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Energy Multiphase Model for Biocoal Conversion Systems by Means of a Nodal Network

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Abstract: The coal-producing territories in the world are facing the production of renewable energy in their thermal systems. The production of biocoal has emerged as one of the most promising thermo-energetic conversion technologies, intended as an alternative fuel to coal. The aim of this research is to assess how the model of biomass to biocoal conversion in mining areas is applied for thermal systems engineering. The Central Asturian Coal Basin (CACB; Spain) is the study area. The methodology used allows for the analysis of the resource as well as the thermo-energetic conversion and the management of the bioenergy throughout the different phases in a process of analytical hierarchy. This is carried out using a multiphase mathematical algorithm based on the availability of resources, the thermo-energetic conversion, and the energy management in the area of study. Based on the working conditions, this research highlights the potential of forest biomass as a raw material for biocoal production as well as for electrical and thermal purposes. The selected node operates through the bioenergy-match mode, which has yielded outputs of 23 MW_e and 172 MW_{th}, respectively.

Keywords: biomass; bioenergy; energy production system

1. Introduction

The constant technological progress and the increasing industrialization of society have boosted the demand for energy. Fossil fuel deposits, such as those in coal basins, are limited and have been extensively exploited, so modelling the biomass potential of renewable sources in these areas is a challenge for the future in the European Union (EU). Spain boasts a wide variety of renewable resources such as biomass and wind and solar energy, all available as renewable energy sources [1]. The technological capacity of Spanish industry has made it a benchmark in the use of renewable resources [2]. The potential of Spain in renewable energies is well above both the domestic energy demand and the existing fossil fuel resources [3]. Despite this situation, Spain is highly dependent on foreign energy from fossil fuels, coal being the main source of indigenous energy in Spain [4].

Renewable energy sources are found in nature, have the capacity to be totally or partially regenerated, and can be used for energy purposes. Biomass is part of a continual cycle of mass and energy consumption and production in the environment. It can be used to produce energy, either directly by combustion or indirectly by way of biofuels. EU Directive 2003/30/EC [5] defines biomass as a biodegradable fraction of products, waste and residues from agriculture, including vegetal and animal substances, forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste. Such a definition has a comprehensive character since it includes a variety of energy sources sharing certain characteristics but differing in their origin and the technology used to obtain and use them, one of the main sources being forest biomass.

The EU Forestry Action Plan [6] calls for an assessment of forest biomass availability for energy production in both national and regional energy systems. The most promising scenarios for future use are

1. Production of electricity either by co-combustion or direct combustion;
2. Thermal applications for domestic or industrial consumers;
3. Production of solid biofuels to be used in the cement or steel industry.

This study is to be carried out in the Region of Asturias in northern Spain, a region rich in fossil fuels, i.e., coal, where the production of alternative biofuels has been of interest in the context of the EU [7,8]. Its producing industry uses coal as the main source of indigenous primary energy, a part of which is produced in its mining basins [9]. Mining has gradually declined in recent years following the reduction of its activity [10]. Biomass from forests and forest management in the mining areas is conditioned upon its frequency of occurrence along with its topography. It is, therefore, necessary to carefully plan management procedures based on the distribution of potentials throughout the whole territory. This strategic framework calls for an analysis of the most appropriate techniques for extraction, storage, transport and use of biomass in forests. However, there is limited use of forest biomass to provide an alternative to fossil fuels owing to its low energy density [11].

Biocoal is achieved through a roasting process (i.e., torrefaction process), a high potential process to be applied in the production of solid biofuels from lignocellulosic biomass [12]. In this way, the quality of this fuel increases by virtue of its hydrophobicity and higher calorific value compared to the initial biomass [13]. Biofuels considerably improve the potential of biomass for industry and thermal systems [14]. Furthermore, it is of interest for both industrial energy transition and industry 4.0 [15]. However, modelling, conversion and energy management of resource supply are some of the main challenges in the current energy context [16]. In this regard, Visa et al. [17] have defined the importance of characterizing energy production systems according to the nature of the energy resource used. Paredes-Sánchez and Ochoa-Lopez [18] established the importance of biomass modelling as an alternative to coal in the energy production systems. Therefore, a proper implementation in a traditionally coal-based industry, as is the case of the Principality of Asturias, requires the development of mathematical models for the energy conversion of its resources.

