	Solid mass concentration c_m, 20%				
Median particle size x_{50}, μm	Filling ratio φ_m, 70%		2.43	2.07	1.76
Maximum particle size x_{max}, μm			26.96	21.88	9.60
Weight fraction < 5 μm, %			80.1	85.52	91.91
Weight fraction < 1.1 μm, %			18.99	23.31	27.54
	Solid mass concentration c_m, 20%				
Median particle size, μm	Filling ratio φ_m, 80%		2.24	1.68	1.64
Maximum particle size x_{max}, μm			24.55	22.50	8.70
Weight fraction < 5 μm, %			82.54	90.98	92.42
Weight fraction < 1.1 μm, %			20.93	29.53	30.72

EMPIRICAL MODELING: VALUES OF EXPONENT "N" AS A FUNCTION OF GRINDING TIME (LIMESTONE)



$$\mathbf{F(x) = 100\left[1 - \exp\left[-\left(\frac{x}{a}\right)\right]^{n}\right.} \qquad (1)$$

$$n = -0.00432\, t + 1.098 \qquad (2)$$

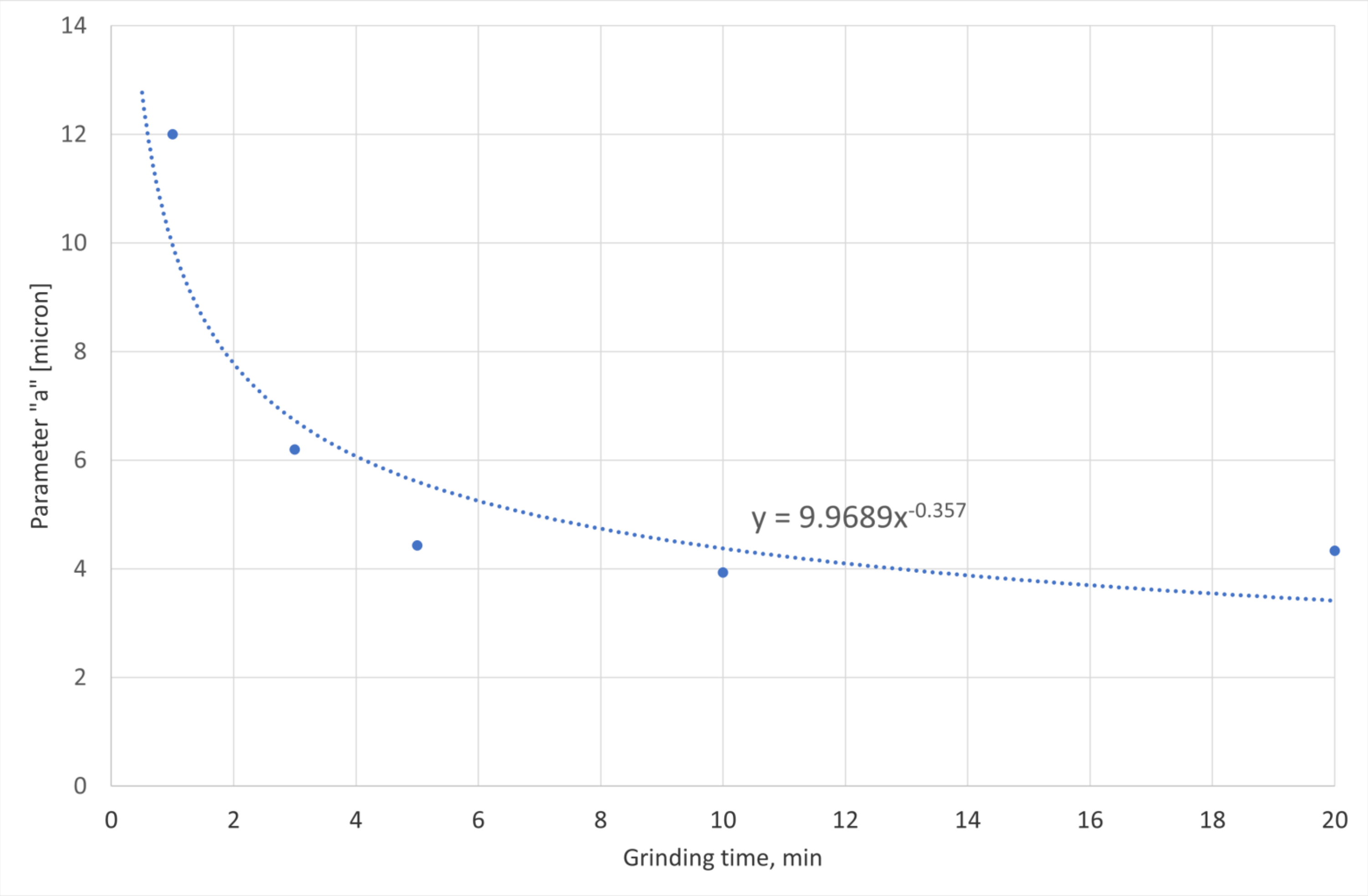
Eq. (1) :

particle size distribution in general, where the parameter "a" is the particle size at which 63.2% of the ground particles are finer, "n" is the standard deviation and "x" is the relative particle size.

Eq. (2):

Determination of the exponent "n".

