

# Towards Framework Development for Benchmarking Energy Efficiency in Foundation Industries: A Case Study of Granulation Process

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## Abstract

The manufacturing sector depends mainly on the foundation industries which have a major contribution to the country's economy. These foundation industries include glass, metals, ceramics, cement, paper and chemical sectors that support the demands of our modern lives. On the other hand, these industries are energy intensive. Energy requirements in foundation industries can be improved by benchmarking and comparing the actual energy consumption of individual processes with their theoretical minimum value. In this study, an energy taxonomy approach has been used to identify the elements responsible for energy consumption in the granulation process. Bond's law has been used to calculate the theoretical minimum energy consumption of one such individual process i.e., granulation - A common process among the foundation industries which accounts for an average of 50% of the total energy consumption. A framework has also been developed that can be used by foundation industries to benchmark their energy efficiency and that provides an insight into the practical and theoretical potential for reducing their energy requirements.

**Keywords:** Benchmarking; Energy efficiency; Foundation industries; Manufacturing; Theoretical minimum.

## 1 Introduction

Manufacturing sector is the backbone of the economic output of a country. On the other hand, it is responsible for 38% of global energy consumption [1]. The manufacturing sector can be split into energy-intensive industries and non-energy-intensive industries based on their energy usage [2]. Food and electronics industries are examples of non-energy-intensive industries. On the other hand, energy-intensive industries include glass, metals, ceramics, cement, paper and chemical industries, also known as foundation industries. These industries provide essential commodities as well as a major contribution to the overall economy of a country. For instance, in the UK economy around £52 billion is contributed by the foundation industries [3]. In the last few decades, a growing trend has been observed in the manufacturing industry production in response to consumption per capita. Along with labour and raw material costs, energy is a major component of production costs in these "foundation" industries, driving a shift toward improved energy efficiency. Moreover, global environmental concerns raise the focus on energy efficiency. According to IEA [4], energy efficiency is the most contributing factor towards reducing CO<sub>2</sub> emissions by up to 53%. Rogelij et al. [5] stated energy efficiency as one of the keys to retain the potential of keeping global warming to below 1.5°C.

Benchmarking is a traditional approach for identifying and prioritising particular opportunities to improve energy efficiency in the industry. It has been used in steel and iron [6], construction [7], automotive [8], glass [9] and majority of other processing industries [10], acknowledging the benefits of benchmarking in identifying energy efficiency improvements. Hagenbruch and Zeumer [11] provided a proven benchmarking approach for the steel industry. They also explained how benchmarking can produce useful data and provide performance transparency that creates sound discussions, which can result in new concepts and improved operating procedures. All of this contributes to creating an industrial culture that is focused on performance and improvement. The study concluded that while benchmarking is a widely used tool, many production businesses are sceptical of its practical application due to the difficulty in identifying reliable reference point for the evaluation of their performance versus a specified "best" standard.

Mahamud et al. [12] and Fresner and Krenn [13] recommended using the approach of theoretical minimum consumption calculation to support benchmarking as it can provide an unbiased reference for the specific manufacturing industry. The studies also suggested using the mentioned approach as a base point for looking for

ways to improve energy efficiency. The majority of industrial processes consume at least 50% more energy than the theoretical minimum defined by the fundamental rules of thermodynamics [4]. The theoretical minimum energy use is being approached by many countries, particularly in the chemical [14], cement [15] and metal [16] sectors. Although theoretical minimum energy consumption has been investigated as a target for energy reduction measures at the industry level, it has not been generally employed to direct energy reduction efforts at the process level, especially for energy-intensive processes, such as granulation.

Granulation could refer to a size enlargement process such as agglomeration, or to a size reduction such as crushing and grinding. This paper focuses on the size reduction aspect as it is one of the most important processes in the foundation industries. The energy efficiency of the granulation process is usually 5-10% only, with the rest being transformed to heat [4]. It is also an energy-intensive process; for instance, in a typical cement industry, 62% of overall power is consumed by the granulation process [17]. Determining and understanding the energy use of the manufacturing process is important to improve energy efficiency.