Extensive research has been carried out using both resource characterization and energy conversion models from different perspectives [19–22]. These current works discuss numerous challenging issues, including the increasing number of assumptions that ensure consistency between the models used and the large amount of data required for energy conversion. The combination of modelling methods allows for a significant number of variables to be taken into account to solve the problems of energy conversion [22]. The multiphase model is an important step in developing the knowledge needed to improve energy fuels in thermal systems. In this context, research and development activities on biomass torrefaction have been particularly active in exploring its potential as a fuel [23,24]. However, the modelling and management of the torrefaction process can be found in the literature as a current challenge [25,26]. Kumar et al. [27] have studied the processes of bioenergy transformation, pointing out the necessity to search for comprehensive analytical models to overcome the existing limitations and provide the necessary technology to enable industrial use of high value-added biofuels. Huntington et al. [28] stress the importance of developing advanced mathematical models focused on the potential supply of biomass resources as a source of bioenergy. Paredes-Sánchez et al. [29] point out the limitations in modelling the potential use of biofuels for energy production systems considering the scope of the energy conversion system. In this regard, Bach et al. [30] define the demand for a comprehensive model of biomass torrefaction, which can provide interdisciplinary information to industrialize and commercialize the process. In this framework, a comprehensive analysis of the energy use of biocoal, starting with the supply of biomass as raw material and ending with its final energy conversion through fossil-fuel-based technologies for thermal systems, is a difficult undertaking in the field of bioenergy. Therefore, the present paper aims to develop a mathematical model that would allow a comprehensive analysis of the potential use of available biomass in the mining areas to produce biocoal for thermal systems engineering. The main breakthrough consists of applying a multiphase model to the data to characterize thermo-energetic conversion and energy management of biomass as a raw material for the production of biocoal. These studies are carried out in the Carboniferous Basin of the Principality of Asturias (CACB).

This work is organized as follows: Section 1 introduces the context of the research and the aim of the work. Section 2 shows the methodology used for the study area and the modelling process to produce biocoal. Section 3 shows both its findings and the details of its implementation as results. Section 4 provides a more detailed analysis of and discussion on biocoal as an alternative fuel to coal in mining areas for energy production systems. Section 5 provides the main conclusions of the study in the mining area by means of energy production systems.

2. Materials and Methods

2.1. Study Area and Mine Nodes

The National Renewable Energy Action Plan (NREAP) in Spain is aimed at complying with European Directives 2009/28/EC and 2009/29 EC on the contribution of renewable energy and the reduction of greenhouse gas (GHG) emissions by 2020 [3]. Located in the north of Spain, the Principality of Asturias is an Autonomous Community where 45% of the land is forested. The energy structure of the Principality of Asturias is conditioned by the contribution of fossil fuels to the national energy system as a whole. The Central Asturian Coal Basin (CACB) spreads over the southern councils of the central area of the region (Figure 1).

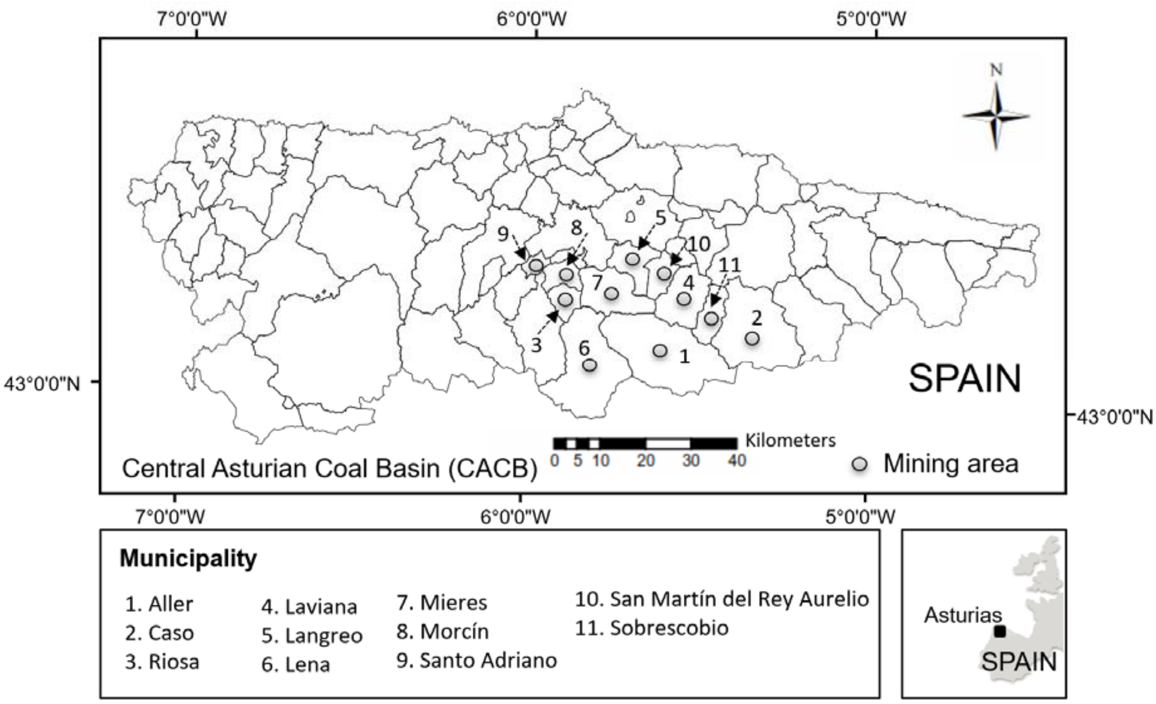

Figure 1. Location of the study area—Principality of Asturias (Spain).

