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Review article

A brief review on coal reserves, production and possible non-power uses: The case of Mexico

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ABSTRACT

Coal has been a valuable natural resource for Mexico not just for its relative abundance but for its critical role in the development of the steel and energy industries. It has been also important in the socioeconomic context of the northeast of the country. However, since years ago, coal mining is facing a transition due to the emergence of new energy sources and the public concern about global warming. A brief review on coal reserves, production and possible non-power uses was carried out to provide insight on the reserves in a global context, extraction patterns and alternatives that the Mexican coal industry has to evolve. For this purpose, Mexican coal reserves were overviewed and contextualized at a global level and total coal production figures from 1970 to 2021 were analyzed to identify fluctuations and differences in the amounts produced between coking and non-coking coal. Further, rare earth elements, carbon fiber and humic acid from coal were briefly reviewed with the aim of initiating a debate on the high value-added products that can be obtained and the technologies that can be adopted to develop the coal industry of Mexico. Coal proven reserves in Mexico are of 1211 million tonnes and, from 1970 to 2021, 428.11 million tonnes have been produced. Of the total cumulative production, 68.8% corresponds to non-coking coal and 31.2% to coking coal.

1. Introduction

Coal is a sedimentary rock formed from the partially decomposed remains of plant material. Its main constituents are organic material, mineral mater and water [1,2]. Coal is widely distributed around the world and its uses ranges from simple combustion for heat to complex partial oxidation to produce heat, gaseous/liquid fuels and chemical feedstock [3,4]. Currently, coal is mainly used to generate electric power by combustion in electric utilities and although this use holds a major share in global power generation [5], the tendency is to switch to cleaner energy sources. It is expected that natural gas, which is considered a "bridge fuel", will surpass coal in 2030, smoothing the transition of the global energy system from fossil fuels to zero carbon energy [6,7].

Burning coal has environmental drawbacks, so efforts have long been made to develop alternative energy sources. These efforts have led to cheaper natural gas, increased environmental regulation and increasing penetration of renewables. As a result, coal demand is being decreased and, although is likely to rebound in the short term, the industry is in decline [6,8,9].

According to the International Energy Agency (i.e., IEA), global coal demand fell by 4.4% in 2020 [8]. The figures are as follows: China coal demand increased 1%, US and EU coal demand decreased nearly 20%, and India and South Africa coal demand decreased 8%.

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The decline of the coal industry has generated serious economic and social issues in specific areas of some countries where coal production has been the main economic activity. For example, coal production in the United States dropped between 33 and 37% from 2007 to 2017 and the number of producing coal mines have been reduced more than 60% from 2008 to 2020, affecting the communities that have been historically reliant on this industry [9,10].

Coal production in Mexico began approximately in 1884 near Sabinas, located in the northeast of Coahuila, but it was until 1921 that small companies began to proliferate. The coal production on small scale serviced the railroads manufacturing and nascent metallurgical and steel industries; but since 1960, Mexico began employing coal to generate electricity through the Federal Commission of Electricity (i.e., CFE) [11,12], which is the state-owned electric utility of Mexico. As will be shown later, the Mexican coal industry shifted from producing coking coal to non-coking coal, in order to produce electric power. Fig. 1 shows the life cycle of coal in Mexico which includes the exploitation, preparation and transport stages.

Two obstacles arise from the above description (see Fig. 1). First, the electric power generation is managed by CFE, leaving very low margins to the coal producing companies since it is not possible to aggregate value by integrating the exploitation and the electric power generation. Second, alternative non-power uses of coal, with high value-added, have not been explored. Explore, develop and implement alternative non-power uses of coal would add value to the coal producing companies at the same time that it would reduce their dependence on CFE.

The assessment of alternatives to coal combustion and the concerns about coal's role in climate change emissions and air pollution, have put intense pressure on coal markets. There is renewed interest in how to use coal sustainably and effectively without burning it. There are attractive alternatives that can be tested and developed, such as advanced materials and chemicals derived from coal [6]. A modern approach of the coal industry must include industrial and research fields related to the production of rare earth elements and carbon dioxide storage [3–14].

The aim of the present brief review was to contextualize reserves and critically assess the coal production in Mexico from 1970 to 2021 to identify the location and production patterns; as well as to identify the shift from coking coal to non-coking coal. It is also an intention to provide insight on the alternative fields of research to diversify the coal industry in Mexico, therefore, the discussion was complemented considering some possible non-power uses of coal, such as rare earth elements extraction, carbon-based materials and humic acids from coal. Coal mining companies, particularly in Mexico, must integrate the exploitation of coal with some advanced processes to obtain high value-added products in order to thrive.

