

REVIEW

Mining industry and sustainable development: time for change

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Keywords

coal, environmental impact, metals, mining resources, phosphate, rare-earth elements, sustainable development, uranium.

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Received: 29 March 2017; Revised: 26 April 2017; Accepted: 6 May 2017

Food and Energy Security 2017; 6(2): 61–77

doi: 10.1002/fes3.109

Abstract

Mining industries provide most of the materials we rely on to build infrastructures and instruments of daily use, to obtain large amounts of energy, and to supply agriculture with fertilizers that enable most of foods produced. At the same time, mining is the human activity that has been more disturbing to environment and is linked to large social impacts and inequalities. Notwithstanding, our future is deeply depending on mining. Several mining sectors, from phosphate to uranium, are reviewed and their current impacts and challenges are discussed. The mining legacy and environmental remediation, the present mining and challenges, and the future mining and society are discussed in relationship with environmental health and sustainable development. It is concluded that current mining practices need to change and contribute to community development with more equity, and to protect better natural resources and ecosystems in order to be environmentally acceptable and compliant with sustainable development objectives.

Introduction

Mining industries provide many of the raw materials for equipment we use daily, from aluminum cans up to electronic chips of cell phones and computers. To arrive here, metal mining steadily increased over the centuries, with occasional “rushes” for several minerals (silver, gold, radium, etc.) which occurred in connection with booms in demand. The common mining practice until very recently could be summarized in a few steps: from obtaining a license, dig the ore, sell the metal, and, once the deposit was exhausted, walk-away and start another mine elsewhere (Jain et al. 2016; EB 2017). Not surprisingly, mining is among the human activities with widest environmental and social impacts.

Herein, several mining sectors are revisited to highlight mining procedures, their effects, and current challenges. Mining for base metals (e.g. Al, Fe, Mn, and Ni) and energy fuels (oil, gas, coal, and uranium) requires large investments, and it is capital intensive, being carried out mostly by major corporate companies. However, precious metals (e.g. Au, Ag, and Ta) in many regions are often

targeted by artisanal mining also. All have deep environmental impacts. The legacy of radium and uranium mines in Europe is used to illustrate old mining practices, their environmental and social impacts, and remediation costs. New mining projects are expected today to incorporate lessons from past mining activities and meet societal and development needs in a more efficient and less damaging way to the environment.

This article summarizes how important have been past mining activities and how important can be in the future, at least for some types of mining, and discusses the effects of mining, the trends in mining impacts on environment and society, and how they shall avoid compromising sustainable development.

Mining industry and legacy impacts

Mining activities are not new and indeed may have started in Neolithic (Chalcolithic) times to obtain the first metals for tool fabrication (Reardon 2011). In the Classic Greece and in the Roman Empire, many mines were exploited for

production of iron, lead, copper, gold, and other metals. Many of those old mines are still known, and some have been operated over several centuries or were rediscovered (Fernandez-Lozano et al. 2015). With time, mining have expanded and increasing amounts of fossil fuels (e.g. coal) and metals (e.g. iron) were extracted in quantities generally commensurate with man power available and thus with human population over the centuries. With technological developments, especially with explosives and machinery, mining could expand further on the 19th century and sky rocketed during the 20th century (EB, 2017). In the last quarter of the 20th century, new and harsh environments, such as ice-covered regions and the deep sea floor, started to be mined for oil, natural gas, and metals. This trend will continue and new frontiers might be trespassed soon.

The comparative importance of mining and contribution to the world Gross Domestic Product (GDP) during the last century shows an increase by a factor of 27 in ores and minerals production, and by a factor of 8 in total materials extraction, while GDP raised 23-fold (Fig. 1). A clear first role of mining in the global average economic growth is highlighted in this assessment (UNEP, 2011).

Mining activities are very diverse and may have different ecological footprints. Past mining activities left such imprints in the environment, but two issues in particular are of major and worldwide importance: mine tailings and acid mine drainage. Tailings in general are voluminous and contain toxic elements that may be released and introduced in the biogeosphere (Nordstrom 2011; Jain et al. 2016). Acid mine drainage often results from exposure of rock minerals and ore deposits to water and oxygen facilitating the mobilization of chemical elements and increasing their concentrations in waters and food chains,

with detrimental effects on ecosystems' health and human health (Carvalho et al. 2007, 2016a,b; Hudson-Edwards et al. 2011; Nordstrom 2011). This mining legacy was accumulated over centuries but only in the last quarter of the 20th century its environmental and human health impacts were finally recognized. Since then, there has been a significant development of legislation for environmental and sanitary protection, and some actions were started to deal with industrial legacy through clean up, remediation, and rehabilitation projects. These remediation actions started in USA with the Superfund project in 1980 and so far have been implemented mainly in North America and West Europe (Mudroch et al. 2002; EPA, 2017).

As a side effect of environmental legislation development and increased costs of waste management, mining moved from developed countries to other regions. Today, international companies often mine for oil, coal, gas, uranium, rare earth elements, and fine metals in regions far from the big consumer markets and final users. Mining regions are now often located in remote areas of north of Canada and Australia, and in developing countries in South America, Asia, and Africa, often with less stringent mining laws and weaker environmental regulations (Miranda et al. 1998; World Bank, 2002, 2017a). Mining impacts, including waste streams and social impacts, were, therefore, generally transferred from developed and densely inhabited regions to other regions.

Mining Sectors and Metals in the Society

Mining ores are generally aggregated in sectors such as base metals, fossil fuels, and precious metals. Metals such

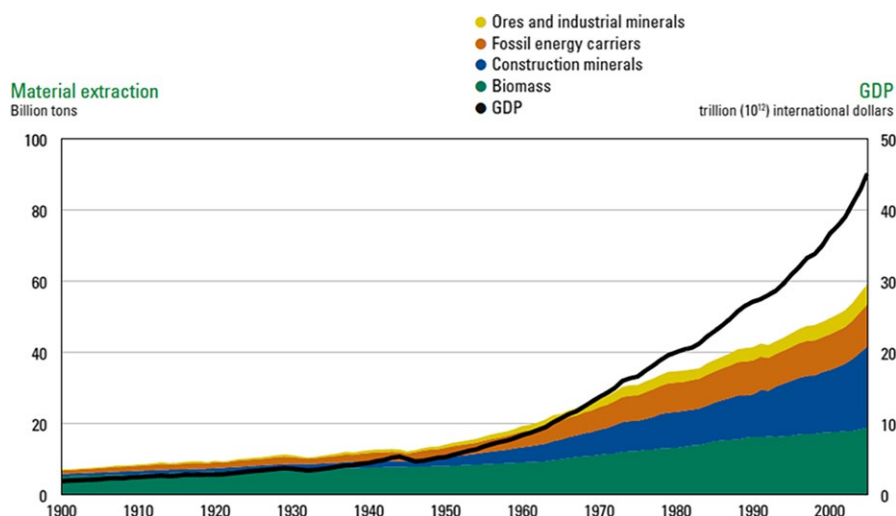


Figure 1. Global material extraction in billion tons and Gross Domestic Product (GDP) growth, in the period 1900-2005 (Reproduced from UNEP, 2011).

