# Chapter 2
# Resources. Production. Depletion

**Wojciech Stanek, Alicia Valero, Guiomar Calvo and Lucyna Czarnowska**

Any activity around the world as well as further development of humankind relies on natural resources. The primary deposits, which represent the work that nature offers us, are essential for current and future civilizations. There are several examples of ancient civilizations that collapsed due to the depletion of local natural resources; the most significant include depletion of the forests in Easter Islands, the depletion of fresh water in Central America or the depletion of the agricultural areas in South-East Asia [1]. Nowadays, these examples should not be underestimated and a rational resource management should be enhanced.

Primary resources are used within the chains of interconnected production processes, where they are transformed into final useful products. Rational management of resources is dependent on the efficiency of particular production processes, as well as on the efficiency of the whole production system. These efficiencies are evaluated based on the physical laws and take into account the real losses in the components of the production systems. The economy and ecology of natural resources management is directly related to these losses.

Primary resources can be divided into non-renewable and renewable ones. Non-renewable natural resources include the following groups:

W. Stanek (✉) · L. Czarnowska
Institute of Thermal Technology (ITT), Silesian University of Technology,
Gliwice, Poland
e-mail: wojciech.stanek@polsl.pl

L. Czarnowska
e-mail: lucyna.czarnowska@polsl.pl

A. Valero · G. Calvo
Research Centre for Energy Resources and Consumption (CIRCE),
Campus Río Ebro, Saragossa, Spain
e-mail: aliciavd@unizar.es

G. Calvo
e-mail: gcalvose@fcirce.es



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- primary energy sources in the form of fossil fuels (hard coal, lignite, crude oil, natural gas),
- primary metallic sources (metal ores),
- construction and building materials (e.g. gravel, clay, sandstone, limestone, granite, basalt).

Solar energy, wind, waves, water, geothermal and biomass energy are considered renewable. In general, the usage of renewable energy is not loaded with the burden of apprehension of resources exhaustion. Yet biomass can be an exception to this, since in the case of wood biomass, if the degree of regeneration is lower than one it should not be qualified as renewable.

Non-renewable primary energy resources as coal or crude oil also come from solar energy; however, they were formed millions of years ago. Their usage is connected with several constraints as limited accessibility, the possibility of exhaustion in a relatively short time, or rejection of different harmful wastes during transformation. Moreover, it should be pointed out that part of them are localized in rather unstable regions of the world.

Despite of the significant progress in renewable power technologies, the majority of production is still based on non-renewable energies. Additionally, industrial activities are strongly connected with the utilization of non-energy non-renewable raw materials such as metal ores. In this case, contrary to primary energy sources, the recovery and recycling processes are possible. Moreover, they can significantly extend the lifetime of those resources.

Non-renewable resources are depleted faster when the degree of national or regional development is higher. Additionally, enhancement of consumption is one of the important factors accelerating the depletion of non-renewable resources. There is a good correlation between the indices characterizing human development and per capita energy consumption. Such correlation can be illustrated by the Human Development Index (HDI) dependent on electricity consumption per capita [2]. The dependence is presented in Fig. 2.1.

Fresh water is a fundamental natural resource which is necessary for human life. Water covers 71% of our planet's surface, but 97% of it is in oceans, in the form of

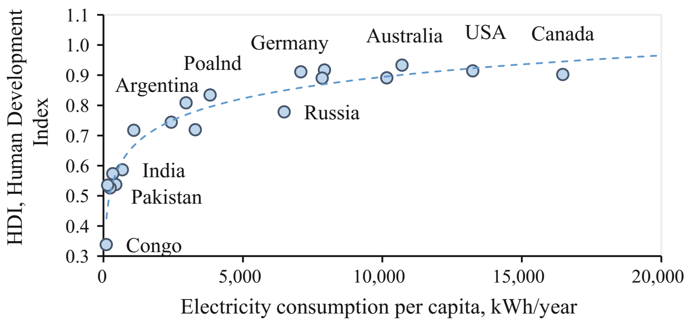



**Fig. 2.1** Dependence of HDI index on electricity consumption (based on [2])

saline water. About 3% is fresh water, whereas only 0.5% can be considered as drinking water (see Fig. 2.2).

The water deficit issue becomes more severe every year. Water scarcity issue is observed when annual water supplies drop below 1000 m$^3$ per person and year. In 1955 there were only five countries with such a problem, 35 years later in 1990, there were 13 countries affected, and currently more than 40 countries face this issue. By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity [2–4].

Production of consumer goods, connected with energy carrier transformation, is always accompanied by the generation of harmful waste products (gas, solid and liquid) discharged into the environment, leading to losses in the environment. Prevention or compensation of these losses leads to an increased demand of non-renewable natural resources. These expenses can be considered as external environmental costs of the human activity, resulting from the necessity of compensation of losses which arise due to the rejection of harmful waste substances [5, 6]. These losses occur within the following areas: human health, losses in infrastructure and losses in agriculture and forestry. Moreover, compensation of these losses requires an additional demand of resources, e.g. for construction and

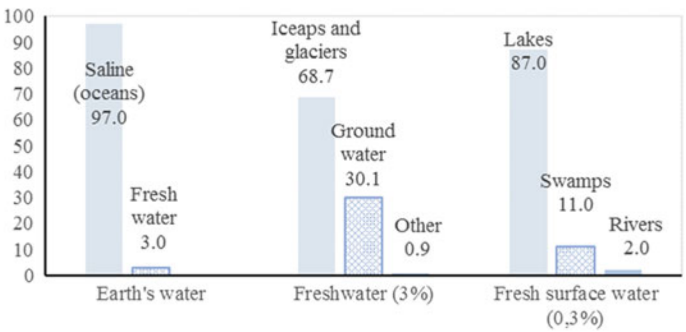
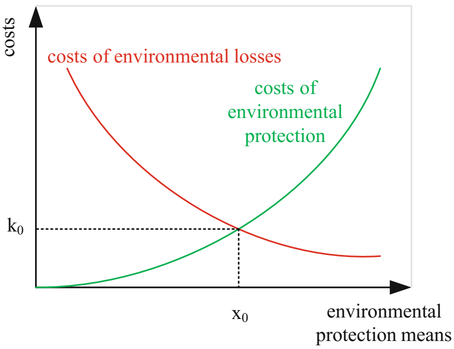



**Fig. 2.2** Characteristic of water resources

**Fig. 2.3** Environmental costs and environmental protection means



operation of the cleaning installations [5, 7]. The dependence between the cost of environmental losses and cost of protection is schematically shown in Fig. 2.3.

The unfavourable influence of human activity upon environment may be divided into the following groups:

1. depletion of limited non-renewable natural resources,
2. emission of harmful substances to the environment.

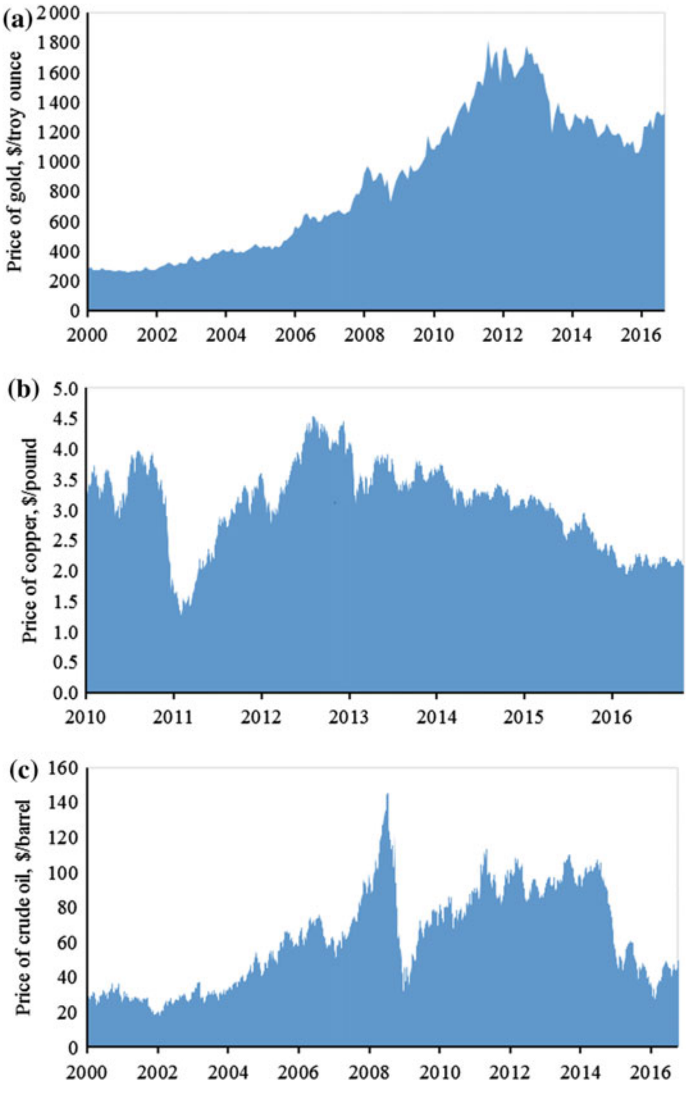



**Fig. 2.4** Monetary value of resources (**a**) gold in USD per troy ounce, (**b**) copper in USD per pound (**c**) crude oil in USD per barrel

Different natural resources are characterized by different qualities, this is why it is necessary to determine the common measure of the quality of resources. Frequently, the quality of resources is evaluated incorrectly using only pure monetary values. However, prices are subject to market and political arbitrariness, and they are not dependent on the fixed quality of resources (see Fig. 2.4).

Usefulness and quality of natural resources can be alternatively assessed through physical parameters. In the case of primary energy resources, those parameters include the composition of fuels, first of all characterizing the content of combustible elements capable of producing heat in exothermic chemical reactions. Primary non-energy resources (e.g. metal ores) can be regarded as more valuable from a physical point of view when the concentration of the considered element is higher (e.g. copper element in copper ore) in comparison with the average concentration in the Earth's crust. It should be pointed out that the higher is the concentration, the lower is the energy required to separate the element from its ore. In both cases, thermodynamics offers a method based on the first and second law to measure quality, through property exergy [5, 6, 8–10]. The concept of exergy will be discussed within the next chapters as a useful thermodynamic tool to measure sustainable management of natural resources. The following section of this chapter is devoted to describing the physical features of natural resources.