The CACB features the geological resources that represent one of the main coal mining deposits in Spain, located above the geological unit of study [31]. The use of coal as an integral source of indigenous energy is the basis of the Asturian economy. Therefore, the CACB constitutes a geographical, economic, and geological unit that is the study area. In this sense, mine shafts are defined as candidate nodes of analysis to implement the use of biocoal in energy production systems. It should be noted that the layout and infrastructure of the coal mine itself, i.e., the electricity grid or the transport network, would favor the use of biocoal as an alternative fuel. Table 1 shows the mine shafts considered as modelling nodes.

Table 1. Nodes defined in the Central Asturian Coal Basin (CACB) study area.

Code	Name of the Node	Municipality
PM	Pozo María Luisa-Samuño	Langreo
PSo	Pozo Sotón	San Martín del Rey Aurelio
PSa	Pozo Santiago	Aller
PMo	Pozo Montsacro	Riosa
PS	Pozo San Nicolás	Mieres
PC	Pozo Candín	Langreo
PCa	Pozo Carrio	Laviana

The analysis of the biomass in the forests surrounding the mine shafts allows unused resources to be valorized for energy production. The use of forest biomass for energy purposes will not only increase the economic development, but also energy self-sufficiency [32,33]. The use of forest residues will also generate environmental benefits [34].

2.2. Multiphase Mathematical Model

The multiphase mathematical model developed for this work comprises three phases in the area of study: resources, thermo-energetic conversion and energy management, each one of which is described in detail in Figure 2.

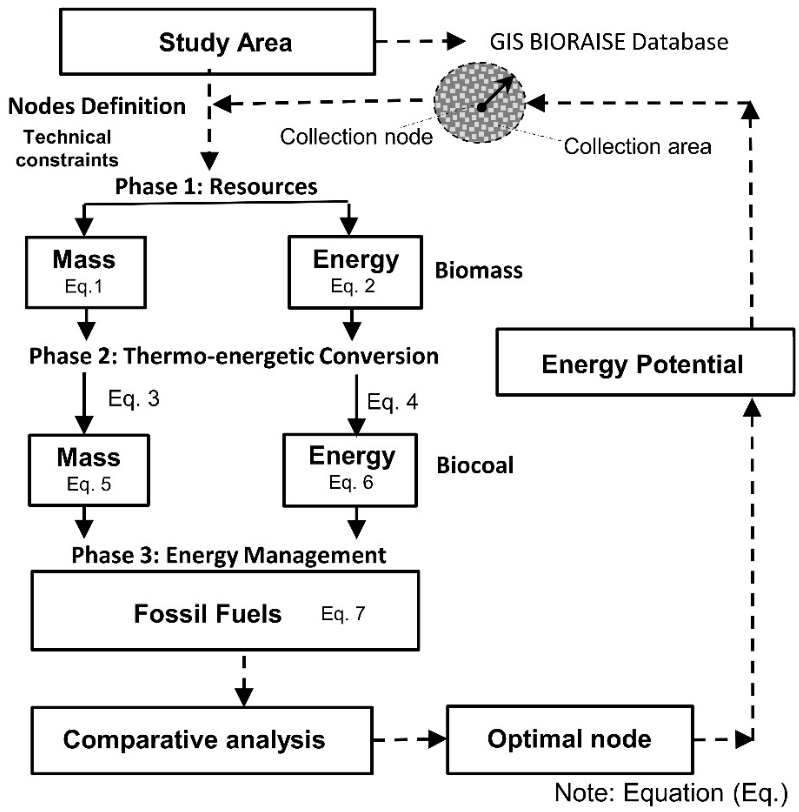

Figure 2. Flowchart of the multiphase mathematical algorithm through mass and energy balance.

2.2.1. Phase 1: Resources

For the assessment of potential resources, the Geographic Information System (GIS) database of the BIORAISE GIS tool from the Research Centre for Energy, Environment and Technology (CIEMAT) was used in order to collect data on forest biomass in the CACB study area [35]. In Phase 1 of the mathematical model, it is estimated that the existing resources for each candidate node come from residues of cleaning activities and forest management operations in the study area and are gathered in each of the considered nodes (Figure 2). Mass and energy are expressed in terms of dry ton (dry t). In this study, this biomass is considered as the raw material to be used to generate biocoal through the torrefaction technology in Phase 2 of the model with the roasting system.