as iron have been mined for long time, while others such as aluminum were recently mined only (Reardon 2011). Total amounts of metals extracted already from the Earth crust and contained in applications (infrastructures, machinery, and tools) are very large. Today, recycling the metals from accumulated scrap and waste in landfills may be in some cases more economical than to mine ore deposits (UNEP, 2013; Fig. 2). For example, in 2008, the world steel industry produced over 1.3 billion tonnes of steel. It used 1.48 billion tons of raw materials, or 470 million tonnes less than, would have been needed to make the same volume of steel in the 1970s (WSA, 2009). Concerning aluminum, it is estimated that since 1880 900 million tons of aluminum were produced of which nearly 75% is still in use today. The demand for aluminum continues to skyrocket and recycling aluminum saves more than 90% of the energy required to producing new metal, thus rendering recycling very attractive (TAA, 2017).

Other metals, such as uranium, and fossil fuels, such as oil and gas, are extracted for energy supply and are largely or totally consumed in their applications (burned), and thus, the recycling does not apply as above (although, in the case of nuclear spent fuel, reprocessing may still recover unused uranium). In both base metals and fuels, the resources in Earth are finite, although a difference between them may be that for some metals (base metals), we may live with a portion of the Earth crust resource, while with others (energy minerals and fossil fuels) the trend is to use them until the Earth crust deposits (reserves) are completely exhausted. If consumption continues as today, the limited amount of energy fuels in geological deposits will be exhausted, and this may compromise growth and development at some point in future time (Gordon et al. 2006; Brown 2011).

Environmental and social-economic impacts of mining may also vary with the ores and regions. Next, we review briefly a few mining sectors to highlight trends and impacts as well as current challenges.

Base metals

This includes copper, nickel, iron, manganese, zinc, and others, but iron (Fe) and aluminum (Al) occupy a leading role in consumption and represent the largest fraction of metals accumulated in the society. Iron has been mined since antiquity, and there are vast iron amounts in built infrastructures. Aluminum has been produced only from the 19th century on but today occupies a wide place in the economy and industry (UNEP, 2013; USGS, 2017a,b). To illustrate this, we may look into statistics of the global extraction of major metals which, in the period from 1970 to 2004 (35-year period), grew by more than 75%, and global extraction of industrial minerals (e.g. rocks, cement), which increased by 53% in the same period (USGS, 2008). In such period, global consumption of aluminum increased from about 12.5 billion tons per year to 38 billion tons per year, that is, more than three times, while the global consumption of ferrous metals (used for production of steel) increased slower reaching about one billion tons per year in 2014, that is, the double of 1974. In USA, aluminum recovered from old scrap in 2016 was equivalent to about 31% of apparent consumption in the same year (USGS, 2017a).

Over the last decades, releases of materials into the environment, which take place in every stage from extraction, to use, and to waste disposal causing environmental and human health impacts, increased at a greater rate because of overburden removed to reach the metal ores. The quantity of waste generated to produce the 12 major metals and commodities was computed to be, in average, four times the weight of the metals extracted, but, in reality, the wastes flow increases faster than the commodity extraction due to declining ore grades and need to tap deeper ore deposits (USGS, 2008; UNEP, 2011).

Global trends in iron and steel consumption show also higher consumption of metals in North America, European Union, China, and India than extraction which relates to economic growth of these countries. The opposite trend



Figure 2. Recycling scrap metal for steel production.

was noticed in the rest of the world (USGS, 2008). It is also known that reserves of these metals (e.g. Fe is 5% of Earth crust) largely exceed the amounts already extracted and will ensure the availability of these resources for long time (USGS, 2017a,b). This is not the case for all metals and metal recycling is needed (Gordon et al. 2006). Recycling is easy for not-alloyed metals, and it is much less costly in energy than extraction from the mine and can extend further the life time of the resource (UNEP, 2013).

The extraction cost of base metals is large and its extraction usually requires intensive investment, the buildup of large infrastructures, and generally produces large environmental impacts (Fig. 3). As an example, we may quote the 10 biggest iron mines in the world and their environmental impacts (Basov 2015). Furthermore, the development of mines such as copper, lead, and arsenic mines in Peru has caused severe environmental losses, and today, it may require intensive dialog with stakeholders to reach a societal agreement to mining, as it happened at Cajamarca and Las Bambas (Bury 2002, 2004). It is also from some of the biggest metal mines in Peru that reports give account of poor safety records and large social and environmental impacts changing the livelihoods of communities and compromising water resources and agriculture soils (Ponce and McClintock 2014; Triscritti 2013; Bebbington and Williams 2008; Jaskoski 2014; Fig. 4).

The current global trends in production of these metals are worrisome: (1) in spite of rising material flows, the worldwide average commodity consumption per capita did not improve globally, but regionally only; (2) the environmental costs with extraction and processing were increasingly borne by lesser developed countries; (3) these combined trends create a situation not sustainable in the long term (USGS, 2008). Why is this? Because metal extraction to satisfy the needs of the world population at the standards enjoyed by most developed countries with current technology would exhaust metal resources



Figure 3. Large landscape footprint of mining (Iron mine of Mount Tom Price, Western Australia).



Figure 4. Silver Mine in Peru surrounded by houses (Cerro de Pasco, 4330 m altitude).

at least for several among them, such as copper, zinc, and platinum (Gordon et al. 2006).

Oil and gas

This mining sector is the world largest in the amount of materials produced and the value of revenues (UNEP, 2011). Access to energy sources and their use constrained and shaped the human society's actions and economic growth over time, and this is particularly true for oil and natural gas during the 20th century. Oil exploitation fully developed during the last century and related ecological impacts occurred, ranging from oil spills and soil contamination in the forests of Ecuador and delta of Niger River to the Arctic coast and oil spills in the sea, such as the recent oil spill of the Deep Horizon platform in Gulf of Mexico, 2010 (Chang et al. 2014).