## 2.1 Characteristics of Primary Energy Resources

Energy is fundamental to human society for many activities including agriculture, residential and service, transportation and communication. To avoid double counting, energy supply is usually splitted into two categories: primary energy, which consists of the energy entering a system, and secondary energy, which is the energy that is transformed within the system, such as electricity. According to the International Energy Agency (IEA) [11], primary energy is defined as the direct use of energy which has not been subjected to any conversion or transformation process. This category includes the main commercial fossil fuels (coal, natural gas and oil) along with biofuels, nuclear, hydro and renewable sources such as geothermal, solar, wind, etc.

Historically, fossil fuels have had the leading role as primary energy sources. It is a fact that fossil fuels continue nowadays to maintain the present state of civilization as they heat and cool buildings, are used for most of the electricity generation worldwide and mobility still relies mostly on them. They also move industry and are used to build the infrastructures on which humankind relies.

As it was mentioned above, energy resources can be divided into renewable and non-renewable. Within the first group, coal, oil and gas are mainly taken into account. Renewables include geothermal energy, solar energy and other forms of energy derived from solar energy which do not require long range of time to regenerate. Operation of power systems supplied by renewable energy requires also some consumption of non-renewable resources, e.g. in the stage of construction or

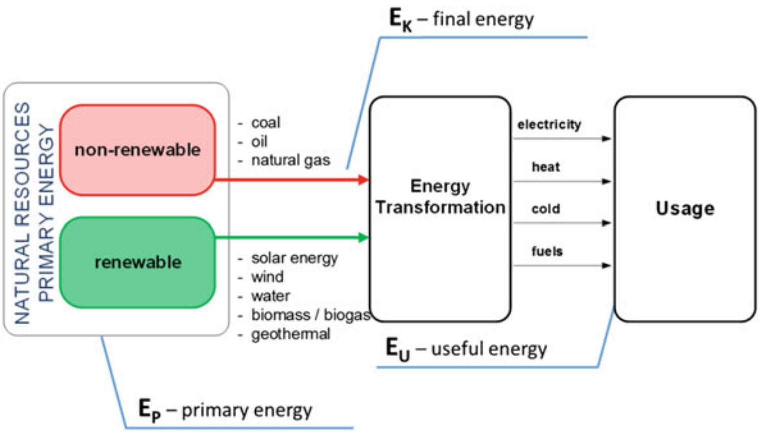



**Fig. 2.5** Energy transformation levels

for transportation purposes. Usage or transformation of energy carriers can be analyzed at different stages or within the different balance boundaries. Usually the following stages, which are presented in Fig. 2.5, are considered within the energy transformation.

Three characteristic stages of energy resources usage are usually taken into account:

1. *Primary energy* ($E_p$)—energy extracted from nature in the non-renewable or renewable form.
2. *Final energy* ($E_k$)—energy bought in order to supply the demand for useful energy: electricity, heat, chemical energy of fuels.
3. *Useful energy* ($E_u$)—energy required to support human live and to develop the human activity: mechanical work, heat, light, sound, chemical energy of food, etc.

As it will be presented in the next chapters of the book, the assumption of the level or balance boundary can be fundamental for the results of analysis. Especially, it is important when systems are fed simultaneously with non-renewable resources.

Basic energy parameters characterizing fuels are the lower heating value (LHV) and higher heating value (HHV). The definitions are given below [12]:

The *LHV* (lower heating value) of a fuel is the amount of heat released when a specified amount of fuel (usually a unit of mass) at room temperature is completely burned, and the combustion products are cooled to the room temperature when the water formed during the combustion process leaves as a vapor.

The *HHV* (higher heating value) of a fuel is the amount of heat released when a specified amount of fuel (usually a unit of mass) at room temperature is completely burned and the combustion products are cooled to the room temperature when the water formed during the combustion process is completely condensed and leaves as a liquid.

LHV and HHV are mainly dependent on the fuel composition. Tables 2.1, 2.2 and 2.3 provide average values of selected fuels as an example.

The composition determines the energy value of the fuel and hence its quality. On the other hand, the fuel characteristics and the technology within which the fuel is used, determines the generation of different harmful substances as well as greenhouse gas emissions. Data on usual emissions derived from fossil fuels are presented in Tables 2.4, 2.5 and 2.6.

## 2.2 Production and Consumption Trends of Primary Energy

Within this section, the basic information on production and consumption of primary energy resources are presented. Additionally, some statistics concerning electricity and $CO_2$ emissions are provided. Figures 2.6 and 2.7 show the change in

**Table 2.1** Characteristics of selected coals [57]

| Component | Energy coals | | | | Special coals | | | Coke | Lignite |
|---|---|---|---|---|---|---|---|---|---|
| | $g_i$ (%) | | | | | | | | |
| C | 45.9 | 58.7 | 61.5 | 58.0 | 62.6 | 64.6 | 71.5 | 78.7 | 26.1 |
| H | 3.1 | 4.3 | 4.0 | 3.9 | 4.0 | 4.3 | 3.9 | 0.8 | 1.9 |
| N | 0.9 | 1.1 | 1.1 | 1.1 | 1.1 | 11 | 1.0 | 1 | 1.2 |
| O | 8.9 | 8.0 | 7.8 | 9.2 | 6.8 | 5.2 | 1.4 | 1.5 | 10.0 |
| S | 1.2 | 0.9 | 0.6 | 0.8 | 0.5 | 0.8 | 0.7 | 0.8 | 0.5 |
| W | 20.0 | 7.0 | 5.0 | 7.0 | 5.0 | 4.0 | 1.5 | 2.2 | 51.7 |
| P | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 15 | 8.6 |
| LHV (MJ/kg) | 17.4 | 22.0 | 24.4 | 23.0 | 24.7 | 25.7 | 27.0 | 29.2 | 7.8 |

Where: $g_i$—mass fraction of *i*-th component, W—moisture, P—ash

**Table 2.2** Characteristics of selected fuel oil [57]

| Component | Mazut | Heating oil | Petroleum |
|---|---|---|---|
| | $g_i$ (%) | | |
| C | 87.4 | 85.0 | 85.5 |
| H | 11.2 | 11.0 | 14.5 |
| S | 0.5 | 2.0 | – |
| O | 0.9 | 0.6 | – |
| N | – | 0.4 | – |
| W | – | 1.0 | – |
| LHV (kJ/kg) | 43,100.0 | 39,300.0 | 43,100.0 |

Where: $g_i$—mass fraction of *i*-th component, W—moisture

**Table 2.3** Characteristics of gaseous fuels [57]

| Component | Natural gas | Natural gas | Coal bed methane | Coke-oven gas | Blast-furnace gas |
|---|---|---|---|---|---|
| | $z_i$ (%) | | | | |
| CO | – | – | – | 7.3 | 28.5 |
| $H_2$ | – | – | – | 54.6 | 2.0 |
| $CH_4$ | 92.0 | 65.0 | 48.6 | 22.7 | 0.3 |
| $C_2H_6$ | 0.7 | – | 1.0 | – | – |
| $C_3H_8$ | 0.6 | – | 0.2 | 2.8 | – |
| $C_4H_{10}$ and higher | 0.7 | – | 0.2 | – | – |
| $CO_2$ | – | – | – | 3.0 | 11.0 |
| $O_2$ | – | 7.4 | – | 1.5 | 0.2 |
| $N_2$ | 6.0 | 27.6 | 50.0 | 8.1 | 58.0 |
| LHV (kJ/k mol) | 778,300 | 521,900 | 413,000 | 375,100 | 87,900 |

Where: $z_i$—molar fraction of *i*-th component

**Table 2.4** Typical values of lower heating value and specific $CO_2$ emissions of fuels [58]

| Fuel | Carbon content in fuel ($c_f$) (%) | $CO_2$ emissions $\mu_{CO_2 f}$ (kg $CO_2$/kg fuel) | Lower heating value LHV (kJ/kg) |
|---|---|---|---|
| Natural gas | 75 | 2.75 | 49,000 |
| Diesel oil | 83 | 3.05 | 42,500 |
| Fuel oil, 0.7%S | 86.5 | 3.17 | 41,500 |
| Fuel oil, 2%S | 85 | 3.12 | 41,000 |
| Peat[a] | 58 | 2.13 | 7800 |
| Lignite[a] | 64 | 2.35 | 24,000 |
| Coal | 80 | 2.93 | 30,000 |

[a]Data are valid for fuels with no moisture and ash

electricity consumption over the years 1985–2013. During this period, the average electricity consumption in the world increased by about one and a half times compared to 1990, while in China the increase was significantly higher—over four times. The increasing demand for non-renewable fossil fuels and the growth of harmful substances released to the environment is a direct consequence of both: growing increase in demand for electricity and overall consumption [3].

Figures 2.8, 2.9, 2.10, 2.11, 2.12 and 2.13 present the changes in the consumption of oil, natural gas and coal in the world taking into account years 1965–2013.