The majority of the published research offers benchmarking at the industry, factory, or machine level, which is unable to precisely predict the energy performance at the process level. Literature review reveals that theoretical energy consumption calculations can assist manufacturing industries in benchmarking their energy efficiency, a step toward energy efficiency improvements. From the ongoing studies, it is observed that little or no studies have been found reporting the theoretical minimum energy calculations for the granulation process. Moreover, there is no framework available to benchmark the energy efficiency of granulation process in the foundation industries. Therefore, this study aims to theoretically determine the minimum required energy for the granulation process based on Bond's law. An effort has also been made to develop a high-level framework to benchmark energy efficiency in foundation industries, focusing on the granulation process.

## 2 Energy Taxonomy

Energy is one of the most fundamental resources for manufacturing industries for future economic growth and prosperity. Its consumption is expected to continue to increase over the coming decades, with world energy demand estimated to be 45% higher in 2030 than today's levels [18]. The foundation industries were responsible for 59% of the total energy used by the manufacturing sector of the United States in 2018, as portrayed in figure 1. The data is obtained from the U.S Energy Information Administration (EIA) [19]. This highlights the need for energy management resources aiming at the foundation industries and their operations.

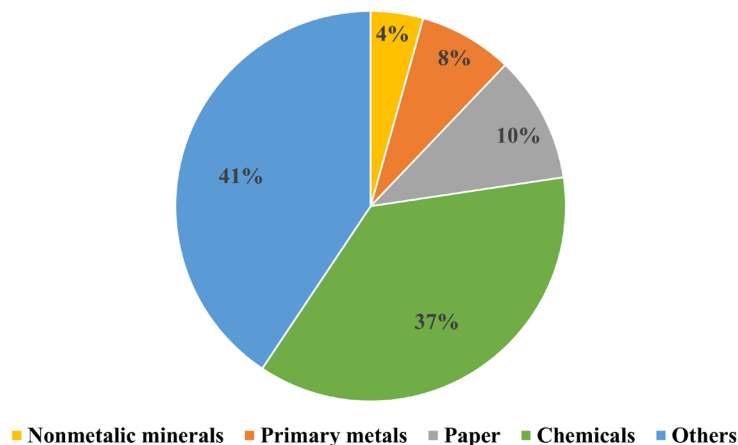


Figure 1 Manufacturing industries' energy consumption by sector in the US (2018); Non-metallic minerals: cement, glass, gypsum and limestone, Primary metals: iron and steel, Paper, Chemicals, Others: non-foundation industries. (Total = 19,436 Btu)

In order to reduce the need for energy, the first step would be identifying and characterising the energy consumption of the process at hand. This includes any element that can influence the required energy of the process. According to Seow and Rahimifard [20], the energy used by various processes required to manufacture a product is defined as direct energy. This energy consists of two components: (i) minimum energy which refers to the lowest possible energy (bound by the physics of the process) and (ii) auxiliary energy which can be defined as the energy required by the supporting activities and auxiliary equipment for the process. Therefore, the parameters affecting energy consumption can be recognised based on their influence on both aspects of direct energy.

In the case of granulation, the minimum energy consists of the energy required for the size reduction of a material and therefore will depend on material characteristics. Meanwhile, auxiliary energy incorporates the energy consumed by machine tools and production related equipment and will depend on its type and efficiency [21], [22]. In reality, the direct energy supplied is mostly converted into heat (losses) whereas only a minor portion is consumed by the main size reducing equipment and auxiliary operations [23]. Hence, the actual energy consumed in the granulation process consists of direct energy and unwanted losses. Figure 2 depicts how the energy supplied for the granulation process is allocated along with the elements responsible for the consumption.

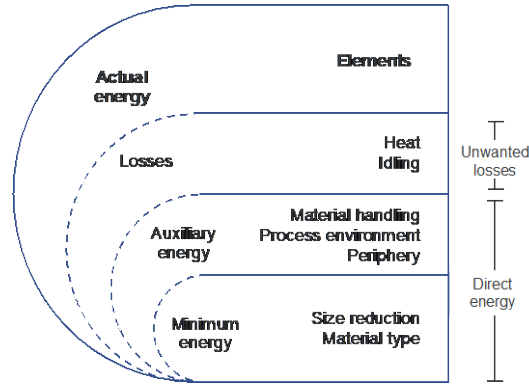


Figure 2 Energy consumption taxonomy of granulation process (not to scale)

### 3 Framework Development

A basic framework has been developed in this study for the purpose of benchmarking, where the theoretical minimum energy acts as a reference point. This will allow for the identification of potential room for improvements once compared against actual consumption by recognising means to minimise the gap between the minimum energy required for the process and the actual consumption. It is essential to have an accurate measure of the actual energy consumed during a process and cannot solely rely on theoretical modelling for estimating energy consumption [24].

