Centre for Energy Efficiency XXI century (CENEf-XXI)

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RESEARCH
REPORT

THE STUDY INTO EFFECT OF BASIC MATERIALS MODIFICATION (USING CARBON NANOTUBES) ON REDUCTION OF GLOBAL ANTHROPOGENIC GREENHOUSE GAS EMISSIONS

STAGE 3

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Introduction

This paper has been prepared by the Centre for Energy Efficiency XXI century (CENEf-XXI) on order of OCSiAl.ru for study into effect of basic materials modification using CNT on reduction of global anthropogenic greenhouse gas emissions. In the paper, this effect was estimated on the basis of reduced demand for basic materials through enhancement of consumer properties of modified (doped) basic materials, as well as on the basis of reduced demand for fuel combustion through operation of light-weight vehicles (motor cars and aircraft).

All the key results of this paper are summarised in Chapter 1. Chapter 2 describes the role of basic materials in the development of the global economy, shows very-long-term (over 115 years) and current trends of the past 40 years, growth drivers of material use and their relative importance; it shows that for the climate stabilisation purposes, mankind should learn to make use of materials using half as much of the physical volume of such materials.

Chapter 3 shows the role of energy consumed for production and transportation of materials in the global energy balance, considers the concepts of direct and indirect energy consumption, as well as the concept of embodied (materialised) energy; it shows that the potential for energy saving in production of materials is not exhausted but limited; the Chapter also contains data on embodied energy consumed for production of basic materials.

Chapter Four estimates greenhouse gas emissions from production, transportation, and use of basic materials; shows historical data on greenhouse gas emissions by economic sectors; considers concepts and estimates direct, indirect, and embodied GHG emissions.

Chapter Five provides the long-term forecasts for global anthropogenic GHG emissions up to 2100, which serve as a basis for estimating the effect of basic materials modification (using CNT) on reduction of global anthropogenic greenhouse gas emissions and shows the main factors affecting their trends.

Chapter Six selects, from the variety of basic materials production forecasts, the 'baseline' forecasts with up to 2100 horizon corresponding to the most probable trend of their production. There are a lot of very-long-term forecasts for a number of materials and practically no forecasts for other materials. For such cases, CENEf-XXI has developed its own forecasts using the data on trends in specific consumption of materials per capita or per unit of GDP, as well as saturation factors, resource limitation and other limitations.

Data on reduced demand for basic materials modified with CNT has been received based on the analysis of a wide range of literary sources. This data is summarised in Chapter 7.

Chapter Eight examines the possibilities of reducing the global GHG emission for the period until 2100 in production of individual basic materials through reduction in materials intensity while increasing the strength and other properties of materials through doping with CNT. The examinations were conducted on the basis of dedicated mathematical models. The additional volume of GHG emissions for SWCNT production was also examined. Apart from the effects at the stage of basic materials production, effects may be brought about at the stage of light-weight products operation. This paper will focus on effects from motor cars and aircraft.

Finally, Chapter Nine summarises the forecast results of possible contribution of increased use of CNT for doping of certain materials to reduction of global anthropogenic greenhouse gas emissions, estimates the role of this technology versus the long-term contribution of other technologies, and analyses sensitivity of results to the assumptions made in the paper.

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1 Executive Summary

1.1 The Role of the Basic Materials in the Global Economic Development

For centuries the mankind has been producing and using hundreds of materials.

Total extraction of all basic materials in 2015 can be assessed at around 90 billion tonnes, i.e. 20 times above the 1900 level.

The development of the human society is accompanied by:

- changes in both the scale and structure of materials use;
- eventual replacement of biomass with mineral materials and fossil fuels --
  - ✓ along with efficiency improvements, yet
  - ✓ absolute growth in the consumption and related growth in associated emissions and waste that have adverse environmental impacts;
- the lion's share of energy consumption and greenhouse gas (GHG) emissions associated with materials production and consumption are related to a limited number of the basic materials;
- total emissions are largely determined by the "Big Five": steel, cement, paper (and cardboard), aluminium, and plastic (as aggregated groups).

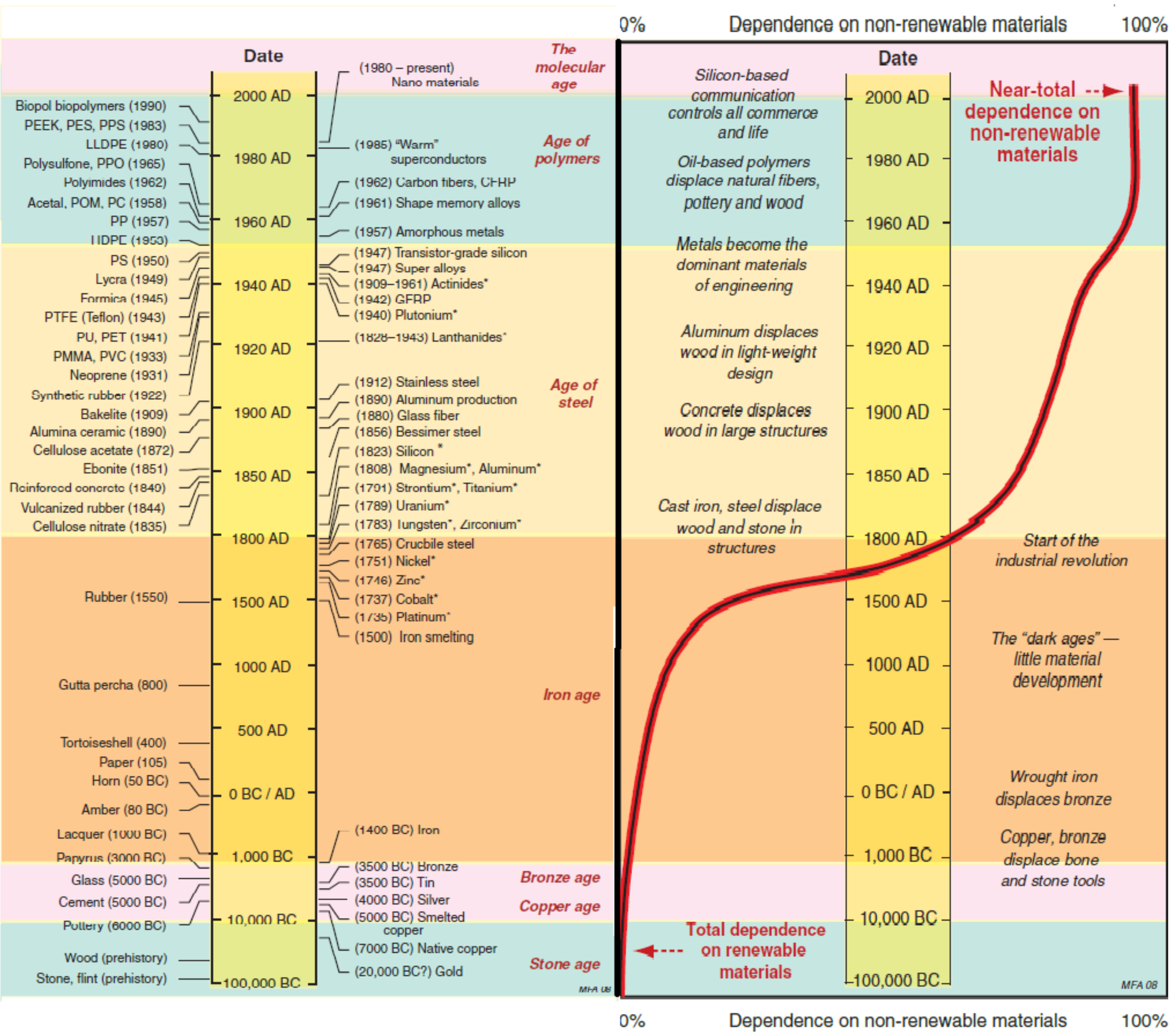
The entire history of the humanity has never seen anything like the 20th or early 21st century

- The global population has escalated 4.6-fold;
- The global GDP has scaled up 33-fold;
- The consumption of all materials is up 12-fold, including:
  - ✓ biomass 4.4-fold;
  - ✓ primary energy 12-fold;
  - ✓ fossil fuels 16-fold;
  - ✓ metal ores 43-fold;
  - ✓ construction raw materials 59-fold.

Population and global GDP growth are the key drivers behind materials demand evolution

- While biomass use has been growing at a rate close to that of the population increase, fossil resources extraction growth rate has been close to, or even exceeding, the global GDP growth rate;
- After a long stabilization period, the year 2000 marked the beginning of a new global per capita materials use growth era;
- Materials use per unit of global GDP dropped nearly 3-fold over 1900–2015;
- However, this drop was mostly determined by the reduction in biomass demand due to the innovative properties (including design options) of new mineral materials;
- During the last 115 years, mineral materials intensity per unit of GDP has been fluctuating around a pretty stable level driven by economic long waves;
- The century-long relative stability of the global material intensity (net of biomass) means that, given initial gap in the materials intensities, reduction in some regions was leveled by the growing share of regions with relatively high material intensities.

Figure 1.1 The Materials Timeline



The materials timeline. The scale is nonlinear, with big steps at the bottom, small ones at the top. A star (*) indicates the date at which an element was first identified. Unstarred labels give the date at which the material became of practical importance.

The increasing dependence on nonrenewable materials over time, unimportant when they are plentiful but an emerging problem as they become scarce.

Source: Ashby MF. 2012. Materials and the environment: eco-informed material choice, 2nd edn. Oxford, UK: Butterworth-Heinemann.

Super-longterm (over 115 years) and more recent (last 40 years) trends may be summarized as follows:

- In the 20th and 21st centuries, the use of basic materials has shown substantial growth, largely determined by the transformation of the economic development energy base;
- In full concordance with the Rome Club's *"Limits To Growth"* report (1972), materials use shows practically exponential growth and has increased 12-fold over 115 years;
- The use of mineral (fossil) materials was growing much faster, than the use of biomass, and so the share of biomass has dropped nearly 2.5-fold. This has determined a fundamental shift in the materials use structure from the dominance of biomass to the dominance of fossils;

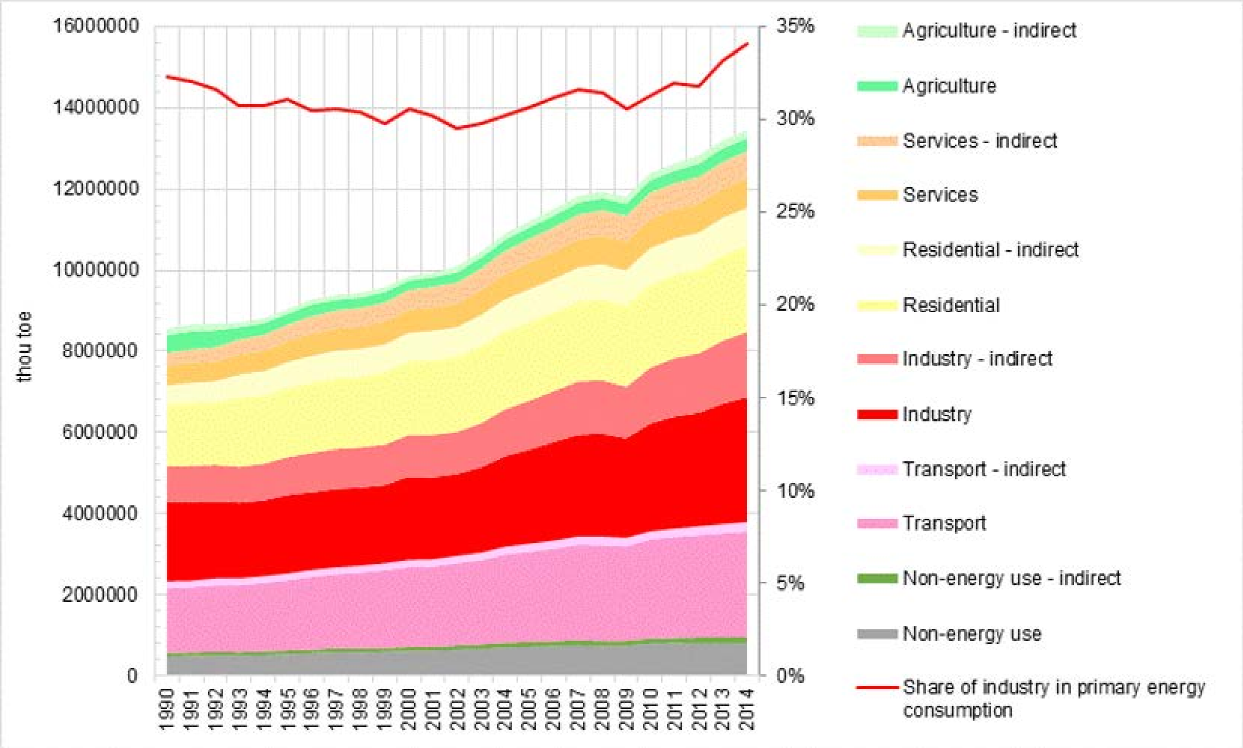
- The use of building materials has demonstrated particularly fast growth;
- Per capita use of basic materials kept growing in long acceleration and deceleration cycles and has increased 2.8-fold;
- Per capita use of materials (excluding biomass) has increased 7.5-fold;
- Materials intensity of global GDP has dropped 2.7-fold;
- However, materials intensity of global GDP (basic materials net of biomass) has been cyclically fluctuating around a stable level on the 115 years' time horizon;
- As the economy develops, specific materials use is saturated (first, per unit of GDP and then per capita) and the dematerialization of the economic growth begins;
- Developed countries have already reached this stage;
- The gap in the economic development levels between developed and developing economies is quite substantial, and the latter have a long way to go before they can reach the dematerialization stage;
- Since the share of developing countries in the global economy is increasing:
  - ✓ global per capita materials use will not reach saturation in the near future;
  - ✓ material intensity of global GDP may demonstrate slow cyclic fluctuations around a relatively stable level for decades to come.

1.2 The Proportion of Energy Use for Materials Production and Transportation in the Global Energy Balance

In 2014, direct energy use for basic materials mining and manufacturing was 1.9 billion toe, and the share of energy use for basic materials production increased from 11% in 2003 to 14% in 2014

- 2014 global industry direct energy consumption was estimated at 3.1 billion toe. It grew up by 57% since 1990;
- In 1990–2002, the share of industry in total primary energy consumption was decreasing, but reversed to the growth pathway since 2002 to regain its position in the global energy balance by 2014 having reached 22% of primary energy consumption and 32% of final energy consumption;
- As knowledge-based technologies and machine-building developed, the share of basic materials in the overall industry energy consumption was slowly declining, yet still kept high: it was estimated at 62% for 2014 versus 65% for 2003.

Figure 1.2 Global Direct and Indirect Energy Use by Sectors in 1990–2014

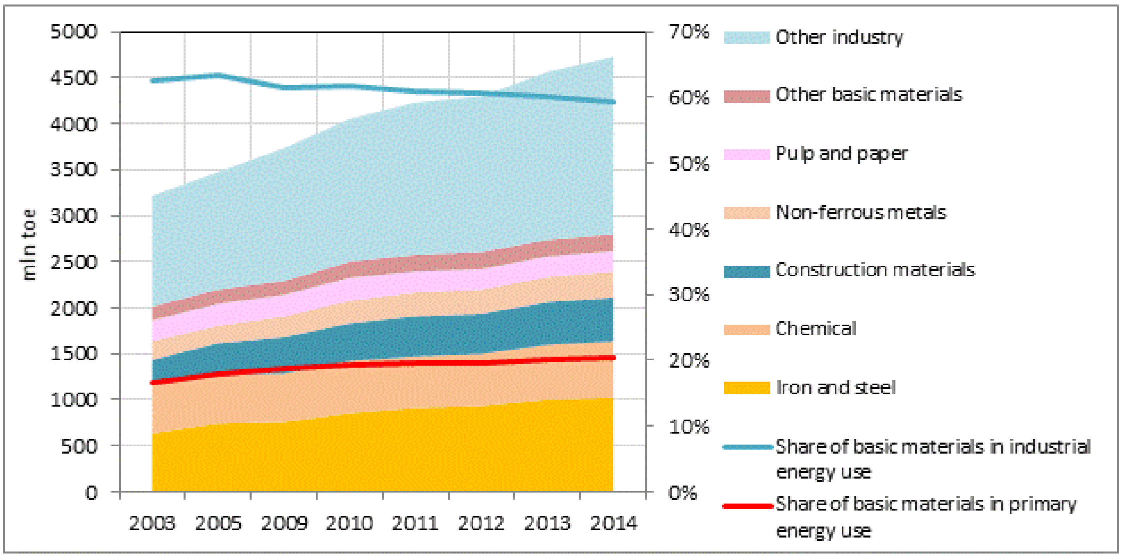


Source: estimated by authors based on IEA (2014).