**Table 2.5** General information and emission factors for selected power technologies (emission factors are expressed per unit of fuel consumption) [59, 60]

| Power plant data including emissions | Units | IGCC | | | EXPC | SCPC | NGCC | CHP avg |
|---|---|---|---|---|---|---|---|---|
| | | GEE R+Q | CoP E-Gas FSQ | Shell | Subcritical | Supercritical | | |
| Gross power output | $MW_e$ | 748 | 738 | 737 | 583 | 580 | 565 | |
| Net power output | $MW_e$ | 622 | 625 | 629 | 550 | 550 | 555 | |
| Coal flow rate | kg/s | 58.83 | 57.95 | 55.02 | 55.11 | 51.60 | | |
| Natural gas flow rate | kg/s | | | | | | 21.08 | Fuel: natural gas |
| Chemical energy of fuel | MW | 1595 | 1574 | 1494 | 1495 | 1399 | 1106 | |
| Net plant HHV efficiency | – | 0.39 | 0.40 | 0.42 | 0.37 | 0.39 | 0.50 | |
| HHV | MJ/kg | 27.11 | 27.17 | 27.16 | 27.12 | 27.12 | 52.45 | |
| $CO_2$ | kg/GJ | 84.69 | 85.55 | 84.69 | 87.70 | 87.70 | 50.73 | 56 |
| $SO_2$ | g/GJ | 0.52 | 5.03 | 1.81 | 36.89 | 36.89 | 0.00 | 0.55 |
| $NO_x$ | g/GJ | 25.37 | 21.07 | 21.07 | 21.07 | 30.09 | 3.87 | 15 |
| PM | g/GJ | 3.05 | 3.05 | 3.05 | 5.59 | 5.59 | 0.00 | 0.15 |

*NGCC*—Natural Gas Combined Cycle, *IGCC*—Integrated Gasification Combined Cycle, *SCPC*—Supercritical Pulverized Coal, *EXPC*—Existing Pulverized Coal, *GEE R+Q*—General Electric Energy Radiant Only, *CoP E-Gas FSQ*—ConocoPhillips gasifier technology, *Shell*—Shell Global Solutions (Shell) gasifiers, *CHP*—fed by natural gas with three way catalyst lambda 1

**Table 2.6** Emission factors for solid fuels combustion, in kg of pollutant per tonne of fuel [61]

| Emission | Pulverized boilers | | | Mechanical grid | | | Boilers with fixed grid | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Deslagging | | Cyclonic | More than 20 t/h | 5–20 t/h | Less than 5 t/h | Coal | | | | Coke | |
| | Wet | Dry | | | | | Water | | Steam | | | |
| | | | | | | | nt | fr | nt | fr | nt | fr |
| Dust | 6p | 9p | 1.5p | 3p | 2.5p | 2p | 1p | 2p | 1p | 2p | 1p | 2p |
| $SO_x$ | 19s | 19s | 19s | 17s | 16s | 16s | 16s | 16s | 16s | 16s | 16s | 16s |
| $NO_x$ | 14.5 | 8.5 | 27.4 | 4.3 | 3.4 | 3.0 | 1.7 | 2.6 | 1.7 | 2.6 | 2.6 | 3.0 |
| CO | 1 | 1 | 1 | 1 | 3.5 | 5.0 | 45 | 45 | 45 | 45 | 25 | 25 |

*Notes* The results of calculation are expressed in kg/t; mass fraction of the dust (p) and sulphur (s) in the fuel should be expressed as a percentage; *nt*—passage of natural air; *fr*—passage of forced air

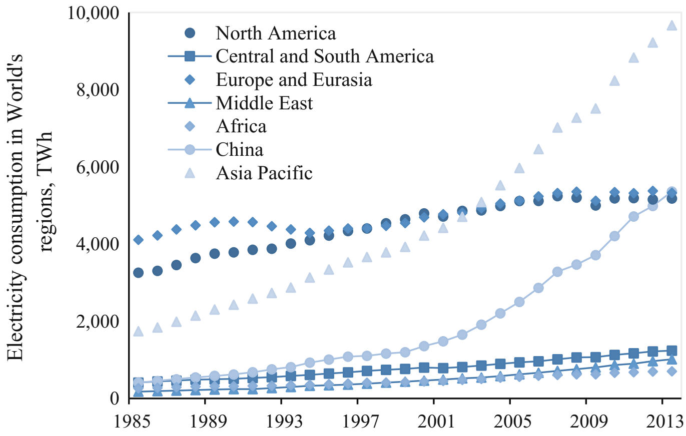



**Fig. 2.6** Electricity consumption divided by regions of the world (based on [16])

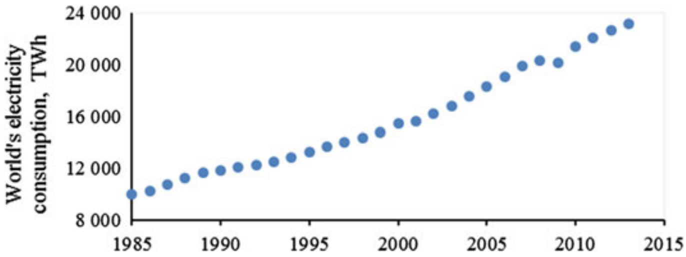



**Fig. 2.7** World's electricity consumption (based on [16])

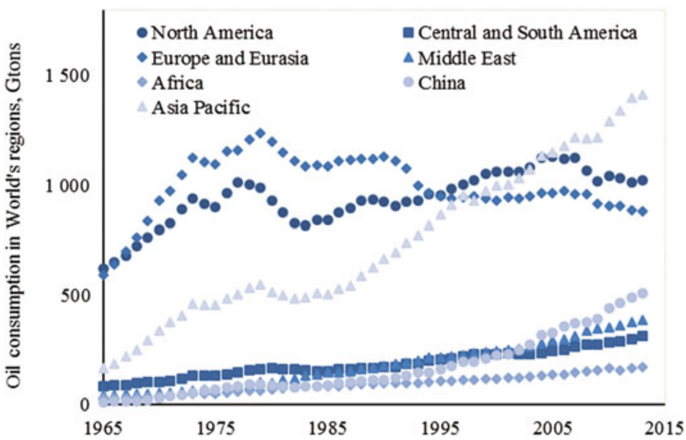



**Fig. 2.8** Oil consumption divided by regions of the world (based on [16])

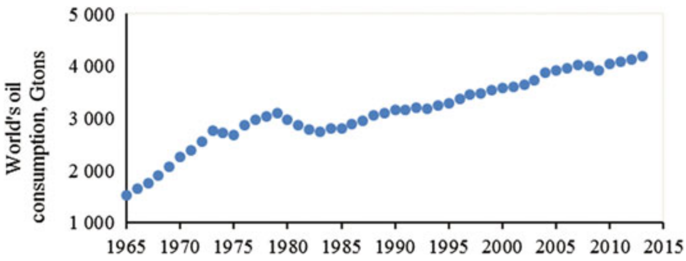



**Fig. 2.9** World's oil consumption (based on [16])

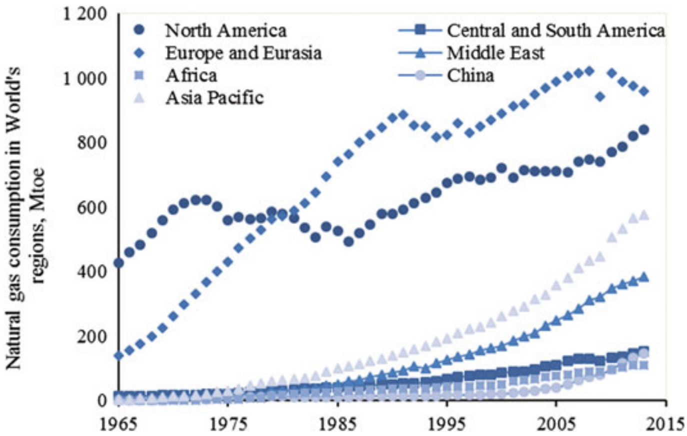



**Fig. 2.10** Natural gas consumption divided by regions of the world (based on [16])

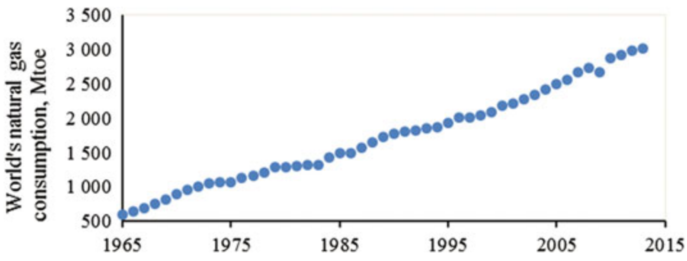



**Fig. 2.11** World's natural gas consumption (based on [16])

In all cases (Figs. 2.8, 2.9, 2.10, 2.11, 2.12 and 2.13), an increase in consumption of non-renewable primary fuels is observed. In the case of oil, the average world consumption increased 2.5 times during the considered period; while the highest increase of consumption (seven times higher than in 1980), was observed in the Asia-Pacific region. Only in Europe and Eurasia oil consumption decreased

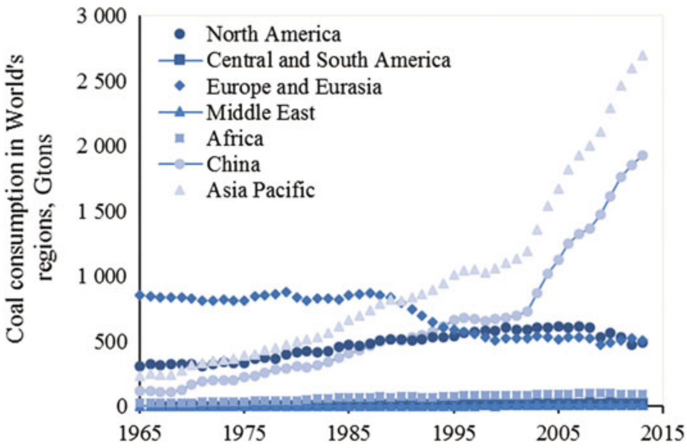



**Fig. 2.12** Coal consumption divided by regions of the world (based on [16])

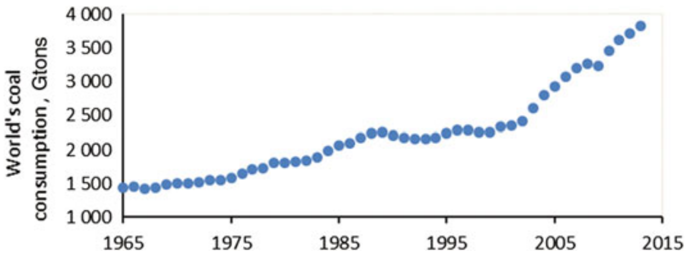



**Fig. 2.13** World's coal consumption (based on [16])

between 1980 and 2000. After 2000, a slight upward trend was observed. A relatively strong increase was observed in the case of natural gas consumption. It should be noted that between 1965 and 2005 world consumption has increased almost six times. This is the highest growth among fossil fuels. In Europe and Eurasia the relative increase in gas consumption was particularly high—almost seven times. In the case of coal, the average world consumption increased almost twice, and in the Asia Pacific region, it increased more than six times. Between 2000 and 2013 very rapid increase in coal consumption in China was observed (Fig. 2.12). The opposite trend is observed in the region of Europe and Eurasia.