According to Klein et al. [25], the energy efficiency of the granulation process can be defined as the energy required for size reduction divided by the energy used by the mechanical system. Based on that, and the work done by Nadolski et al. [26], the benchmarking of granulation energy efficiency will involve the use of the following proposed parameters:

- $B$  = Baseline efficiency of existing scenario = theoretical minimum energy (TME) / Baseline actual energy ( $AE_b$ )
- $B_n$  = Improved efficiency of potential scenario (where  $n$  represents the number of potential scenarios) = theoretical minimum energy (TME) / Actual energy after improvements ( $AE_i$ )
- Efficiency improvement =  $B_n - B$

The theoretical minimum energy (TME) represents the lowest energy theoretically required to reduce the size of a material, where its calculation will be examined in the following section. The actual energy (AE) is the value of the energy consumed during real-time operations of a granulation system. As seen in figure 3, the benchmarking is done by computing the efficiency parameters  $B$  and  $B_n$ , which represent the baseline efficiency and the improved efficiency, respectively. Possible improvements could target the process and the way in which it is being conducted, or the equipment being utilised.

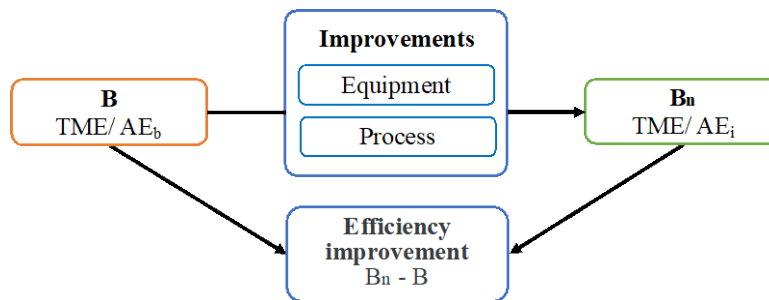


Figure 3 Basic benchmarking framework overview

It would be challenging to identify an inclusive list of material properties that affect the energy required to reduce the size of a particular material. For instance, the hardness of a material, which is one of the most important factors in the amount of energy consumed by the milling unit, has a minor impact on the amount of energy consumed by jaw crushers [21]. To solve this problem, a material property, known as Bond's work index [27] which expresses the resistance of the material to crushing and grinding was introduced. Crushing and grinding are the two industrial means of conducting the granulation process. The following section describes the theoretical minimum calculations using the work index.

### 3.1 Theoretical Minimum Energy Calculation

Although it is impossible to estimate accurately the amount of energy required to reduce the size of a given material, a number of empirical laws have been proposed. Earlier two laws were introduced by Kick [28] and Rittinger [29] in 1885 and 1867 respectively, then the third law by Bond [27] was proposed in 1952. These three laws may all be derived from the basic differential equation [30]:

$$\frac{dE}{dL} = -KL^n \quad (1)$$

which states that the energy  $dE$  required to result in a change in the size  $dL$  of a unit mass of material is a simple power function of the size ( $L$ ) and the crushing strength of the material ( $K$ ) [31]. It has been found that Rittinger's expression,  $n = -2$ , is more applicable for coarse size reduction while that of Kick,  $n = -1$ , is more appropriate for finer size reductions in the region where large surface areas of particles are exposed as in the case of grinding operations. Bond has suggested a law intermediate between Rittinger's and Kick's laws which covers almost the entire range of particles, by equating  $n = -3/2$  leads to:

$$E = -10W_i \left[ \frac{1}{\sqrt{L_1}} - \frac{1}{\sqrt{L_2}} \right] (kWh/t) \quad (2)$$

Where  $E$  expresses the minimum amount of specific energy required to reduce the size of a particle from  $L_1$  to  $L_2$ .  $W_i$  presents the Bond's work index which is defined as the amount of energy required to reduce the unit mass of material from infinite particle size to a size of 100  $\mu m$ , which is usually computed experimentally with standardised tests.

