

Energy Return on Investment (EROI) of Brazilian Coal Production

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Abstract— The rapid growth in energy demand globally sets the need for studies that evaluate the capacity of a fuel to provide an energy surplus after accounting for all the energy needed to make it available for society. The energy indicator known as energy return on investment (EROI) has been widely used for that purpose, analyzing both renewable and non-renewable fuels ability to provide useful energy. However, there are no study which estimate the EROI for Brazilian fossil fuel production. In this sense, the goal of this study is to calculate the EROI for Brazilian coal production, analyzing how much surplus energy this fuel yield after accounting the energy necessary to its extraction, processing and transportation. The results show that the EROI value highly depends on the data source, with values ranging from 30 to 57 for the Santa Catarina States' coal production and going as high as 115 for the Rio Grande do Sul States' coal production. LCA software SimaPro was also used as a way to estimate the EROI for Brazilian coal production due to its extensive database. Results from both methods are in agreement when considering only the extraction and processing steps, but diverge when the transportation energy costs are added. Differences in the transportation process are the probable cause for the discrepancies in the EROI value. Despite this difference, both methods show that the Brazilian coal is a net energy source.

Keywords— CED, coal, EROI, LCA, net energy analysis.

I. INTRODUCTION

Coal use worldwide has been growing significantly in the past decades due to its availability, supply stability and low cost [1]. As of 2018, coal remains a major component of global fuel supplies, accounting for 27% of all energy used [2]. It was only in 2015 that the global demand for coal met its first decline since the late 1990's, mainly due the efforts to combat air pollution in China, the decreasing profitability of the industry as a direct cause of coal low prices – the result of over-capacity – and the urge to reduce greenhouse gas emissions [3]. Still, according to the International Energy Agency (IEA), by 2040 the global coal demand is likely to be about 2100 million tonnes of oil equivalent (Mtoe) in the lower case scenario, corresponding to 13% of the world primary energy demand, or higher than 4900 Mtoe in the current policies scenario, which in turn would correspond to 27% of the world primary energy demand [3].

Brazil is not a leading coal producer in the global market, but the southern States of *Santa Catarina* and *Rio Grande do Sul* offer reasonable coal reserves which are used for electricity production and industrial processes [4]. As a result, a growing number of studies have been

performed to improve its production process [5], better understand its environmental impacts [6], its chemical properties [7] as well as the possibilities to reduce the coal burning emissions with carbon capture technologies [8]. However, there are no study that aims to investigate how much net energy the Brazilian coal is capable of producing after accounting for all the energy needed to make it available for society. In a increasing energy demand world, knowing the amount of surplus energy a fuel can provide is an important aspect to be taken into account in order to avoid unnecessary financial investment in the energy infrastructure [9].

There are many energy indicators designed to evaluate different aspects of an energy system, including its ability to provide surplus energy. The energy indicator known as energy return on investment (EROI) is probably one of the most used to that purpose. It can be defined as the ratio between the energy delivered to society and the energy spent by society to produce that energy [10,11,12]:

$$EROI = \frac{\text{Energy delivered to society}}{\text{Energy required to produce that energy}} \quad (1)$$

Initial analysis focused in determining the EROI for oil production as it was clear that the so called easy oil have already been exhausted, with new developments needing an ever increasing amount of energy and financial investments to produce the same amount of oil [13]. There is now a widespread concern in the literature that the energy return from oil and gas is declining and likely to continue [14], whereas coal is the only fossil fuel whose EROI hasn't reached a peak yet [15]. Many analysts also raise the issue of the low EROI values of low-carbon energy technologies [14,16,17]. Implications for the declining EROI value of fossil fuels are discussed in many studies, e.g., [12,18,19]. They all tend to show the need for more comprehensive studies about the EROI of different fuels and how its value could impact the future energy policies which need to take place in a transition energy mix.