Figure 2.14 shows historical data on cumulative fossil fuel extraction [13], represented in million tonnes of oil equivalent for simplification purposes.

As reflected in Fig. 2.14, over the last century the extraction of fossil fuels has been increasing almost exponentially, and especially striking is the case of oil. In 2014, the main oil producing countries were Saudi Arabia, Russia and United States, accounting for 12.9, 12.7 and 12.3% of the total world production,

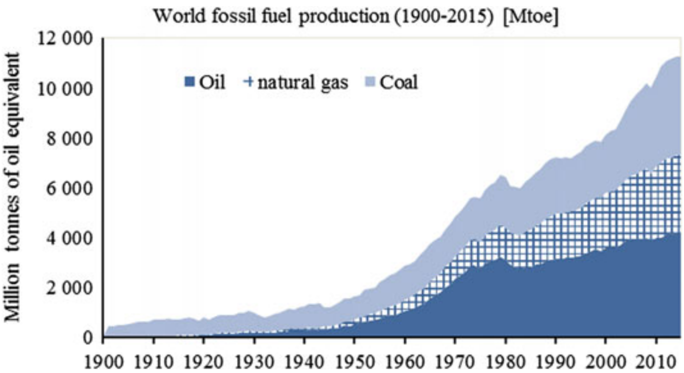



**Fig. 2.14** Cumulative fossil fuel extraction at world level from 1900 to 2014 (based on [13])

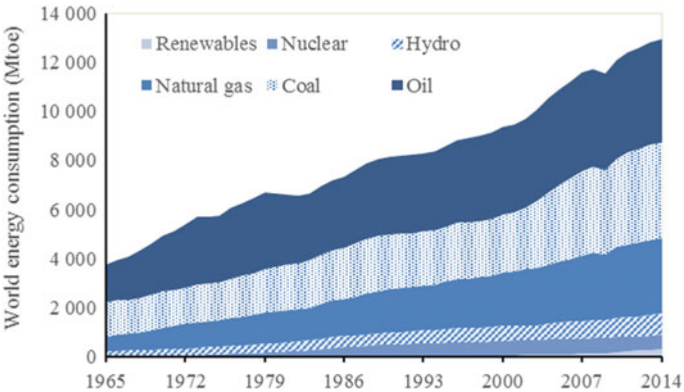



**Fig. 2.15** Cumulative primary world energy consumption by fuel type from 1965 to 2014 (based on [13])

respectively. Regarding natural gas, the Middle East as a whole accounted for 17.3% of the total world production, along with the United States and Russia, which accounted for 21.4 and 16.7%, respectively. Last, in the case of coal, it is noteworthy that approximately 47% of the total world production was centered in China, highlighting that it is a country that is growing rapidly at the expense of producing significant amounts of coal and with coal-based industries. China production is followed distantly by the United States with a share of 12.9% of the world production.

When analyzing the primary world energy consumption by fuel type from 1965 to 2014 (Fig. 2.15), it can be stated that again oil, coal and natural gas account for the vast majority but still, the relevance of hydro, nuclear and especially renewable sources has experienced a burst in the last few decades.

Additionally, there are other types of fossil fuels consumed, the so-called non-conventional fossil fuels, that require extra processing such as those derived

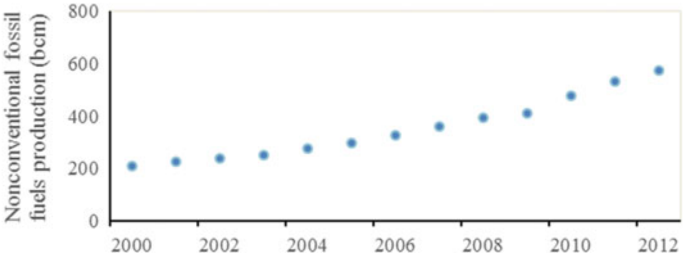



**Fig. 2.16** Non-conventional fossil fuel production (based on [19])

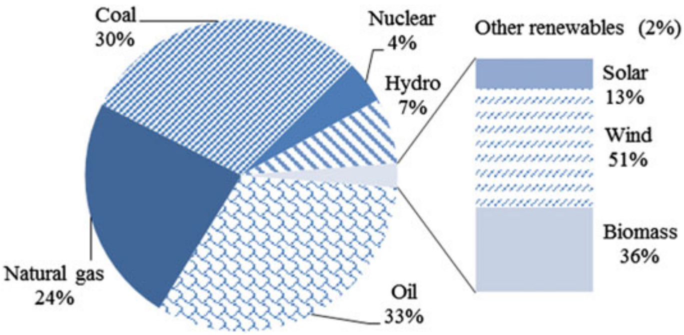



**Fig. 2.17** World primary energy consumption share in 2014 (based on [13])

from shales, heavy oils and sands. Still, their contribution to the world total energy is very low, this is why they are going to be considered separately (Fig. 2.16).

The main producer of non-conventional fossil fuels, taking into account unconventional gas, is the United States, with an average share of 77.6%. When compared to the total world production of oil, natural gas and coal, production of unconventional gas accounted for 4.2% in 2012.

Figure 2.17 shows the distribution of the world energy consumption in 2014. The main energy consumption (87%) came from coal, natural gas and oil. In the case of renewable energy, the main sources were solar, wind and biomass, accounting for less than 2% of the world total energy consumption. Of the 1,400 TWh consumed at world level coming from renewable sources, approximately 39% were consumed in Europe and Eurasia, 28% in Asia Pacific and 23% in North America.

Additionally, world energy consumption by sources can be analyzed. All these commodities have experienced a continuous increase over the last few decades, being the average annual growth rate 3%. China oil consumption accounted for 3.2% of the total share in 1985 while in 2014 it accounted for almost 12.5%. Meanwhile in Europe and Eurasia, the oil consumption was considerably reduced during the same period of time, going from 1,085 to 859 million tonnes.

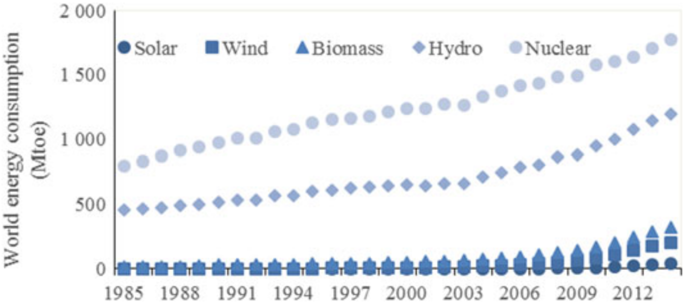



**Fig. 2.18** World consumption of solar, wind, biomass, hydro and nuclear energy from 1985 to 2014 (in Mtoe) (based on [13])

Information regarding the consumption of solar, wind, biomass, hydro and nuclear energy is presented in Fig. 2.18 Nuclear energy is the only source that has experienced a decrease since 2007, and almost at the same year hydroelectricity consumption began to increase. In the case of renewable energies, solar and wind have experienced the highest increases in recent years. The consumption of solar energy almost doubled from 2012 to 2014. Still, biomass consumption has been increasing, but more constantly than the other sources.

This increase of the total share of renewable energies can be observed at global level but also at regional level. According to Eurostat [14, 15], the primary production of renewable energy within the EU-28 in 2013 accounted to approximately 24.3% of the total primary production from all sources, and this number has increased almost to 85% from 2003 to 2013, with an average increase of 6.3% per year.

One of the most significant problems of primary energy resources transformation is emissions of greenhouse gasses (GHG). Figures 2.19 and 2.20 show the change in $CO_2$ emissions in the period between 1980 and 2013. The total global $CO_2$ emission is growing up. In the Asia Pacific region, the largest growth of $CO_2$ emissions is observed. This is a direct effect of the upward trend of the coal consumption in the region. In Europe and Eurasia, a reduction of $CO_2$ emissions has been observed between 1985 and 2013. The world average $CO_2$ emission per capita was at almost constant level of 4 Mg $CO_2$/(capita $\times$ year). However, average emissions in the region of North America reached a level of 16 Mg $CO_2$/(capita $\times$ year), four times more than the global average. In 2004, in Europe, this indicator reached about 8 Mg $CO_2$/(capita $\times$ year) and it is more than twice the average value. The efforts to reduce the level of $CO_2$ emissions require additional consumption of primary energy and should be taken into account when resource management efficiency is evaluated.

Availability is an important factor when studying the depletion of non-renewable resources. This value, expressed in years, is defined as the ratio between resources R to production P. Figure 2.21 shows the availability of oil, natural gas and coal for the period from 2000 to 2011.