Since the main consequence of granulation is the change in size  $dL$ , this parameter is considered crucial for determining the minimum required energy  $E$  for the process. Similarly, it is a process in which the dispersion state of solids changes with the action of mechanical forces. To use equation 2, Bond considered the energy required for the reduction of feed particle size ( $L_1$ ) that passed 80% of a particular sieve to a product particle size ( $L_2$ ) that passed 80% of a sieve opening. In case this certain size is not reached, the recovery of material processing or the quality of the final product will be greatly reduced. On the other hand, over-grinding not only reduces the efficiency due to fine particle generation but also dramatically increases the granulation costs [32].

The fundamental work by Bond has been accepted universally to predict the specific energy consumption of crushing machines during material size reduction [33], [34]. The limitation to bond's law is its dependence on the work index of the material which is obtained experimentally. However, since the development of the concept many decades ago, the work index  $W_i$  of several materials has been computed and documented regularly. This led to an abundance of data for each material based on its type and composition. The final version of the TME equation for a particular size change in mm is given as:

$$TME = -0.3162W_i \left[ \frac{1}{\sqrt{L_1}} - \frac{1}{\sqrt{L_2}} \right] (kWh/t) \quad (3)$$

#### 4 Case Study of Granulation Process

As mentioned before, granulation could refer to the grinding process which consumes the most electricity in the cement industry. It is responsible for about 50% of the whole electrical energy utilization [35]–[37]. The consumption is strongly influenced by the production method, compositions of raw materials and grinding fineness [38]. Clinker grinding consumes the largest amount of electrical energy in a cement plant [39]. This is attributed to various types of equipment incorporated in a circuit revolved commonly around a mill. The minimum power required is consumed by the main drive systems of mills, system fans and separators. However, the process also includes the consumption of auxiliary equipment such as material transport systems, weigh-feeders, and pneumatic and hydraulic units. The input energy is lost in the form of heat produced from the frictional forces encountered by the mill as it rotates [40]. To demonstrate the use of the framework, the benchmarking process was implemented on possible improvements on equipment changeover bases.

Accordingly, a cement ball mill was used as a baseline case while the roller press and ring roller mill (Horomill) were taken as the potential equipment for the improved cases. The work index of Limestone, the main ingredient of clinker, was determined by Heiskari [41] as 10.21 kWh/t. The size of the feed and product together with the actual energy consumption values are presented in table 1 as obtained from [43] and TransFIRE industry partner. The values represent an estimation of the general figures across the grinding stage of the cement industry.

*Table 1 Grinding parameters and energy consumption values for case study*

|                        |                  |                          |                  |
|------------------------|------------------|--------------------------|------------------|
| L <sub>1</sub> (mm)    | 30               |                          |                  |
| L <sub>2</sub> (mm)    | 0.045 – 0.01     |                          |                  |
| Limestone Wi (kWh/t)   | 10.21            |                          |                  |
|                        | <b>Ball mill</b> | <b>Roller press mill</b> | <b>Horomill®</b> |
| AE (kWh/t) specified   | 40               | 27.50                    | 21               |
| TME (kWh/t) calculated | 18.88            | 14.63                    | 15.55            |
| B                      | 47.20            | -                        | -                |
| B1                     | -                | 53.20                    | -                |
| B2                     | -                | -                        | 74.06            |

Accordingly, using the formulas presented in section 3, the benchmarking was performed for the base case and the subsequent possible improved scenarios. The values, presented in table 1, indicate that the ball mill system is highly inefficient due to the large difference between its actual consumption (40 kWh/t) and the theoretically calculated minimum energy (18.88 kWh/t) required for such size reduction. On the other hand, the Horomill machine had the highest efficiency when compared to the other scenarios as seen in figure 4. Hence, a 27% increase in efficiency is possible just by replacing the grinding equipment.