2. Overview of the coal resources of Mexico

To assess the production of coal in Mexico is necessary to contextualize the reserves of the country with those of other countries, as well as to bear in mind the coal alternative non-power uses. It is worth mentioning that in some cases is used data of proven or total reserves, depending on the reference; thus, text, figures and tables are specific to give clear information.

2.1. Coal reserves of Mexico in the global context

According to BP [15], the coal proven reserves of the world were estimated at approximately 1.07 trillion tonnes. Fig. 2 shows the distribution of coal proven reserves by region. It can be observed that Asia Pacific accounts for 42.8% of the total reserves followed by North America, CIS, Europe, Middle East and Africa, and South and Central America with 23.9, 17.8, 12.8, 1.5, and 1.3%, respectively. The largest share of proven reserves in the Asia Pacific region are in Australia, China and India with 14.0, 13.3, and 10.3%, respectively.

North America and Asia Pacific have 66.7% of the world total coal proven reserves but its distribution, between the countries that make up these regions, is drastically uneven. Table 1 shows that North America has 256,734 million tonnes of the world total coal proven reserves, namely 224,444 tonnes of anthracite and bituminous and 32,290 of sub-bituminous and lignite. It means that the 87.4% of the coal proven reserves corresponds to anthracite and bituminous coal and the remaining 12.6% to sub-bituminous and lignite.

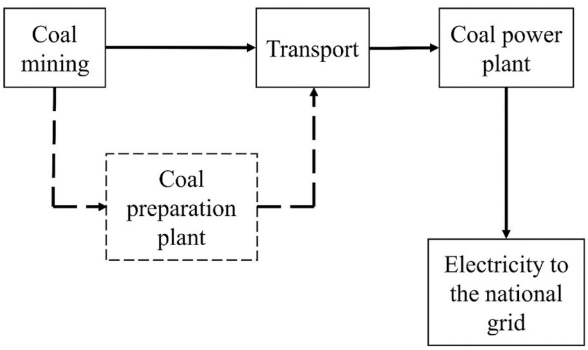

Fig. 1. Life cycle of coal in Mexico.

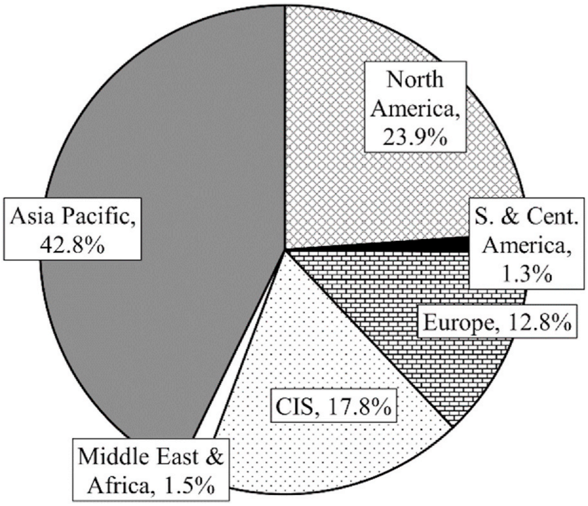

Fig. 2. Share of total coal proven reserves by region, constructed with data from BP [15].

Table 1
Coal proven reserves in North America at the end of 2020, constructed with data from BP [15].

Million tonnes	Anthracite and bituminous	Sub-bituminous and lignite	Total	Share of total
Canada	4,346	2,236	6,582	2.56%
Mexico	1,160	51	1,211	0.47%
US	218,938	30,003	248,941	96.97%
Total North America	224,444	32,290	256,734	100%

The North America total coal proven reserves are distributed between Canada, Mexico and US with 2.56, 0.47 and 96.97%, respectively. Mexico only has 1,211 million tonnes of proven reserves that comprise 1,160 million of anthracite and bituminous and 51 million of sub-bituminous and lignite, 95.8 and 4.2%, respectively.

It can be seen in Fig. 3 the coal proven reserves of countries from North, South and Central America, excluding the United States which has 248,941 million tonnes of coal proven reserves (the world's largest). Brazil, Canada, Colombia, Mexico and Venezuela have 6,596, 6,582, 4,554, 1,211 and 731 million tonnes, respectively. As can be seen, the proven reserves of Mexico are not as abundant as those of other countries.

Although coal proven reserves of Mexico account for a small proportion of the North America total share, coal mining has been a very important economic activity in the northeast of the country. Data of Fig. 3 is also important since in order to propose alternative non-power uses of coal should be taken into account the amount and quality of the reserves and the importance that these aspects have in the continent.