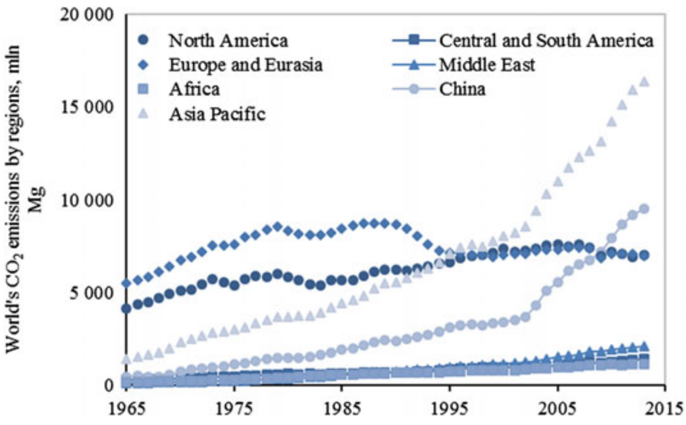



**Fig. 2.19** $CO_2$ emissions divided by regions of the world (based on [16])

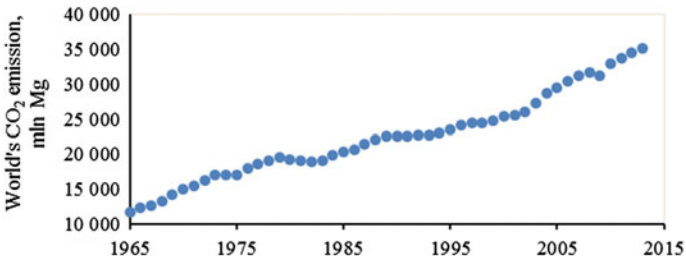



**Fig. 2.20** World's $CO_2$ emissions (based on [16])

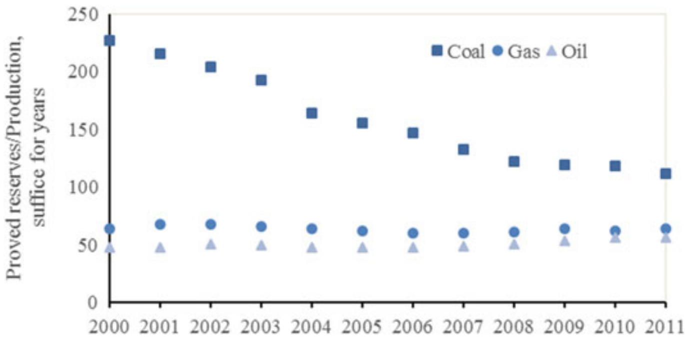



**Fig. 2.21** Life-time of primary energy resources (based on [16])

In the case of crude oil, average availability is at the level of around 40 and natural gas of about 60 years. It should be noted that a particularly rapid increase in the consumption of coal in Asia Pacific, especially in China since 2001, resulted in a significant decrease in the mean availability of coal from 220 years in 2001 to a level of 113 years in 2011 [16].

## 2.3 Characteristics of Mineral Resources

In addition to primary energy sources, non-fuel minerals are key to maintain current society. There are virtually no products that contain no minerals or where minerals have not been used in their production.

A mineral is a pure inorganic substance formed naturally in the Earth's crust, which can appear concentrated forming mineral deposits as a consequence of geological processes in specific areas. Mineral deposits can be categorized as follows: fuels, metallic and non-metallic. As fossil fuel characteristics have been already defined in the previous section, this section will only focus on metallic and non-metallic mineral deposits.

Mineral deposits can be classified according to their formation (hydrothermal, magmatic, volcanic, sedimentary) or according to the type of mineral that is extracted (ferrous, non-ferrous, construction minerals, industrial minerals). Each mineral deposit can be characterized by different factors, being ore grade the most used when economically assessing a deposit, but there are two other terms used to evaluate the mineral endowment of a determined area: reserves and resources.

The degree of concentration of a mineral deposit is called the "grade" of a deposit, measured in percentage in the case of abundant minerals and in parts per million or billion in case of scarce metals such as gold or platinum. The "ore" is the amount of rock that contains sufficient minerals that can be economically extracted. The type of ore, as well as the ore grade and the type of deposit, will affect the associated costs of mining, extraction and beneficiation. Usually these terms are used to characterize metallic mineral deposits, but they can sometimes be used for non-metallic deposits as well.

Both reserves and resources can be divided into different subcategories which are, in order of increasing geological confidence: inferred, indicated and measured reserves or resources. A mineral resource is defined as the concentration of a material of economic interest in the crust, in such form that economic extraction is feasible, either currently or in the future. A mineral reserve is the portion of the identified resource where the mineral can be economically and legally extracted at a specific time and it can be divided into probable or proved reserves. Probable reserves have lower level of confidence than proved reserves but the data has enough quality to be used as a basis for the decision making process to open an exploitation.

Additionally, there is a strong link between mineral and energy resources as stated before, as the ore grade, the type of rock in which the mineral is extracted from, the mineralogy of the deposit and the geological setting can influence the energy needed to extract and process it. Transformation of raw materials to final products can require high amounts of energy.

## 2.4 Production of the Main Mineral Commodities

Consumption of natural stock is a key element in current society, being economically, socially and culturally dependent. Base metals such as copper and zinc have a key role in those countries that are undergoing quick increases in social welfare, as they are essential for buildings, infrastructure, energy systems, automobiles, computers and mobile phones.

According to the Institute for Mineral Information, the average American in their lifetime (78.8 years) will consume approximately 1.4 million kg of minerals, metals and fuels [17]. Additionally, every year 17,940 kg of new minerals must be provided for every person in the United States to make the goods they use every day, including more than 2,600 kg of coal, 22 barrels of petroleum and 2,500 cubic meters of natural gas. Among others, 30 kg of aluminum are used to make buildings, beverage containers, cars and airplanes, 5 kg of lead are used for batteries, for communication and TV screen, as well as 3 kg of zinc are used to make rust resistant metals, various metals and alloys, paint, rubber or skin creams. Regarding industrial and construction minerals, more than 1,500 kg between stone, sand, gravel, cement and clays must be provided to make bricks, buildings, roads, houses, bridges and paper [17].

In Europe, meanwhile, the average amount of extraction of resources during 2000 was around 13 tonnes per capita, or 36 kg per day [18]. When compared with North America, Oceania or Africa, being 68, 58, and 15 kg per person per day respectively, one can easily state that globally there is a great variation. When analyzing the consumption per capita, these numbers change drastically. In Europe, 43 kg are consumed per person per day, 88 in North America, 100 in Oceania and only 10 in Africa, meaning that an average European consumes as many as four times more resources than an average African. When observing European countries individually, differences in both material consumption per capita and material productivity can be observed, ranging from 3.8 tonnes of domestic material consumption per capita in Malta to over 50 in Ireland [19]. With this consumption rate, we might be compromising the availability of natural resources for future generations; this is why it is critical to invest in research and exploration as well as in recycling and particularly in natural resources management and assessment techniques.

Due to this intensive consumption of mineral resources, on a worldwide scale, there has been an exponential increasing trend of resource consumption in the last century. Studies that analyzed the growth in global material use in the twentieth century have shown that the global total material extraction increased over the 1900–2005 period by a factor of eight, the strongest increase corresponding to construction minerals and ores and industrial minerals, which grew by a factor of 34 and 27 respectively [20].

The total world production from 1900 to 2015 of the 54 most common extracted mineral commodities is represented in Fig. 2.22 [21].

Of all these commodities, aluminum, iron ore, gypsum, limestone, phosphate rock and salt extraction represent approximately 95% of the total world production in mass terms. In Fig. 2.23 these commodities have been removed so the extraction of the other minerals can be better observed.

In both cases, the tendency is quite clear, world mineral production has been continuously increasing over time, reaching in the last few decades an exponential trend. The most striking and visual cases are iron ore and gypsum production, which have increased by a factor of 3 in the last 20 years. Moreover, there are other commodities that have experienced highest increases during that same period. For instance, the world total gallium production increased from 62 tonnes in 1995 to 435 in 2015. The industrial usage in gallium began in the 1940s, but it was not until