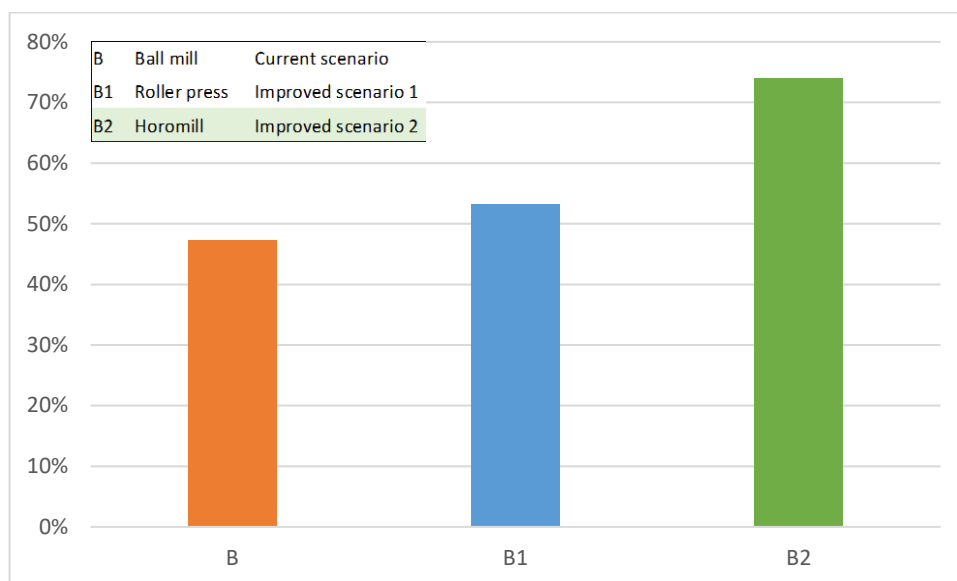


*Figure 4 Efficiency values for current and potential improved scenarios*

While it is not always possible to completely change the equipment used without incurring large capital costs. However, by altering just the process conditions, the overall energy required could be reduced. For instance, modifying the charge amount and pattern of the ball mill to increase the average surface area and the effective contact surface of balls can enhance the production rate and therefore, reduce electricity consumption [44]. Moreover, implementing closed-circuit grinding enhances the overall efficiency of the mills [45]. Altun [46] discovered that altering the flow sheet of the circuit can result in up to 4% in energy savings. Additionally, if both coarse particles and very fine particles are minimized overall and the particle size distribution is made more uniform, the energy consumption would be more stable [40]. Advancements made in Waste Heat Recovery (WHR) systems make it a viable option to improve overall efficiency beyond reducing the input energy [47]. The currently available WHR systems are established in dealing with the heat produced by the kilns [48] however systems targeting grinding circuits are lacking. According to Napier [49], much can be done now to reduce granulation energy consumption by up to 30%, energy savings of over 50% will be attainable in the next 10 years with technological advances currently under development.

## 5 Conclusions

Enhancing energy efficiency is the most effective and environmentally benign approach to meet the world's energy demands. Reduction in energy supply investment is also a benefit of energy efficiency improvements. Many industrial processes are energy inefficient and therefore the overall energy consumption is significantly higher than what the best technology would allow.

This study is a step towards developing a framework for benchmarking energy efficiency of foundation industries in relation to the minimum energy required to execute the process. The framework incorporates benchmarking parameters that have been established to benchmark energy efficiency for the granulation process. This is due to its importance in the foundation industries and the fact that it is one of the most energy-intensive processes. The energy taxonomy approach reveals the elements accountable for actual energy use in the process. In this paper, a case study has been presented to demonstrate how the proposed benchmarking concept can be applied to a granulation process for cement production. The efficiencies of three types of grinding machines have been computed relative to their theoretically obtained minimum energy required. This allowed for the recognition of the most efficient equipment as well as the energy that is not used directly for production. However, optimising the process conditions could also enhance the efficiency without having to change the equipment.

This is an ongoing project and will be explored further towards an advanced level of the framework by introducing practical minimum and best practice values to identify further energy saving and energy recovery opportunities. Moreover, some case studies will be performed to evaluate the framework with the industrial partners of TransFIRE. Further research is in progress to identify and benchmark the resource efficiency of the common processes across the foundation industries.

## Acknowledgement

The authors would like to acknowledge the Transforming Foundation Industries Research and Innovation hub (TransFIRE) for the support of this work. TransFIRE (EP/V054627/1) is funded by UKRI (<https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/V054627/1>).

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## **Towards framework development for benchmarking energy efficiency in foundation industries: a case study of granulation process**

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**2023-02-14**

Springer

[https://doi.org/10.1007/978-3-031-22765-3\\_23](https://doi.org/10.1007/978-3-031-22765-3_23)

Sarfraz S, Sherif Z, Jolly M, Salonitis K. (2023) Towards framework development for benchmarking energy efficiency in foundation industries: a case study of granulation process. In: TMS 2023 152nd Annual Meeting & Exhibition, 19-23 March 2023, San Diego, USA, The Minerals, Metals & Materials Series, pp. 245-256