Reliable sources and readily available data are probably the main cause for the lack in EROI studies [11]. Most processes in the life cycle of a fuel are performed by private companies which makes it difficult to access sensible production information. Analysts tend to rely on financial data to derive energy properties of a system [10], even though some argue that the dependency on market prices removes the EROI ability to measure only physical properties of said system [12]. In recent years, however, there is a growing trend in the number of studies that use the life cycle assessment (LCA) databases as an alternative to perform EROI calculations. Ecoinvent is the most widely applied database in LCA studies and it includes a method for determine the so called cumulative energy demand (CED) indicator. The CED accounts for all use of energy in a product life cycle, tracing back to the natural resource origin and including both energy losses along the way and the energy content in the product [14]. As such, the CED is frequently used to determine or define EROI [14,20].

EROI from PV technologies is calculated by [21] using LCA data and then compared to the EROI from

coal and oil electricity production in Europe. In the same way, [22] uses the CED concept to define guidelines for EROI calculation of PV power systems. CED is used by [23] to define and calculate the EROI in a meta-analysis of the electricity production using wind technology. The work by [24] goes a little further and the CED is used as the base for the calculation of many energy indicators, including EROI, from different fuels in a way to analyze the impact that these different indicators have on an energy system evaluation. The use of recycled material had an overall good impact on both CED and EROI for the life cycle assessment of offshore wind technologies as reported by [25]. Lastly, the relationship between the CED and EROI for PV power systems is analyzed by [26], where the results indicate that a low energy demand measured by the CED produces a higher EROI.

Despite the difficulties to estimate the EROI from different fuels, the growth in energy demand sets the need for studies which calculate an energy source capacity to provide surplus energy to meet the society's energy needs. The lack of such studies for the Brazilian fuel production prevents a full analyzes of the country energy options measured by different and important aspects. As such, the goal of this work is to estimate the EROI for Brazilian coal production when considering the coal extraction, beneficiation and transportation to the final user. SimaPro's database was also used to calculate the EROI from Brazilian coal production and the results by the two methods were then compared.

II. METHODOLOGY

2.1 System boundary

As shown in Fig. 1, the system boundary consists of three main stages: (i) mining, (ii) processing and (iii) coal transportation to the final user. Following the boundary definitions by [10], the EROI is then labeled as $EROI_{2,i}$, where "2" indicates the boundary for the energy output, i.e., up to which stage in the coal production the energy flows will be accounted and "i" indicates the

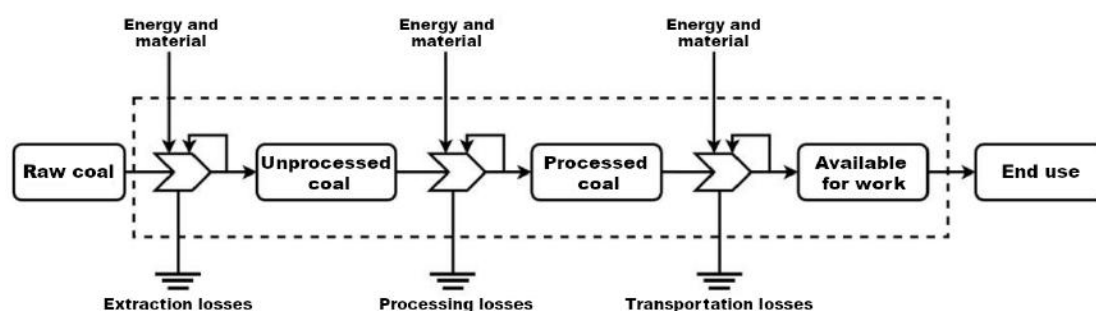


Fig 1: System boundary

boundary for energy input, meaning that both the direct and indirect energy flows will be accounted as inputs. The precise meaning of direct and indirect flow may vary depending on the study. Here, the direct energy flows represents the energy and material produced and used within the boundary in Fig. 1. Diesel burned in the mining machinery and explosives used in the mining process are examples of direct energy flows. Indirect energy flows are the ones produced outside the limits of the mine and used within its boundary, like electricity. Although it's not the main focus of the study, the $EROI_{STND}$ was also estimated. It's called "standard EROI" as most analysts calculate and compare it among studies. The $EROI_{STND}$ measures the surplus energy a fuel can provide by only accounting the direct and indirect energy inputs and outputs in the extraction stage.