In the Gulf of Mexico, only there are more than 2000 oil platforms in operation and other oil spills had occurred, and are likely to occur again. Also, oil tankers suffered shipwrecks in seas around the world that originated oil spills with significant impacts in coastal areas (e.g. *Torrey Canyon*, *Exon Valdez*, and *Prestige*). The most iconic case of impact in the marine environment was the oil spill of the supertanker *Torrey Canyon* in 1967 at the Cornwall coast, English channel, exactly 50 years ago, that initiated a period of wide concern with ecological disasters (Wells 2017). Scientific reports have documented the toxic effects of crude oil on biota including humans, the lasting contamination by petroleum hydrocarbons, and the slow recovery of marine ecosystems (Chang et al. 2014). Reports from several countries have highlighted also serious impacts on terrestrial environments, human communities, and economics. Impacts of Deep Horizon 2010 oil spill cost 62 billion USD to British Petroleum (USA Today, 2016), and the cost of oil spills following shipwreck of oil

tankers, such as the *Prestige* at the Spanish and Portuguese coasts in 2002, were estimated in billion dollars (Loureiro et al. 2009; Chang et al. 2014; Fig. 5). Oil spills showed also the diversity of toxic pathways and ecological impacts of crude oil and how unprepared the nations are to face such ecological catastrophes (Chang et al. 2014).

Needless to say, that in spite of oil spill impacts, most countries depend on oil and natural gas supplies and its production is an ongoing activity. Many estimates have been made of the oil and gas reserves and, repeatedly, new oil and gas fields were discovered, and the expected lifetime of resources has been expanded. Eventually, they may last for another 50 years to 5 centuries, depending on estimates. Nevertheless, although known with some uncertainty, there is a wide conscience that fossil fuels do exist in finite amounts and campaigns for the best use of resources and energy savings have been introduced worldwide to constrain also the fast release of carbon dioxide into the atmosphere.

Other impacts associated to oil and gas production are the disposal of scales from pipe cleaning, which generally are highly radioactive, and of sands associated with bottom of oil reservoirs which contain metals and radionuclides in high concentrations as well. For example, scales from oil pipes contain radium-226 (^{226}Ra) in

concentrations above 1000 Bq/g, and other radionuclides are present as well. For comparison, the IAEA classifies materials as radioactive waste when radionuclide activity concentrations exceed 1 Bq/g (EU, 1997). This requires careful waste management and waste disposal by oil companies although, often, the regions where oil production is on-going are not prepared or not aware of this radioactive waste. Despite currently available knowledge, still the environmental impacts of oil and gas exploration are very high, often not fully regulated and controlled and, if waste is not properly managed, the effects may last for thousands of years (e.g. ^{226}Ra radioactive half-life is 1600 years). Their environmental impact and potential impact on human health may thus last much longer than the resource.

Fossil fuel resources are consumed at high rates, and there is no hope that biogeochemical cycle and natural processes will replenish the fossil fuel reservoirs in Earth in a time scale useful to human societies. Therefore, other energy sources will be needed and must be sought (Brown 2011; Michaelides 2012). Interestingly, it has been questioned how the access and use of energy sources (fossil in particular) could have been key to development of successful human societies. It is a matter of consensus that the access to energy sources, such as coal in the Industrial Revolution, was instrumental to enhanced growth. However, plotting the Human Development Index against the annual average energy consumption per capita clearly shows that there are no quality of life gains above a certain energy consumption level (Smil 2004). The only guaranteed outcome of higher energy use is greater environmental burdens which may endanger habitability of the biosphere. Indeed, today there is scientific agreement that oil and gas, together with coal burning, have a major environmental footprint and are responsible for increased concentrations of atmospheric carbon dioxide and accelerated climate changes (IPCC, 2014; IEA, 2017).

Coal

Coal has been used as a fuel for thousand years, but really become the most important fuel with the Industrial Revolution and the steam powered engines (Freese 2004). In the 19th and 20th centuries, coal was the primary source of energy in metal smelting and to produce electricity, and it was extracted in many countries, from United Kingdom to Australia and from United States of America to Russia. In 1980 in the United Kingdom, coal was replaced by the cheaper and abundant natural gas and oil and this was the end of an era. Today, coal still accounts for the production of near to 25% of the world's energy, but is declining fast, and by 2050, coal will contribute to about one-third only (IEA, 2017). There are

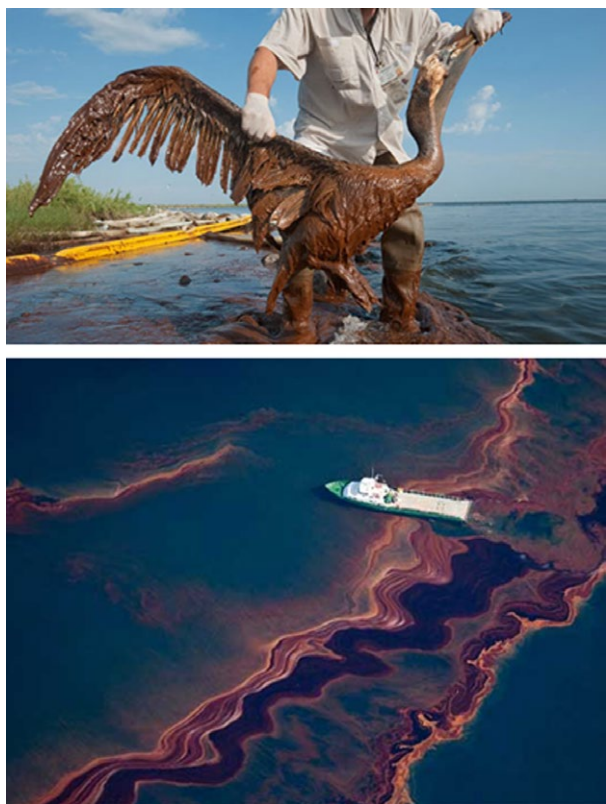


Figure 5. Deep Horizon oil spill, Gulf of Mexico, 2010.

an estimated 892 billion tonnes of proven coal reserves worldwide. This means that, according to the World Coal Association, there is enough coal to last us around 110 years at current rates of consumption. In contrast, according to some estimates, the proven oil and gas reserves are equivalent to around 52 and 54 years, respectively, at current production levels (World Coal Association, 2017). Safety in coal mining is a very urgent issue as it is estimated that around 500 coal miners die every year in mine accidents in China only (World Bank, 2007).

Environmental impacts of coal burning include increased amounts of carbon dioxide in the atmosphere, that together with other greenhouse gases, such as nitrogen protoxide (N_2O) and methane (CH_4), are the causes for present global warming (IPCC 2014). The evidence of climate change and its potential effects led to international negotiations on reduction of carbon emissions and creation of a carbon market (IEA, 2017). Notwithstanding, coal still is a lever for the economic growth of many countries (e.g. electricity production and steel making), while others currently decrease coal burning because of atmospheric and global impacts. Besides global impacts, countries that consume very large amounts of coal, such as China, have to deal with the heavy environmental and public health effects from coal mining and coal burning (World Bank, 2007; IEA, 2017).