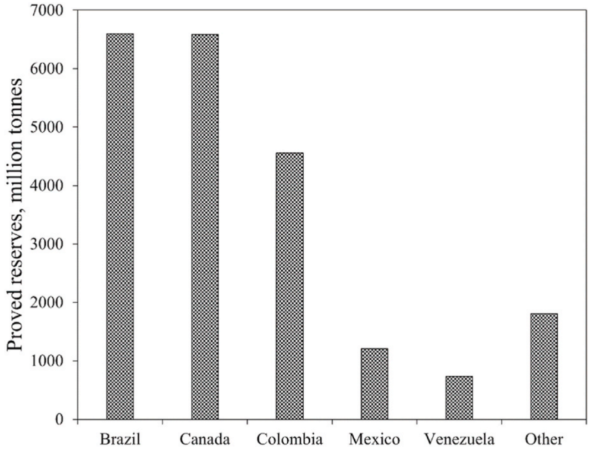

Fig. 3. Coal Proven reserves by country in North, Central and South America; excluding the US. Constructed with data form BP [15].

2.2. Distribution of coal resources in Mexico

Coal deposits in Mexico are distributed in the northeast, northwest and south. Most of the reserves are in the northeast region that includes Coahuila de Zaragoza and an adjoining area between Nuevo León and Tamaulipas. In the south of Mexico, Oaxaca represents another important region, though vastly inferior. In the northwest, the reserves are in the Barranca formation in Sonora [11,12]. The location of the regions described above can observed in Fig. 4.

Below is an evaluation of the distribution of coal reserves in each region, emphasizing the northeast of Mexico since it has the largest number of reserves and produces the largest amount of coal in the country. Indeed, the northeast of Mexico is the only relevant producer of coal.

The northeast region, including Fuentes-Río Escondido, Sabinas and Colombia-Nuevo Laredo basins, covers 12,000 km^2 mostly of the late Cretaceous Period and of the Eocene Epoch in the Tertiary Period and represents the most important coal source of Mexico [12].

Fuentes-Río Escondido basin contains bituminous coal which cannot be converted to coke, and it is considered thermal coal due to its physical and chemical properties [11,12]. Fig. 5 shows the distribution of the proven, probable and possible reserves in the Fuentes-Río Escondido basin. 576 million tonnes are considered as proven, 140 million tonnes are considered probable and 185 million tonnes are considered possible.

The Sabinas field, located in Coahuila de Zaragoza, is a geological extension of the southwestern field of Texas which contains tertiary coals. Coal seams in the Sabinas basin vary from 1 to 2 m in thickness and produce a coal whose middle-range volatile matter content (20–25%) and low sulfur content (1.2%) are acceptable, but whose high average ash content (23%) lowers its grading [12]. This basin includes the Sabinas, Saltillito, Las Esperanzas and San Patricio sub-basins and its medium-volatile bituminous coal has good physical properties that allows its agglomeration to be converted to coke. At the end of 1980 the reserves of the Sabinas field were estimated between 2,300 and 2,900 million tonnes, this includes proven, probable and possible reserves [11,12]. It means that the Sabinas basin has approximately 3 times the total coal reserves of Fuentes-Río Escondido but, it is worth noting, they are not of comparable quality.

The south and northwest regions of Mexico are of secondary importance. In Oaxaca are the Tlaxiaco, Niltepec and Tezoatlán basins that contain anthracite, semi-anthracite and bituminous coal. It is estimated that seams from a few centimeters to 3 m contain approximately 30 million tonnes. In Sonora, the Barranca formation that extends from Sn. Marcial to Alamos contains anthracite and meta-anthracite coal and its estimated reserves are of approximately 85 million tonnes [12].

It can be observed in Table 2 the summary of the estimated total coal reserves of Mexico. The northeast, mainly the state of Coahuila de Zaragoza, has the largest number of reserves, subdivided in three basins containing bituminous and sub-bituminous coal. Otherwise, although of high quality (e.g., anthracite and semi-anthracite), Sonora and Oaxaca only have 85 and 30 million tonnes of coal, respectively. Due to the abundance, the Coahuila's coal resources are considered the most important in the country.