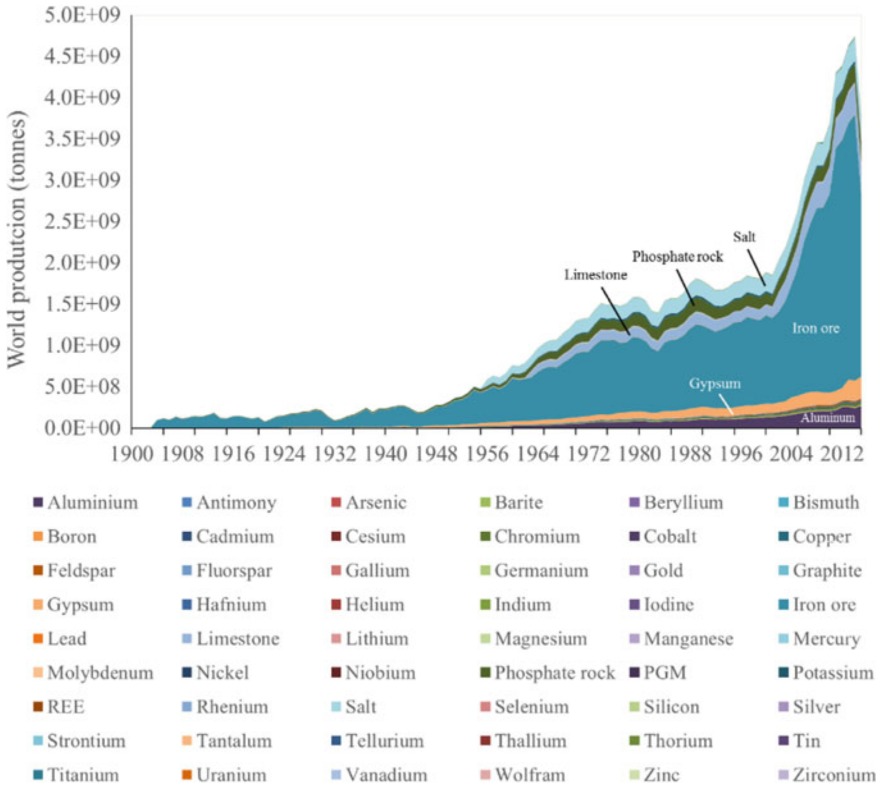



**Fig. 2.22** World production of main mineral commodities from 1900 to 2015

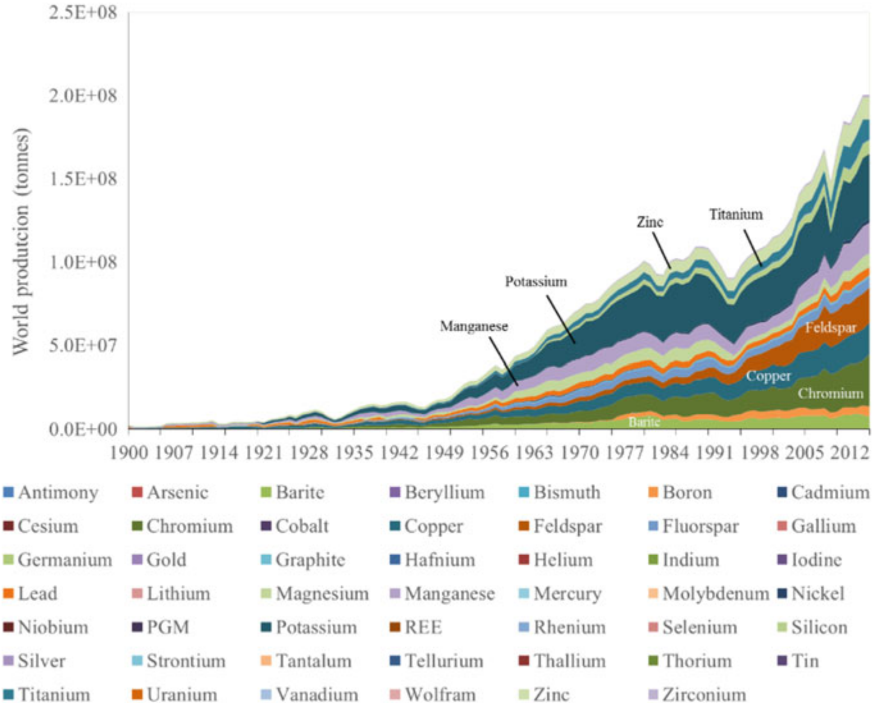



**Fig. 2.23** World production of selected mineral commodities from 1900 to 2015

1970s when it was discovered that, when combined with other elements, it has semiconducting properties [22]. Since then a surge in demand has taken place to create gallium arsenide and gallium nitride compounds, widely used in LED's, in cell phone circuitry, in solar cells as semiconducting materials, among others. The same situation can be seen with the world production of germanium and indium, which increased more than 200% from 1995 to 2015.

Figure 2.24 represents the annual world production of mineral resources for 2014 [56]. Metallic minerals, represented in green, are mainly in the upper half of the diagram, while industrial and construction minerals, represented in light gray, are in the lower part. In the base of the pyramid we can find the most extracted minerals, mainly industrial minerals, with the exception of iron ore, which is the most extracted commodity.

More than 4,700 million tonnes of non-fuel minerals were extracted during 2014, being produced in more than 90 different countries. The main countries that extracted non-fuel minerals were China, whose extraction accounted for almost 45% of the total world extraction, Australia, Brazil, United States and India, which accounted for 16, 8, 5 and 4%, respectively. According to the United States Geological Service (USGS) [21], the production of rare earth elements (REE) in 2014 was 123,000 tonnes, measured in rare-earth oxides equivalent content, and 85% was produced in China. Additionally, half of the world reserves of REE are

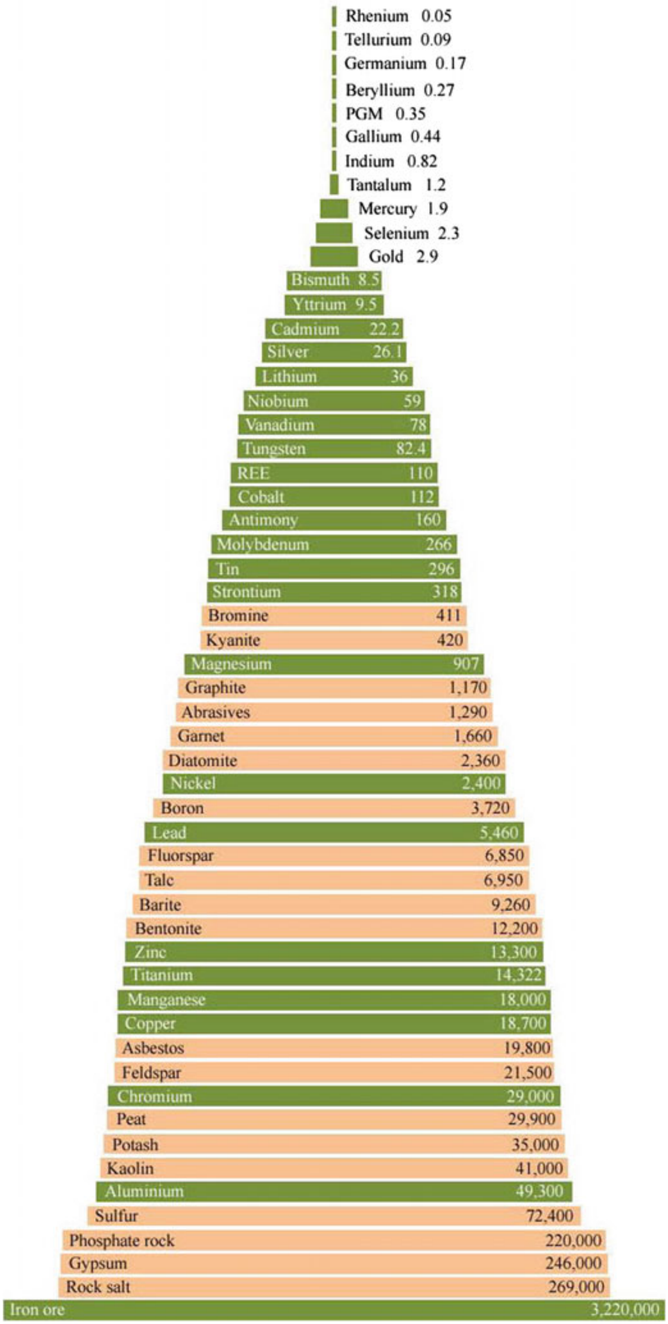



**Fig. 2.24** World primary production of mineral resources in 2014; production is in thousand metric tonnes [56]

located in China and policies regarding tightening the REE exports were introduced in recent years, thereby increasing the trade value of these minerals [23]. Bearing in mind this information, it becomes fundamental to assess the scarcity and criticality of each different commodity to ensure future availability for next generations.

## 2.5 Scarcity Assessment of Minerals

The scarcity of minerals is controlled by two terms, supply and demand. Usually supply refers to the amount of raw materials that is made available to the industry and depends mainly on the extraction of minerals from the Earth. This extraction is limited by the amount of minerals present in the crust, by the identified resources and reserves. As the technology and commodities prices change, the reserves vary as well. If new production technologies are developed, unattainable resources can be reachable or profitable. In the case of demand, it is a more volatile variable as it is related to several factors, such as population growth, development of new products and technologies, use of materials, among others. If emerging products and technologies that demand certain minerals expands, such as hybrid cars, photovoltaic cells, permanent magnets, etc., global material demand could increase drastically.

Jointly analyzing these two variables, the scarcity of natural resources, and especially the scarcity of mineral resources, can be evaluated with different approaches. For instance, several authors have used the correlation between historical extraction and commodity prices to measure the economic scarcity of minerals [24–26]. Other methods focus on social, political and physical aspects, analyzing aggregated factors such as the main global production, availability, stocks, production costs, supply risk, technology, recyclability, etc. [27, 28].

One extended method to predict future availability of non-renewable resources and measure the depletion degree is the ratio between known reserves and production (R/P ratio), to estimate the number of years that a certain raw material will still be present. Using long-term projection for selected minerals, the years to exhaustion using 1979 and 2000 production levels were predicted using reserve base and reserves information [29, 30]. Accordingly, a similar study was carried out for energy projections of coal, natural gas and oil for a 30 year interval [31]. Additionally, more recent studies have predicted depletion years of scarce minerals and their relationship with sustainability [32, 33] as well as historical analysis of specific commodities, such is the case of phosphorous, a critical element for global agricultural production [34].

With this similar R/P approach Valero and Valero [35], with 2008 production and reserves data, obtained that humankind had approximately depleted 26% of its world non-fuel mineral reserves, being mercury, silver, gold, tin and arsenic the most depleted commodities (Fig. 2.25).

Another way for better prediction of mineral behavior is the so-called Hubbert peak theory, which has been extensively used to evaluate fossil fuel peaking

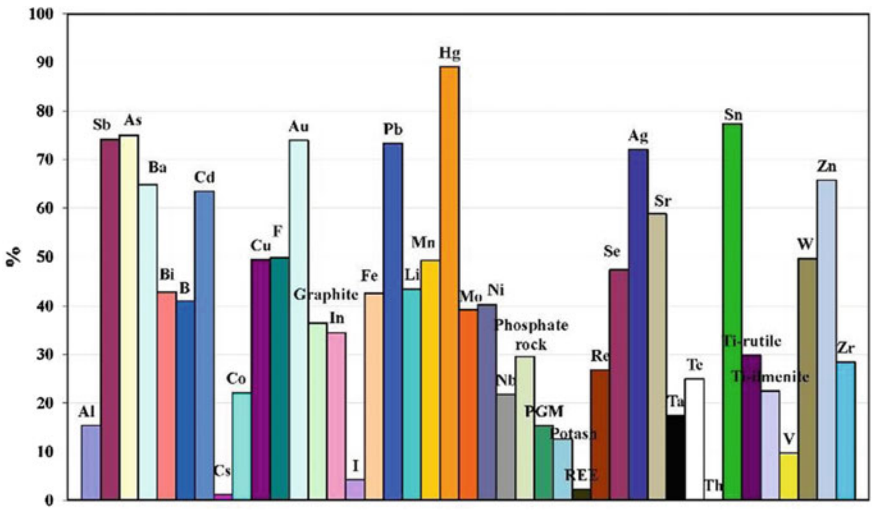
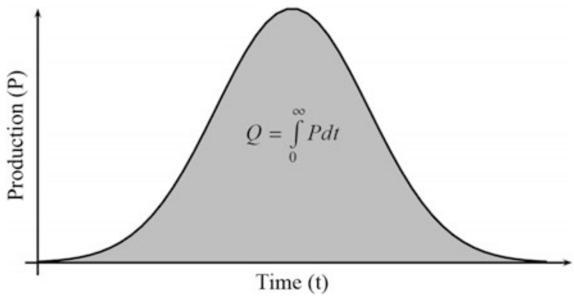



**Fig. 2.25** Depletion degree of the main non-fuel mineral commodity reserves [35]

**Fig. 2.26** Hubbert's prediction of world petroleum production rates [36]




production and depletion [36, 37]. Contrarily to the previous one, it is a dynamic model in terms of production and assumes that after fossil fuels reserves are discovered, production first increases exponentially but at some point a peak is reached and then production begins to decline again, generating a bell-shaped curve when the production is represented as a function of time. Hubbert originally predicted that the petroleum peak worldwide would be reached in 2005 (Fig. 2.26). However, this theory fails to consider resource growth, new deposit discoveries, and application of new technologies to deposits that were not economically feasible before.