Less known than CO_2 emissions, but well documented too, are soot and particle emissions into the atmosphere as well as the release of radioactive elements volatilized and injected into the atmosphere (UNSCEAR, 2017). The radionuclides emitted from fossil fuels burning are the primordial radionuclides of uranium, thorium, and actinium radioactive series. These include alpha-, beta-, and gamma-emitting radionuclides that become constituents of flue gas and particle emissions into the atmosphere. Several among these radionuclides, such as ^{226}Ra , ^{210}Pb , and ^{210}Po have been reported in aerosols from coal powered plants (UNSCEAR, 2017). Energy agencies have made comparisons of CO_2 and radioactive emissions from coal power plants and from nuclear power plants and concluded that nuclear power plants in normal operation have lower CO_2 emissions and less radioactive emissions into the environment than coal power plants and, thus, have lesser contributions to climate change and to radiation exposure (UNSCEAR, 2017). However, releases of radioactivity that occurred with major nuclear accidents (e.g. Three Mile Island, Chernobyl, Fukushima) outweighed radioactivity released by coal power plants. Furthermore, several reports indicate that release of smoke and gas from fossil fuel and biomass burning may indeed increase the radioactivity exposure of human population through inhalation, and this issue might have been neglected in the past (Yan et al. 2012; Carvalho et al. 2014a).

Phosphate

Phosphate industry is crucial to agriculture and food production. Phosphate production grew over the past century and continues to increase in order to supply fertilizers to agriculture and enable high yields in food production (Carvalho 2017). From phosphate rock produced annually, most is converted into phosphoric acid and, from this, 82% is used in fertilizer, 9% in animal feed and beverages, and 9% into nonfood industrial production (e.g. detergents) (Heckenmüller et al. 2014).

Phosphate sedimentary rocks contain fluorapatite with phosphorus (P) and calcium (Ca), but also fluor (F), cadmium (Cd), arsenic (As), mercury (Hg), and uranium (U). While P and Ca are essential elements to plant growth, and thus important elements in agriculture fertilizers, metals such as As, Cd, and U are undesired elements and may contaminate crops and soils.

Many of the co-occurring metals in phosphate rock are partly retained with phosphogypsum, a by-product of phosphoric acid production, while other part goes with the fertilizer (Carvalho 1995). Due to radionuclides and other contaminants, phosphogypsum stacks have found no meaningful application. Phosphate fertilizers are often criticized also because of contaminants they contain. In the future, it is likely that phosphate fertilizers will be purified, a step likely to be driven mainly by uranium recuperation, and henceforward phosphate fertilizers will not add further amounts of Cd and U and other contaminants to soils.

During last century, phosphate fertilizers were overused in some regions, and this increased the P content in soils in Europe and North America and now in China. This P excess ends up in aquatic environments causing eutrophication and representing also a loss of P for agriculture (Scholz et al. 2013). Meanwhile, the piles of phosphogypsum amount to about 3×10^9 tons worldwide, and this industrial legacy is often seen as a source of environmental contaminants. Most of the phosphogypsum disposal sites were not remediated and attempts have been made to reuse this material, for example, as soil amendment and in construction materials, but generally with limited success. One solution currently pushed by phosphate industry (to disperse the phosphogypsum in soils in order to get rid of stacks) is not desirable because this would spread contaminants in soils and waters and would prevent the eventual recover of uranium from phosphogypsum (Fig. 6).

The main phosphate producers are USA, China, and Morocco, and the largest world phosphate reserves exist in the West Sahara. A debate about limited resources of phosphate and possible scarcity of phosphorus to agriculture has been raging since the last decade (Cordell et al. 2009;



Figure 6. Phosphogypsum piles, at Florida, USA.

Gilbert 2009; Van Vuuren et al. 2010). Some authors claim that phosphate production attained already the peak production and resources will be exhausted in about one century and then shortage in food production is inevitable. Others argue that with the current consumption rates, phosphorus resources may last several centuries (Vaccari 2009; Rosemarin 2010).

Currently, we are using more P in a short time and faster than nature can redistribute it, and the obvious advice is that phosphorus must be better used in current practices. However, phosphor recycling is feasible, and this may afford additional time to resource availability. For example, P may be recuperated and recycled from wastewater, animal metabolism, and aquatic environments in order to maintain food production yields in agriculture (Schnug and De Kok 2016). Therefore, contrarily to predictions of phosphor scarcity it seems very unlikely that phosphor may become a limiting factor in food production (Scholz et al. 2013; Heckenmüller et al. 2014). Regionally, it may be needed to intervene in the biogeochemical cycle of phosphor in order to redistribute this element and make phosphor available according to soil and food production needs. Globally, due to the uneven geographic distribution of phosphate deposits, it may become a reason for future geostrategic dispute, as the fossil energy sources today.

Heavy mineral sands

This is a new mining sector that recently developed for extraction of zirconium and rare Earth elements (REE), such as lanthanum, europium, tantalum, and erbium, which are demanded by the production of cell phones, computers, permanent magnets, etc. The production of REE increased from about 1000 tonnes/year in the 1950s to 135,000 tonnes/year in 2009, although afterwards declined slightly. The overall skyrocketing trend will be

maintained to supply electronics and telecommunication industries and to support the upcoming automation in industry, transports, and services (Lima and Filho 2015).

The largest resources of REE are in China that is also the largest consumer of REE (Lima and Filho 2015). Outside China, most REE mines exploit littoral sand dune deposits (monazite sands) in African coasts, South Asia, and Australia. Coastal areas of Bangladesh, India, Mozambique, Senegal, currently have heavy minerals sand mining and much larger projects are now in the process of approval and implementation in Africa (Fig. 7).

Extraction of heavy minerals from sand dunes is carried out by wet sieving and gravimetric separation. Large barges, floating on a dynamic fresh water pool, move along the dunes and revolve the sand. The sand fraction with no value (silica, hematite, carbonates) is returned to the beach in the rear of extracting barges. The wet mineral concentrate is further processed to segregate the heavier minerals using gravimetric and magnetic procedures. The



Figure 7. Mining heavy mineral sands in coastal sand dunes, North of Mozambique.

outcome of the exploitation is to export heavy mineral fractions (zircon, garnet, ilmenite) to metallurgical facilities able to achieve full metals' separation.

In the field, this mining process conduces to destruction of consolidated sand dune barriers otherwise able to stop hurricanes and prevent coastal erosion and, also, affording protection to back dune ecosystems and stabilized coastal ecosystems. If appropriate regulations and measures are not enforced, the agriculture, fisheries, and tourism assets of such coastal areas may be jeopardized (Carvalho et al. 2017).