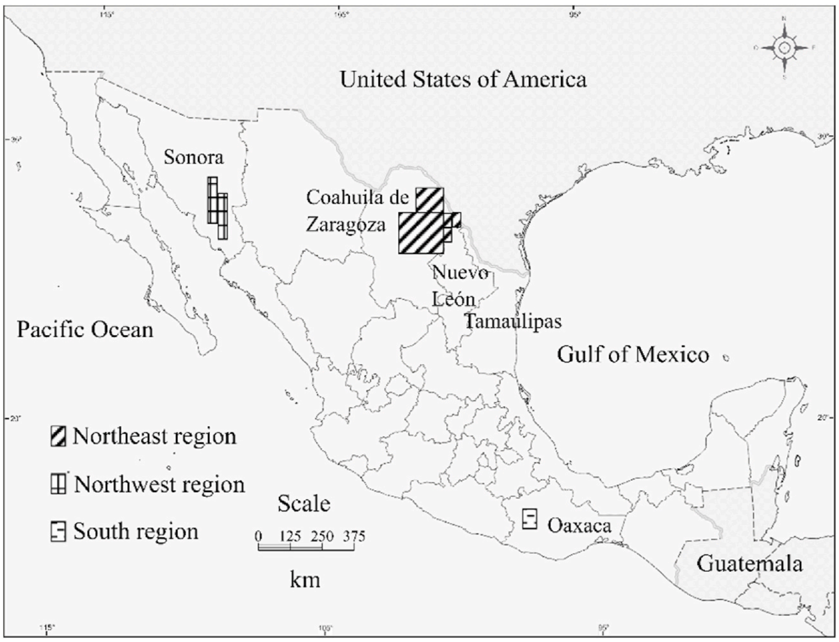

Fig. 4. Map showing the regions where are located the coal deposits of Mexico.

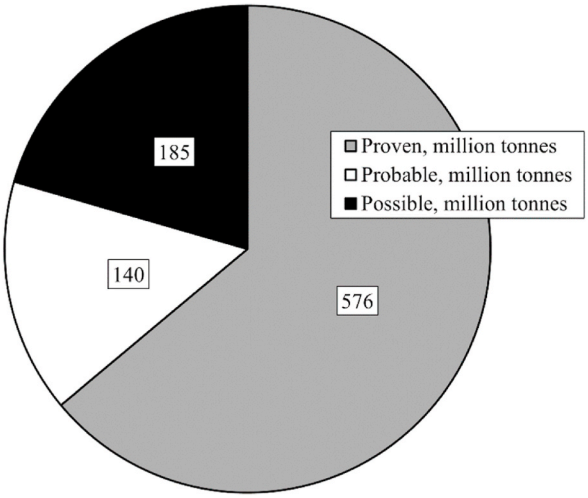

Fig. 5. Coal reserves in the Fuentes-Río Escondido basin, constructed with data from Castaneda and Iza [11].

Table 2
Summary of the total estimated coal reserves of Mexico, location and main characteristics. Constructed with data form Castaneda and Iza [11] and Wallace [12].

Region	States	Basins	Characteristics	Estimated, million tonnes
Northeast	Coahuila and an adjoining area of Nvo. León and Tamaulipas	Fuentes-Río Escondido, Sabinas and Colombia-Nvo. Laredo	Bituminous and sub-bituminous	3,201–3,801
Northwest	Sonora	Barranca formation	Anthracite and semi-anthracite	85
South	Oaxaca	Tlaxiaco, Niltepec and Tezoatlán	Anthracite, semi-antrhacite and bituminous	30

3. Coal production in Mexico

3.1. Total coal production in Mexico and its annual variation

The first coal mining operation began production in 1884 in the northeast of Mexico (Sabinas, Coahuila). According to Corona-Esquivel et al. [16] between 1902 and 1910 were produced 10.1 million tonnes of coal, and from 1911 to 1921 were produced 4 million tonnes. Further, in the period from 1921 to 1940, in which small and big companies began to proliferate, 32 million of tonnes of coal were produced.

The Sabinas and Fuentes-Río Escondido basins have always been the largest coal producers of Mexico due to their coal quality, relative abundance, ease of access and location. Accordingly, the coal exploitation in the northeast of Mexico represents the largest share of the coal industry of the country.

Fig. 6 shows the total coal production by year and cumulative coal production from 1970 to 2021. It can be observed, in Fig. 6a, a steady increase in the coal production from 1970 to 1980 to later give rise to the first important decline; coal production fell from 7.12 million tonnes in 1980 to 3.66 million tonnes in 1981. From 1982 to 1996 coal production had a positive tendency, it increased from 3.24 to 10.96 million tonnes. Later, production fell from 10.96 million tonnes from 1996 to 7.82 million tonnes in 2002. It is observed a production increase from 7.82 million tonnes from 2002 to 13.42 million tonnes in 2007. Production fell from 13.49 million tonnes to 10.81 million tonnes in 2009. The largest amount of coal was produced in 2011, reaching 15.84 million tonnes. In 2012, 2013 and 2014 production reached 15.82, 15.28 and 15.68 million tonnes, respectively. Production fell from 15.68 million tonnes in 2014 to 9.27 million tonnes in 2015 and to 4.23 million tonnes in 2020. In 2021, 778,746 tonnes more were produced than the previous year.