Direct and indirect energy consumption (energy sector use, including electricity and district heat generation) for the production of basic materials amounted to 2.8 billion toe in 2014, or nearly 59% of total direct and indirect industry energy use, or 20% of total primary energy use (Fig. 1.3).

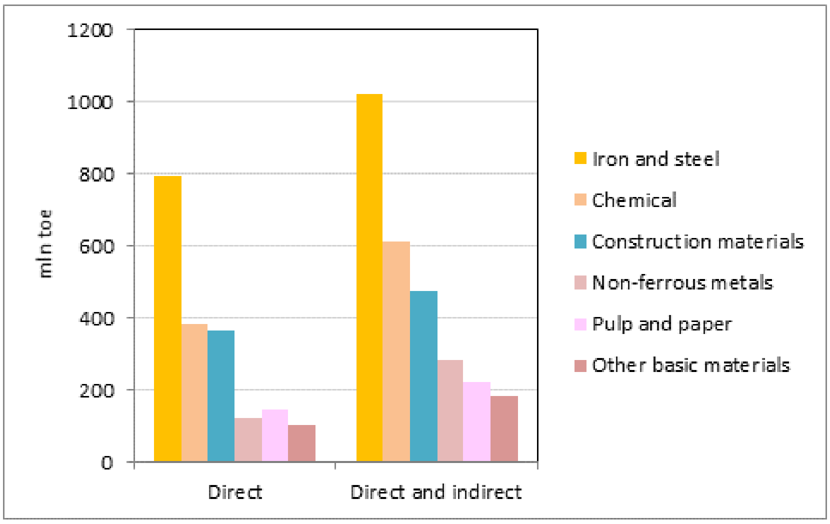
- Direct and indirect industry energy use equalled 4.7 billion toe in 2014, i.e. 34% of total global primary energy use (Fig. 1.2);
- Average ratio of direct to indirect industry energy use is 1 : 0.54;
- The proportion of indirect effects varies by sectors and materials; it is higher, where the share of electricity and district heat use for production purposes is larger;
- A small group of materials (steel, cement, paper and cardboard, plastics, ethylene, and aluminium) is the largest (80%) contributor to direct and indirect energy use for the basic materials production (Fig. 1.4).

Figure 1.3 Direct and Indirect Global Industry Energy Use in 2003–2014



Source: estimated by authors based on IEA (2014)

Figure 1.4 DIRECT and Indirect Energy Use by Key Basic Materials Industries in 2014



Source: estimated by authors based on IEA (2014) and data from Table 3.1.

There are a number of concepts related to specific energy use for products and services.

Indirect effects are best integrated in the embodied energy concept.

- Specific energy use concepts basically differ in the boundaries of product manufacture analysis that determine the outcomes: the wider the boundaries, the higher specific energy use;
- Specific embodied energy use accounts for energy consumption over the whole product supply chain and lifetime, including production of components; energy use for transportation; energy embodied in the process equipment, industrial buildings and facilities; and sometimes even energy consumption related to the product use over its lifetime;
- Specific embodied energy consumption is largely determined by the proportion of materials recycling;
- In order to avoid multiple counting in total embodied

energy use assessments, energy consumption for product manufacturing is not to be summed up with that for the production of raw materials and components that were used to make this product.

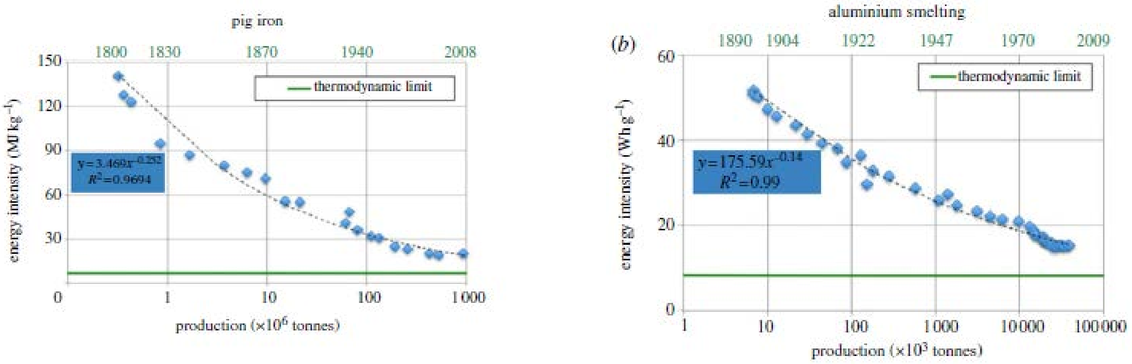
As the potential thermodynamic (theoretical) minimum is approached, specific energy consumption reduction rates slow down.

- Specific energy use for the production of materials declines, as technologies improve and materials production scale grows (Fig. 1.5);
- Over 2000–2012, energy intensity of global industrial production was 12% down, i.e. was declining by nearly 1% per year;
- Average global specific energy use for steel production was down by only 5% over the same period, and for primary aluminium production it kept nearly stable (declining by just 0.4% per year since 1980).

Energy saving potential in materials manufacture is not exhausted, yet limited.

- According to IPCC, IEA, and UNIDO, global industrial energy intensity can be reduced by 20–25% through the replacement of all current technologies with BATs;
- Additional 20% reduction in specific energy use can be obtained through innovations and improvement of BAT parameters;
- IEA estimates specific energy use reduction potential at 19% in steel production, 30% in cement production, 15% in chemicals and petrochemicals, and 15% in pulp and paper.

Figure 1.5 Learning Curves—Specific Energy Use Reduction Trend Driven by Scaled up Materials Production



Source: Gutowski TG, Sahni S, Allwood JM, Ashby MF, Worrell E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. PhilTrans R Soc A 371: 20120003.http://dx.doi.org/10.1098/rsta.2012.0003.

Only part of this potential can be implemented before 2050:

- No substantial reduction in specific energy use for basic materials production can be expected before 2025-2030;
- A significant reduction in specific energy use for steel production can hardly be expected, and specific energy use for cement production will be down by only 9%;
- By 2050, reductions in specific energy use may be 24-36% for steel, 28% for cement, and 20-27% for aluminium.[1]

[1] IEA. 2015. Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action. IEA/OECD. Paris. 2015.

Total embodied energy use for the production of 32 basic materials is 3,815 million toe. It is 28% of 2014 global primary energy consumption and more than 4 times higher, than direct energy consumption for these materials production.

3.2 billion toe, or 24% of 2014 total global primary energy consumption, were used to produce the materials specified for this study.

The major part of embodied energy use is related to the production of (Fig. 1.6):

- steel: 33.3%;
- plastics: 19.8%;
- cement: 13.6%;
- paper and cardboard: 7.6%;
- commercial wood: 6.7%;
- aluminium: 4.8%;
- ammonia: 3.2%;
- ethylene: 2.3%;
- chrome: 1.5%;
- synthetic rubber: 1%.

These 10 groups of materials are responsible for 93% of embodied energy use for the production of all basic materials.

Figure 1.6 Embodied Energy Use for the Key Basic Materials Production

Source: estimated by authors.

1.3 Greenhouse Gas Emissions Related to Basic Materials Production, Transportation, and Use

In 2011–2014, anthropogenic global GHG emission was growing a bit slower, than in

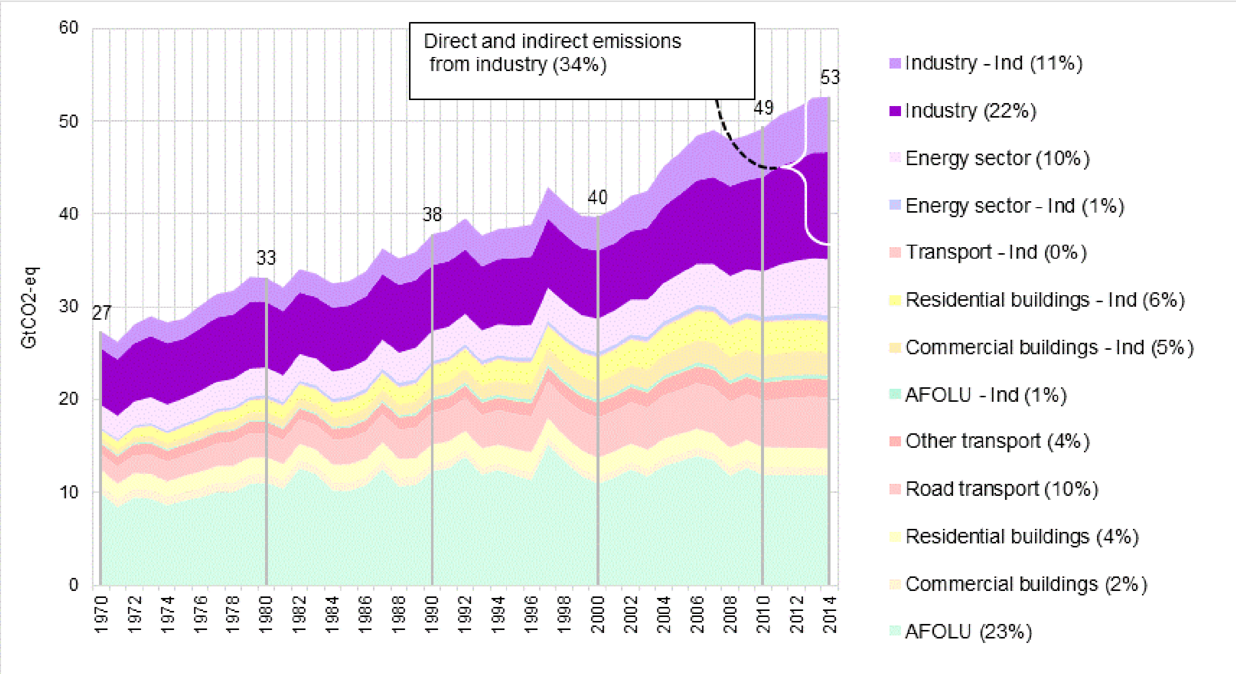
- Emissions from the transport sector showed the most dynamic growth in 1970–2000, but after 2000 industry took the lead;

2001–2010, and by 2014 it approached 53 billion t CO_2eq.

In 2014, industry directly contributed 11.6 billion t CO_2eq. to the total GHG emission, or 22% of the anthropogenic emission.

- Industry GHG emission grew up by 64% over 2000–2014, outpacing total emissions growth 1.5–2-fold (Fig. 1.7);
- Industry comes second (26%) after heat and power generation in direct global anthropogenic GHG emissions;
- Industry (net of AFOLU) is responsible for 28% therein.

Figure 1.7 Evolution of GHG Emissions from the Key Sectors and Distribution of Emissions from Heat and Electricity Generation by Sectors (Indirect Emissions) in 1970–2014



	Average annual growth rates				
	1971–1980	1981–1990	1991–2000	2001–2010	2011–2014
Total	**1.94%**	**1.33%**	**0.51%**	**2.19%**	**1.56%**
AFOLU	1.07%	1.19%	-1.08%	0.81%	0.00%
Residential buildings	2.64%	2.61%	1.09%	1.87%	-1.43%
Public buildings	3.35%	1.51%	2.23%	2.57%	-1.23%
Energy sector	2.21%	0.78%	1.06%	2.79%	2.16%
Industry	**2.01%**	**0.73%**	**0.55%**	**3.49%**	**3.17%**
Transport	3.04%	2.27%	2.14%	1.70%	1.75%

Note: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use. Energy sector does not include emissions from heat and electricity production, as they are allocated to end-use sectors.

Source: 1970–2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

2014 total direct and indirect industry GHG emissions are estimated at 17.5 billion t CO_2eq, which is 33% of the anthropogenic emission, or 43% (net of AFOLU).

- Indirect GHG emissions (i.e. emissions from fuel combustion in the production of heat and electricity used in the industrial sector) are responsible for 11% (Fig. 1.7);
- Since 2000, total direct and indirect industry GHG emissions are 60% up (Fig. 1.8).

In 2014, basic materials were responsible for 7.1 billion t CO_2eq of direct emission and 3.0

- It equals 58% of industry GHG emissions and 19% of total anthropogenic GHG emissions;
- While total industry GHG emission increment over 1970–

billion t CO_2eq of indirect emission, or 10.1 billion t CO_2eq in all.

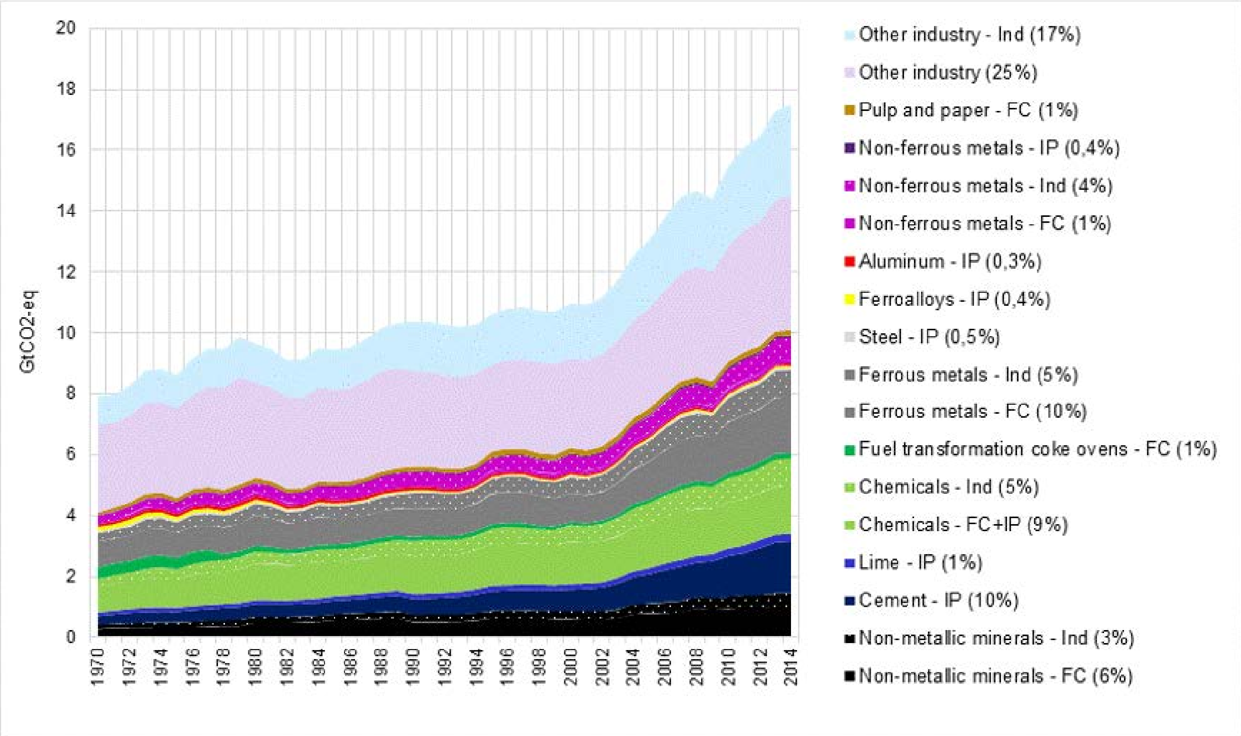
2000 was 3 billion t CO_2eq., it equalled 6.5 billion t CO_2eq over a twice shorter period—in 2000–2014;

- Corresponding increments in emissions from materials production are 2.1 and 3.9 billion t CO_2eq. In other words, average annual increase grew up 4-fold.