The potential mass (M) is the residual forestry biomass, such as branches and leaves, found within the study area and therefore, in the surroundings of each modelling node. The available mass (m) consists of branches and tops (including leaves). It is obtained from cleaning, thinning and felling operations from BIORASE GIS database (Figure 2), which takes into account the techno-economic constraints of the potential biomass to define the useful resources [35]. Such restrictions derive from harvesting procedures, which depend on the terrain conditions to access the raw material [7] that will define the useful resources, including available mass of conifers, wood and mixtures (dry t/year). Techno-economic constraints affect its use from the point of view of mass and energy balance. The biomass is evaluated in the surroundings of the selected node in the study area using Equation (1).

$$m = \sum_{i=1}^{n} m_i \tag{1}$$

where

m is total available mass (dry t/year); and
m_i is total available mass of conifers, hardwood and mixtures (dry t/year).

The energy of the available residues (E) is the result of Equation (2), where the Lower Heating Value (LHV) is used.

$$E = \sum_{i=1}^{n} (m_i \cdot LHV_i) \tag{2}$$

where

E is energy from available mass (GJ/year);
m_i is total available mass of conifers, hardwood and mixtures (dry t/year); and
LHV_i is Lower Heating Value of conifers, hardwood and mixtures (GJ/dry t).

Phase 2 of the calculation algorithm is defined from the available resource and energy (Figure 2).

2.2.2. Phase 2: Thermo-Energetic Conversion

In Phase 2, the thermo-energetic calculation algorithm used to calculate the mass and energy potential of biocoal to be produced is based on Equations (1) and (2), respectively. Torrefaction is a thermal pre-treatment carried out by a reactor system at atmospheric pressure, with no oxygen. The roasting process takes place at temperatures between 200 °C and 300 °C to achieve more uniform solid biofuel, whose two main thermo-energetic characteristics are energy yield and mass yield. The energy and mass yields [36] are defined from the reactive part of the biomass, which is turned into biocoal through torrefaction as energy and mass percentages or fractions [36,37]; therefore, both ash and free water content are excluded from the definition. The mass yield (α_y) is the correlation between the mass of the biocoal produced (m_b) and the mass of the raw material, i.e., total available mass (m), obtained from the resources in the roasting system per candidate node (Equation (3)).

$$\alpha_y = \left(\frac{m_b}{m}\right) \tag{3}$$

Energy yield (β_y) is defined in the model according to Equation (4)

$$\beta_y = \alpha_y \cdot \left(\frac{LHV_b}{LHV}\right) \tag{4}$$

where

"β_y" is the yield referred to the LHV parameter already considered in Phase 1;
"α_y" is mass yield; and
LHV_b and LHV are lower heating value of biocoal mass and raw material, respectively [36].

The available energy per unit of mass corresponds to LHV because it represents the energy that can be efficiently recovered after combustion. To this objetive, the torrefaction process is assumed to be carried out on the available mass as a whole within the areas surrounding each node, thus obtaining Equation (5):

$$m_b = \left(\sum_{i=1}^{n} m_i\right)\cdot\alpha_y \tag{5}$$

where

m_b is biocoal mass from available mass per node (dry t/year);
m_i is mass of available biomass (dry t/year); and
α_y is mass yield.

For the calculation of energy potential to be obtained as primary energy from biocoal, Equation (6) is applied as an approach.

$$E_b = \sum_{i=1}^{n} (m_i \cdot LHV_i)\cdot\beta_y \tag{6}$$

where

E_b is bioenergy as biocoal per node (GJ/year);
m_i is available mass (dry t/year);
LHV_i is lower heating value of conifers, hardwood and mixtures (GJ/dry t); and
β_y is energy yield.

Equations (3) and (4) show the technical feasibility of placing a roasting system at a candidate node in the study area by bioenergy-match mode. Such operating conditions correspond to short residence periods, less than 30 min, with temperatures above 260 °C. Favorable conditions are considered to be those with energy and mass efficiency above 95% and 90% respectively. If the initial biomass to be torrefacted is dry, with moisture content below 10–15%, lower energy efficiency can be expected [37].

2.2.3. Phase 3: Energy Management

Biomass represents the main manageable renewable energy and should therefore play a role in energy production to replace or complement fossil fuels (Phase 3). Introducing biocoal in the industrial sector, and especially in thermal demand, calls for a change in the energy supply management model [38]. Energy production systems consist of sets of technologies that transform raw energy from one fuel into final use energy [17], allowing for the production of heat and/or electricity and of new biofuels. Based on the analysis of energy management, the energy to be produced will be assessed on the basis of the biocoal production in the roasting system as compared to its energy-based equivalence to the mass (m_f) of other conventional fuels, Equation (7).

$$m_f = E_b\ /CV_i \tag{7}$$

This is done by taking the calorific value (CV_i) of the fuels in Table 2 [39] as an approximation.