Fig. 6b shows a cumulative coal production from 1970 to 2021 of 428.11 million tonnes, from which approximately the half (i.e., 215.62 million tonnes) has been produced in the last 20 years (from 2001 to 2021), which represent an important expansion in the production capacity over time.

Fig. 7 shows the coal production annual variation and the coal production variation considering the average coal production from 1970 to 2021. It can be identified five periods of increasing production (see Fig. 7a), namely 1971–1979, 1983–1987, 1990–1996, 2003–2007 and 2010–2011. It can be also clearly identified 3 considerable drops in coal production in 1981, 2015 and 2020 (−48.6, −40.9 and 36.1%, respectively).

In Fig. 7b can be observed the variation of coal production considering the average coal production from 1970 to 2021 (i.e., 8,394,272 tonnes). It can be observed that from 1995 to 2017 the coal mining industry performed well since the annual production was

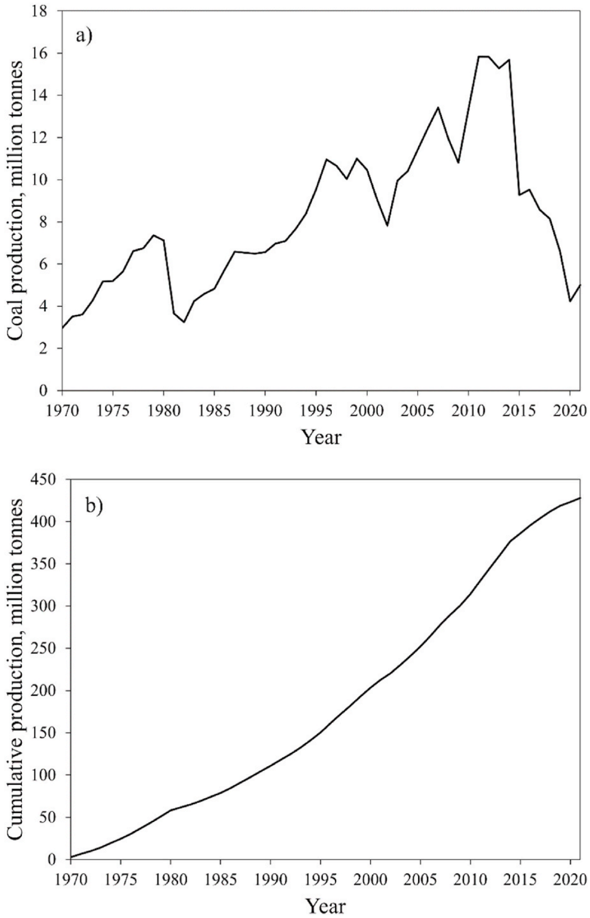

Fig. 6. Total coal production in Mexico by (a) year and (b) cumulative, constructed with data from Castañeda and Iza (from 1970 to 1980) [11] and INEGI (from 1980 to 2021) [17].

above the average except for 2002.

3.2. *Non-coking and coking coal production of Mexico*

Fig. 8 shows the (a) non-coking and coking coal annual production and (b) cumulative non-coking and coking coal production from 1970 to 2021.

It is very interesting to observe in Fig. 8a that in the period from 1970 to 1979 the non-coking coal production was practically null while the coking coke production rise from 2.84 to 7.30 million tonnes. Coking coal production abruptly decline from 7.30 million tonnes in 1979 to 2.43 million tonnes in 1981. In 1984–1985 coking coal ceased to be the more exploited coal in Mexico, although it slightly increased from 2.37 to 2.39 million tonnes. Non-coking coal production increased from 2.21 to 2.44 million tonnes from 1984 to 1985. From 1985 to 2021, non-coking coal production was always greater than coking coal production. Non-coking coal production shows a steady positive tendency from 2.44 million tonnes in 1985 to 13.72 million tonees in 2011. Otherwise, coking coal production shows a slightly negative tendency from 2.39 million tonnes in 1985 to 0.48 million tonnes in 2021. Non-coking coal production was dramatically reduced from 13.72 million tonnes in 2011 to 3.53 million tonnes in 2020, then it slightly increased to 4.52 million tonnes in 2021.