Transportation of basic materials further contributes around 1 billion t CO_2eq to direct and indirect GHG emissions related to basic materials supply.

- GHG emissions from freight transport can be estimated at 3 billion t CO_2eq;
- The share of materials in freight turnover amounts to approximately 50%, and so materials transportation is responsible for around 1.5 billion t CO_2eq;
- If net of oil and natural gas transportation, the figure is around 1 billion t CO_2eq

Figure 1.8 Evolution of direct and indirect GHG emissions from key industries



	Average annual growth rates				
	1971–1980	1981–1990	1991–2000	2001–2010	2011–2014
Industry	**2.01%**	**0.73%**	**0.55%**	**3.49%**	**3.17%**
Non-metallic minerals	4.03%	1.56%	2.11%	5.28%	3.93%
Chemicals	3.90%	0.82%	1.08%	1.79%	1.65%
Ferrous metals	-0.10%	-0.20%	-0.04%	5.13%	2.65%
Non-ferrous metals	3.73%	1.15%	0.81%	2.59%	2.67%
Other industry	2.07%	0.64%	0.25%	2.52%	3.12%

Note: proportions in the legend are shares of sectors in 2014 total industry emission. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use. IP—Industrial processes, FC—fuel combustion, Ind—indirect emissions.

Source: before 2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

Total embodied GHG emissions from the supply of 32 basic materials amount to 11.5 billion t CO_2eq. This equals 21.5% of global anthropogenic GHG

- Embodied GHG emissions concept builds on specific embodied energy use concept. Embodied GHG emissions include GHG emissions from materials transportation;
- The largest embodied emissions (in billion t CO_2eq)

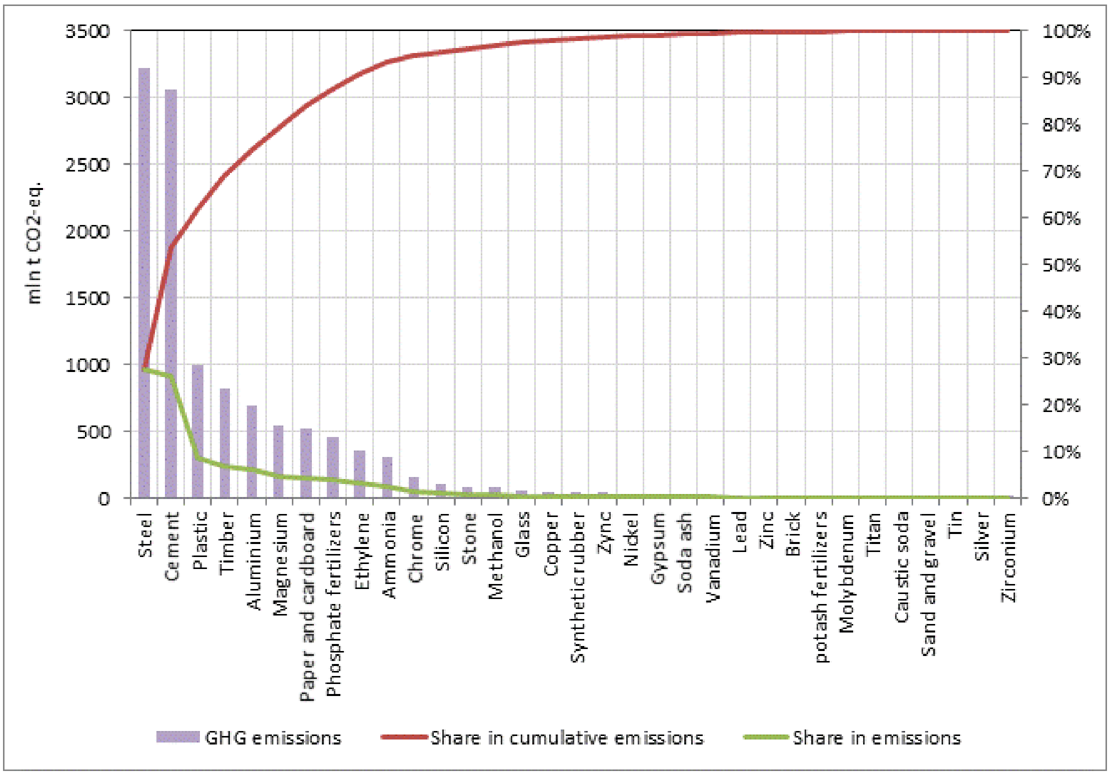
emission in 2014 (or 27% net of AFOLU).

Emissions from the production of basic materials specified for this study equal 8.3 billion t CO_2eq

come from the production of: steel—3.2; cement—3.1; plastics—1; commercial wood—0.8; aluminium—0.68; magnesium—0.55; paper and cardboard—0.52; phosphate fertilizers—0.45; ethylene—0.36; ammonia—0.3 (Fig. 1.9);

- These 10 groups of basic materials are responsible for 93% of total embodied GHG emissions from 32 basic materials.

Figure 1.9 Embodied GHG Emissions from the Key Basic Materials Production



Source: estimated by authors.

1.4 Long-Term Projections of Global Anthropogenic GHG Emissions

Key factors behind the GHG emissions evolution are:

- population;
- per capita GDP;
- GDP energy intensity;
- carbon intensity of primary energy.

Baseline projections of the four above factors evolution were assessed using the key findings of hundreds of long-term scenarios provided in the IPCC Fifth Assessment Report of the Working Group III, as well as IEA and IIASA projections (IIASA, Global Energy Assessment).

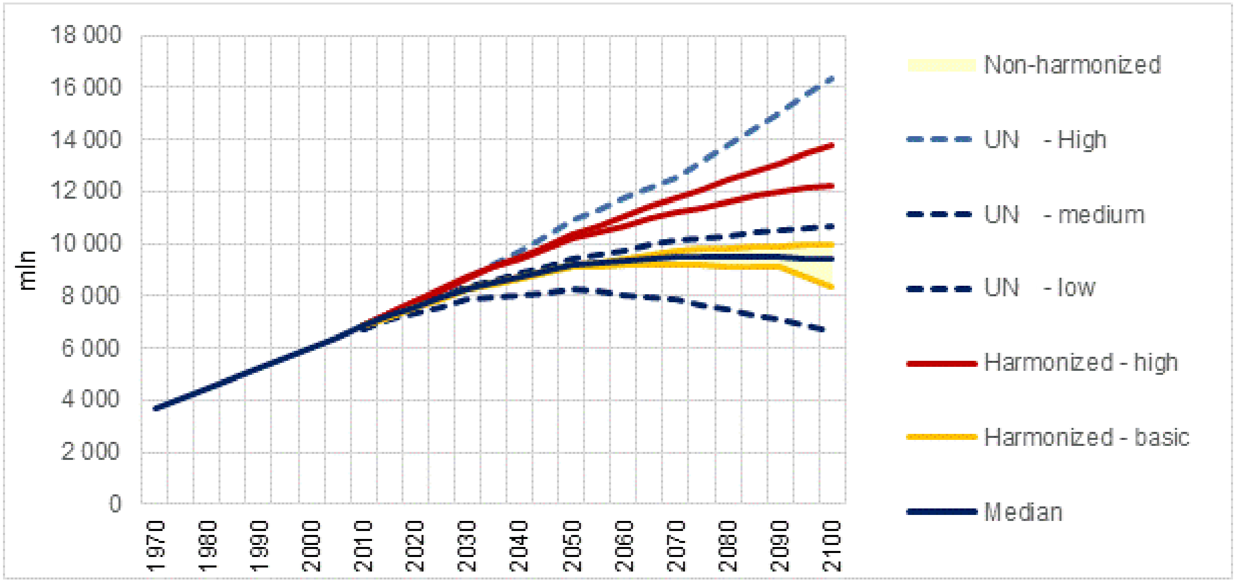
While the global population last doubled over 45 years, and historically, population doubling time declined 2 or 3-fold, there may be no more doubling on the

- However, this may only happen beyond 2050, and before that the global population is likely to be growing;
- There is a large range of projections (Fig. 1.10);
- Based on the median IPCC projection, global population will increase to:

2100 time horizon at all, and the population may stabilize after a peak.

- ✓ 8.5 billion by 2035 (24% growth since 2010);
- ✓ 9 billion by 2050 (34% growth since 2010);
- ✓ 9.4 billion by the end of the 21st century (37% growth since 2010).

Figure 1.10 Global population growth projections until 2100



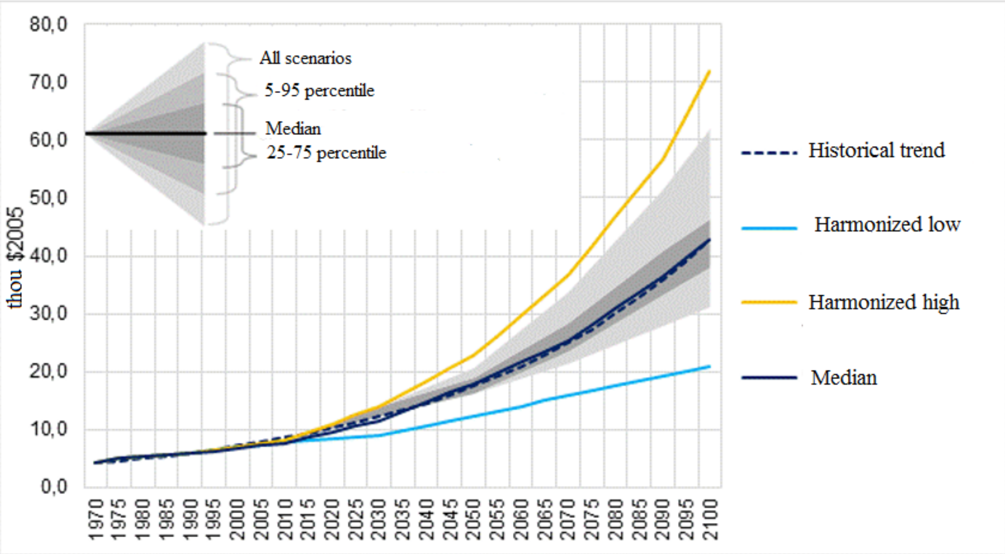
Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened. Scenarios were normalized using IEA 2010 data.

Source: IPCC (2015), IEA (2014).

The range of global per capita GDP projections is even wider (Fig. 1.11).

- It may grow up 3–3.5-fold by 2035 (as compared to the 2010 level); 3.8–4.9-fold by 2050; and 7.5–14.7-fold by 2100;
- According to the median scenario, it will be above USD 13 thousand in 2035, USD 18 thousand in 2050 and USD 43 thousand in 2100 (in 2005 MER prices);
- Average annual growth rates will keep nearly constant (1.8% per year) in 2010–2100.

Figure 1.11 Global per Capita GDP Projections Until 2100 (2005 Exchange Rates)



Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), and full range (lightest). Scenarios were normalized using IEA 2010 data.

Source: IPCC (2015), IEA (2014).

Driven by the population growth and per capita income growth, global GDP may escalate nearly 8-fold by 2100.

- In the median scenario, it will grow up from $US 51.9 trillion in 2100 (in 2005 prices) to $US 111.4 trillion in 2035, to $US 164.6 trillion in 2050, and to $US 404.8 trillion in 2100;
- As the global population growth slows down, average annual GDP growth rates will be eventually declining: from 3% in 2010–2035 to 2.5% in 2035–2050 and to 1.8% in 2050–2100.

In the median scenario, GDP energy intensity will drop by 27% of the 2010 level in 2035, by 40% in 2050, and by 67% in 2100.

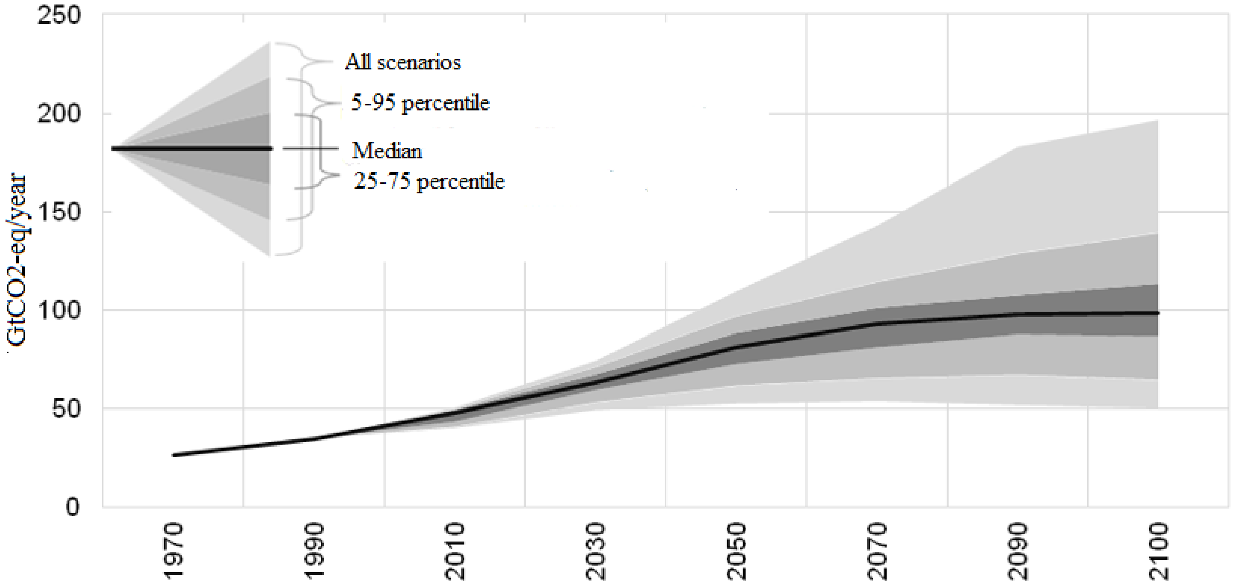
In other words, the average decline will be 1.2% per year, keeping the retrospective decline rate.

- In the baseline scenario, GDP energy intensity declines by 1.2% per year in 2010–2035, by 1.3% in 2035–2050, and by 1.16% in 2050–2100;
- In the Fast Decline group of scenarios, GDP energy intensity drops by 37%, 54%, and 80% respectively, and annual reduction rates amount to 1.9%, 2%, and 1.6% respectively;
- These optimistic projections correspond to the 2 °C warming scenario.

In the baseline scenario, evolution of carbon intensity of primary energy is not expected to show substantial reduction.

- Carbon intensity fluctuation range is pretty wide, varying between 54% reduction and 60% growth in 2100;
- Carbon intensity will likely equal 94–109% of the 2010 level in 2100.

Figure 1.12 Evolution of Global Anthropogenic GHG Emissions to 2100



Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5^{th}–95^{th} percentile range (lighter), and full range (lightest). Scenarios were normalized using IEA 2010 data.

Source: IPCC (2015).

In the IPCC median baseline projection, total anthropogenic GHG emission may stabilize in 2090 at a level close to 100 Gt of CO_2eq (which is twice higher than the current level).

- In the baseline scenario, emissions may amount to 67 Gt CO_2eq in 2035 (Fig. 1.12), and to 81 Gt CO_2eq in 2050;
- In the baseline (median) scenario, GHG emission average annual growth rate will equal:
  - ✓ 1.4% in 2010–2035,
  - ✓ 1.2% in 2035–2050,
  - ✓ 0.4% in 2050–2100.
- If the analysis is limited to CO_2 emissions from fuel combustion and industrial processes alone, in the baseline scenario emissions grow up to 52 Gt CO_2 by 2035, to 64 Gt CO_2 by 2050, and 84 Gt CO_2 by 2100, which is 2.6 times above the 2010 level.

In the baseline scenario, direct and indirect GHG emissions from the industrial sector will exceed 26 Gt CO_2eq by 2100 (70% growth compared to the 2010 level).

- According to the baseline projection, GHG emissions from the industrial sector will be (Fig. 1.13):
  - ✓ 19.4 Gt CO_2eq in 2035 (26% growth compared to the 2010 level);
  - ✓ 21 Gt CO_2eq in 2050 (36% growth compared to the 2010 level).
- Average annual growth rate will be 0.9% in 2010–2035, 0.6% in 2035–2050, and 0.4% in 2050–2100.