Recent reports claimed that heavy mineral sands exploitations may cause radioactive contamination of the environment also (Schüler et al. 2011). Heavy REE minerals in sand deposits usually are associated with uranium and thorium, and segregation of zirconium and REE increase the concentration of those naturally occurring radionuclides in the material fractions produced. For example, in a field investigation carried out in Mozambique, uranium (^{238}U) concentration in unprocessed sand from the top of sand dunes was about 9 ± 1 Bq/kg, and in the final zirconium produced, the ^{238}U concentration was about 2700 ± 80 Bq/kg (Carvalho et al. 2017). The ambient radiation dose on the top of natural sand dunes was about $0.08 \mu\text{Sv/h}$, while in the processing plant facility, it averaged $1.5 \mu\text{Sv/h}$, and after minerals segregation by the piles of ilmenite, it was about $7.8 \mu\text{Sv/h}$. For plant workers, spending 2000 h a year in the facilities and exposed to the average dose rate of $1.5 \mu\text{Sv/h}$, the accumulated radiation dose from external radiation can attain 3 mSv/year, and up to 15.5 mSv/year by the ilmenite piles, thus well above the radiation dose limit of 1 mSv/year (excluding contribution from the natural radiation background; IAEA, 2014). These results confirmed the enhanced concentrations of radionuclides associated with the heavy minerals in coastal sands and that its exploitation may originate occupational radiation exposure, but no environmental radioactive contamination was reported (Carvalho et al. 2014b, 2017).

As these heavy mineral sands mining is expanding very rapidly, the development of conservation strategies for coastal areas concerned must become a priority, as well as the enforcement of regulations for radiation protection of workers and members of the public in relationship with the extraction and handling of these naturally occurring radioactive minerals.

Shale gas

Shale gas produced by hydraulic fracturing or “hydrofracking” is a new type of natural gas and oil mining industry that developed recently, mostly from the year 2000 in USA (U.S. EPA, 2016). This extraction procedure

is generating enthusiasm in other regions, including Europe. In this process, deep boreholes are made in the Earth crust and water with sand grains, or zirconium, surfactants, and fluidifier/emulsion agents are injected with high pressure in the productive rock layers underneath, usually shale. The high-pressure injection of water and sand breaks the shale layers opening fissures that facilitate the escape of natural gas (gaseous hydrocarbons including methane, propane, etc.) from the rock matrix, rendering possible to pump them to the surface (Fig. 8).

Current “hydrofracking” technology, tapping hydrocarbon resources relevant to the economy, allowed the USA to increase natural gas production and replace coal by natural gas. Burning natural gas for electricity generation is expected to improve air quality and decrease greenhouse effects derived from coal burning. However, hydraulic fracturing does not meet “spontaneously” the safety requirements for water protection and radiation protection and got no public acceptance (Jackson et al. 2014). Thousands of wells for natural gas production have been drilled in several regions of USA. Reports highlighted also that areas of “hydrofracking” are affected also by frequent earthquakes due to stress redistribution.

Hydraulic fracturing releases also large amounts of radon (^{222}Rn), the radioactive gas formed from radioactive decay of naturally occurring ^{226}Ra , often present in high concentrations in shale (Fig. 8). Reports, including a technical report made available by the *New York Times*, indicate very high radioactive water from the wells discharged into rivers and containing radium and radon concentrations at thousands of Bq/L and thus significantly exceeding safety standards (NYT, 2011). Furthermore, aquifers become contaminated with the injected materials (U.S. EPA 2016). The chemical and radioactive impacts of shale

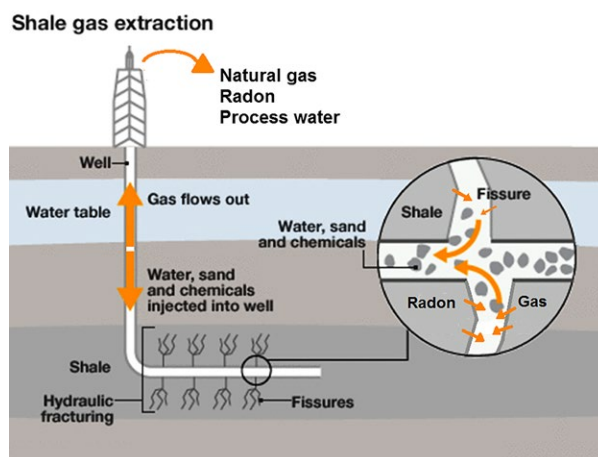


Figure 8. Hydraulic fracturing for natural gas (gaseous hydrocarbons) mining in shale formations.

gas production seem very high, and contamination of aquifers currently is a major issue (U.S. EPA 2016). A recent evaluation of the hydraulic fracturing impacts on water quality and quantity in USA has compiled records of a number of impacts, although the scientific evidence was considered insufficient for a final assessment at national level (U.S. EPA 2016).

The collateral effects of this mining procedure underline what was known from long time: mining may be very valuable but often brings to surface and put in contact with biosphere elevated concentrations of naturally occurring elements that might be toxic to life. Introduction of new techniques requires precaution in its use and maturation of techniques. The precautionary principle should be applied.

Uranium

Uranium mining taps radioactive ores that are of interest to industrialized countries as fuel for electricity generating nuclear industry (IAEA and NEA/OECD, 2016). As it happens with other energy commodities, the geographic distribution of uranium deposits and uranium consumers does not coincide, and the extracted uranium is traded and transported worldwide. Uranium world reserves were estimated at about 5.7 Mtonnes and at current rates of consumption for a universe of about 450 nuclear reactors used for electricity generation, with current technology and a current usage of about 63,000 tonnesU/yr, reserves could last about 90 years. This represents a higher level

of assured resources than is normal for most minerals (WNA, 2017).

Uranium mining is, indeed, a first stage in a set of uranium-related industries, globally designated as nuclear fuel cycle, aiming to prepare suitable fuel for the nuclear industry (Fig. 9). Those industries are spread over a number of countries (Hore-Lacy 2016).

Generally, the uranium ore extracted from the mine is processed by an associated mill order to obtain yellow cake (uranium oxide) for export (Fig. 10). This mining and milling stage generates significant amounts of mining waste and radioactive waste tailings, where most of the radioactivity of uranium ore due to uranium radioactive daughters will remain. These uranium tailings create environmental impacts and long-term issues that need careful consideration (IAEA, 2005, 2006; Carvalho 2011).