Cumulative non-coking and coking coal production also has some interesting features (see Fig. 8b). From 1999 to 2000, cumulative non-coking coal production surpass the cumulative coking coal production. Cumulative non-coking coal production for the period 1970–2021 is 294.54 million tonnes and cumulative coking coal production is 133.56 million tonnes. It means that cumulative non-coking coal production represents 68.8% of the total cumulative coal production from 1970 to 2021, or that cumulative non-coking coal production was 2.2-fold greater than cumulative coking coal production.

At the beginning, the coal production was focused on the coking coal, and this gave rise to the consolidation of the nascent metallurgical industry (steel industry) in Coahuila de Zaragoza and Nuevo León. According to the coal quality of the fields described above, it is clear that coal production began in the Sabinas field. Later, coal production expanded to Fuentes-Río Escondido basin due to the need to produce themal coal.

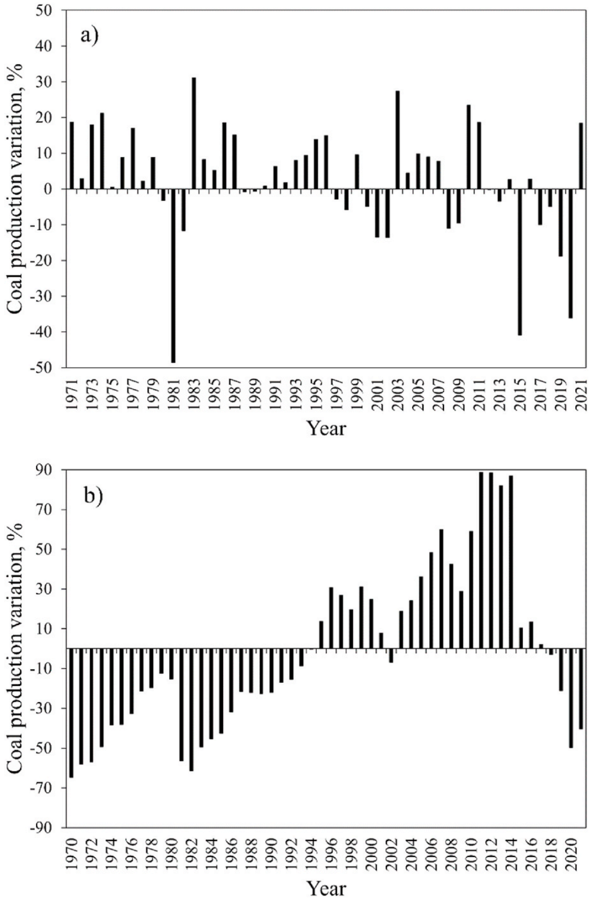

Fig. 7. Total coal production variation in Mexico by (a) year and (b) considering the average coal production from 1970 to 2021, constructed with data from Castañeda and Iza [11] and INEGI [17].

In Fig. 9 can be observed the non-coking and coking share of the total coal production in Mexico from 1970 to 2021. It can be observed that between 1970 and 1980 coking coal production represented between the 95.3 and 99.1% of the total coal production, the non-coking coal production share was minimal. 1981 was the first year in which non-coking coal production exceed the 5% share of the total coal production to reach 33.8%. In 1985, non-coking coal production share surpass the coking coal production share and since then non-coking coal production share has been greater than 50%. From 2002 to 2021 the non-coking coal production share has been between 81.4 and 90.3%.

When compared to the main coal producers worldwide, the coal industry in Mexico is very small. However, it is essential as an economic activity. Further, the decline of the coal industry is not just a "job creation" issue. Economic, social and policy implications that emerge when communities are disrupted as part of the energy transition have been documented and it is necessary to implement industrial and social policies to ensure a smooth energy transition [6,10].

The largest use of coal today is in the generation of electric power by electric utilities. According to the U.S. Energy Information Administration (i.e., EIA), about 65% of coal mined in the world is used for power generation [8]. According to Ember [18], Mexico electricity generation by source in 2021 was as follows: 55.72% gas, 10.28% other fossil, 9.79% hydro, 6.65% wind, 5.39% solar, 4.86% coal, 3.67% nuclear, 2.31% bioenergy and 1.32% other renewables. In order to take advantage of the Mexico's coal endowment and to do not leave behind the communities that historically depend on the coal mining industry, other uses of coal must be explored, preferably non-power uses.

Some coals are used to manufacture coke, its high pure carbon content, porous structure and high resistance to crushing has made it a necessary material in the production of molten iron. For many years the coke industry grew concurrently with the growth of the iron and steel industry but currently, methods of producing steel without coke are under development and some are in operation. The most common approach is the recycling of steel using electric arc furnace that melt and process scrap steel for reuse. Direct reduced iron is another process that reduces coke need by directly reducing iron ore without the use of coke.