From the development of this methodology a large number of studies have been conducted, analyzing the global and local current and future patterns of oil consumption and depletion [38–40]. In the case of non-fuel minerals, this issue has been addressed from several points of view but still there is a disagreement in the mineral depletion approach. Studies regarding several base metals, including studies of declining ore grades in mines and mining associated environmental constraints have been carried out analyzing the historical production and furthermore trying to assess future availability [41–45]. The shape of cumulative availability curves, meaning the amount of a mineral commodity that can be recovered profitably at various prices from different types of mineral deposits under the current conditions, can also provide helpful information about the potential shortages caused by depletion. It should be stated that the information needed to construct these cumulative availability curves is not always available for all the commodities [26, 46].

In any case, all these studies assume that no more resources are discovered or are available in the future, so the results obtained must be considered only as an approximation of the depletion state of the reserves under "business as usual" scenarios. Indeed, using the case of copper extraction, Meinert et al. [47] compared the historic mine production, the reserves and the copper used per capita with economic and population factors. With this information, the estimations obtained for the peak production of copper in other studies were proved to be underestimating the currently identified and the yet-to-be discovered copper resources.

As shortage of natural resources could become an international problem in the near future, different international organizations and regions are gradually focusing on raw material needs and raw material supply, moving towards a more sustainable and resource efficient society. Such is the criticality of this issue that in November

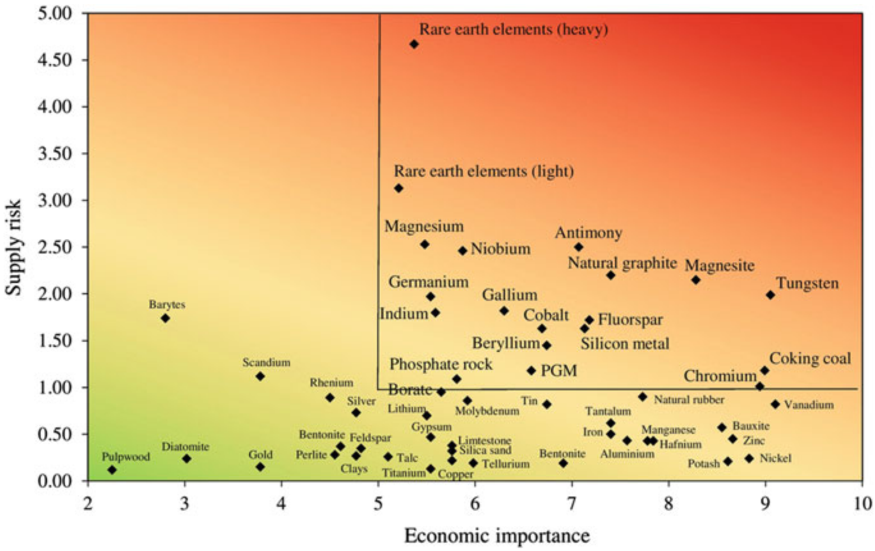



**Fig. 2.27** Criticality assessment for the EU [50]

2008 the European Commission promoted the Raw Materials Initiative to establish the raw material strategy and a list of actions that the member states should implement [48]. Additionally, in June 2010 the European Commission published a report on critical raw materials for the European Union [49] which identified 14 minerals as critical for the EU according to their economic importance and supply risk. This report was later updated [50] expanding the list to 20 commodities, including borates, coking coal, chromium, magnesite, phosphate rock and silicon metal (Fig. 2.27).

Following this report [50], the EU Joint Research Center analyzed the critical materials that could threaten the objective of the European Union Strategic Energy Technology Plan (SET plan) and analyzing the potential risk of supply shortage for the critical elements needed for six low-carbon energy technologies: nuclear, solar, wind, bioenergy, carbon capture storage and electricity grids [51]. A total of 14 critical elements whose annual demand between 2013 and 2020 would imply more than 1% of the 2010 annual production rate were identified (Fig. 2.28). Of these 14 critical elements, five (rare earths, neodymium and dysprosium, indium, tellurium and gallium) were considered to be at high risk for future supply-chain bottlenecks, according to political risk, concentration of supply and market factors.

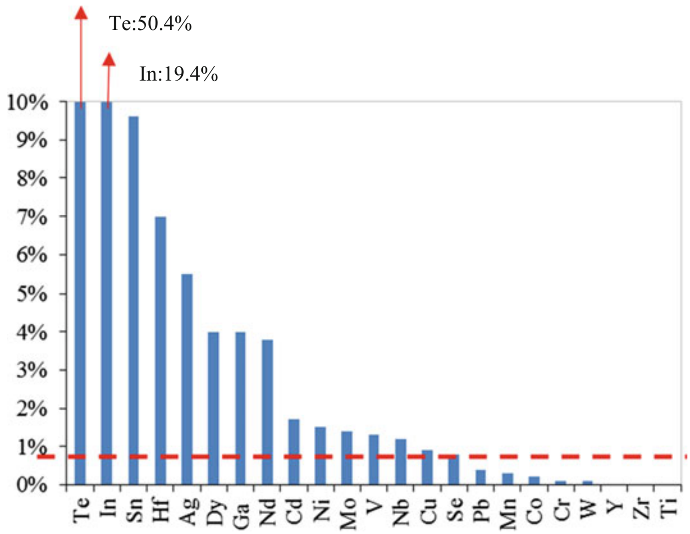



**Fig. 2.28** Metals requirements of SET-Plan in 2013 as % of the 2010 world supply (extracted from [51])

With similar concerns, the Committee on Critical Mineral Impacts of the U.S. Economy also published an experts report on critical minerals to the U.S. to aid decision makers [52]. The report was subsequently updated by the U.S. Department of Energy in December 2011 [53]. A criticality matrix was developed, taking into account five factors that can limit the long-term availability in the case of non-fuel minerals: geology, technology, environmental and social issues, politics and economics. This matrix was applied to eleven minerals: copper, gallium, indium, lithium, manganese, niobium, platinum group elements, rare earths, tantalum, titanium and vanadium. After carrying out an analysis of the minerals and materials used in the United States taking into account availability and reliability of supply, the United States proved to be completely dependent on imports on five: indium, manganese, niobium, platinum group metals (PGM) and REE (Fig. 2.29).

Similar studies were also produced by other institutions. For instance, the American Physical Society (APS) and the Materials Research Society (MRS) released a report in 2011 regarding the Energy Critical Elements (ECEs), chemical elements that have the capacity transforming the way of capturing, transmitting, storing or conserving energy, that are necessary to develop one or more new, energy-related technologies, i.e., electric cars, wind turbines and solar cells [54].

Accordingly, the British Geological Survey released in 2015 a risk list of 41 elements that are of economic value needed to maintain the economy [55]. The list includes variables related to non-geological factors, such as geopolitics, infrastructure availability, recycling rates, substitutability among others. Of the 41 elements analyzed, 6 presented a relative supply risk index higher than 8.5, being 10 the maximum supply risk. These elements are rare earth elements, antimony, bismuth, germanium, vanadium and gallium, several of which were already identified as critical elements in other reports.

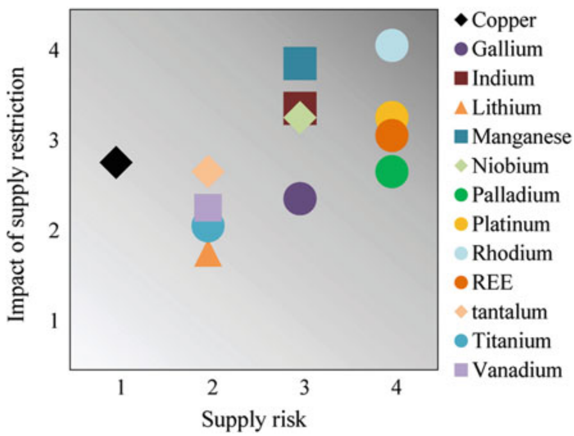



**Fig. 2.29** Criticality matrix for the 11 materials assessed by the Committee on Critical Mineral Impacts on the U.S. Economy [52]

All these reports have the same purposes, to highlight the rapid growth in demand of natural resources and to emphasize that shortage of critical materials could become a reality.