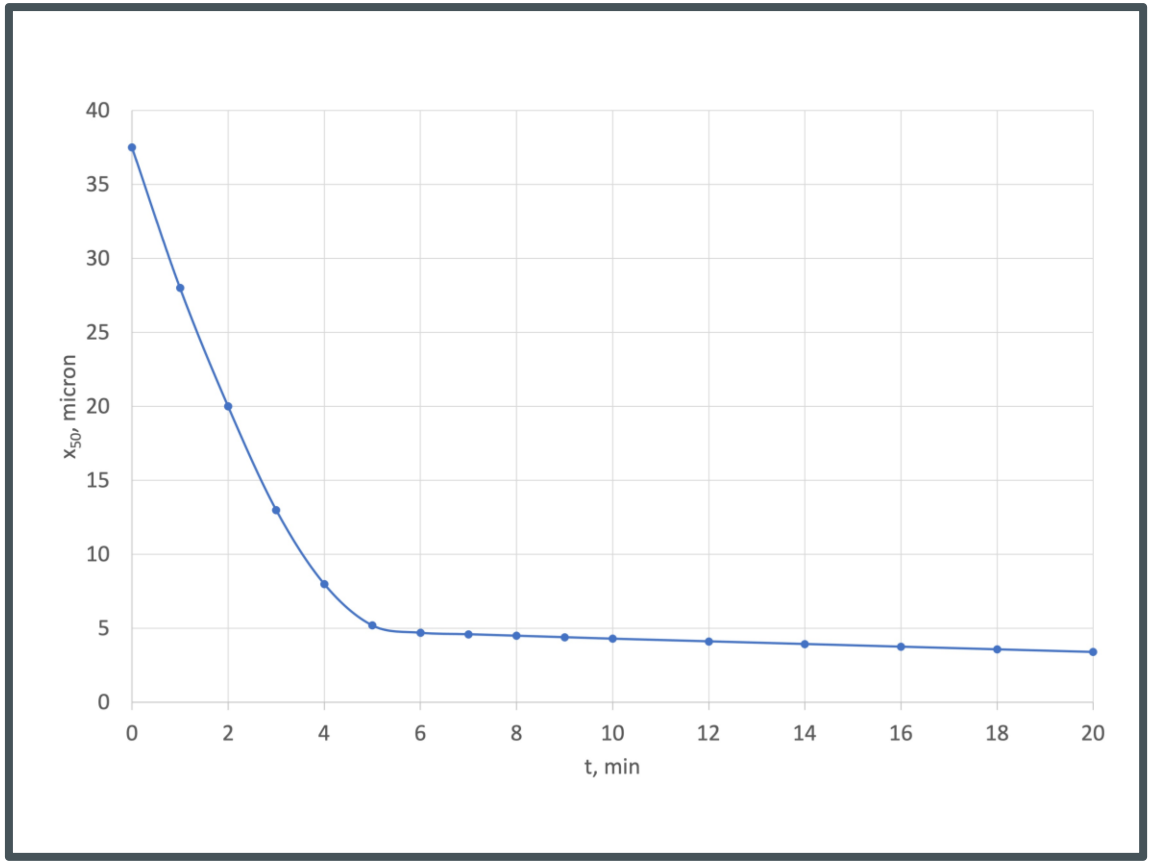
EMPIRICAL MODELING:
PARAMETER „A" AS A FUNCTION OF GRINDING TIME (LIMESTONE)



- While the exponent "n" value can be described almost linearly, the parameter "a" shows a decreasing trend as the grinding time increases.
- Calculated values:
  - a = 4.252 µm
  - n = 1.098.

$$F(x) = 100[1 - exp\left[-\left(\frac{x}{4{,}252}\right)\right]^{1{,}098}$$

WET GRINDING OF **PUMICE** IN A LABORATORY STIRRED BALL MILL



The median particle size-grinding time function.

WET GRINDING RESULTS (PUMICE)

The relation between the median particle size (x_{50}) and the specific grinding work (W_f) can be described mathematically based on the Grindability Index number (GI) with the following equation:

$$x_{50} = GI/W_f^{0.19}$$

Mill filling ratio: 70%
Stirrer speed: 1440 1/min
Solid mass concentration: 20%

	5 minutes	10 minutes	20 minutes
Median particle size x_{50}, μm	5.00	4.46	3.4
Power consumption of mill P_m, kW	0.196	0.196	0.203
Specific grinding work W_f, $kWh \cdot t^{-1}$	423	846	1758

„GRINDING FINENESS - SPECIFIC GRINDING WORK" FUNCTIONS

(MARKINGS: **+ LIMESTONE** ▲ ANDESITE ○ **PUMICE** ×MINING TAILINGS ORE)