There are many potential ways of using coal, combustion is the most common choice, but other utilization strategies also deserve attention. Some authors have explored alternative non-power uses, which can be considered as alternatives to develop the industry in Mexico. These include the use of coal (1) for extraction of rare earth elements, (2) in manufacturing carbon materials, (3) for making

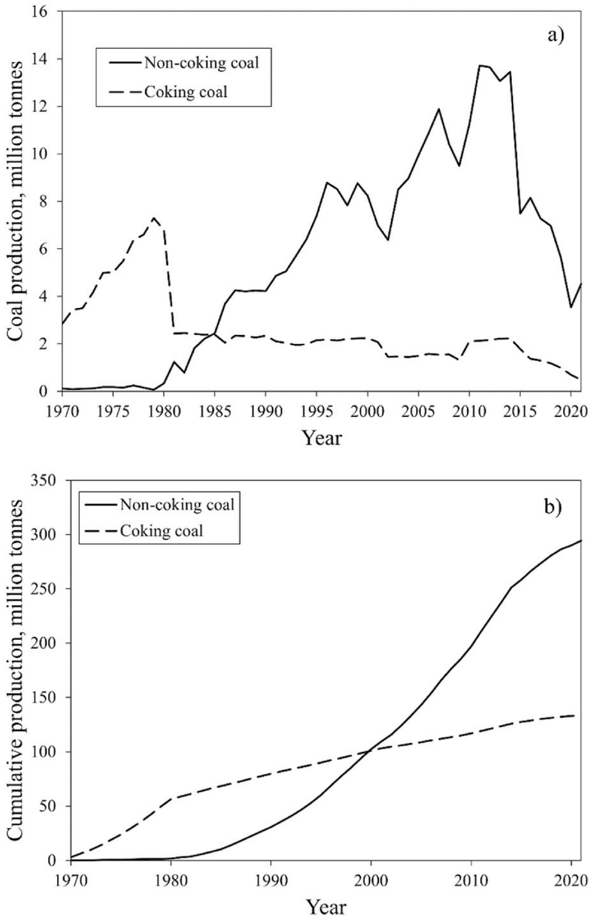

Fig. 8. Mexico non-coking and coking coal production by a) type of coal and b) cumulative by type of coal. Constructed with data from Castañeda and Iza (from 1970 to 1980) [11] and INEGI (from 1980 to 2021) [17].

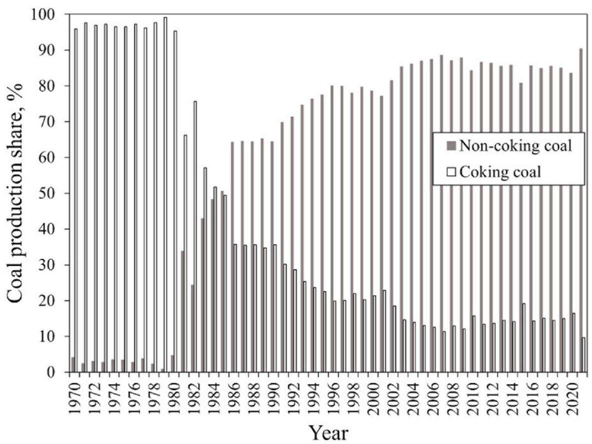

Fig. 9. Share of the total non-coking and coking coal production of Mexico. Constructed with data from Castañeda and Iza (from 1970 to 1980) [11] and INEGI (from 1980 to 2021) [17].

humic substances/materials, etc. [6,19]. According to the above, some potential non-power uses of coal, which can be explored by the stakeholders in Mexico, are briefly reviewed.

4. Possible non-power uses of coal in Mexico

4.1. Rare earth elements from coal and coal ash

Rare earth elements are 17 strategic elements which are necessary in technologies such as catalysis, cell phones, hard drives, hybrid engines, lasers, magnets, etc. Rare earths can be extracted from monazite sand, bastnasite ore, phosphate rock of igneous origin, eudialyte group minerals and coal-related materials [6,20–22].

Coal-related materials include coal, coal refuse, coal mine drainage and coal combustion byproducts which can contain rare earth elements in higher concentrations than traditional ores. Nowadays the extraction of rare earth elements from these materials is a reality, since it has progressed from feasibility assessment to pilot-scale production [23,24].

The rare earth elements extraction from coal-related material operations implies a great challenge since it would include a more complex unit operations arrangement than those used in conventional extractive metallurgy [23]; as a reference are the processes proposed for the recovery of this strategic elements from minerals in Foxtrot Project [25,26].