Table 2. Energy-based equivalence of certain fuels.

Type of Fuel	Calorific Value (CV_i) (GJ/t)
Brown coal	18.8
Distilled oil	41.2
Natural gas	45.6

The model of analysis using the multiphase mathematical algorithm considers a maximum distance of 50 km for the resources around each candidate node, which is a limit distance determined for their transformation into conventional biofuels that can be used in that territory [40]. Consequently, the calculation area is restricted to a maximum of about 50 km away from each candidate node for the entire analysis (Phases 1, 2, and 3). Once the final combination of the results per candidate node has been determined, the optimal node, i.e., the location of the roasting system in one mine shaft, will be defined for the harvesting of the available resources in the study area.

3. Results

In Phase 1, the analysis model established by the multiphase mathematical algorithm (Figure 2) shows the quantities of both potential biomass and available biomass in the study area for each of the nodes considered, as shown in Figure 3.

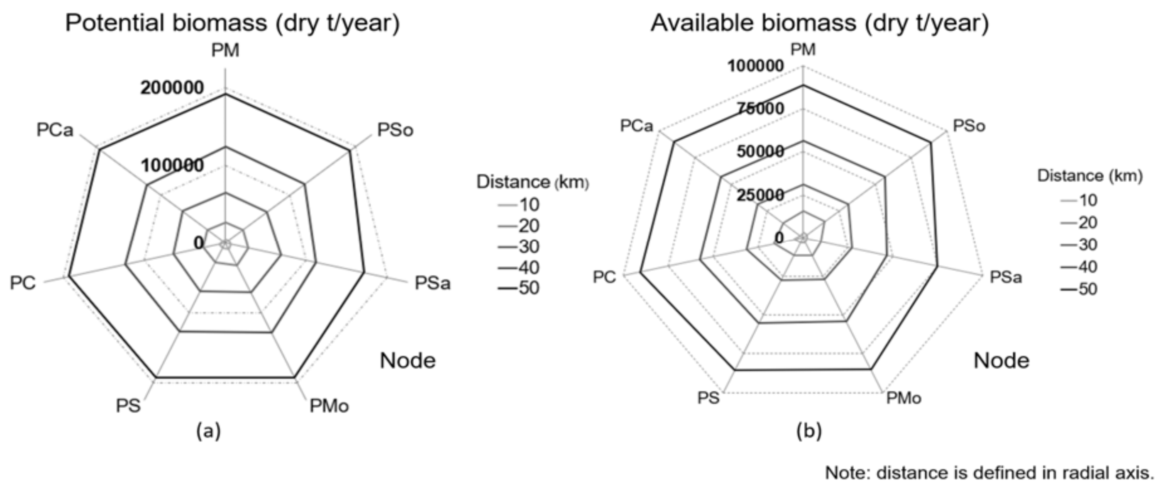

Figure 3. Mass per candidate node in the study area: (**a**) potential biomass (M) and (**b**) available biomass (m).

Figure 3 shows some linearity in the distribution of the potential biomass around each modelling node considered in the CACB. It indicates a regular distribution of the biomass with the increase of the distance from 10 km to 50 km. Increasing the distance yields more available biomass around each candidate node (Equation (1)). The available energy based on the available biomass per candidate node is shown in Figure 4.

For each node, the amounts of the available biomass that can be collected are above 75 dry kt/year, around 1300 TJ/year. The available biomass will be used as raw material to be converted into biocoal (Figure 4).