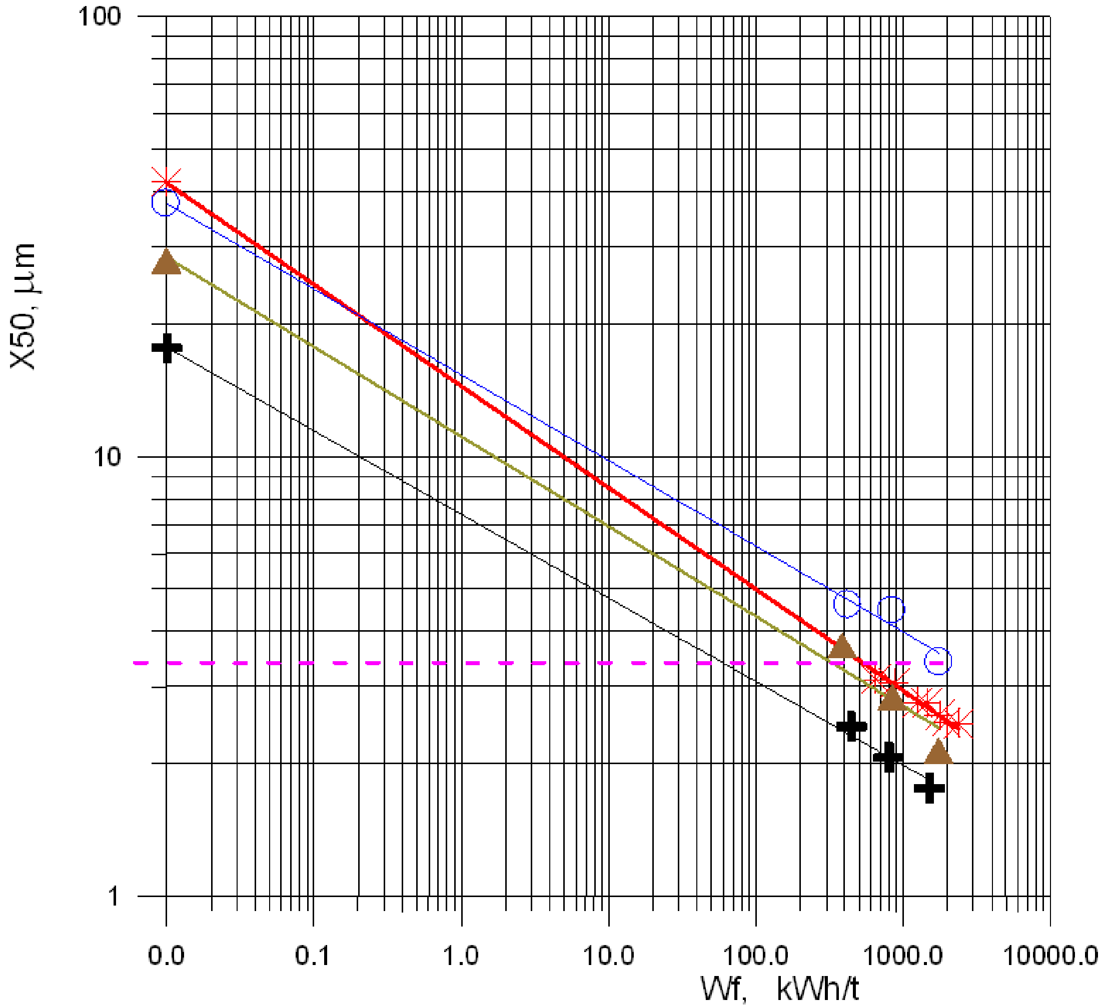


Fig.3 Relation between the grinding fineness and specific grinding work for several materials

Regarding the wet grindings, the Grindability Index numbers are:

GI = 15.32 (pumice) and **GI = 7.38 (limestone)**

- The relationships between grinding fineness and specific grinding work can be described as follows:

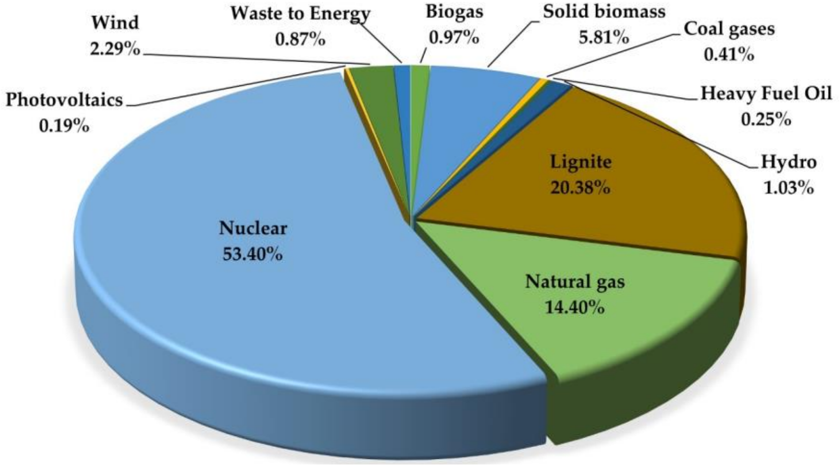
$$x_{50} = 7.38/W_f^{0.19} \quad \text{(limestone)}$$

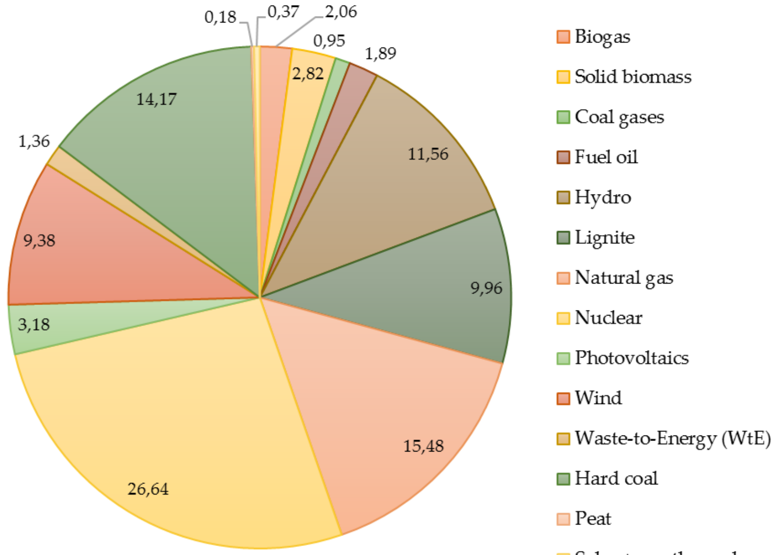
$$x_{50} = 15.32/W_f^{0.19} \quad \text{(pumice)}$$

- The specific grinding energy can be determined from the mill output of 178 Nm/s (limestone) and 203.58 Nm/s (pumice).
- Specific grinding work: 1515 kWh/t (limestone).
- (All values are measured at 70% mill filling ratio, 1440 rpm, and 20% solid mass concentration).