Figure 1.13 Industry GHG Emissions from Fuel Combustion and Industrial Processes, Including Indirect Emissions

Industry sector scenarios over the 21st century that lead to low (430–530 ppm CO_2eq), medium (530–650 ppm CO_2eq) and high (> 650 ppm CO_2eq) atmospheric CO_2eq concentrations in 2100. Median values are depicted with black dots. Shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full range (lightest). White dots depict IEA scenarios (only CO_2).

Source: IPCC (2015), EDGAR/IEA (baseline 2010 value).

The mankind should learn to make a product or supply a service using half of currently consumed physical material.

- GHG emission is to be reduced by 40–70% by 2050 to ensure sustainable development and minimize anthropogenic impacts on climate;
- Basic materials production is expected to double by 2050;
- This means, that specific emission per unit of material is to be cut by 70–85% by 2050;
- In the past, specific energy consumption per unit of material declined by 1–1.5% per year;
- If this rate persists, by 2050 energy intensity will be down only by 30–42% versus the required 70–85%;
- Therefore, if the anthropogenic impact on climate and GHG emissions from materials production are to be further reduced, it will be necessary to improve the efficiency of materials use or, which is the same, halve the materials intensity.

1.5 Long-Term Projections for Basic Materials Production

In some developed countries, steel in use stock saturation has been achieved at 14±2 t/person. On the contrary, aluminium and

- Unlike energy projections, materials demand projection methods and practices are relatively poor;
- Many of integrated global models that evaluate the impacts provided by anthropogenic emissions on the

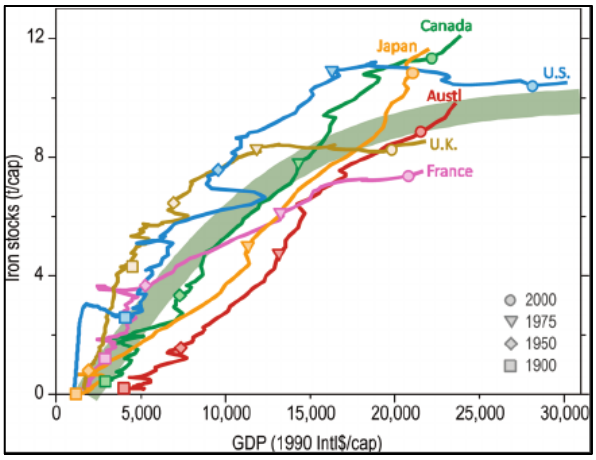
plastics saturation is not achieved so far anywhere in the world, and specific per capita "stock" use keeps growing along with per capita income (Fig. 1.14).

climate either do not use or do not provide basic materials production projections;

- A new projection instrument was developed in the recent years based on the material service concept and on the difference between accumulated in use stock materials and materials flow;
- This approach is only applicable to materials for which accumulated stock assessments are available and per capita saturation timeline and level are known;
- A high level of material saturation enables better recycling rates on the expiry of various facilities' lifetimes.

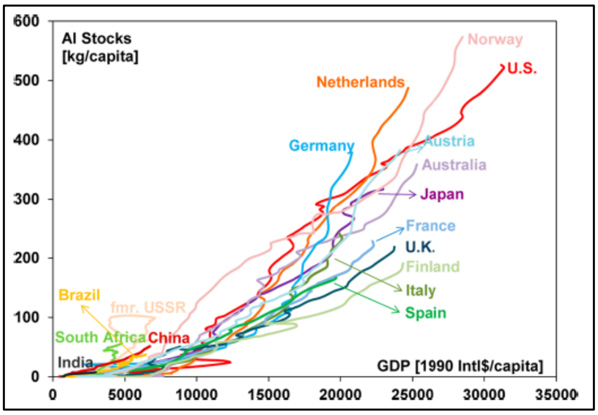
Figure 1.14 Dynamics of steel stocks (a) and aluminium stocks (b) in world countries (per capita)

a



(a) Per capita iron stocks in use versus per capita GDP PPP (1990 international dollars).

b



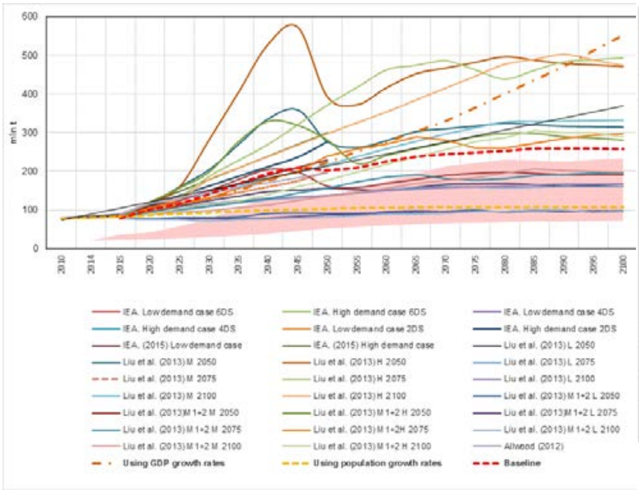
(b) Per-capita aluminium stocks in use relative to per capita GDP PPP for selected countries. The GDP data are measured based on 1990 purchasing power parity (PPP). The stock data are shown only until 2008 because of GDP data availability.

Sources: Liu and Muller (2013); Muller et al. (2011).

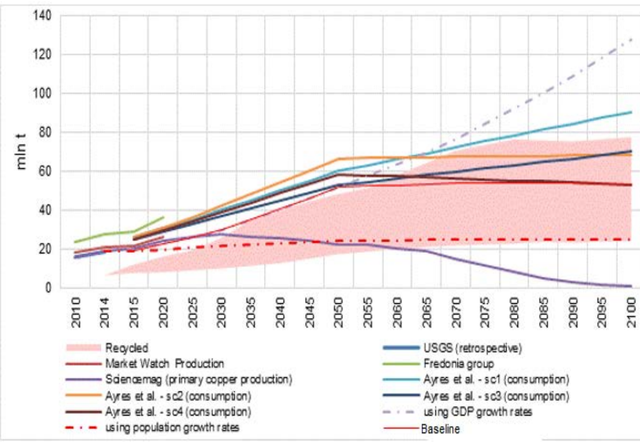
Production of many basic materials is expected to scale up 2 or 3-fold by 2050 and 2 or 5-fold by 2100

- Only 2035, 2050, and 2100 baseline projections that are in line with the most likely production dynamics were selected from the variety of forecasts (Fig. 1.15);
- For some materials (primarily, for the "Big Five") super-long-term projections are available, whereas for others they are scarce or missing;
- In such cases the authors developed their own projections using data on the evolution of specific per capita (or per unit of GDP) materials use, stock accumulation, resource deposits and other limitations, and anticipated evolution profile of similar materials.

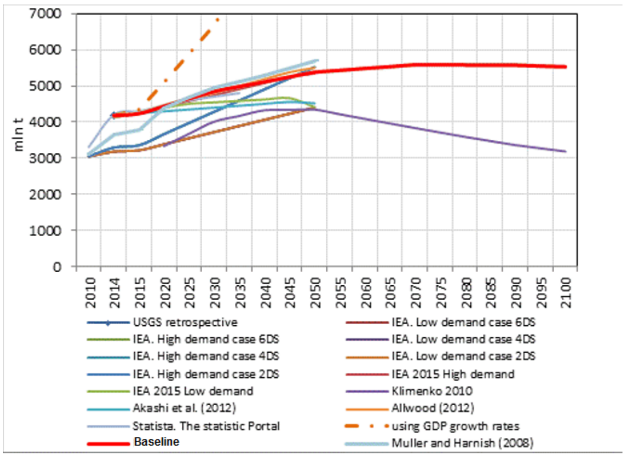
Figure 1.15 Evolution of selected basic materials production to 2100



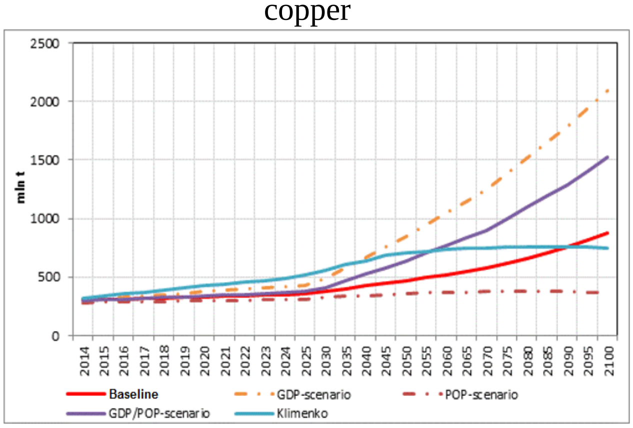
aluminium



copper



cement



plastics

1.6 The Impacts Provided by Carbon Nanotubes Augmentation of the Basic Materials on Basic Materials Demand

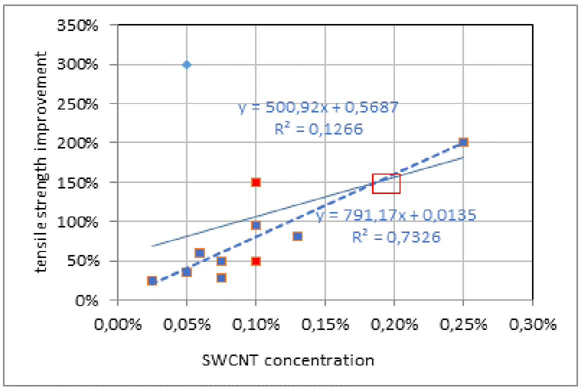
The low-carbon effect of SWCNT-augmentation can be expected only if such augmentation requires small concentrations of nanotubes (from points of percent to a few percent), with simultaneous substantial reduction in basic materials use per unit of function performed.

- This is possible, because SWCNT has a breath-taking strength to weight ratio: 462 times that for steel;
- Only small SWCNT concentrations are required to improve the performance of basic materials;
- High carbon intensity of SWCNT production sets limits to SWCNT augmentation of basic materials to ensure overall emissions reduction per unit of function;
- These limits are higher, the larger is the reduction in basic material consumption determined by SWCNT augmentation-induced performance improvement.

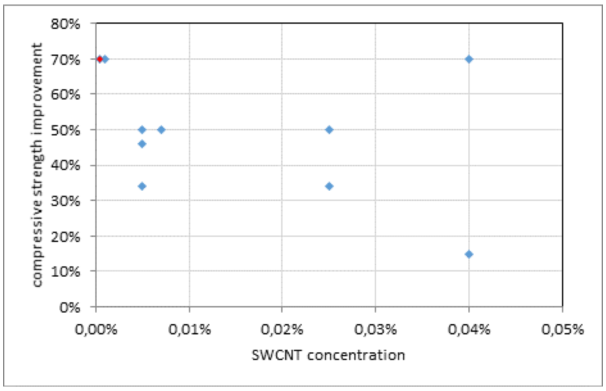
Information on the reduction of basic materials demand due to carbon nanotubes augmentation was obtained by OCSiAl company from a large variety of sources.

- Since expert evaluations substantially vary, they were explored to obtain concrete pointwise values that were further used in this study (Fig. 1.16);
- In each case, two key parameters were identified: SWCNT concentrations in a basic material and the reduction in the material demand due to improved performance (tensile strength, Young's modulus, etc.).

Figure 1.16 Impacts of SWCNT augmentation on aluminium and concrete performance



aluminium



concrete

Evaluation of net emissions reduction. $V_i = V_{swcnt} / d_i$ is volume of augmented material *i*, where V_{swcnt} is scale of SWCNT use, and d_i is SWCNT concentration in material *i*. k_i*V_i is replacement of traditional basic material, where k_i is order of improvement of basic material performance. Then reduction of demand for basic material *i* is $V_i*(k_i - 1)$. Total GHG emissions reduction (net of emissions associated with SWCNT production) is $em_i*V_i*(k_i-1) - V_i*d_i*em_{swcnt}$, where em_i and em_{swcnt} are embodied GHG emissions from basic material *i* and SWCNT production respectively. The replacement is effective, if $(k_i-1)/d_i>em_{swcnt}/em_i$. The limit to GHG emission reduction from basic material *i* production is approached, if the entire basic material *i* production volume, corrected for improved performance, is SWCNT-augmented and equals $em_i*V_{iprojection}*(1-1/k_i)$, where $V_{iprojection}$ is projected production volume of traditional basic material *i*.

No assessments of specific embodied emissions for carbon nanotubes (SWCNT) production are available in the literature. CENEf-XXI estimates them at 567 t CO_2eq/tonne of SWCNT. This estimate does not take into account energy consumption for the production of raw materials for SWCNT manufacture.

- According to OCSiAl company, energy use for the production of 1 kg carbon nanotubes (SWCNT) is 800 kWh. Other energy consumption is negligible;
- This is equivalent to 800 thousand kWh direct energy use, or 98.4 tce/t, and 426 t CO_2/tonne SWCNT direct CO_2 emission (based on the global average specific GHG emission per 1 kWh -- 533 gCO_2/kWh in 2012);
- In Russia, specific emissions from electricity generation were 429 gCO_2/kWh in 2012; therefore, Russian specific direct CO_2 emission is 343 t CO_2/tonne SWCNT.

1.7 Global GHG Emission Reduction Assessments to 2100 for Some Basic Materials Production

There is a large variety (menu) of methods to reduce GHG emissions from the key basic materials production. Seven key methods are:

- Reduced material intensity through improved strength and other performance along with light-weighting. This method includes SWCNT-augmentation;
- Reduced share of industrial waste at all stages of final product manufacture from the basic materials;
- Increased materials recycling rate;
- Increased share of additives (for example, to cement);
- Improved energy efficiency along the whole basic materials and final product supply chains;
- Reduced carbon intensity of fuel and electricity use through improved efficiency of generation equipment, reduced transmission/distribution losses, changes in the fuel mix towards less carbon-intense fuels and renewable energy sources;
- CCS technology application.

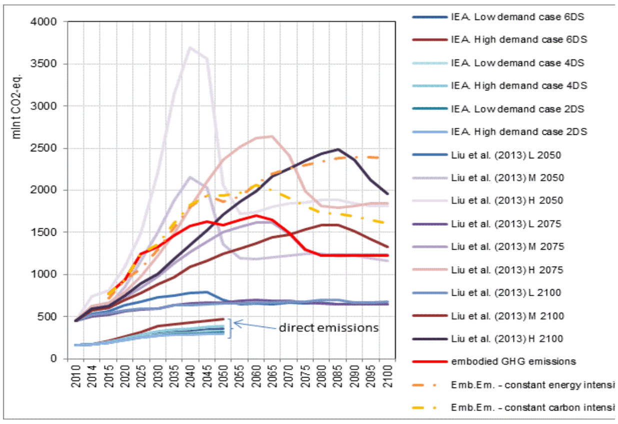
Combinations of potential contributions made by these seven methods differ for different materials

- However, none of the above methods taken separately can guarantee that the goal of reducing GHG emissions by 2050 by 40–70% of the 2010 level (IPCC, 2014) will be attained for any basic material;
- This ambitious target requires the use of all the above methods (to a certain extent).

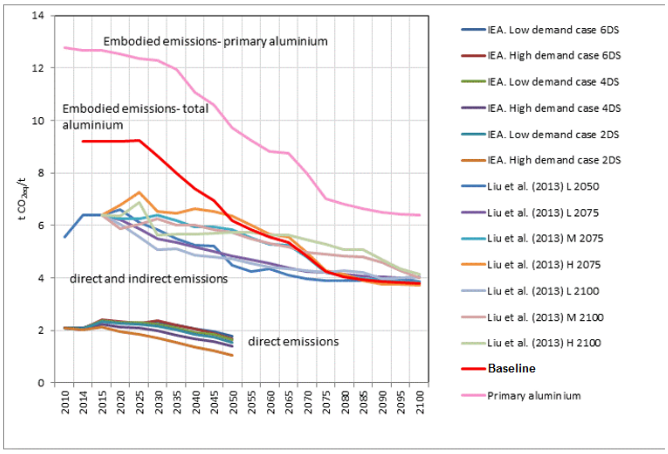
Evaluation of the contribution made by SWCNT augmentation-induced reduction of material intensity is based on the assumption that energy efficiency improvement, transition to low-carbon energy sources, and material intensity reduction go in parallel.