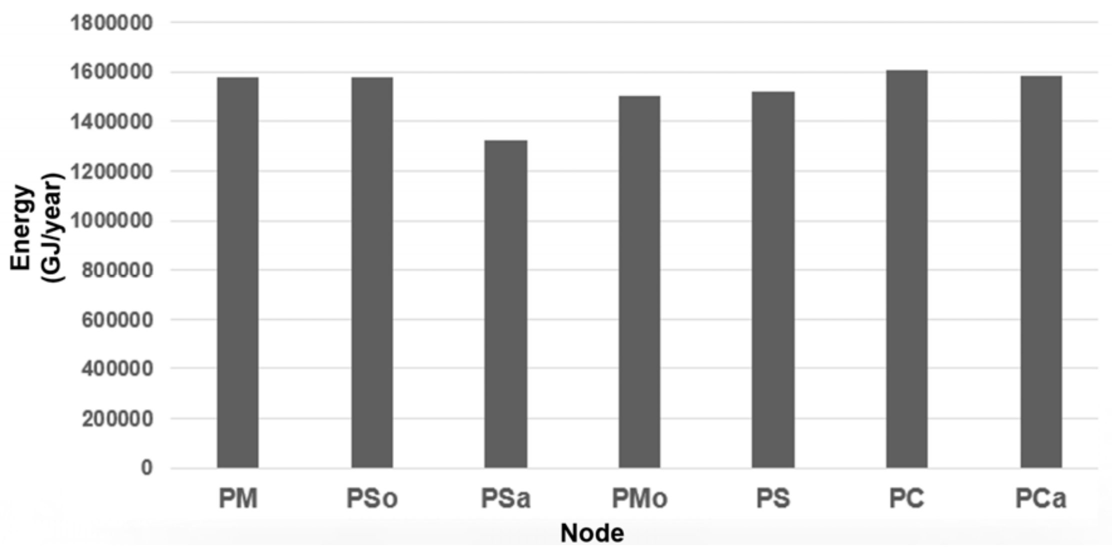

Figure 4. The energy (E) of the available biomass per candidate node as calculated by Equation (2).

Phase 2 takes into account the thermo-energetic conversion of the available biomass into biocoal as per Equations (5) and (6). Figure 5 shows the results of the biocoal potential and its equivalent energy per modelling node with the increase of the distance from 10 km to 50 km. The thermo-energetic conversion does not affect the distribution because it has a similar shift of the mass and energy per candidate node in the study area.

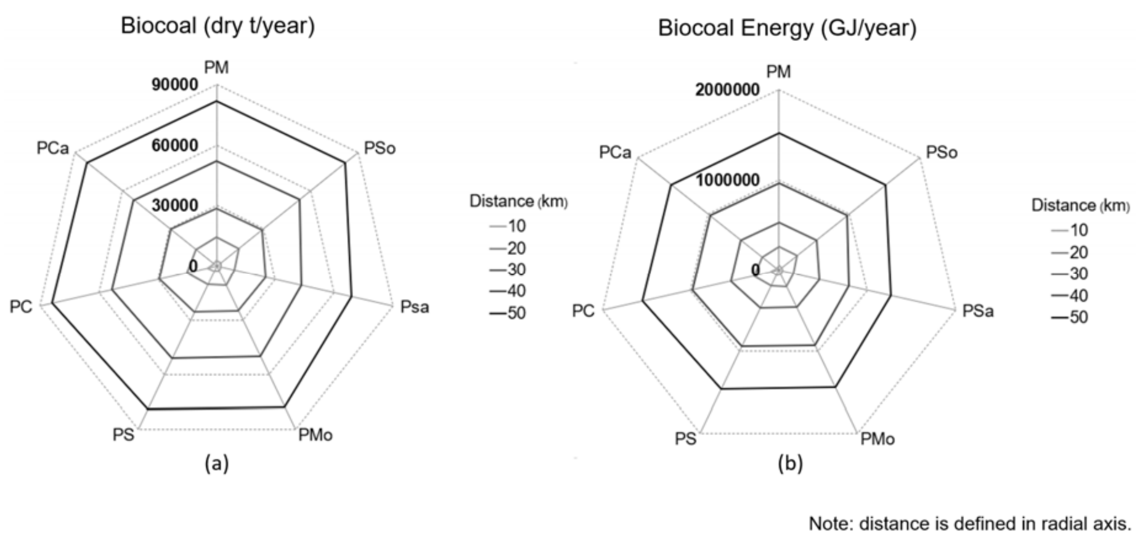

Figure 5. Mass and energy per candidate node in the study area: (**a**) biocoal (m_b), (**b**) bioenergy (E_b).

Furthermore, the LHV distribution of the biocoal obtained from the raw material collected in the study area has been evaluated per candidate node (Figure 6).

As can be seen, there is a homogeneous distribution of the energy quality of the theoretical biocoal to be obtained, reaching an overall average value of about 18.5 GJ/dry t.

Finally, Phase 3 of the algorithm is implemented in each node, based on the data in Table 2. Equation (7) shows this potential as an alternative fuel to coal for energy conversion. This assessment characterizes biocoal as compared to different types of fossil fuels for energy production systems (Figure 7).