RESEARCH METHODOLOGY FOR THE LIFE CYCLE ASSESSMENT

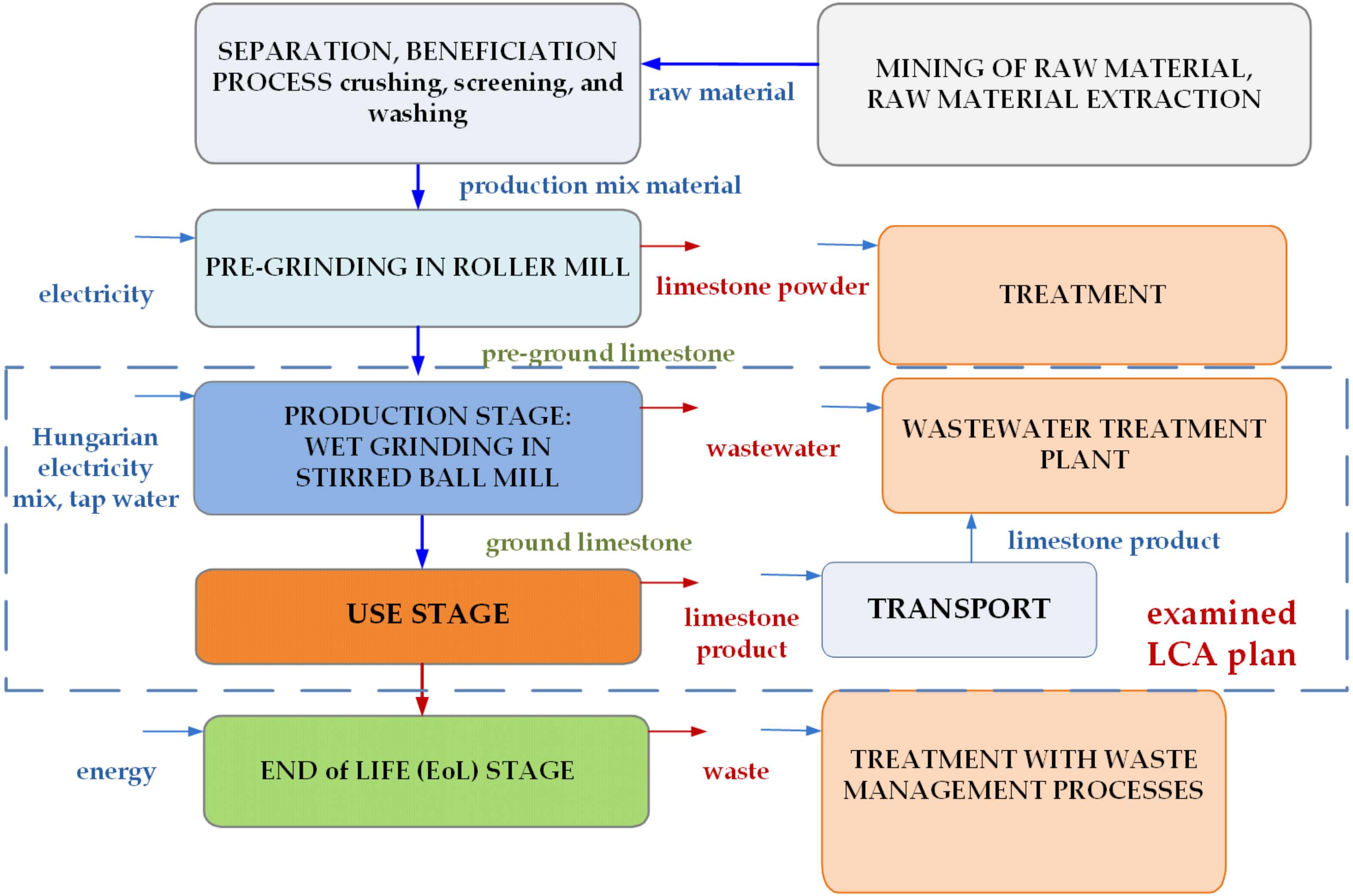
- Application of the Hungarian and EU energy mixes.
- Wastewater is treated at a municipal wastewater treatment plant.
- The ground materials are transported by truck.
  (Euro 6, EU-28 diesel mix)
- Assumed delivery distance: 100 km
- Transport utilization: 80%.





Hungarian and EU energy mixes, 2018 (source: GaBi 8.0 software)