2.2 Data acquisition

Coal production is limited to the Southern Brazilian States of *Santa Catarina* and *Rio Grande do Sul*, thus narrowing the geographic scope for the data acquisition. Data for coal production is often unavailable as its mining, beneficiation and transportation processes are mainly performed by private companies. LCA studies were then used as the main source for data acquisition in the EROI calculation. Information on energy and material flows were taken as given, only being converted to their energy equivalent with the use of the quantities' HHV. As an example, Table 1 shows the energy and material needed to extract and process 1 kg of coal from an underground mine in Santa Catarina State.

Table 1: Inventory for the production of 1 kg of coal in Santa Catarina

Inputs	Amount	Units
ROM coal	2.39	kg
Water	6.99×10^{-3}	m ³
Explosives	1.48×10^{-3}	kg
Diesel	5.42×10^{-2}	MJ
Electricity	4.61×10^{-2}	kWh
Limestone	3.50×10^{-3}	kg

Source: [5]

The HHV was used to convert the material flows to its energy equivalent, as the CED results on SimaPro are given in terms of HHV, thus allowing a consistent comparison between the EROI calculated by the two methods. Data on HHV, densities and other important

metrics are usually reported on each study used as source of information. Missing and additional data can be found in the Brazilian Energy Balance, a yearly publication by the *Empresa de Pesquisa Energética* that details the Brazilian energy mix.

2.3 Equations

The EROI here calculated can be defined as shown in (2)

$$EROI = \frac{\sum_{i=1}^n \lambda_i E_{OUT,i}}{\sum_{j=1}^m \lambda_j E_{IN,j}} \quad (2)$$

The coefficients λ are used to convert each energy flow $E_{OUT,i}$ and $E_{IN,j}$ to its primary energy equivalent, thus making it possible to sum different energy components with different energy qualities. This equation can be used to calculate both the $EROI_{STND}$ and the $EROI_{2,i}$ just by changing the quantities in the denominator. Table 2 shows the primary energy coefficients (λ) used here.

Table 2: Conversion factors for accounting different energy qualities

Product	Conversion factor (λ)
Electricity	1,6
Diesel	1,1
Coal	1

Source: [27]

The energy flows E_{IN} depend on the specificity of each process and may vary based on the data source, but as shown in Table 1, explosives, diesel and electricity can be considered as the main energy and materials required to extract, process and transport the coal, as diesel is usually employed to power the vehicles responsible for the coal transportation. The $EROI_{STND}$ can be then estimated by (3)

$$EROI_{STND} = \frac{\lambda_C \times Q_C \times HHV_C}{(\lambda_{el} \times E_{el}) + (\lambda_D \times Q_D \times HHV_D) + E_{exp}} \quad (3)$$

where λ_C is the primary energy coefficient for the coal Q_C is the amount of the coal produced in kg and HHV_C is its high heating value in MJ/kg. As for the denominator, λ_{el} and λ_D are the primary energy coefficients for the

electricity and diesel, E_{el} is the electricity measured in MJ, Q_D is the diesel amount in kg and HHV_D its high heating value in MJ/kg. Finally, E_{exp} represents the energy content in the explosives. No primary energy equivalent was used to account for the energy quality of the explosives because no study was found that deals with it. Thus the term E_{exp} can be written as $Q_{exp} \times E_{cont}$, where Q_{exp} is the amount of explosives used to extract the quantity Q_C in units of kg and E_{cont} is the energy content of the explosives in MJ/kg.