Most of uranium mining and milling legacy sites worldwide, even taking a look only into short-term radioactive exposure, were not in line with current radiological protection Safety Standards developed by the IAEA and applied internationally for protection of workers, members of the public, and the environment (IAEA, 2014). Environmental impacts of past radium and uranium sites have been assessed in several countries. For example, in USA, Germany, France, and Portugal, it was concluded that tailings and acid mine drainage were sources of radioactive contaminants enhancing environmental radioactivity in water, soils, and agriculture products (IAEA, 2005; Merkel and Arab (2015); Carvalho et al. 2014b, 2016a,b). Environmental remediation projects were implemented

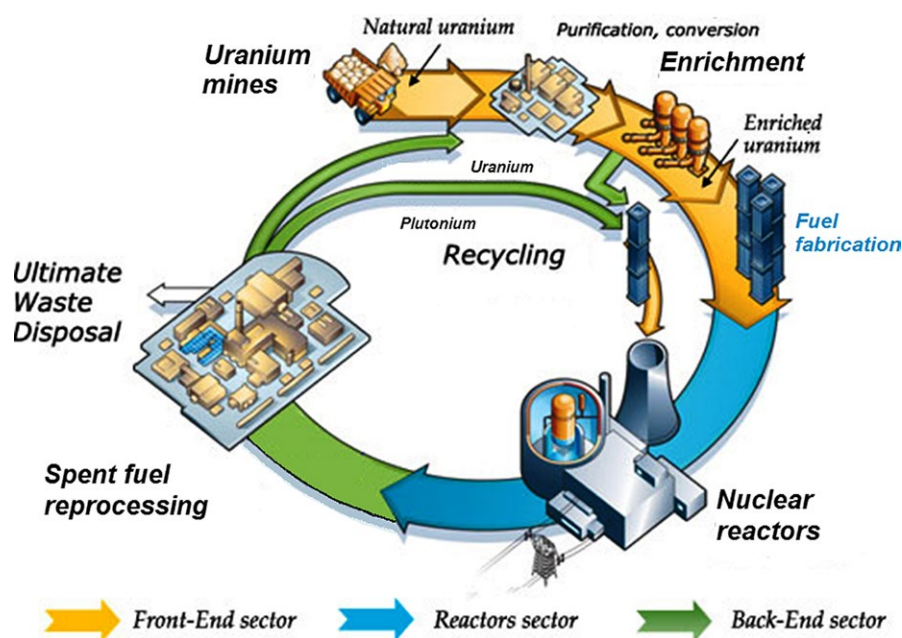


Figure 9. Uranium and nuclear fuel cycle sectors.



Figure 10. Production of yellow cake (filtration) in uranium mine and milling facility.

and many of these former uranium sites went through clean up and remediation measures which include relocation of waste piles, coverage of solid waste, and treatment of radioactive water and even replacement of water supplies in contaminated areas with noncontaminated water brought from elsewhere. Environmental remediation of these legacy areas is a costly process and in general has been paid from public funds (Fig. 11).

Public concerns with the safety of nuclear power plants (NPPs), especially after the nuclear accidents of Chernobyl and Fukushima, question the future of nuclear energy and several countries decided to move away from nuclear energy and bet on renewables (e.g. Germany), although renewables may also have significant life-cycle impacts and carbon emissions and require mining for the necessary raw materials, for example, REE and fertilizers. Other countries (e.g. China) do have NPPs in construction. A number of countries in Africa and central Asia expressed also interest in nuclear energy and are currently planning to initiate uranium mining as well.

It is possible to extract and produce uranium applying occupational safety standards that ensure radiation protection of workers and environment (IAEA, 2014). The current big challenge to uranium mining companies is to organize mining and milling in a way that the radiation safety and environmental protection, including after mine remediation, are included in the commodity prices, and to avoid contaminated legacy sites.

Artisanal mining

Artisanal mining is the nonindustrial mining activity, generally carried out illegally by large number of people who extract and sell small amounts of a mineral to survive to poverty. Artisanal and small-scale mining occur in approximately 80 countries. It is widespread in developing countries in Africa, Asia, Oceania, and Central and South America, and it ensures the existence for millions of families in rural areas of developing countries. Globally, about 100 million people – workers and their families – depend on artisanal mining compared to about 7

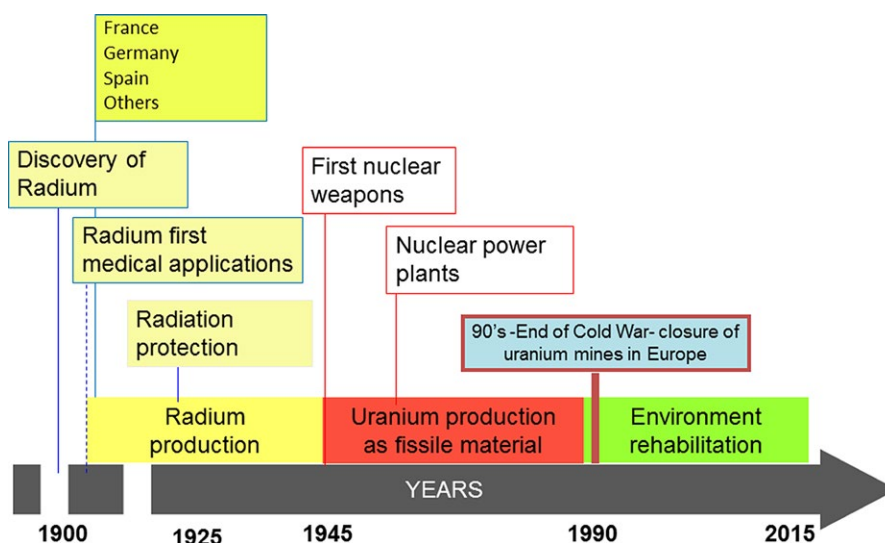


Figure 11. Timeline of uranium mining and remediation (from Carvalho and Edge 2013).

million people worldwide engaged in industrial mining (World Bank, 2017a,b).

Artisanal gold mining in Africa is mostly an illegal activity, and tons of gold are produced and traded without paying taxes. Artisanal gold mining is estimated to produce some 330 tonnes of gold per year or 12% of official world production (Artisanal Gold Council). Governments oscillate between repressing artisanal mining and regulating this activity through buying the gold from artisanal miners (World Bank, 2009). The artisanal gold mining in Africa raises several serious social problems, such as child labor, poor safety and high number of accidents, substance addiction, and high criminality in gold mining areas. International organizations and the International Gold Council try to minimize such problems through several initiatives (<http://www.artisanalgold.org/>; Fig. 12).