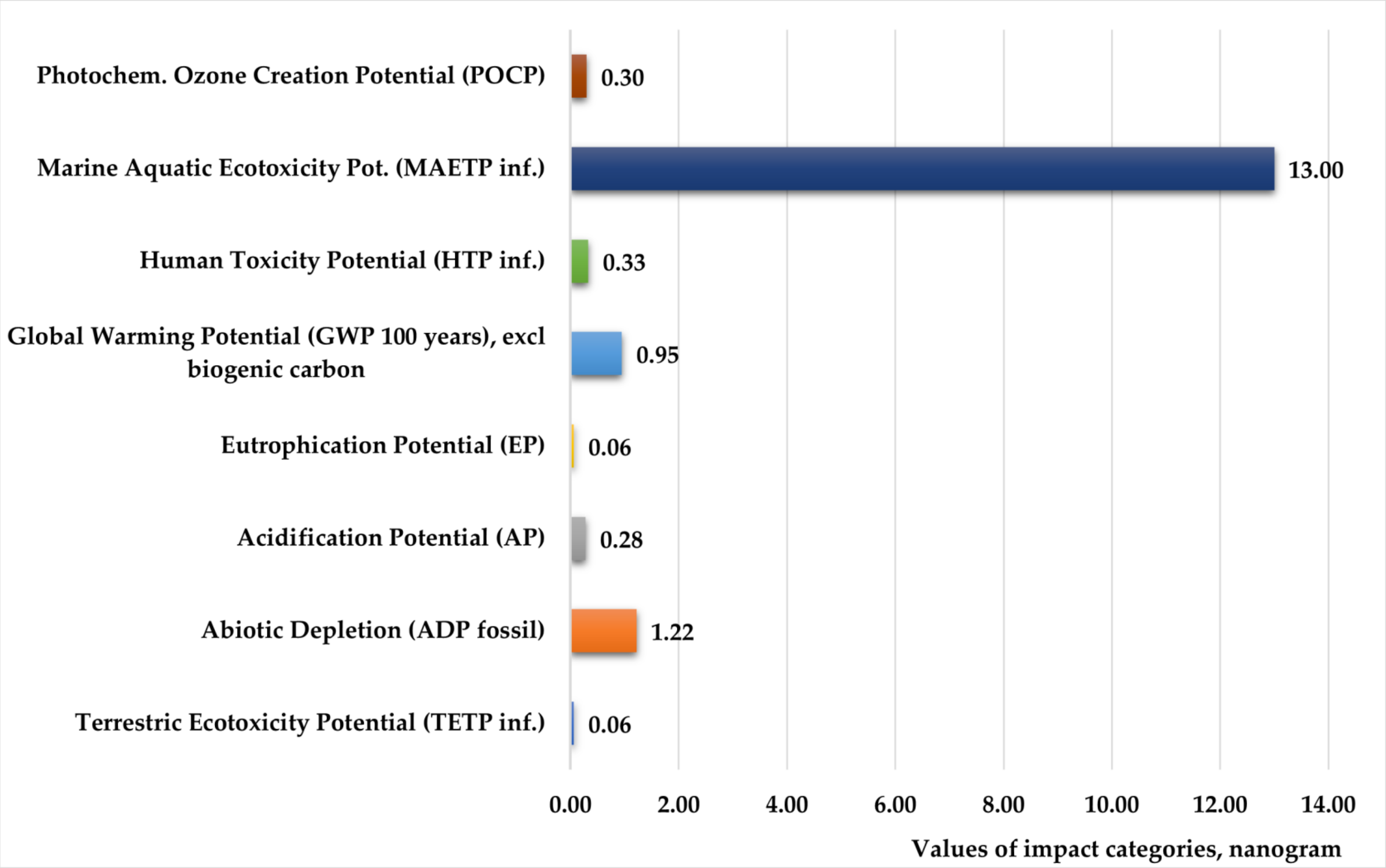
LIFE CYCLE ASSESSMENT MODEL FOR WET GRINDING OF LIMESTONE



„CRADLE-TO-GATE" LIFE CYCLE ASSESSMENT

Ocean-going and inland ship transport as well as rail, truck and pipeline transport of bulk commodities are considered.