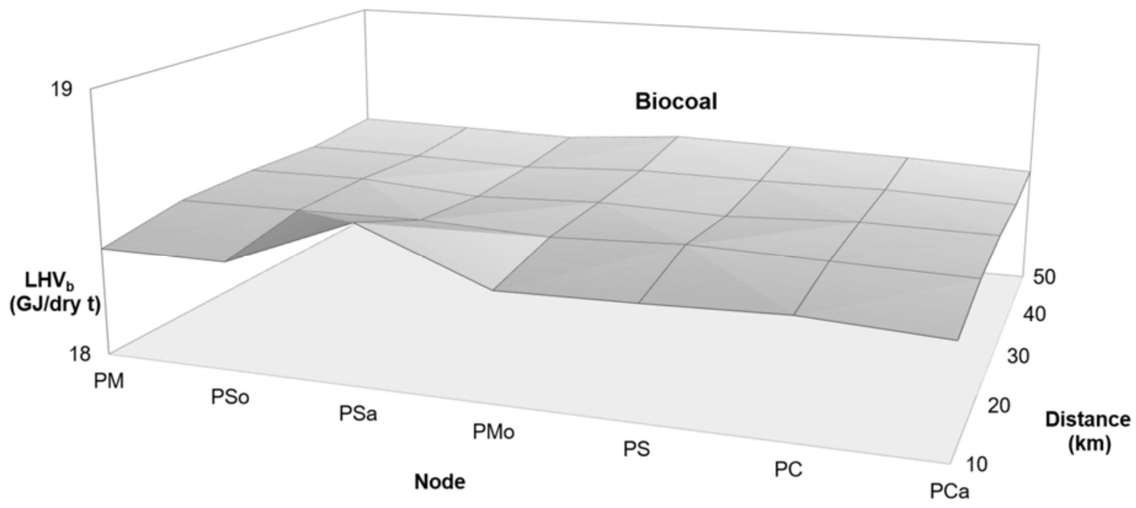

Figure 6. Lower heating value (LHV_b) distribution of the obtainable biocoal in the study area.

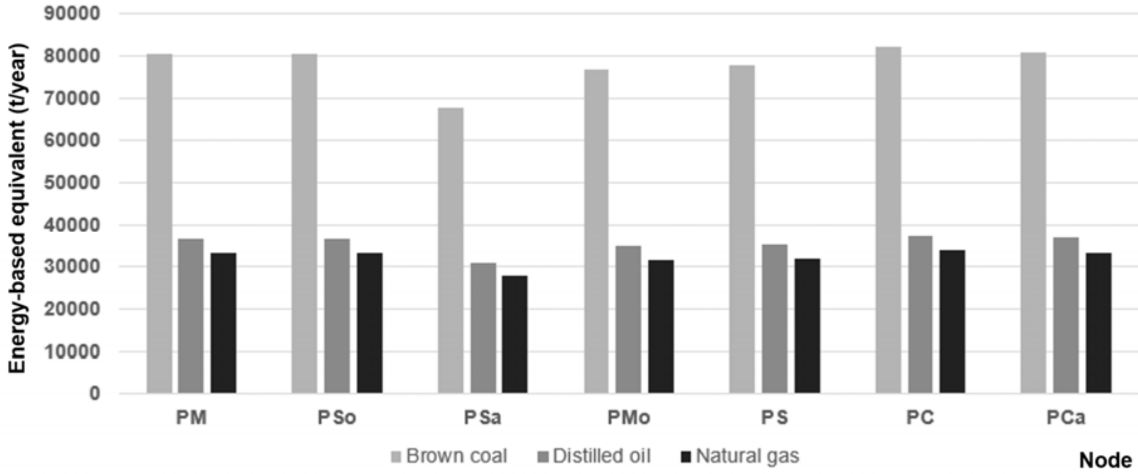

Figure 7. Energy-based equivalent fuels from biocoal, as a substitute in energy production systems.

Taking all candidate nodes, the potentially producible biocoal in terms of energy is equivalent of above 28 kt/year of natural gas, 31 kt/year of distilled oil, and 68 kt/year of brown coal.

4. Discussion

Implementing a technological alternative requires splitting up the analysis by considering the different aspects involved [41]. The paper explores biocoal use as an alternative to coal production in mining basins by using mine shafts as energy conversion nodes that draw on the surrounding forest biomass as raw material. The findings of the study reveal that the proposed model, based on a multiphase algorithm, is highly useful in the study of energy conversion and management for thermal systems. A cumulative analysis of these facts, augmented by other findings of this work, is summarized below.

The potential renewable in the world is diverse and widely distributed in nature [1]. However, most of it may present supply fluctuations, giving rise to risks and uncertainties in serving regional energy markets. In this sense, the use of biocoal in mining environments, as proposed, guarantees the use of renewable resources and their conversion, since it is based on substituting the use of fuel, i.e., coal, with one of similar characteristics, i.e., biocoal. Moreover, there is a whole industrial structure with mature technologies for the use of this coal. Despite this, one of the remaining challenges for the development of biofuels in the industry is whether a sufficient amount of raw material can be generated to meet the growing demand and achieve a shift from fossil fuels to biofuels [42].