- Contributions from energy efficiency improvements and carbon intensity reduction were evaluated based on the parameters of baseline scenarios, i.e. assuming no additional policies aimed at the introduction of energy efficiency and low-carbon technologies will be deployed (Fig. 1.17);
- Moreover, additional GHG emission from SWCNT production is also evaluated to obtain net GHG emission reduction through SWCNT augmentation;
- Since at the initial stage SWCNT production is limited, SWCNT applications for various basic materials are to be prioritized using the GHG emission reduction efficiency coefficient for augmented materials (Fig. 1.18);
- In addition to the benefits obtained in the production of the basic materials there may be benefits related to the light-weighted products use.

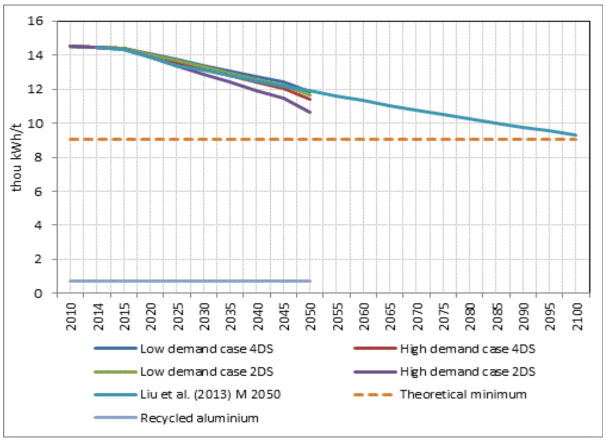
Figure 1.17 Evolution and Drivers of GHG Emissions from Aluminium Production



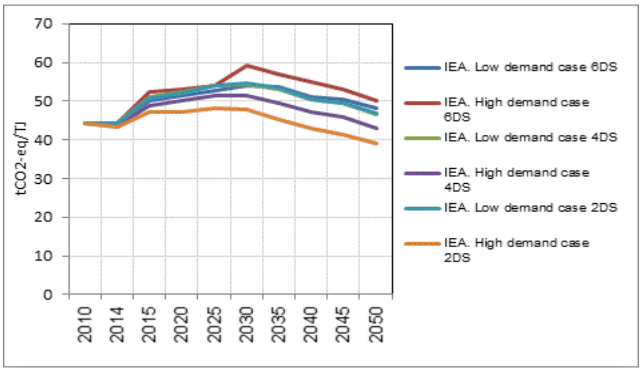
Evolution of GHG emissions from aluminium production



Evolution of specific GHG emissions from aluminium production



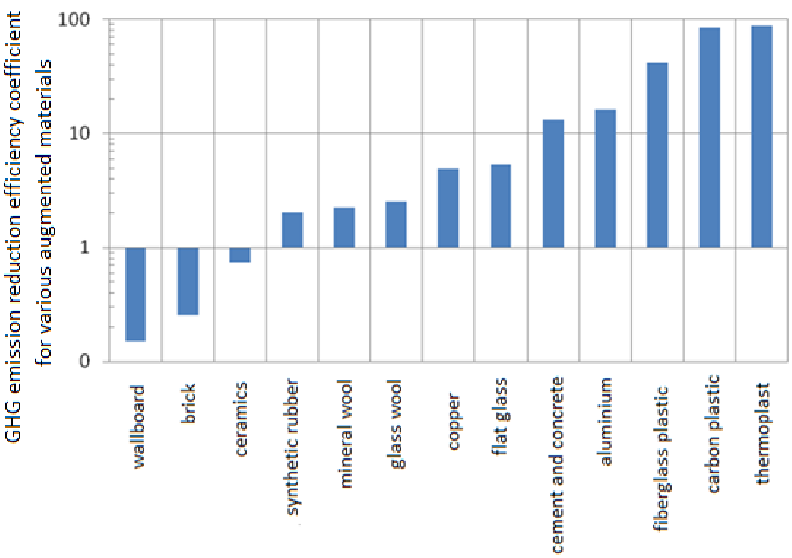
Evolution of specific energy consumption for aluminium production



Evolution of carbon intensity of energy used for aluminium production

Sources: IEA (2012); Liu et al. (2013).

Figure 1.18 GHG Emission Reduction Efficiency Coefficient for Various Augmented Materials

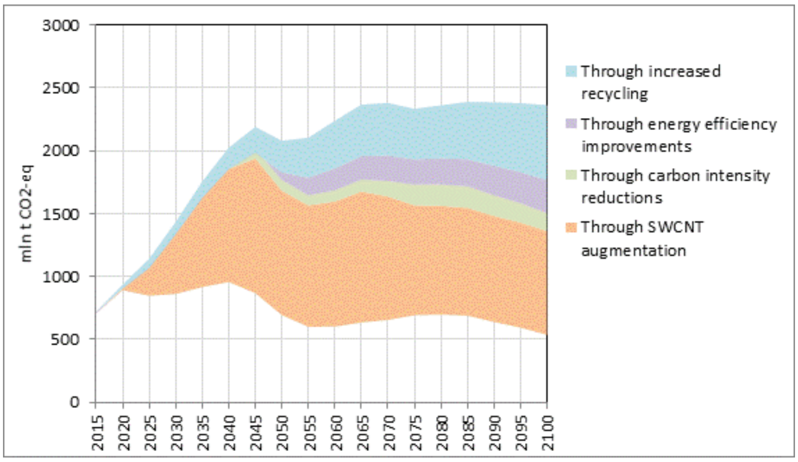


GHG emission reduction efficiency coefficient for various augmented materials equals $(k_i\text{-}1)/d_i * em_i/em_{swcnt}$, where d_i is SWCNT concentration in material i, k_i is the order of improvement of basic material i performance; em_i and em_{swcnt} are embodied GHG emissions from a basic material i and SWCNT production respectively.

Source: CENEf-XXI.

Aluminium

Contribution of SWCNT augmentation to GHG emission reduction is 781 mln t CO_2eq in 2050 and 840 mln t CO_2eq in 2100. It is more prominent, than the combined contributions of aluminium recycling rate growth, energy efficiency improvements, and reduced carbon intensity of energy use.

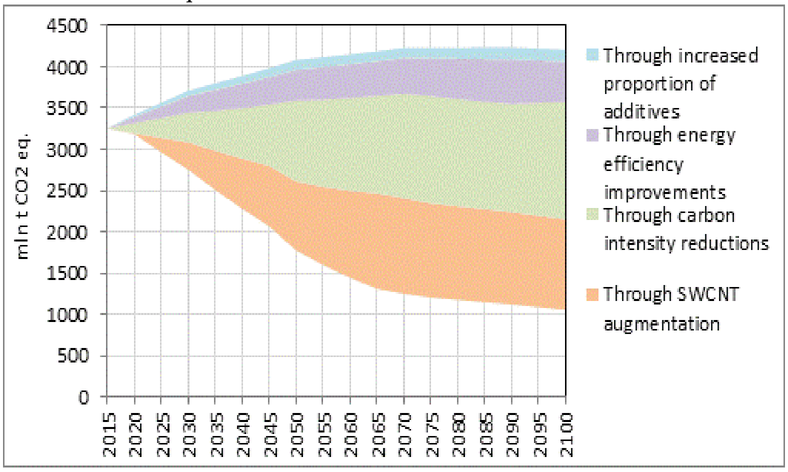


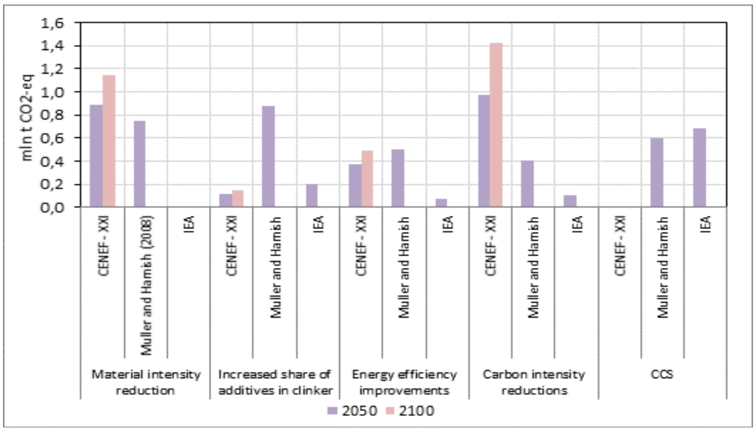
Net GHG emissions reduction equals 738 mln t CO_2eq in 2050 and 811 mln t CO_2eq in 2100.

Cement and concrete

Improved efficiency of cement use through better tensile strength determined by SWCNT augmentation allows for GHG reduction by 891 mln t CO_2eq in 2050 and by 1,143 mln t CO_2eq in 2100.

Emissions reduction potential that can be captured through SWCNT augmentation of concrete is comparable to the potential that can be captured through energy efficiency improvements and carbon capture and storage by 2050, and is larger, than the potential that can be captured through energy efficiency improvements beyond 2050.

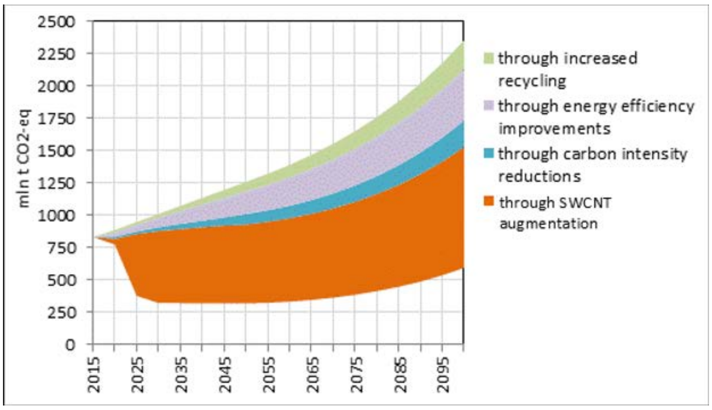




Plastics

Contribution of SWCNT augmentation of thermoplasts to GHG emissions reduction equals 610 million t CO_2eq in 2050 and 933 million t CO_2eq in 2100.

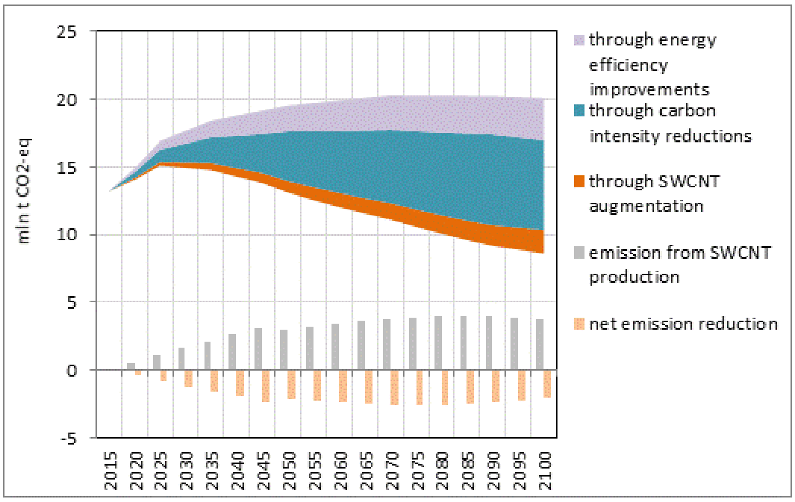
Net GHG emission reduction is 603 million t CO_2eq in 2050 and 926 million t CO_2eq in 2100.



Total **thermoplasts** production is assessed at 269 million tonnes in 2014, or 88.5% of the overall plastics production.

Brick

Embodied emission from the production of required SWCNT exceeds potential reduction of emissions determined by the use of augmented bricks making net emission flow negative.



The reason is low specific embodied energy value and insignificant (just 30%) reduction of demand resulting from SWCNT augmentation of brick (emission reduction efficiency coefficient is below unity, Fig. 1.18).

In addition, the effects were evaluated for:

- copper;
- sheet glass;
- ceramics;
- synthetic rubber;
- mineral wool;
- fibreglass wool;
- fiberglass;
- carbon fibre.

1.8 Global GHG Emission Reduction Assessments to 2100 through Vehicles Curb Weight Reduction

Average curb weight of a new USA car has doubled and exceeds 1,730 kg.

- A Ford-T car (Tin Lizzie) weighted only 850–880 kg;
- Just before the first oil shock, average new USA car doubled in weight and exceeded 1,700 kg;
- It then declined to 1,350 kg by 1980, driven by a substantial liquid fuel price escalation, and kept at that level until 1986;
- However, after liquid fuel became cheaper, it began growing again by approximately 1.2% per year back to

the 1975 level (1,730 kg) and stabilized thereafter;

- In other countries, cars curb weight is smaller, than in the USA, but the trends are similar.

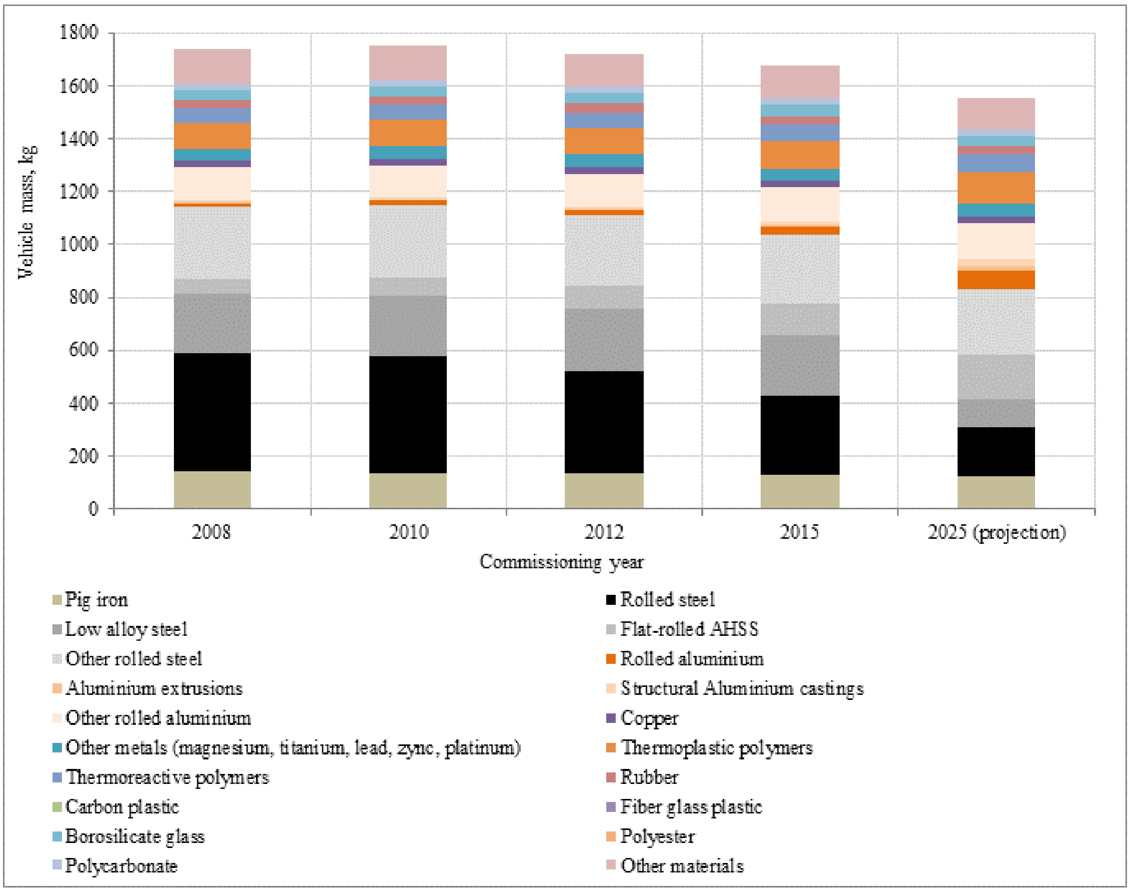
Since vehicle fuel efficiency is obviously not on the top of the consumer priorities list, it did not receive its due attention for a long time

- **The situation changed after emission per mile was regulated; in Europe, this is limited to 130 gCO_2/km for 2015 and 95 gCO_2/km for 2020;**
- It was not until the recent years that light-duty vehicles curb weight started to decline due to the increased share of light-weight materials use (Fig. 1.19); however, carbon intensity of their production has increased (Fig. 1.20);
- There are three possible strategies to reduce curb weight: use of light-weight materials; design modifications; and size reduction.