WET GRINDING LCA RESULTS (LIMESTONE) – **MAIN ENVIRONMENTAL IMPACTS [NG]**

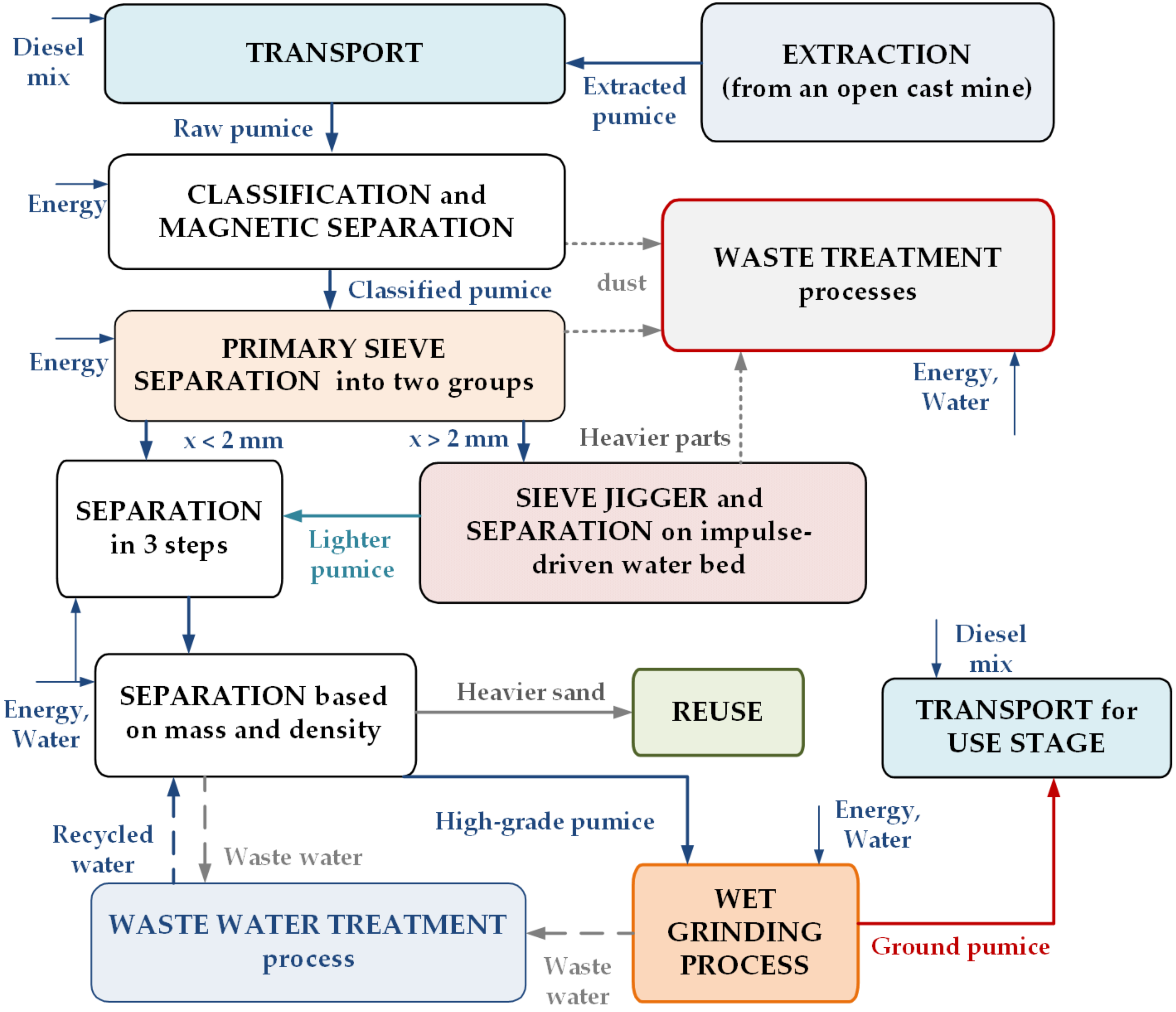


Normalization method:
CML 2016, EU 28, year: 2000.

Weighting method:
CML 2016, EU, thinkstep LCIA, 2012

The value of the primary energy produced is 16.73 MJ (of which 2.23 MJ comes from renewable energy sources). Regarding emissions, discharge into fresh water is the highest (56%) - in the case of limestone testing.

LIFE CYCLE ASSESSMENT MODEL FOR WET GRINDING OF PUMICE



ENERGY-LCA INTEGRATION MODEL FOR LIMESTONE WET GRINDING I.

$$F(xi) = 100\left[1 - exp\left[-\left(\frac{x_i}{4{,}252}\right)\right]^{1{,}098}\right] \quad (1)$$

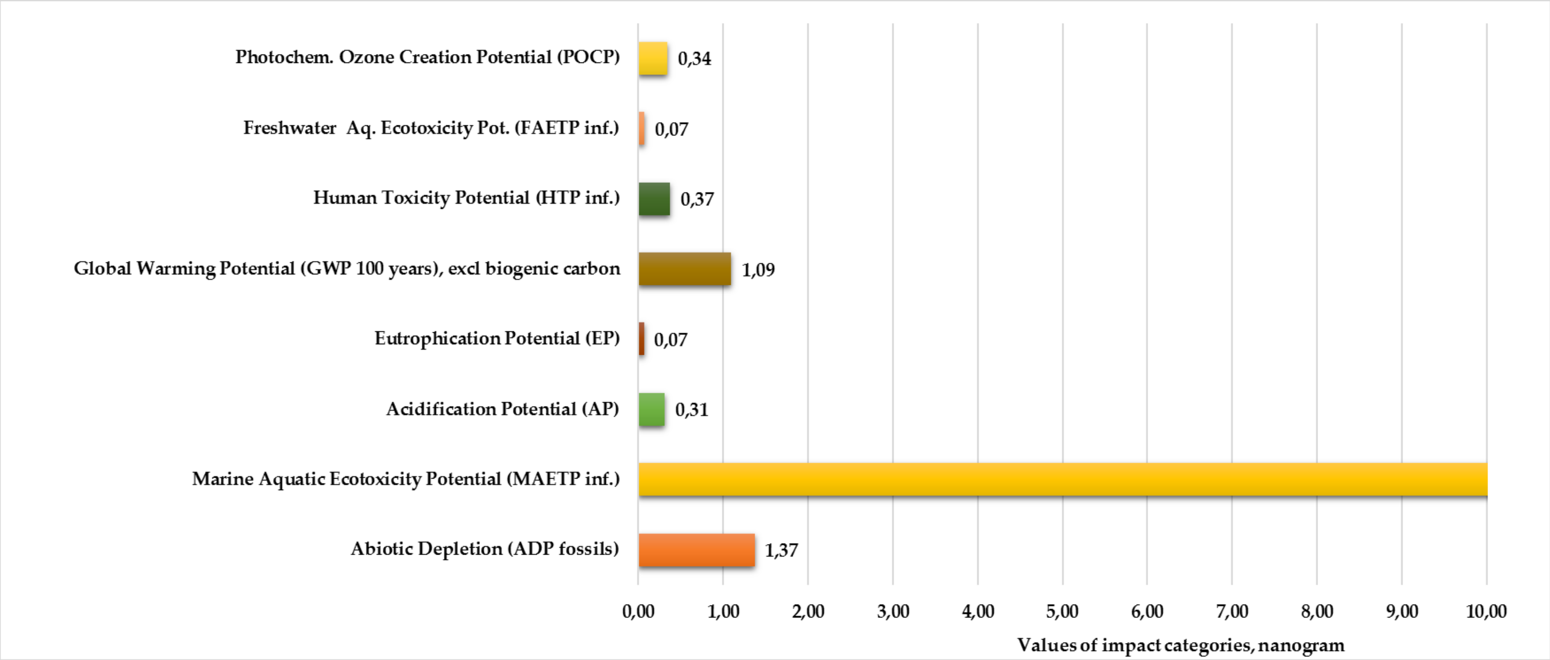
$$m_{xi} = m_p \cdot F(xi) = m_p \cdot \left[1 - exp\left[-\left(\frac{x_i}{a}\right)\right]^n\right] \quad (2)$$