The $EROI_{2,i}$ can be calculated by adding a term E_T in the denominator of (3). This term represents the energy spent to transport the coal to the final user and it has no definitive form because various fuels can be employed for the coal transportation. Nonetheless, the fuel quantity in kg, its high heating value in MJ/kg and the adequate primary energy equivalent were used to make (3) consistent with the EROI calculation.

2.4 EROI calculation using SimaPro

The life cycle assessment software SimaPro and the cumulative energy indicator were also used to estimate the EROI for the Brazilian coal production and as a mean of comparison with the values calculated using (3). However there are no processes in the software's database that represent the same exact conditions found in the production of this fuel in Brazil, as most of the data is concentrated on the North America and Europe economies. Still, there are processes which are similar enough and can be used for EROI calculation. For the coal extraction the process "Hard coal {RLA} hard coal mine operation and hard coal preparation" was chosen for two reasons. First, it deals with the extraction and processing of coal in the Latin America and the Caribbean region, stated by the abbreviation RLA (which is the abbreviation used in Ecoinvent for Latin America and the Caribbean). Second, the materials and energy employed in the coal production match those found in Brazil. To account for the transportation stage the process "Hard coal {RLA} market for" was chosen for the same reasons discussed above.

Data on the coal production for each stage were then loaded in the aforementioned processes on SimaPro for the CED calculation. Fig. 2 shows an example of the CED results obtained on SimaPro for the process "Hard coal {RLA} hard coal mine operation and hard coal preparation". The CED in this case was 49.9 MJ, as shown in the bottom portion of Fig 2.

Name [Hard coal {RLA} hard coal mine operation and hard coal preparation]			
Contribution		49,3	98,8 %
Sub-process (7)	Flow	Unit	
Totalt	0,604	MJ	
Blasting {GLO} market for	0,0378	MJ	
Coal slurry {GLO} market for	0	MJ	
Diesel, burned in building machine {GLO} market for	0,109	MJ	
Electricity, high voltage {RLA} market group for	0,364	MJ	
Mine infrastructure, open cast, hard coal {GLO} market for	0,0916	MJ	
Spoil from hard coal mining {GLO} market for	0	MJ	
Tap water {RoW} market for	0,00252	MJ	
Used by (0)	Flow	Unit	
Totalt	49,9	MJ	

Fig 2: Example of CED results

In order to calculate the EROI using the CED the energy losses and the energy content of the fuel must be subtracted from the CED. As seen in section 1, the CED accounts for all energy in a product life cycle, including energy flows that are not invested by society. Therefore, these quantities must be removed from the CED results and the EROI can then be calculated using (4)

$$EROI = \frac{E_{OUT}}{CED - (E_C + E_L)} \quad (4)$$

where E_C is the energy content in the fuel and E_L represents the energy losses in the process being analyzed. However, it must be noted that there is no way to ensure the complete removal of all losses accounted in the CED results. Some processes in the SimaPro database explicitly show the energy and material losses in each stage of a product life cycle but implicit losses may also be accounted [14]. As such, the resulting EROI may diverge by some degree from what it would be expected, which do not invalidate the use of SimaPro as a tool to calculate energy indicators.

According to the documentation of the process shown in Fig. 2, the HHV of the coal is 19.1 MJ/kg and it was needed 2.59 kg of coal to produce 1 kg of the fuel. It also states that 0.0002 m³ of methane was emitted as fugitive gas in the coal extraction. Considering a HHV of 39.8 MJ/m³ for the methane and using (4), the EROI of this process is given by

$$EROI = \frac{1 \times 19.1}{49.9 - (2.59 \times 19.1 + 0.0002 \times 39.8)}$$

$$EROI = 28$$

III. RESULTS AND DISCUSSION

Brazilian coal is deemed volatile and has huge amounts of both ash and sulfur in its composition [4,28]. Nevertheless there is a huge potential in the full exploration of the coal from the *Rio Grande do Sul* State, with the possibility of implementing a thermoelectric power plant with a nominal power of 28.8 GW [29]. However, there are few scientific studies that report in great detail the energy and materials used in the Brazilian coal production. It reflects the fact that coal production is restricted geographically to southern region of the country, as shown in Fig. 3, and economically to few mining companies. LCA studies are often the only reliable source for data acquisition and further EROI calculation which limits the possibility for a more comprehensive study on the surplus energy the Brazilian coal is able to produce. Still, the LCA studies used as data source were enough as a first approach to estimate the EROI from Brazilian coal. The results are presented hereafter.