In gold mining, two main processes, one based on mercury and the other based on cyanide, are used to aggregate gold dust after its segregation from the placer deposit or from the ore-bearing rock. These processes are very toxic to the artisanal community and to the environment, in particular, to rivers where all the chemical waste is dumped (e.g. Amazon River). Reports on the contamination by mercury have described the situation in Ecuador, Amazon forest, and in several African countries (Miranda et al., 1998). The use of large amounts of mercury and its volatilization release mercury into the atmosphere and also into soils and water. Mercury enters the food chain and it is transferred to humans. Today mercury is considered a global pollutant and a threat to human health and the environmental, and health costs are high. Initiatives to assist diminishing the use of toxic chemicals have been implemented by several organizations but with mitigated results yet (<http://www.artisanalgold.org/>).



Figure 12. Underground artisanal gold mining in Niger.

Artisanal mining is growing also now in the sector of REE and tantalum extraction, particularly in Africa (Fig. 13, REE artisanal mining). Miners segregate heavy minerals from sands and ore deposits to produce coltan (columbite and tantalite mineral) and tantalite, and stock at home sometimes significant quantities of these minerals. Because these contain also uranium and thorium series radionuclides, miners and their families expose themselves to significant radiation doses (Carvalho et al. 2014b). No initiative is addressing this issue yet, despite the obvious safety risk for the populations and the environmental impact of such activities.

Environmental and Social Impacts of Mining and Remediation

Throughout eras mining provided most of the materials accumulated today in the technosphere, understood herein as the total of infrastructures including buildings, machines, tools, etc., that support the world population. Recent estimates suggest that the technosphere mass might be of about 30 trillion (10^{12}) tonnes, while, for comparison, human biomass is about five orders of magnitude lower (Zalasiewicz et al. 2016). This means that mining and ore milling activities produced a very high volume of materials using procedures often very disruptive to the environment and, for long time, without evaluation of impacts.

In very recent years, the development of Environmental Impact Assessment (EIA) procedures aiming at identifying the potential effects and damages caused by developments in the environment and society are helping to foresee and estimate gains, costs, losses, and consequences of such projects (Jain et al. 2016). Variations of EIA have been developed such as the Strategic Environmental Impact



Figure 13. Artisanal rare earth mining in Mozambique.

Assessment (SEIA) to help evaluating and planning beyond the narrow scope of one project and even the Radiological Environmental Impact Assessment (REIA) for projects involving radioactive materials, such as an uranium mine or a nuclear facility.

One key aspect in all mining projects is the risk assessment of mine operations to surrounding human settlements. In the past, in European countries for example, it was common to see mines and cities and their activities entangled in a small territory. This has been the case, for example, of the Ruhr basin in Germany, Loire in France, and West Midlands (Birmingham) in UK, to cite just a few very old mining regions. In recent years, the regulations and concerns with environmental resources lead to mitigation of pollution and remediation of the environmental impact. One good example is the Erzgebirge (Ore Mountains) in Saxony, Germany, near the border with Czech Republic, where first silver and associated base metals and later uranium was extracted to supply the URSS nuclear program. With Germany reunification, in 1991 started a large environmental remediation program that involved clean-up of contaminated areas, radioactive waste confinement, installation of mine water treatment plants, and rebuilding the landscape and villages. The state-owned former mining company Wismut GmbH has been implementing this work (<http://www.wismut.de/en/>). Remediation was needed because the exposure of large human communities to radiation and radioactive waste is not acceptable according to current radiation protection standards (IAEA, 2014). Similar scenarios of exposure to harmful contaminants (uranium or other metals) exist in many regions including west Europe where, due to dense occupation of territory and miners' settlements near the former mines, almost every mine has villages or cities nearby (IAEA, 2005; NEA/OECD, 2014).

In some regions, the cost of environmental remediation of mining legacies has been high and paid by public funds because the former mining companies do not exist any longer. For example, the environmental remediation cost of the Saxony areas in Germany amounts already to 65 billion Euros, the cost of remediation abandoned mine sites in Portugal is of 139 million Euros, and the project to relocate and confine the uranium mining waste in Colorado (MOAB project) is budgeted at 1 billion dollars (NEA/OECD, 2014). The value of a healthy environment and control of soil, air, and water quality justifies the cost of these environmental remediation works and recuperation of contaminated areas (Fig. 14).

With the move of mining activities to other continents and remote areas, some unforeseen exposures did occur. For example, uranium mining in Niger started in the Sahara desert where no settlements existed and mining



Figure 14. Remediation of legacy uranium tailings (Urgeirica Mine, Portugal) placing a cap of geotextile membrane and several soil layers to confine radioactive uranium mill tailings.

companies built the mining infrastructure from scratch. Because it was the desert, there was no population critical group to protect and, in the absence of water in the surface, mining impact was foreseen as minimal. However, in a short time, the access to water from the wells drilled by the mine and the opportunity to recycle scrap materials (metal, timber, plastic) attracted people. Rapidly a city grew around the mine site, counting today 80 000 inhabitants. Agriculture, using wastewater from the mines developed also to supply vegetables and fruits to the miner's families, and this way a large potentially exposed critical group was born in the desert. All these artisanal and agricultural activities created pathways for the transfer of radioactive contaminants and radiation exposure of population, requiring measures to reduce exposure to radioactivity.

Mining outside Africa, for example, in Indonesia, China, and Peru, has also developed in situations of elevated risk to humans and the environment, with large mines surrounded by cities where conventional safety and prevention of contamination and exposure to toxic metals was not ensured (Fig. 4).

The main lessons to learn here are the need to cope with uranium mining legacy and to keep risk assessment methodologies open to review and improvement, especially when facing the unusual. May be the next opportunity with a strong need for development of EIA and risk assessment methodologies will be the upcoming metal exploitation at and around hydrothermal vents in the deep sea. Remediation of mining environmental impacts on these ecosystems might be nearly impossible at the present. Enforcement of safety measures and regulations are thus needed as a critical step to protect the fragile ecosystems of deep ocean.

Sustainable Development and Mining

Mining impacts always existed and we still have mines opened in Roman times with acid mine drainage, waste piles, and environmental contamination. Large-scale mining grew during the 19th and 20th centuries with impacts neglected and hidden costs. Impacts on miners' health due to occupational exposure to toxic contaminants (lung cancer, silicosis, lead poisoning, etc.) were not accounted for, for a long time. Until very recently, environmental impacts on nature and on populations at large were not duly considered either.

With exhaustion of rich ore deposits and enforcement of environmental protection regulations, many mining companies moved to developing regions where regulations were less strict. Implementation of large mining projects in developing countries created many situations of vast wealth for a minority, while the large majority of the population has not seen improvement of their socioeconomic status and welfare. To the contrary, the mining impacts often degraded their living conditions (Jaskoski 2014). Developing countries, the new hosts of mining projects, are adapting and modernizing their legislation to implement environmental and public health protection measures.