$$Q_{xi} = \frac{m_{xi}}{t_r} = \frac{m_p \cdot F(xi)}{t_r} = \frac{m_p \cdot \left[1 - exp\left[-\left(\frac{x_i}{a}\right)\right]^n\right]}{t_r} \quad (3)$$

$$SEC_{xi} = \frac{EC}{m_{xi}} = \frac{Q_{xi}}{P} \quad (4)$$

- Eq. (2) describes the mass of the useful product - $\mathbf{m_{xi}}$, given the estimated particle size distribution of the limestone product, where $\mathbf{m_p}$ is the total output mass of the grinding process.
- Eq. (3) gives the capacity per useful product - $\mathbf{Q_{xi}}$ (in t/h) from the quotient of useful product weight and grinding time - $\mathbf{t_r}$.
- Eq. (4) describes the specific energy per useful product - **SECxi** (in kWh/t), where **EC** is the total energy consumption for the total output mass (in kWh) and **P** is the average power consumption.
- If we assume that the functional unit (FU) is the mass of the useful product **(FU = $\mathbf{m_{xi}}$)** (for example, only limestone particles below 1.5 µm), then we can model the change of environmental impacts on the specific energy per useful product **($\mathbf{SEC_{xi}}$)**.

WET GRINDING LCA RESULTS (PUMICE) – **MAIN ENVIRONMENTAL IMPACTS [NG]**



Normalization method:
CML 2016, EU 28, year: 2000.

Weighting method:
CML 2016, EU, thinkstep LCIA, 2012

The relative contribution of environmental impacts is 80% from marine aquatic ecotoxicity, 7.3% from fossil abiotic depletion, 5.8% from global warming, 2% from human toxicity, and 1.7% from acidification.

ENERGY-LCA INTEGRATION MODEL FOR LIMESTONE WET GRINDING II.

$$\mathbf{x_{50} = 7.38/W_f^{0.19}}$$

$$\boldsymbol{EC = W_f \cdot m_p} = \sqrt[0,19]{\frac{GI}{x_{50}}} \cdot m_p = m_p \cdot \sqrt[0,19]{\frac{GI}{a\ln(2)^{\frac{1}{n}}}}$$

$$SEC_{xi} = \frac{EC}{m_{xi}} = \frac{m_p \cdot \sqrt[0,19]{\frac{GI}{a\ln(2)^{\frac{1}{n}}}}}{m_p \cdot F(xi)} = \frac{\sqrt[0,19]{\frac{GI}{a\ln(2)^{\frac{1}{n}}}}}{1 - exp\left[-\left(\frac{x_i}{a}\right)\right]^n}$$

- The **total energy consumption (EC)** for the wet grinding of limestone can be written using the specific grinding work <u>derived from the grinding fineness-specific grinding work function</u> previously written.

In the results of the LCA, we can obtain the environmental effects related to the mass of the useful product/$\mathbf{m_{xi}}$ for the different specific energy levels. We can also add an approximate function to this, which can be used to obtain, for example, the **<u>CO_2 emission potential per kg of useful product function as a function of specific energy</u>**.

SCALE-UP-LCA INTEGRATION MODEL FOR PUMICE WET GRINDING I.

$$P_m = A \cdot {d_d}^5 \cdot n^3 \cdot \rho_s \left(\frac{{d_d}^2 n \rho_s}{\eta}\right)^{-m} \cdot \left(\frac{d_d n^2}{g}\right)^{-n} \cdot \left(\frac{w_k}{d_d}\right)^{c} \cdot \left(\frac{D_m}{d_d}\right)^{e} \cdot \left(\frac{d_b}{d_d}\right)^{f}$$

$$P_{m(ind)} = P_{m(\mathrm{lab})}\ P_{m(ind)} = P_{m(\mathrm{lab})}$$

$$\frac{A \cdot {n_{(ind)}}^3 {d_{d(\mathrm{ind})}}^5 \rho_s}{d_{d(ind)})^3} = \frac{A \cdot {n_{(lab)}}^3 {d_{d(lab)}}^5 \rho_s}{{d_{d(lab)}}^3}$$

$$n_{(ind)} = n_{(lab)} \left(\frac{d_{(lab)}}{d_d}\right)^{\frac{2}{3}} = n_{(lab)} \cdot k^{-\frac{2}{3}} = n_{(lab)} \left(\frac{1}{k}\right)^{\frac{2}{3}}$$

- The dimensional analysis method determined the stirred media mill power consumption (P_m) for scale-up.
- If the industrial stirred media mill and the laboratory stirred media mill have similar geometric proportions (w_d/d_d, D_m/d_d and d_b/d_d), the scale-up can be designed for the laboratory stirred media mill based on laboratory measurements.
- The <u>first aspect</u> is that the power consumption per unit volume remains unchanged. The <u>second viewpoint</u> is that the circumferential speed of the stirrer is constant.
- The stirrer speed for the industrial stirred media mill can be given by knowing the laboratory stirrer speed if *A* and **r** are equal. <u>Constant "k" is the scale for the industrial and laboratory sizes.</u>