An aggregated global model for road vehicles (with specific blocks on light- and heavy-duty vehicles) was developed to enable assessments of the emission reduction potential to be captured through additional reduction of cars curb weight

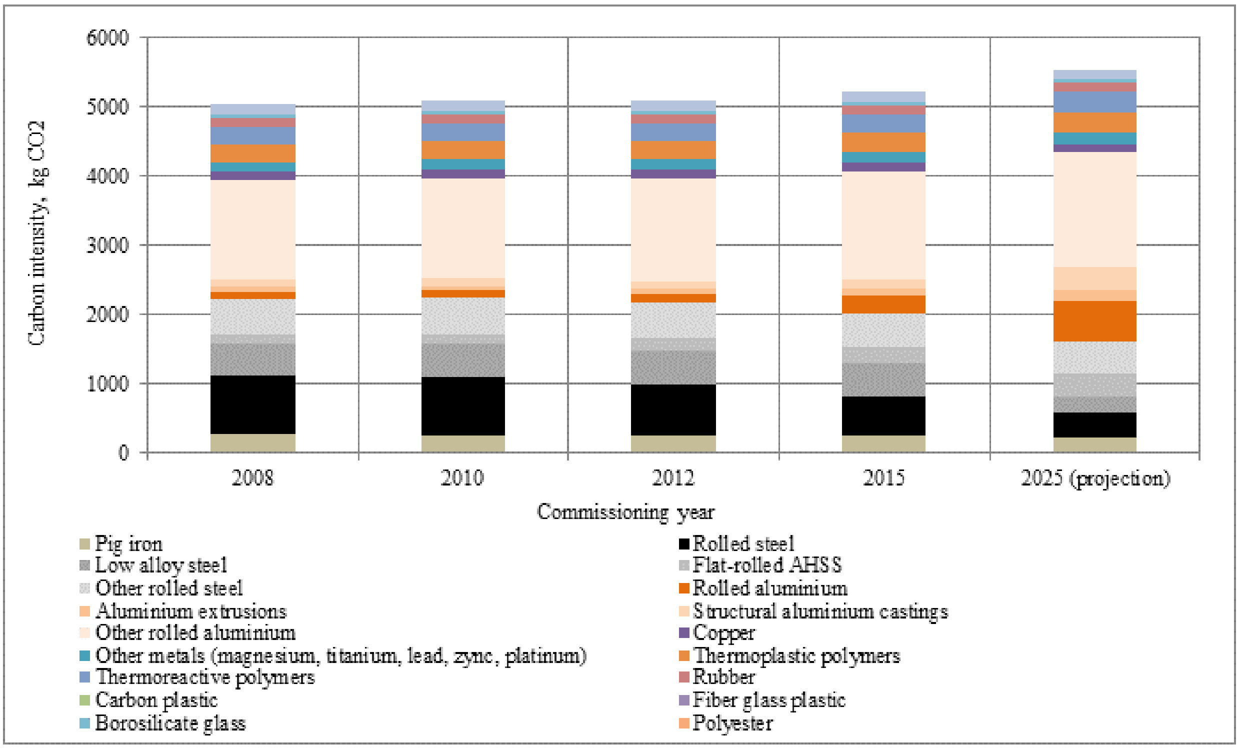
- The share of ferrous metals is anticipated to drop from the current 66% to 54% in 2025 and then further to 45% in 2050 and to 30% in 2100;
- This means that the contributions from aluminium, plastics, and composite materials will grow accordingly;
- If SWCNT augmentation of these materials (0.1% concentration) allows to nearly halve the specific materials demand, then reduction of cars curb weight can be substantially accelerated comparing to the baseline scenario;
- This is expected to help reduce average new car curb weight to 600 kg in 2100. Average car curb weight will ultimately reduce by 400 kg;
- Empirical relationships between road vehicle specific fuel consumption and its curb weight were used in the study (Fig. 1.21).

Figure 1.19 Materials Used in Production of New Light-Duty Vehicles for Sale in USA



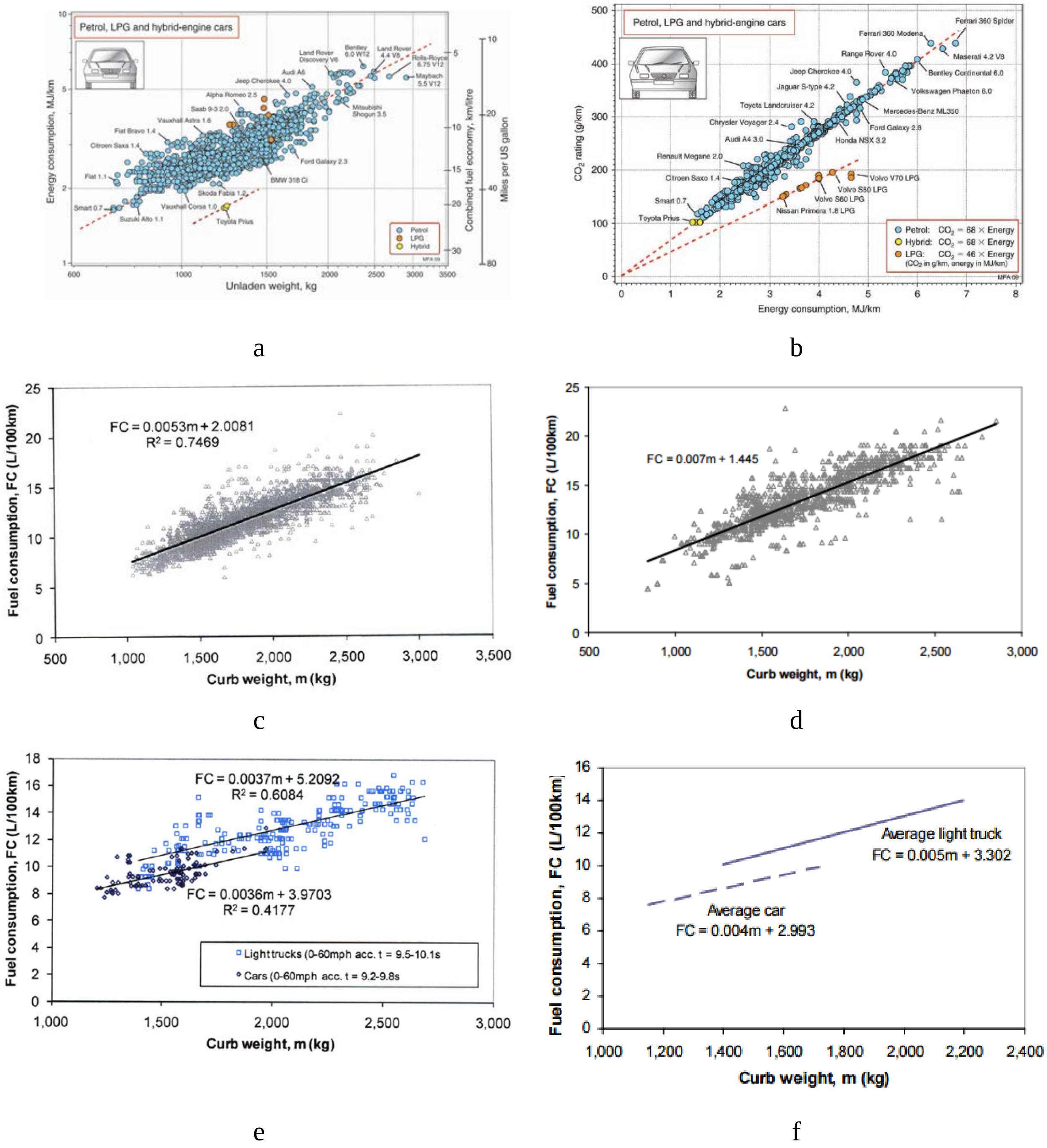
Source: Reisman L. Car Wars: Aluminum v. Steel, Episode Two. https://agmetalminer.com/2011/05/06/car-wars-aluminum-v-steel-episode-two/; https://agmetalminer.com/2011/09/19/aluminum-cars-all-time-high-alcoa-novelis-taking-the-bank-part-one/.

Figure 1.20 Carbon Intensity (Using Embodied Energy) of Production of New Light-Duty Vehicles for Sale in USA



Source: estimated by CENEf-XXI based on data in Fig. 1.7.

Figure 1.21 Specific Fuel Consumption to Curb Weight Ratio



Note: a—energy consumption by petrol, LPG and hybrid engine cars (Ashby, 2009); b—CO_2 emission by petrol, LPG and hybrid engine cars (Ashby, 2009); c—curb weight and fuel consumption of USA 2006–2008 vehicle (Cheah, 2010); d—curb weight and fuel consumption of USA model year 2005 vehicles (Bandivadekar et al. (2008); e—curb weight and fuel consumption of selected 2006–2008 USA gasoline cars and pickups (Cheah, 2010); f—simulation results: curb weight-fuel consumption relationship for today's vehicles (Bandivadekar et al., 2008).

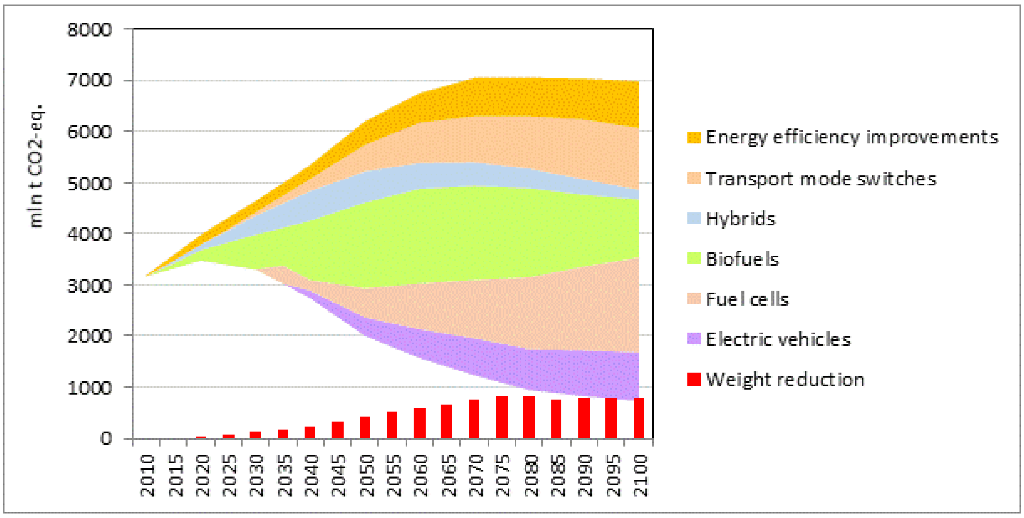
Reduction in road vehicles curb weight allows for fuel savings and related GHG emission reduction by 0.94 billion t CO_2 in 2050 and 2.35 billion t

- **Additional reduction in vehicle curb weight resulting from SWCNT augmentation of materials is equally important for the reduction of GHG emission from the transport sector, as vehicle fuel efficiency improvements through other technical solutions; transition to hybrid engine, electric, and fuel cell automobiles; increased share of biofuels; and transport mode switches (Fig. 1.22);**

CO_2 in 2100.

- Unlike some of the above competing technical solutions, GHG emission reduction through additional reduction in car curb weight resulting from SWCNT augmentation of materials does not require infrastructure development or changes in the driving habits;
- Production of SWCNT for the augmentation of basic materials that are applied in road vehicles will result in the emission increase by 76 million t CO_2 in 2050 and by 183 million t CO_2 in 2100;
- Net effect of vehicle light-weighting equals 0.86 billion t CO_2 in 2050 and 2.2 billion t CO_2 in 2100.

Figure 1.22 Contributions by Various Measures to Possible Reduction of Well-to-Wheel GHG Emissions from Light-Duty Vehicles



Sources: CENEf-XXI and GEA (2012).

Use of light-weight materials allows for substantial aircraft weight reduction and so for a significant decline in the fuel consumption by planes.

According to ICAO, further reduction in airplanes weight can result in 10–20% drop in fuel consumption by 2020 and 15–25% drop by 2030.

- Historically, fuel efficiency of aircrafts was not given its due attention, as speed and comfort were all that mattered. In terms of fuel consumption per 1 passenger-km, a typical modern airliner is no better than a piston passenger aircraft of the mid-50'es;
- In the latest models (Airbus A380, Airbus A350 XWB, Boeing 787, C-series Bombardier), cutting-edge composite materials and aluminium-lithium alloys are widely used allowing for improved fuel economy as compared to traditionally designed planes with large-scale application of aluminium alloys.

An aggregated global aviation model was developed to assess the potential effect of SWCNT augmentation

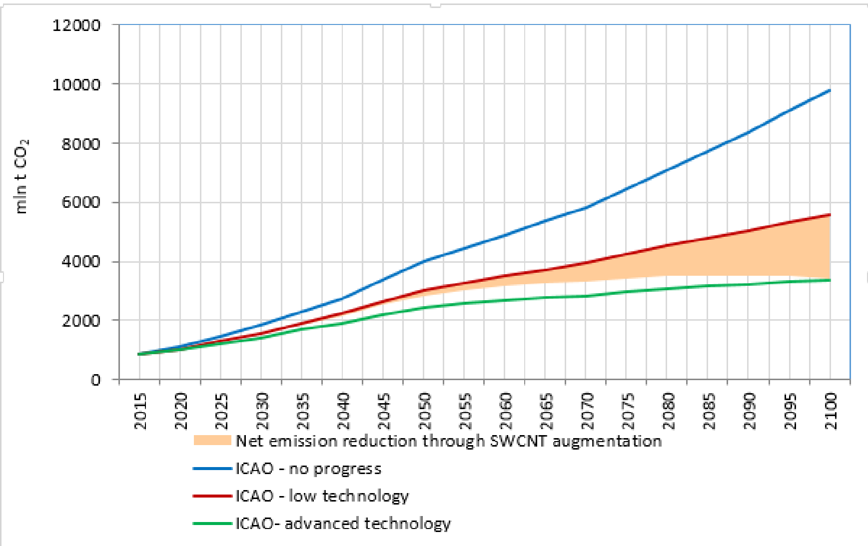
- According to ICAO, the aircraft fleet was 27,810 planes in 2013, including 3,008 cargo and mail aircrafts;
- Apart from these, business aviation (small airplanes) fleet amounts to 17,786 aircrafts; however, they are responsible for just 2% of total aviation fuel burn;
- 1,500–1,700 passenger and freight aircrafts and around 1,000 small aircrafts are manufactured annually;
- Total mass of annually manufactured aircrafts does not exceed 100 thousand tonnes;
- Aircraft transport service (net of business aviation) in the "most likely" ICAO scenario will increase from 974 billion paid t-km in 2015 to 2,832 billion t-km in 2040; 4,062 billion t-km in 2050; and 9,990 billion t-km in 2100;

- Passenger and freight aircraft fleet is growing at about the same rate as GDP, and per capita aircraft ratio will escalate nearly 5-fold by 2100;
- It was assumed, that SWCNT augmentation of materials that are used for the aircraft manufacture (0.1% of the total aircraft weight) will allow it to halve the materials demand;
- Fuel savings from the aircraft light-weighting were estimated based on the data for A319-321 class aircrafts and Boing-737 adjusted for average aircraft mass;
- 50% aircraft mass reduction by 2100 will reduce average fuel burn by 20%;
- Long-term perspectives for alternative fuel use in aviation are vague;
- The use of alternative fuels and technologies substantially enhances the requirements to aircraft mass reduction.

Cut in GHG emission due to air plane light-weighting resulting from SWCNT augmentation of materials (net of emissions from SWCNT production) is 43 million t CO_2 in 2035, 174 million t CO_2 in 2050 and 2136 million t CO_2 in 2100.