4.2. Carbon fiber from coal

Coal can be considered as a carbon-based material and its appropriate processing conditions could render it into active carbons, graphite, or other carbon materials. To obtain carbon fiber from coal, it is heated and broken down into pitch. Then, it is melted and spun into carbon fiber [19].

Carbon fiber is important in manufacturing due to its mechanical properties such as its high tensile strength and lightness, even surpassing those of steel. This material also has better resistance to chemicals and high temperatures and can serve as a good electrical and thermal conductor.

According to Gagarin et al. [6], taking advantage of the domestic coal resources to economically produce carbon fiber could have impact on several industries. This could favor the development of the coal industry in Mexico since the country is an important player in the automobile manufacturing industry where carbon fiber is widely used.

4.3. Humic acid from coal

According to Helal [27], humic substances are commonly described as a series of yellow to black colored acids that are poorly understood. However, it is known that the high content of oxygen containing functional groups is their most notable characteristic. These substances are widely distributed in carbonaceous materials as shale, peat, lignite and brown coal.

There are three major types of humic substances which are operationally defined in terms of their solubility as fulvic acid (FA), humic acid (HA) and humin (Hu) [27,28].

At present, the potential uses of humic acids in many fields are well recognized and they can be defined as agricultural and non-agricultural, which are based on their capacity to bind metals [29]. The most common agricultural uses are fertilizer base, combination fertilizer, chelating agent and bio stimulant for plants [30]. Otherwise, the non-agricultural uses of humic acids include drilling mud additive, manufacture of zeolites, cement additives, cosmetic additives, innovative materials and water treatment.

Humic acids can also be used for the preparation of co-polymer materials, and it appears that the results of these recent applications could have some positive impacts on industrial developments where low-rank coals are readily available [19].

The humic substances can be obtained from carbonaceous matter by extracting methods based on their solubility, allowing its separation into HA, FA and Hu [28,31]. The most common techniques and procedures applicable are alkaline extraction, acidic precipitation and membrane separation [32].

The elemental composition, functional groups content and the molecular weights of the humic substances produced are dependent on the nature and rank of the coal from which is extracted. Low-rank coals lead to humic acids having the highest COOH and phenolic content while high-rank coals (e.g., bituminous) contain fewer acidic functional groups. The quality of the coal also influences the range of the humic acid carboxylic group values. Peat and leonardite reach a yield production of 31.6 and 58.5% humic acid, respectively [28]. Therefore, the use of low-rank coal for the direct synthesis of humic substances is the correct focus and it has been the perspective that various research groups have tried [33].

The extraction yield of humic acids from middle-rank coal is commonly low, but this extraction yield can be enhanced by employing an oxidizing pretreatment using hydrochloric acid, or air/oxygen mixtures. Ideally, the oxidation reaction could be considered as an inverse diagenetic process able to regenerate the molecules which originally led to the insoluble structure of coal. Thus, the products of the extraction process have similar characteristics and chemical behavior to these molecules [28].

According to the above, the quality of the coal of the Northeast Mexico could be a perfect match to extract humic substances; therefore, research is being developed to evaluate the humic acid extraction yield from leonardite.

It is worth noting that although carbon is an organic material and minerals are inorganic species, the process of extraction of humic acids is an aqueous-purification/precipitation process as those employed in hydrometallurgy.

5. Conclusions

The "brief review on coal reserves, production and possible non-power uses: the case of Mexico" has shown the following:

(1) Even though proven coal reserves of Mexico are relatively small compared to those of other countries, it is in the interest of Mexico to evaluate alternative non-power uses of coal and to develop the industry to produce high value-added alternative products.
(2) In 1984–1985 coking coal ceased to be the more exploited coal in Mexico and since then non-coking coal production has always been greater than coking coal. This is due to a supply and demand relationship, since free-coke technologies to produce molten iron and steel have arisen.
(3) Cumulative non-coking coal production for the period 1970–2021 is 294.54 million tonnes and cumulative coking coal production is 133.56 million tonnes, it means that cumulative non-coking coal production represents 68.8% of the total cumulative coal production.
(4) Production of humic substance form coal is a first-research suitable alternative, since the process is like the one implemented in the hydrometallurgical extraction of metals. Further the middle-rank quality of the coal from the northeast region of Mexico would not be an obstacle and oxidizing pretreatments could be implemented.

Efforts must be made to develop the coal industry in Mexico. Such efforts must be based on the evaluation of the resources and fields in which immediate action can be taken. It is necessary to establish priorities in this field and coordinate the work carried out in the spheres of research, development and production. Tax policy should be included and implemented to encourage the production and marketing of high value-added products from coal.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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