SCALE-UP-LCA INTEGRATION MODEL FOR PUMICE WET GRINDING II.

$$W_x = \sum_{i=1}^{n} (X_i \cdot P_i)$$

$$W_{x(lab)} = m_{w(lab)} \cdot t_r \cdot X_w + Q_{r(lab)} \cdot t_r \cdot X_p + EC_{(lab)} \cdot X_E + m_{ww(lab)} \cdot t_r \cdot X_{ww} + m_{t(lab)} \cdot X_t$$

$$W_{x(ind)} = m_{w(ind)} \cdot t_r \cdot X_w + Q_{r(ind)} \cdot t_r \cdot X_p + EC_{(ind)} \cdot X_E + m_{ww(ind)} \cdot t_r \cdot X_{ww} + m_{t(ind)} \cdot X_t$$

- The **W_x** life cycle emission factor can be expressed as a general relationship where X_i – unit emission factor for the material/process, in units, e.g., kg CO_2/kg of material kg/m^3 and P_i – number of units, e.g., volume, mass, etc. of materials/processes within the analysed system.

m_w - water mass in the grinding process, kg/h

X - unit emission factors

Q_r– efficiency/capacity of grinding pumice, kg /h

t_r - grinding time, h

EC - energy consumption for grinding of the material, kWh

m_{ww} – the mass of wastewater for grinding, kg/h

m_t – the mass of used fuel during the transport of the obtained product

SCALE-UP-LCA INTEGRATION MODEL FOR PUMICE WET GRINDING III.

$$\frac{m_{w(ind)}}{m_{w(lab)}} = \boldsymbol{C} \Rightarrow m_{w(ind)} = C \cdot m_{w(lab)}$$

$$\frac{Q_{r(ind)}}{Q_{r(lab)}} = \boldsymbol{K} \Rightarrow Q_{r(ind)} = K \cdot Q_{r(lab)}$$

$$\frac{EC_{(ind)}}{EC_{(lab)}} = \boldsymbol{S} \Rightarrow EC_{(ind)} = S \cdot EC_{(lab)}$$

$$\frac{m_{ww(ind)}}{m_{ww(lab)}} = \boldsymbol{F} \Rightarrow m_{ww(ind)} = F \cdot m_{ww(lab)}$$

$$\frac{m_{t(ind)}}{m_{t(lab)}} = \boldsymbol{G} \Rightarrow m_{t(ind)} = G \cdot m_{t(lab)}$$

- C, K, S, F and G - **constants** representing the scale-up of the mill depend on the external dimensions of the mill and can be expressed by the constant k derived is the scale for the industrial and laboratory sizes.

SCALE-UP-LCA INTEGRATION MODEL FOR PUMICE WET GRINDING IV.

$$Q_r = \frac{m_p}{t_r} \qquad EC = P_{m,t} \cdot t_r \qquad m_t = \frac{m_p}{W_t} \cdot U_D \cdot D$$

$$W_{x(ind)} = C \cdot m_{w(lab)} \cdot X_w + K \cdot m_{p_{(lab)1h}} \cdot X_p + S \cdot P_{m,t(lab)} \cdot X_E + F \cdot m_{ww(lab)} \cdot X_{ww} + G \cdot \frac{m_{p(lab)1h}}{W_t} \cdot U_D \cdot D \cdot X_t$$

- m_p - mass of the ground material
- $P_{m,t}$ - average total power consumption during grinding
- W_t - load capacity of the transport
- U_D - unit fuel consumption
- D - the distance the vehicle must travel to reach its destination

CONCLUSIONS

- The integration models indicate the grinding technological solutions that meet the expectations of sustainable development by having more significant energy efficiency and lower environmental impacts.
- The input material mass, energy consumption, and grinding parameters strongly influence the environmental impact of limestone and pumice products during their life cycles.
- The most significant environmental impact comes from the use of electricity and the preparation of raw materials.
- This research establishes new models (which have not been known until now), enabling the preparation of forecasts for industrial grinding processes and improving grinding systems' energy and environmental efficiency.

PUBLICATION RESULTS IN THIS RESEARCH TOPIC

V. Mannheim, W. Kruszelnicka (2022) Energy-Model and Life Cycle-Model for Grinding Processes of Limestone Products, Energies 15, no. 10: 3816.

DOI: 10.3390/en15103816.

published on May 2, 2022

V. Mannheim, W. Kruszelnicka (2023) Relation between Scale-Up and Life Cycle Assessment for Wet Grinding Process of Pumice

was accepted for publication on 30 May 2023

energies

an Open Access Journal by MDPI

Indexed in: Ei Compendex

CITESCORE 5.0

IMPACT FACTOR 3.252

CERTIFICATE OF ACCEPTANCE

Certificate of acceptance for the manuscript (**energies-2368538**) titled:

Relation between Scale-Up and Life Cycle Assessment for Wet Grinding Process of Pumice

Authored by:

Viktoria Mannheim; Weronika Kruszelnicka

has been accepted in *Energies* (ISSN 1996-1073) on 30 May 2023

MDPI Academic Open Access Publishing since 1996

Basel, May 2023

Thank you very much for your attention!

Děkuji za pozornost!

Dziękuję za uwagę!

Ďakujem za tvoju pozornosť!

Köszönöm szépen a figyelmet!

Visegrad Fund

The project is supported by The International Visegrad Fund, project ID22120032.

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