From corporate viewpoint, a key aspect to the success of mining is to obtain, besides the official and legal mining permit, also the social license from community, that is, their consent and adhesion to mining in their region. Corporate responsibility of mining companies has developed also to share the wealth from mining with communities, and this has been achieved through investment in building infrastructures for the region, such as schools and hospitals, and minimizing the impacts. The future for mining is, therefore, dependent from adhering to good mining practices in order to preserve the environment everywhere and also to take social responsibility in the development of the region and contributing to life quality of the community.

This was expressed in the Earth Summit held in Rio de Janeiro, 1992, where 27 Principles of Sustainable Development were agreed by representatives of 172 Governments and 2400 nongovernmental organizations. Those principles fall into three key areas, where cooperation and integration of technical and economic activities were agreed as necessary to ensure economic growth, ecological protection of natural resources and environment, and social development including safety at workplaces and community development.

In spite of such international agreements, the reality has been resilient to changes and the abundance of oil, gas, and mineral resources is seen by many as a curse. The expression “resource curse” has been used to identify

a process often observed that natural resource wealth tends to adversely affect a country's governance and has three main harmful effects: tends to increase corruption, make authoritarian regimes last longer, and trigger violent conflicts (Ross 2015). Although there are natural resources wealth countries that fail to reach their full potential, governments can make policy decisions that help avoid some of the negative consequences of resources extraction and invest profits in social and economic development of the country. International endeavors, such as the Open Government Initiative (OGP) and Extractive Industries Transparency Initiative (EITI), are voluntary initiatives that try to beat the “resource curse.”

Attempts have been made by international organizations to develop theoretical concepts to afford growth decoupling from resource mining and to decouple environmental impact from mining (UNEP, 2011). Notwithstanding, the main social impacts of “resource curse” in Africa have been the complete disorganization of societies and food production, and war and conflicts that lead to migratory mass movements concerning nowadays 65.3 million individuals displaced from their homes (<http://www.unhcr.org/statistics/>). The United Nations considered this a major humanitarian failure. However, mining and agriculture could play a major role in community development and contributing to the welfare and stabilization of populations.

The Unshaped Future of Mining

As today, any future society will have similar or even bigger needs for water, food, and energy, and hence, the availability of these resources has to be ensured to future generations. Current economic growth must not blindly exhaust available resources or miss to developing alternative means to provide them and leave future generations at the edge of starvation and extinction. This is basic ethics of intergeneration solidarity. Furthermore, that would compromise sustainable development whose concept was formulated in an enlightening way in the Brundtland report, “Our common future” (WCED, 1987).

Mining is, thus, a vast field of human activity that will go on to respond to societal needs, such as to fixing and improving the technosphere, but today with the additional responsibility that comes with knowledge: to make responsible management of the resources and keep healthy ecosystems capable to support human society with life quality, today and in the future.

Current challenges posed to mining include remediation of legacy impacts, implementation of better protection of water resources, and generally caring of environment and human health much better than in the past. Current and upcoming mining projects need to coordinate with all

stakeholders and achieve satisfactory legal and social approval to be successful. Local communities, particularly in deprived and poor regions, want to share the wealth of mining and obtain from mining a positive effect in their lives.

Not every mine is a good example, but some mining projects have been able to achieve positive agreements with the community and contribute to positive societal and environmental outcomes. This has been achieved, for example, through allowing some degree of artisanal mining in the local community and buying the production from them; allowing recycling of scrap from the mine; paying the community to work in re-forestation and remediation efforts in parallel with mining activity; and invest in capacity building of local community members. This coordination and share with stakeholders, although already late for many places, is progressing and may allow for the improvement of mining, as we know it today.

Future mining is another thing. The enhanced valuation of environmental preservation and ecosystem services for ensuring public health and life quality has pushed mining to become better performing than it was in the past. Nonetheless, mining companies are seen today as inefficient and, due to volatilization of prices, the sector may resume efforts to cut production costs dramatically (IBM, 2009). Very soon, metal and fuel mining will certainly introduce automation in all phases, from ore drilling to ore chemical processing, thus reducing or even completely removing the miners from galleries, and other workers from ore transportation and from chemical plants. This will reduce jobs offer in many developing countries – as in the past happened in developed countries. Such move may increase the profit of corporate companies, but the expectations of local communities will remain intact as well as corporate responsibility towards them. Societal license from local communities to mining activities will become harder to obtain. As an example, one may refer to the recent negotiations with local communities around mining areas in Peru (Jaskoski 2014; Flor 2014).

To be successful, mining projects will need to find better ways to link with local communities, may be through serious participation in to social development, enhanced respect of human rights, and helping to overcome poverty. In Africa, for example, mining could become part of the effort to fix populations running away from poverty and conflicts in their home countries.

Conclusions

New and current mining projects are expected to incorporate the lessons from past mining activities and thus solve their detrimental collateral effects on environment

and public health. As these effects often relate to contamination from tailings and acid mine drainage produced during and after mining operations, the EIA of mining projects should encompass the entire life cycle of the mine, should incorporate the assessment of negative impacts and societal benefits also, and must incorporate the liability and the cost – and thus make funding provisions timely – for postmine environmental rehabilitation.

Current mining activities need to reinforce procedures for protection of environment and public health, as it is today easier to see that mining usually brings into the biosphere large amounts of nontargeted chemical elements often with toxic properties to the environment and humans (e.g. radioelements and toxic metals) and previously neglected.

Mining laws and legal and technical capacity in many countries still need to be enhanced in order to include new internationally recommended good mining practices (ALSF, 2017; AMLA, 2017). The good signs about this are that responsible mining companies tend to adopt everywhere good mining procedures according to the best international standards, although this might be far from being the general behavior yet. Some international initiatives, such as EITI, are important in this process.

Moreover, emerging technological developments allowing for intense automation (robotization) of many tasks, the entire process of mining may deeply change very soon. Societal implications of automation will be vast and require advanced foresight and planning to carry out mining in many regions of the world. Current developments of society values, in particular the growing value ascribed to environment and life quality, makes unavoidable that future mining depends on achieving better conservation of the environment, long-term management of natural resources, and fair social-economic impacts in the life of local communities combined with improved safety in mining activities.

Mining activities shall be intertwined with sustainable development goals and ensure that present and future generations will have resources or alternative means to satisfy their basic needs of food, water, and energy. This implies that metal recycling must increase and alternative sources of energy must be tapped in order to decrease environmental impacts and depletion of conventional energy resources. A component of internationally coordinated management of mineral resources exploitation seems today needed to avoid jeopardy of nonrenewable resources and implement sustainable development at global scale.

Conflict of Interest

None declared.

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