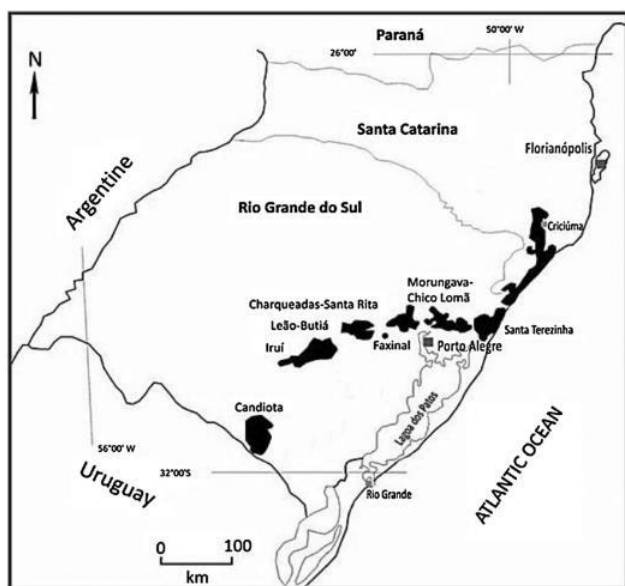


Fig 3: Main coal mining areas in southern Brazilian States. Source: [4]

The LCA study done by [30] provides data for the coal extraction for two different companies in *Santa Catarina* State. Table 3 shows the material and energy reported in said study to extract 1 kg of coal. The ROM coal is the unprocessed coal recently mined and that will be transferred for further processing. There is a considerable difference between the inputs' quantities in Table 3 from each company to produce 1 kg of coal. Company 2 uses more than 50 times more diesel than company 1, probably due to different mining processes and equipment which in turn can greatly influence the

EROI results. Coal from both companies is then transported by train to the *Jorge Lacerda* thermoelectric power plant, where 0.05 liters of diesel are used to transport 1 tonne of coal.

Table 3: Energy and material needed to produce 1 kg of coal from Santa Catarina State

Inputs	Amount (company 1)	Amount (company 2)	Units
ROM coal	2.49	2.58	kg
Explosives	1.1×10^{-5}	7.7×10^{-4}	kg
Diesel	2.6×10^{-5}	1.42×10^{-3}	kg
Electricity	3.2×10^{-2}	4.6×10^{-2}	kWh
Limestone	1.43×10^{-4}	1.79×10^{-3}	kg

Source: [30]

Also according to [30], the coal analyzed has approximately 42.9% of ash in its composition. This percentage of ash were assumed as not retrievable and thus removed from the EROI calculations. Using this information, along with data in Table 3 and the fact that this coal has a HHV of 18.83 MJ/kg, the calculated $EROI_{2,i}$ was 57 and 31 for company 1 and 2 respectively. These values reflect how much the coal is reliable and viable in terms of its energy content, even though almost half of it is made of ash. Literature is scarce in terms of $EROI_{2,i}$ values for the coal. Most studies focus in the evaluation of the $EROI_{STND}$ usually for problems in data availability. Table 4 shows a compilation of $EROI_{STND}$ for some countries as well as for the global production as a whole.