In this regard, the applied algorithm shows that any node considered as a thermo-energetic conversion node for biocoal production has at least 75 dry kt/year of raw material for biocoal production in the study area. Here, given the nature of the area under consideration and the nodes, only one node may be selected, given the territorial extension of the CACB.

Biocoal could replace coal in the production of heat and power through energy production systems. It would also have a large impact on industry [43]. Providing the infrastructure, technology and research to enable the use of renewable energy sources available "on site" is a challenge for industry, in particular for readily available sources such as biomass [38]. The continued development of industrial technology is expected that will ensure more competitive, reliable and sustainable energy production systems [44]. The use of biomass as an alternative to coal in certain contexts has been made feasible by using biocoal technology, but advances in technology alone do not promote its widespread use; therefore, extensive studies are needed. In this sense, from the mass and energy balance of the analysis model, the optimal node appears to be PC, this is selected as the optimal node for the CACB. With the use of a roasting system, this node would produce about 84 kt/year of biocoal, equivalent to 1544 TJ/year of biocoal, the largest amount of all the nodes selected in the proposed analysis.

Renewable energy generation systems are illustrative of the fact that some renewable energy infrastructures are at a significant distance from energy conversion systems [41]. Overcoming this barrier to competitiveness of renewable energies requires a well-planned and carefully managed energy supply infrastructure during and after the infrastructure investment. An environment based on fuel-coal energy production systems in the mining basins benefits both their use and direct conversion for electrical, thermal or industrial purposes, given the development of a coal energy conversion industry in the coal mining environment. However, all this requires some analysis of future techno-economic feasibility as well as in-depth studies based on the development of these technologies.

Biomass holds the potential to be considered the best alternative to meet global energy demand sustainably and reduce the impact of polluting energy resources [45]. In this context, the development of biorefineries for the production of advanced biofuels is encouraged. Biorefinery represents a sustainable means of generating multiple bioenergy products from various biomass raw materials via the incorporation of relevant conversion technologies. Biorefinery is crucial in the transition of various traditional industries into a circular bioeconomy in the context of energy transition [46]. That opens up the door to the development of infrastructures such as the biorefinery in the aforementioned node. The use of biomass in energy production systems such as co-firing coal with biomass to generate energy is gradually increasing even though their performance differs significantly due to the wide variations in its physical and chemical properties [47]. However, biocoal overcomes most of its use limitations for heat or electricity production.

In this context, in the shaft named "Pozo Candín" (PC), considering the efficiency of a heat production system with a thermal efficiency of 80% and about 2000 h of operation per year [48], it is possible to install a total power of 172 MW_{th} for the energy conversion of biocoal. Additionally, if it is considered the alternative objective of electricity production, either by co-combustion or by itself, looking at an electricity efficiency in the complete conversion of 40% for about 7500 h, it would be possible to achieve an electricity potential equivalent to 23 MW_e [49,50]. Detailed studies of biomass conversion stages within the energy production system are working lines for the future in order to further develop more efficient and advanced energy conversion systems.

5. Conclusions

Biocoal makes it possible to overcome many of the barriers that condition its use and the development of biomass in mining basins around the world due to the traditional interrelationship between the resource and conversion technology for its viability. This is an opportunity to focus on using it in energy production systems that use coal as an energy source, as it overcomes many of the limitations traditionally associated with biomass. In this respect, a multiphase mathematical algorithm based on operational resource data, thermo-energetic conversion, and energy management has been developed.

The research in this paper highlights the potential of forest biomass in mining areas around the world, in this case in the CACB in Spain, and identifies possible options for the use of forest residues as raw material for solid biofuels as an alternative to coal in carbon basins, i.e., biocoal. Taking a minimum value considering all the nodes in the study area, the energy potential for biocoal is equivalent to over 28 kt/year of natural gas, 31 kt/year of distilled oil, and 68 kt/year of brown coal.

Overall, the quantities of biomass that can be collected in all the nodes studied are above 75 dry kt/year (about 1300 TJ/year). The optimal node that guarantees the largest amount of energy, from a point of view of the proposed mass and energy balance in the study area, is the "Pozo Candín" (PC), which would allow biocoal to be produced through a roasting system at a rate of 84 kt/year, equivalent to 1544 TJ/year in the considered operation conditions with the biomass of the CACB. The production potential of electrical and thermal energy by thermal systems under the defined conditions in this node amounts to 23 MW_e and 172 MW_{th}, respectively.

Implementing this energy potential on an industrial scale in the CACB requires techno-economic and thermal systems studies based on the specific characteristics and objectives of the facilities that will be using it. Future understanding of the range of benefits and challenges when introducing and up-scaling biocoal production under different scenarios will depend on detailed, comprehensive, and simultaneous assessments, technological options, and final techno-economic factors.

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