- If no progress is achieved in terms of specific fuel consumption decline, GHG emissions from the global aviation will escalate from 800 million t CO_2 in 2015 to 3,986 million t CO_2 in 2050 and to 9,807 million t CO_2 in 2100;
- None of the ICAO scenarios are successful in attaining the specified goal of emissions stabilization beyond 2020;
- **After 2050, additional reduction in aircrafts weight due to SWCNT augmentation is the same order driver behind the abatement of GHG emissions from the air transport, as airplanes fuel economy improvements through all other technical solutions combined (Fig.1.23);**
- Along with the other technical innovations, this will help block, and subsequently reverse, the growth in emissions from the air transport.

Figure 1.23 Evaluation of Contribution Made by SWCNT Augmentation of Materials to the Reduction in Global GHG Emissions from Aviation in 2015–2100



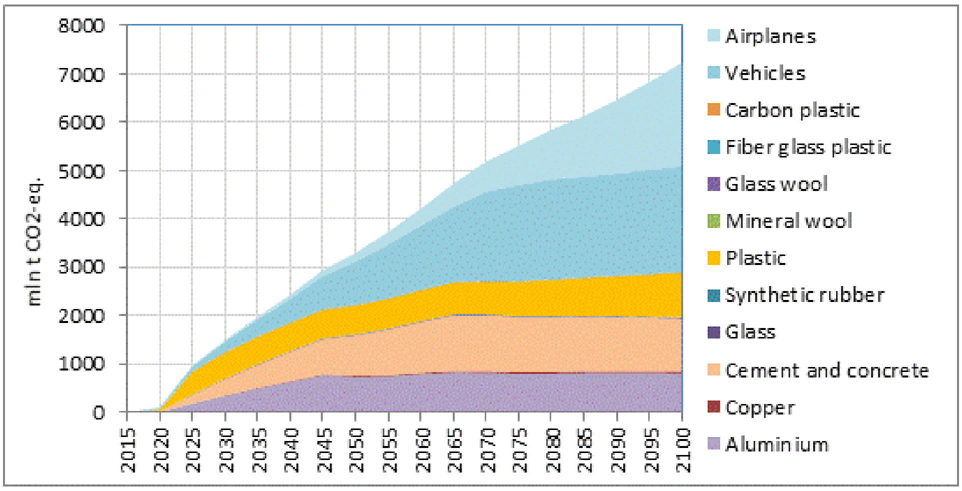
Source: CENEf-XXI.

1.9 Summary Estimates of the Potential to Reduce Global GHG Emissions by 2100 through SWCNT Augmentation of the Basic Materials

Total reduction in anthropogenic GHG emissions from the basic materials production resulting from reduced demand due to SWCNT augmentation, as well as from reduced vehicles and aircrafts weight, equals 1,970 million t CO_2eq in 2035; 3,300 million t CO_2eq in 2050; and 7,230 million t CO_2eq in 2100.

- The lion's share of the effect is generated by only 5 measures: SWCNT augmentation of concrete, plastics and aluminium, plus aircrafts and vehicles weight reduction (Fig. 1.24);
- While on the 2035 time horizon production of the basic materials is the major contributor, beyond that period the role of aircrafts and automobiles weight reduction enhances to a level where the relevant effect amounts to one third of the total effect by 2050 and to 60% thereof by 2100;
- In 2075–2100, the major effect increment is mostly generated by reduced aircraft weight;
- The above data are for the *emissions reduction net of GHG emissions from SWCNT production.*

Figure 1.24 Overall GHG Emissions Reduction through SWCNT Augmentation of the Basic Materials

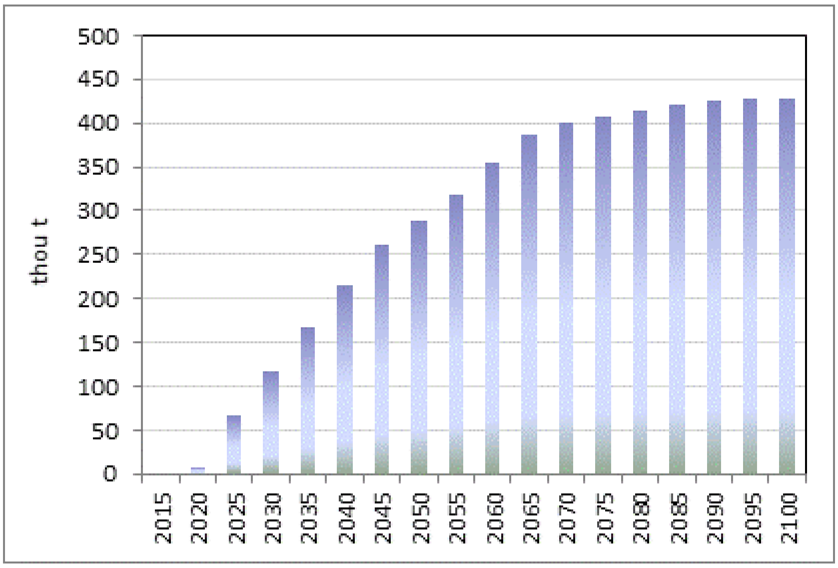


Source: CENEf-XXI.

Cumulative emissions reduction over 2015–2100 equals 331 billion t CO_2eq, which is 6 times overall 2014 anthropogenic emission and 8 times annual GHG emission from fuel combustion and industrial processes. In other words, SWCNT augmentation of the basic materials is equivalent to a 6 years' delay in the global warming.

- This will require scaling up SWCNT production and use to 167 thousand tonnes in 2035; to 289 thousand tonnes in 2050 and to 429 thousand tonnes in 2100 (Fig. 1.25);
- SWCNT production growth to 2050 requires increased investment and addressing a variety of technical and regulatory issues related to light-weighted materials use;
- For the sake of comparison: according to IEA, cumulative use of nuclear energy between 1971 and 2014 allowed for GHG emission reduction by 56 billion t CO_2eq, which is just slightly above 2014 total anthropogenic emission, or 70% above the annual emission from fuel combustion and industrial processes.

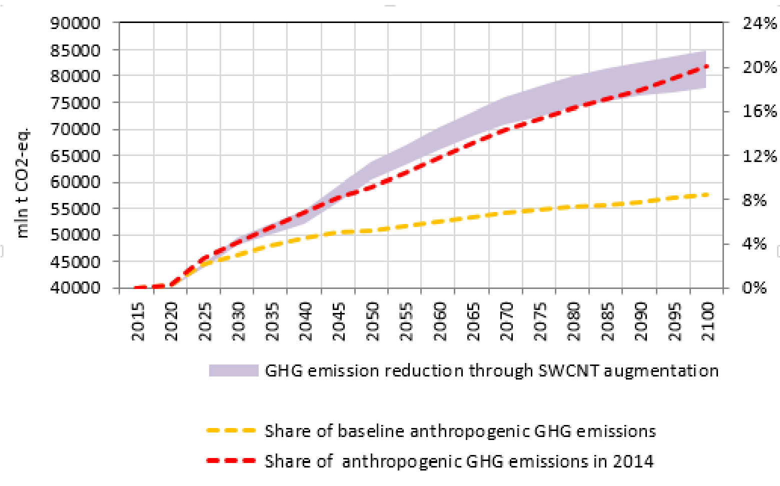
Figure 1.25 Overall SWCNT Demand for Augmentation of the Basic Materials



Source: CENEf-XXI.

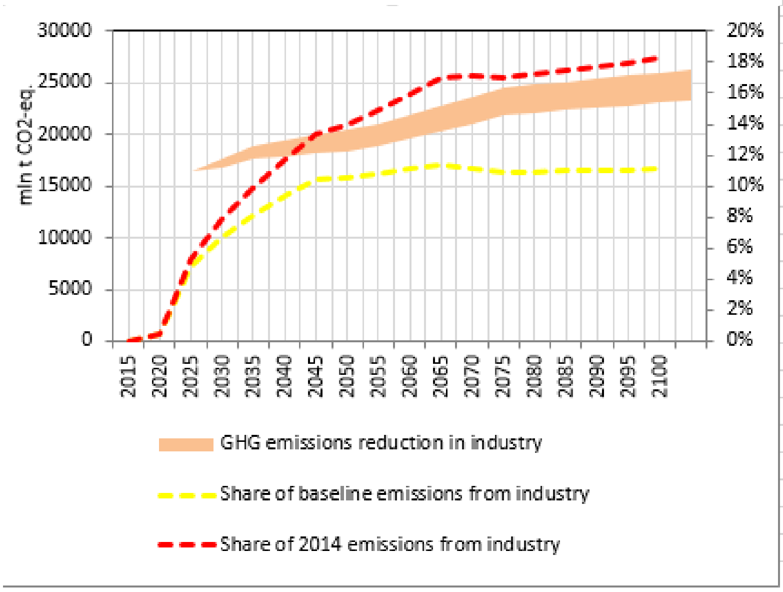
SWCNT augmentation allows it to reduce the anthropogenic GHG emission from fuel combustion and industrial processes by 3.8% in 2035, by nearly 5.2% in 2050, and by 8.1% in 2100 compared to the baseline.

Comparing to the 2014 level, the reduction is 5% in 2035, 7.9% in 2050, and 16.1% in 2100 respectively.

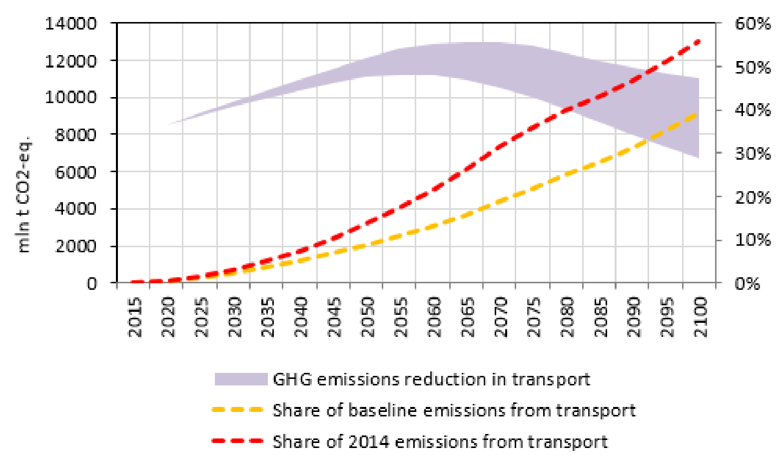


The use of SWCNT allows it to reduce GHG emissions from the industrial sector by 2,233 million t CO_2eq in 2050 and by 2,909 million t CO_2eq in 2100 (or by 10.6% in 2050 and by 11.1% in 2100) of the baseline.

Reduction in direct and indirect GHG emissions from the industrial sector in 2014 equals 14% in 2050 and 18.2% in 2100 respectively.



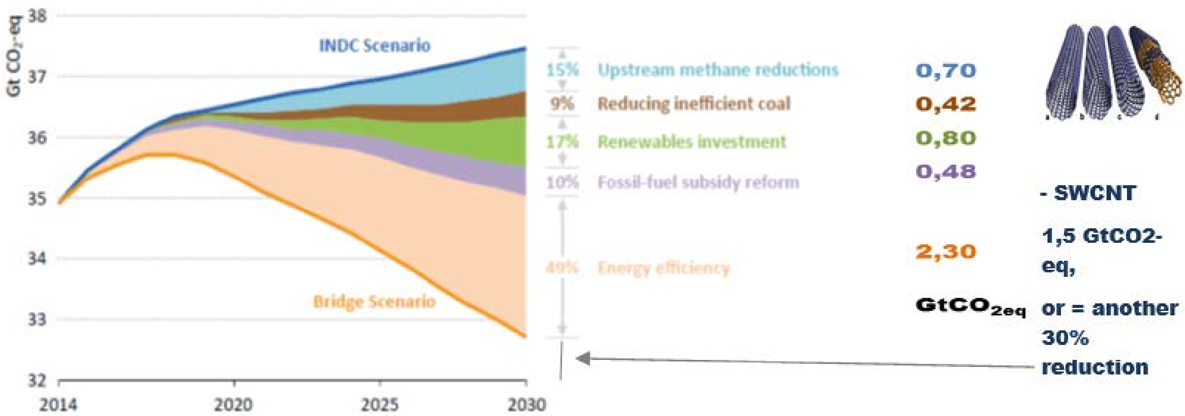
The use of SWCNT-augmented light-weighted road vehicles and aircrafts allows for the abatement of GHG emissions from transport by 1,065 million t CO_2eq in 2050 and by 4,323 million t CO_2eq in 2100, or by 9% in 2050 and by 39% in 2100, of the baseline (by 14% and 56% of 2014 emission from transport).



Contribution of nanotubes augmentation of the basic materials to the emission abatement is comparable with the contributions made by other technologies and measures as early as in 2030.

- Emissions reduction in 2030 due to SWCNT augmentation equals 1,490 million t CO_2eq, or 32% of the difference between two IEA scenarios: Intended Nationally Determined Contributions Scenario and Bridge Scenario, or 22% of the difference between the Bridge Scenario and 450 scenario (Fig. 1.26);
- The effect of SWCNT augmentation exceeds the following effects:
  - o of reduced coal use through the retirement of inefficient power plants;
  - o of energy subsidies system reform suggested by IEA;
  - o of accelerated alternative energy development;
  - o of methane leakage reduction.

Figure 1.26 Contribution of Selected Measures and Technologies to GHG Emission Reduction in the IEA Bridge Scenario versus the INDC Scenario, and SWCNT Augmentation Effect



Source: CENEf-XXI; IEA (2015a).

Investment in SWCNT production that can provide more substantial GHG emission reduction in 2030, than investment in renewable and nuclear energy and CCS (which are currently viewed as basic technologies to ensure GHG emission abatement and climate

- Capacity building to produce 118 thousand tonnes of SWCNT per year in 2030 will cost US$23.6 billion, production increase to 289 thousand tonnes per year will require additional US$34.2 billion, or US$57.8 billion total;
- IPCC estimates the 2010–2030 additional average annual investment in accelerated GHG emission reduction (versus baseline) scenarios at US$147 billion for low-carbon electricity generation technologies (renewable

stabilization), are 64 times smaller on the 2015–2030 time horizon, and 205 times smaller on the 2031–2050 time horizon.

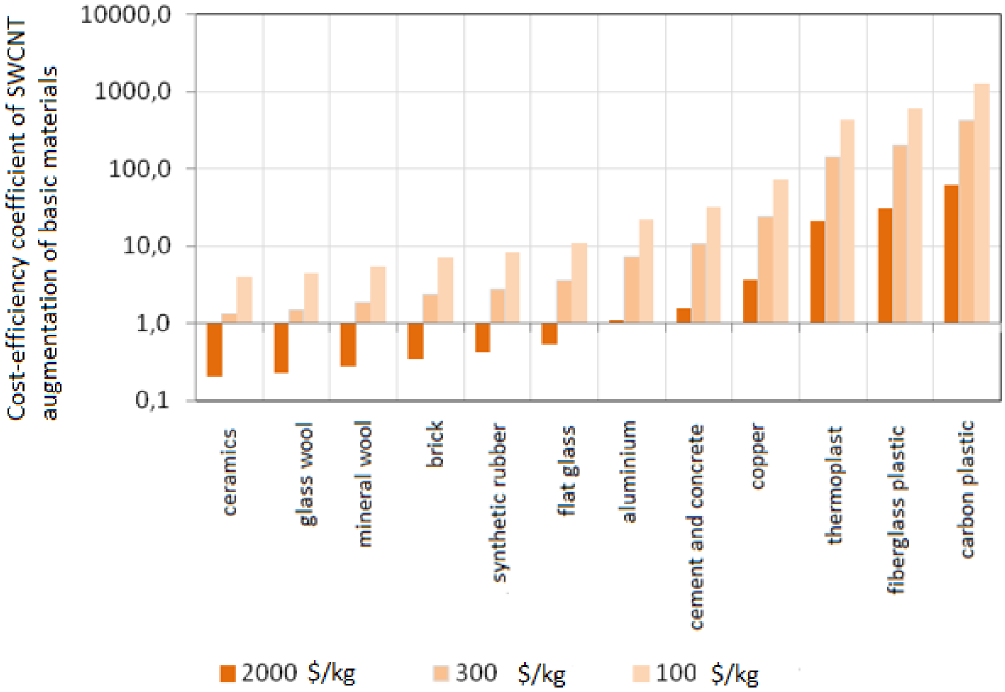
and nuclear energy and CCS) and at US$336 billion for energy efficiency improvements;

- For 2030–2049, additional average annual capital investment grows up to US$227 billion for renewable energy, to US$247 billion for CCS, and to US$680 billion for energy efficiency;
- Total capital investment in the development of low-carbon electricity generation (renewable and nuclear energy and CCS) over 2015–2029 can be assessed at US$2,205 billion (US$147 billion*15 years), and over 2030–2049 at US$11,880 billion (US$594 billion*20 years).