Table 4: Compilation of the $EROI_{STND}$ from various studies

Year	Location	$EROI_{STND}$	Reference
1950	United States	80	[31]
2000	United States	80	[18]
2007	United States	60	[18]
1995	China	35	[32]
2010	China	27	[32]
2012	Europe	40 – 80	[21]
1800 – 2012	Global	15 – 75	[15]

In accordance to the study from [30], [4] performs a LCA for the coal in the same region. Their results are shown in Table 1 in section 3.2 and don't differ much from those in Table 3 for the company 2, suggesting that the LCA study was performed in the same location but years apart. The HHV value from coal in [4] is 18.84

MJ/kg, it has a total of 41.9% of ash in its composition and 0.57 liters of diesel are used to transport 1 tonne of coal by train to the *Jorge Lacerda* thermoelectric plant, the same as in [30]. Using these information the $EROI_{2,i}$ for [4] data is 30, only one unit less when compared to company's $EROI$ founded with [30] data. It once again shows how much surplus energy coal can provide even when accounting for its poor composition. Table 5 shows the $EROI_{2,i}$ for each data source.

Table 5: $EROI_{2,i}$ values for the coal data sources

$EROI_{2,i}$	Data source
57 (company 1)	[30]
31 (company 2)	[30]
30	[4]

$EROI_{STND}$ was also estimated for the coal production and the results are shown in Table 6. When comparing the values on Table 6 with the $EROI_{2,i}$ in Table 5 it is clear to see how little the numbers have changed even though the system boundaries are larger. The energy requirements for the coal transportation are relative small when compared to the mining and processing energy costs. Therefore, adding the transportation costs has little to no effect in changing the $EROI_{2,i}$ when compared to the $EROI_{STND}$. These results suggest that the extraction and processing stages are much more expensive in energy terms than the coal transportation and should thereby be the main target if a measure of energy efficiency were to be applied.

Table 6: $EROI_{STND}$ values for the coal data sources

$EROI_{STND}$	Data source
58 (company 1)	[30]
31 (company 2)	[30]
32	[4]

Even though the processes in SimaPro's database do not accurately represent the reality of Brazilian coal production, the simulated results for the $EROI_{STND}$ using SimaPro are in agreement with the ones presented in Table . This agreement was expected in some extent as the same energy and materials inputs reported in the data sources are presented in the process "hard coal {RLA}| hard coal mine operation and hard coal preparation", used for the $EROI_{STND}$ simulations. Although discrepancies may occur, this result suggest that SimaPro can be a useful tool not only to analyze environmental impacts in a product life cycle, but to also estimate a fuel's capacity to provide useful energy. Table 7 sums up all the results.

However, the simulated values for the $EROI_{2,i}$ are remarkably low when comparing to the ones presented in Table 5. Reasons for this discrepancy are probably due to differences in energy and material flows considered in the SimaPro database for the coal production. In the process "hard coal {RLA}| market for" documentation, the one used here for the $EROI_{2,i}$ simulations, is stated that coal is considered to be transported to harbor or storage. That is clearly not the case for the Brazilian coal which is mainly transferred for few kilometers to a thermoelectric power plant in order to generate electricity. Thus, the energy costs for coal transportation are greater in SimaPro database, which in turn greatly reduces the $EROI_{2,i}$ value.

Table 7: Calculated and simulated $EROI$ results

$EROI_{STND}$	SimaPro ($EROI_{STND}$)	$EROI_{2,i}$	SimaPro ($EROI_{2,i}$)	Source
58	57	57	18	[30] company 1
31	31	31	14	[30] company 2
32	35	30	18	[4]

IV. CONCLUSION

Results indicate that Brazilian coal is a net energy producer with $EROI_{2,i}$ ranging from 30 to 57 depending on the data source. These results mean that for each energy unit invested for society to obtain coal, it yields 30 to 57 more units of energy after accounting for its extraction, processing and transportation. SimaPro simulations reproduced the results for $EROI_{STND}$ but diverged when simulating $EROI_{2,i}$. These differences do not invalidate the use of SimaPro as a tool to evaluate energy indicators of a fuel but it raises the need to correctly choose a process in the software's database that closely portray the actual system boundary being analyzed.

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