## References


1. Diamond, J. M. (2005). *Collapse: How societies choose to fail or succeed*. Viking Penguin.
2. Human Development Index (HDI). http://hdr.undp.org/en/content/human-development-index-hdi. Accessed June, 2016.
3. Worldwatch Institute Annual Report. (2004). www.worldwatch.org. Accessed May, 2016.
4. http://www.un.org/waterforlifedecade/scarcity.shtml
5. Szargut, J. (1999). Depletion of the unrestorable natural exergy resources as a measure of the ecological cost. In *Proceedings of Conference ECOS'99—Efficiency, Cost, Optimization, Simulation of Energy Systems*, Tokyo.
6. Szargut, J., Ziębik, A., & Stanek, W. (2002). Depletion of the unrestorable natural exergy resources as a measure of the ecological cost. *Energy Conversion and Management, 43,* 1149–1163.
7. Rogall, H. (2010). *Nachhaltige Ökonomie. Ökonomische Theorie und Praxix einer Nachhaltigen Entwicklung*. Marburg: Metropolis-Verlag, 2009. Polish translation: *Ekonomia zrównoważonego rozwoju*. Poznań Poland: Zysk Press.
8. Valero, A., & Botero, E. (2002). An exergetic assessment of natural mineral capital (1): Reference environment, a thermodynamic model for degradated earth. In *Proceedings of Conference on ECOS'02—Efficiency, Cost, Optimization, Simulation of Energy Systems*, Berlin.
9. Valero, A., Valero, A., & Arauzo, I. (2006). Exergy as an indicator for resources scarcity. The exergy loss of Australian mineral capita, A case study. In *Proceedings of ASME IMECE2006*, Chicago.
10. Finneveden, G., & Ostlund, P. (1997). Exergies of natura resources in life-cycle assessment and other applications. *Energy, 22*(9), 923–931.
11. International Energy Agency. https://www.iea.org/. Accessed June, 2016.
12. Szargut, J. (2011). *Thermodynamics*. Gliwice: Silesian University of Technology Press.
13. British Petroleum. (2015). *Statistical review of world energy*. Retrieved from: http://www.bp.com/content/dam/bp/excel/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-workbook.xlsx. Accessed March, 2016.
14. Eurostat. (2014). *Energy, transport and environment indicators* (2014 ed.). Luxembourg: Publications Office of the European Union. 280 pp. ISSN: 2363-2372.
15. Eurostat. (2015). *Energy balance sheets, 2013 data*. Luxembourg: Publications Office of the European Union, 84 pp. 2014 ISSN: 1830-7558.
16. British Petroleum Statistics. www.bp.com. Accessed May, 2016.
17. Minerals Education Coalition. (2015). *Minerals education coalition*. Retrieved from: http://www.mineralseducationcoalition.org/. Accessed March, 2016.
18. Friends of the Earth. (2009). *Overconsumption? Our use of the world's natural resources*. 36 pp. Retrieved from: https://www.foe.co.uk/sites/default/files/downloads/overconsumption.pdf. Accessed March, 2016.
19. European Environment Agency. (2012). *Material resources and waste—2012 update*. Retrieved from: http://www.eea.europa.eu/publications/material-resources-and-waste-2014/at_download/file. Accessed March, 2016.
20. Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics, 68*(10), 2696–2705.

21. USGS. (2015). *Mineral commodity summaries 2015*. United States Geological Survey. Retrieved from: http://minerals.usgs.gov/minerals/pubs/mcs/. Accessed March, 2016.
22. Ullmann's Encyclopaedia of Industrial Chemistry. (2002). *Gallium and gallium compounds* (6th ed.). Rexdale, Ontario: Wiley.
23. Mancheri, N. A. (2015). World trade in rare earths, Chinese exports restrictions and implications. *Resources Policy, 46,* 262–271.
24. Gleich, B., Achzet, B., Mayer, H., & Rathgeber, A. (2013). An empirical approach to determine specific weights of driving factors for the price of commodities—A contribution to the measurement of the economic scarcity of minerals and metals. *Resources Policy, 38,* 350–362.
25. Kooroshy, J., Meindersma, C., Podkolinski, R., Rademaker, M., Sweijs, T., & Diederen, A., et al. (2009). *Scarcity of minerals. A strategic security issue*, Tech. Rep. 02-01-10. The Hague Centre for Strategic Studies. Retrieved from: http://www.hcss.nl/reports/scarcity-of-minerals/14/. Accessed March, 2016.
26. Tilton, J. (2003). *On borrowed time? Assessing the threat of mineral depletion*. RFF Press, Taylor & Francis.
27. Bauer, D., Diamond, D., Li, J., Sandalow, D., Telleen, P., & Wanner, B. (2010). *Critical materials strategy*. U.S. Department of Energy.
28. Rosenau-Tornow, D., Buchholz, P., Riemann, A., & Wagner, M. (2009). Assessing the long-term supply risks for mineral raw materials—A combined evaluation of past and future trends. *Resources Policy, 34*(4), 161–175.
29. Leontief, W., Koo, J., Nasar, S., & Sohn, I. (1983). *The future of non-fuel minerals in the US and World Economy*. Lexington, MA: Lexington Books, DC Health and Company.
30. Sohn, I. (2006). Long-term projections of non-fuel minerals: We were wrong, but why? *Resources Policy, 30*(4), 259–284.
31. Sohn, I. (2007). Long-term energy projections: What lessons have we learned? *Energy Policy, 35*(9), 4574–4584.
32. Harmsen, J. H. M., Roes, A. L., & Patel, M. K. (2013). The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. *Energy, 2*(50), 62–73.
33. Henckens, M. L. C. M., Driessen, P. P. J., & Worrell, E. (2014). Metal scarcity and sustainability, analysing the necessity to reduce the extraction of scarce metals. *Resources, Conservation and Recycling, 93,* 1–8.
34. Ulrich, A. E., & Frossard, E. (2014). On the history of a recurring concept: Phosphorous scarcity. *Science of the Total Environment, 490,* 694–707.
35. Valero, A., & Valero, A. (2010). Physical geonomics: Combining the exergy and Hubbert peak analysis for predicting mineral resources depletion. *Resources, Conservation and Recycling, 54*(12), 1074–1083.
36. Hubbert, M. K. (1956). *Nuclear energy and the fossil fuels*. Retrieved from: http://www.hubbertpeak.com/hubbert/1956/1956.pdf. Accessed March, 2016.
37. Hubbert, M. K. (1962). *Energy resources: A report to the Committee on Natural Resources of the National Academy of Sciences*. Washington, D.C.: National Academy of Sciences.
38. Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó., & Miguel, L. J. (2014). Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy, 77,* 641–666.
39. García-Olivares, A., & Ballabrera-Poy, J. (2015). Energy and mineral peaks, and a future steady state economy. *Technological Forecasting and Social Change, 90,* 587–598.
40. Reynolds, D. B. (2014). World oil production trend: Comparing Hubbert multi-cycle curves. *Ecological Economics, 98,* 62–71.
41. Mason, L., Prior, T., Mudd, G. M., & Giurco, D. (2011). Availability, addiction and alternatives: three criteria for assessing the impact of peak minerals on society. *Journal of Cleaner Production, 19*(9–10), 958–966.
42. Mudd, G. M. (2007). An analysis of historic production trends in Australian base metal mining. *Ore Geology Reviews, 32*(1–2), 227–261.

43. Northey, S., Mohr, S., Mudd, G. M., Weng, Z., & Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling, 83,* 190–201.
44. Prior, T., Giurco, D., Mudd, G. M., Mason, L., & Behrisch, J. (2012). Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change, 22*(3), 577–587.
45. Tilton, J. E., & Lagos, G. (2007). Assessing the long-run availability of copper. *Resources Policy, 32*(1–2), 19–23.
46. Yaksic, A., & Tilton, J. E. (2009). Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium. *Resources Policy, 34*(4), 185–194.
47. Meinert, L. D., Robinson, G. R., Jr., & Nassar, N. T. (2016). Mineral resources: Reserves, peak production and the future. *Resources, 5,* 14. doi:10.3390/resources5010014.
48. European Commission. (2008). *The raw materials initiative—Meeting our critical needs for growth and jobs in Europe*.
49. European Commission. (2010). *Critical raw materials for the EU*. Retrieved from: https://ec.europa.eu/eip/raw-materials/en/system/files/ged/79%20report-b_en.pdf. Accessed March, 2016.
50. European Commission. (2014). *Report on critical raw materials for the EU. Report of the Ad hoc working group on defining critical raw materials*. Retrieved from: http://www.amg-nv.com/files/Report-on-Critical-Raw-Materials-for-the-EU-2014.pdf. Accessed March, 2016.
51. Moss, R., Tzimas, E., Willis, P., & Kooroshy, J. (2011). *Critical metals in strategic energy technologies. Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies*, Jerc Pub. No jrc65592. Eur 24884 en, JRC European Commission. Retrieved from: http://publications.jrc.ec.europa.eu/repository/handle/111111111/22726. Accessed March, 2016.
52. Committee on Critical Mineral Impacts of the US Economy. (2008). *Minerals, critical minerals, and the US economy*. Washington DC: The National Academy of Sciences, National Academies Press.
53. U.S. Department of Energy. (2011). *Critical materials strategy*. December 2011. Retrieved from: http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf. Accessed March, 2016.
54. American Physical Society & Materials Research Society. (2011). Energy critical elements: Developing new technologies. Retrieved from http://www.mrs.org/advocacy/ece/report/. Accessed March, 2016.
55. British Geological Survey. (2015). *Risk List 2015. An update to the supply risk index for elements or element groups that are or economic value*. Retrieved from: http://www.bgs.ac.uk/downloads/start.cfm?id=3075. Accessed March, 2016.
56. Calvo, G. (2016). *Exergy assessment of mineral extraction, trade and depletion*. PhD Thesis. Universidad de Zaragoza.
57. Ziębik, A., Szega, M., & Stanek, W. (2015). *Energy systems and environment*. Gliwice: Silesian University of Technology Press.
58. EDUCOGEN. (2001 December). *The European educational tool on cogeneration* (2nd ed.). Cogen Europe.
59. U.S. Department of Energy (2013). Cost and Performance Baseline for Fossil Energy Plants. *Volume 1: Bituminous coal and natural gas to electricity*, DOE/NETL-2010/1397. www.netl.doe.gov.
60. Heck, T. (2007). Warme-Kraft-Kopplung. In: R. Dones, et al. (Eds.), *LCI of the operation of the CHP plant, report No. 6-XIV*. Dubendorf, CH: Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories. www.ecoinvent.ch. Translation Franziska Peter, PSI.
61. Szargut, J., Ziębik, A., & Kozioł, J. (1994). *Racjonalizacja użytkowania energii w zakładach przemysłowych. Poradnik audytora energetycznego*. Warszawa: Fundacja Poszanowania Energii.

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