As the production scale and technology improve, the price for SWCNT substantially declines, and SWCNT becomes cost-effective for many of the basic materials.

- At the initial stage, when the price for SWCNT is US$2,000 per kg, SWCNT augmentation is not cost-effective for many materials (Fig. 1.27);
- For the materials that are the largest contributors to the emissions reduction (i.e. plastics, aluminium, and concrete), the cost-effectiveness coefficient of augmentation is above unity even with the US$2,000 per kg price;
- Overall revenues from SWCNT sales will amount to US$35.4 billion in 2030 (118 thousand tonnes).

Figure 1.27 Cost-Efficiency Coefficient of SWCNT Augmentation of the Basic Materials



Source: CENEf-XXI.

GHG emissions reduction through SWCNT augmentation of the basic materials and light-weighting of road vehicles and aircrafts was estimated based on a variety of assumptions, and so

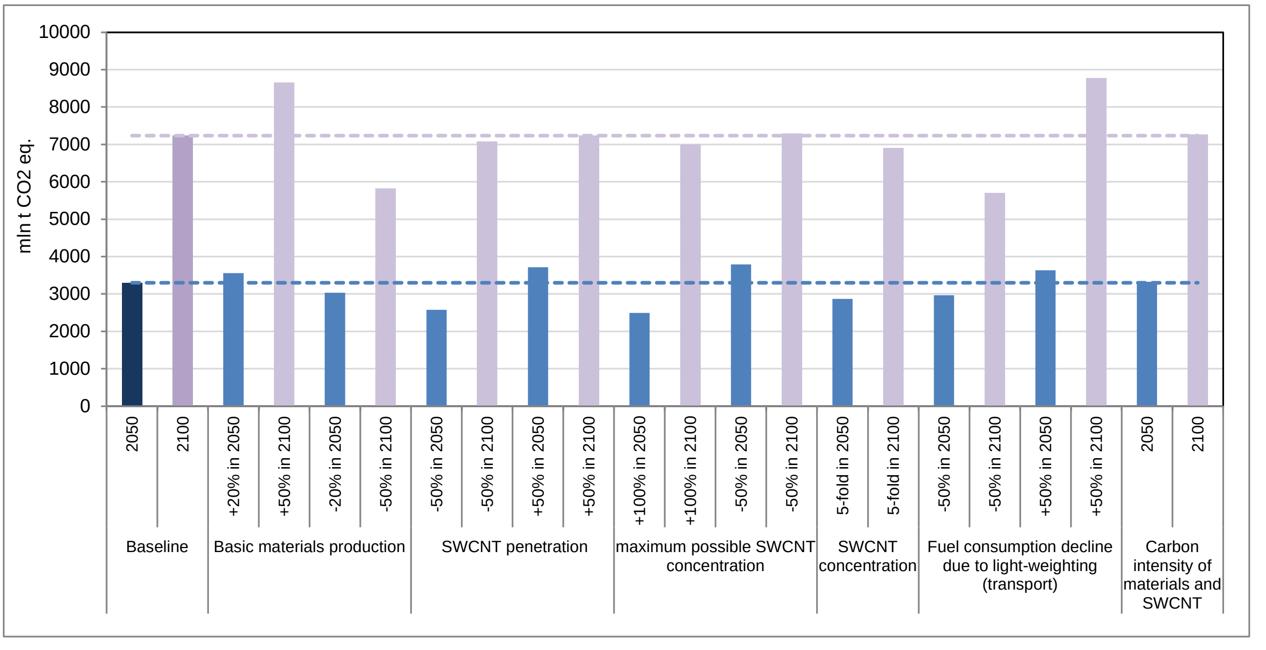
- Key basic materials production scale;
- Possibility to use SWCNT for the augmentation of the entire volume of the basic materials;
- Market niche expansion rate for the SWCNT augmentation technology;
- The ratio of SWCNT concentration and improvement in

the estimates are sensible to factors such as:

basic material strength or other properties that allow for demand reduction;

- SWCNT augmentation-induced reduction in vehicles and aircrafts weight;
- Specific fuel use decline due to reduced vehicle or aircraft weight;
- Embodied GHG emissions from the basic materials and, above all, SWCNT production scale.

Figure 1.28 Sensitivity Analysis of global GHG Emission Reduction Through SWCNT Augmentation and Vehicle and Aircraft Weight Reduction



Source: CENEf-XXI.

With any reasonable assumptions related to SWCNT augmentation of the basic materials, the GHG emission abatement effect of reduced materials demand and light-weighted road vehicles and aircrafts keeps substantial (Fig. 1.28).

- Even if increase in SWCNT production and the relevant effect is half of the anticipated level, it will still be equal to, or exceed, the combined effect of methane emissions reduction measures, retirement of inefficient coal plants, and elimination of energy subsidies;
- Even with a 5-fold increase in SWCNT concentration from the level assumed to guarantee the required performance improvement (providing there are no restrictions regarding SWCNT production scale) GHG emission reduction diminishes by no more than 28% in 2050 and 4% in 2100;
- The reduction in material intensity of global GDP and end-use products light-weighting, including through SWCNT augmentation of the basic materials, is to be regarded as:
  - a new, important, ambitious, and potentially highly effective policy to attain the goal of limiting global warming to no more than 2 °C; and
  - an important additional pier for the Bridge Scenario to ensure transition to sustainable low-carbon development.

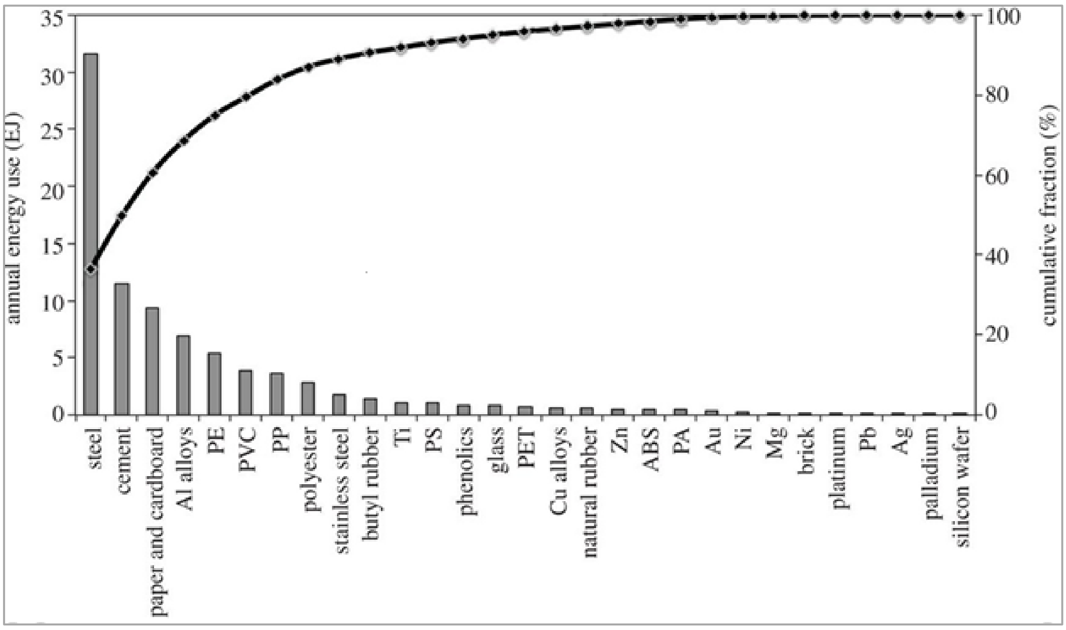
2 Role of Basic Materials in Development of Global Economy

2.1 List of Basic Materials

Mankind has used and produced hundreds of various materials. Thus, USGS provides information on 83 minerals. The annual production of 32 materials out of those exceeded 5 Mt. The USGS list does not include fossil energy resources, refined products, chemical and petrochemical products, agricultural products, woodwork, pulp and paper products.

A limited list of basic materials accounts for the vast majority of energy consumption and GHG emissions in production and consumption processes (Fig. 2.1). The bulk volume of energy consumption is actually accounted for by five groups of materials (the "Big Five"): steel, cement, paper (and cardboard), aluminium, and plastics (as an aggregate group). They account for almost 90% of all energy consumption for production of basic materials (Gutowski et al., 2013).

Figure2.1 Annual Primary Energy used for the Production of 29 Materials Worldwide



Note: PE—polyethylene; PVC—polyvinylchloride; PP—polypropylene; PS—polystyrene; PET—polyethylene terephthalate; ABS—acrylonitrile butadiene styrene; PA—polyamides.

Source: Gutowski T.G., Sahni S., Allwood J.M., Ashby M.F., Worrell E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. PhilTrans R Soc A 371: 20120003.http://dx.doi.org/10.1098/rsta.2012.0003

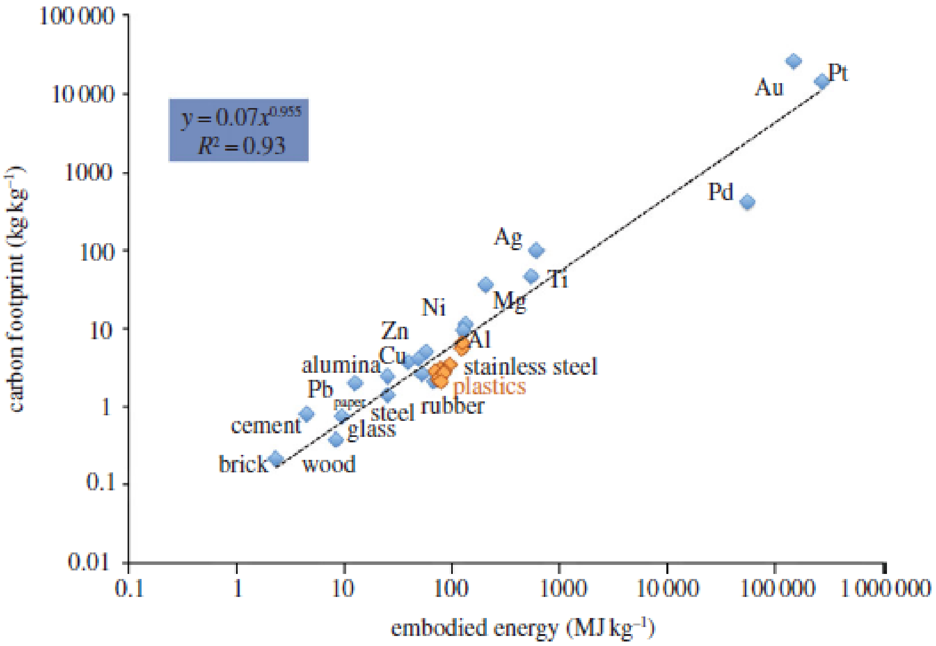
GHG emissions from production of basic materials occur:

- in the course of direct fuel combustion at the stages of mining, crushing and dressing of ore, during smelting or reduction, high-temperature chemical reactions, processing and reshaping of materials produced (direct emissions);
- in the energy sector that provides the above mentioned processes with electric energy and heat, as well as fuel (indirect emissions); and
- through CO_2 generation in recovery processes with carbon being used as a chemical agent (industrial emissions according to the IPCC terminology).

The ratio of the first two and the latter of emission components may range from 1:1 for cement to 1:10 for aluminium smelting (through anode consumption). However, the first and the second component generally prevail.

Specific GHG emission (carbon footprint) strongly correlates with specific value of embodied (materialised) energy (Fig. 2.2). The latter indicator is the energy required to produce material out of fresh raw stock, including all process stages. In terms of embodied energy, carbon footprint elasticity coefficient is nearly 1, and the main part of basic materials practically falls on a straight line. This means that the production of a limited range of basic materials, primarily the "Big Five," also accounts for the main part of GHG emissions.

Figure 2.2 The Carbon Emission in Kilograms of CO2 per Kilogram of Material Produced versus the Embodied Primary Energy

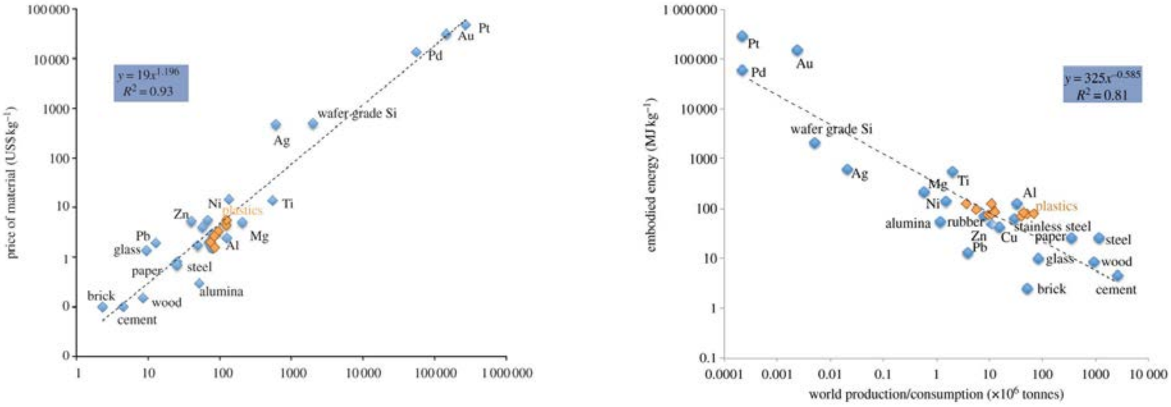


Source: Gutowski T.G., Sahni S., Allwood J.M., Ashby M.F., Worrell E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. PhilTrans R Soc A 371: 20120003.http://dx.doi.org/10.1098/rsta.2012.0003

To ensure sustainable development and minimise anthropogenic effects on climate, it is necessary to reduce GHG emissions by half by 2050. Production of basic materials is expected to double by 2050. This means that specific emission per unit of material should be reduced by 75% by 2050. Analysis shows that specific energy consumption per unit of material used to decrease by 1–1.5% every year (Gutowski et al., 2013). If these rates are maintained, energy intensity will be reduced only by 30–42% instead of 75% by 2050. However, as energy consumption for production of basic materials approaches the thermodynamic minimum, this reduction may slow down. In case of transition to BAT, potential reduction of energy intensity may reach 18–20% throughout the world (Gutowski et al., 2013; IPCC, 2014). Under overoptimistic assumptions, specific energy consumption can be reduced by 56% through improvement of BAT proper by 2050 for primary production of materials, through reuse of such materials to the maximum extent, as well as through reduction of specific energy consumption during their reuse.

It is not clear whether the problem can be solved through substitution of more energy-intensive materials for less energy-intensive ones, because a reverse process often takes place allowing for significant reduction of energy consumption at the operational stage through the use of more energy-intensive materials (Gutowski et al., 2013). For example, a motor car with its weight reduced from 2 tonnes to 1 tonne through the use of energy-intensive aluminium and plastics consumes half as much fuel per unit of distance run. Given that prices for materials directly depend on specific embodied (materialised) energy (Fig. 2.3a), cost optimisation means that the main business solutions already took into account the optimum combination of prices, energy intensity, and properties of new materials in the process of their substitution. The efforts to reduce specific energy consumption were focused on materials with maximum production outputs and made it possible to reduce the price.

Figure 2.3 Price of Various Materials Plotted against the Embodied Energy of the Materials (a) and Energy Intensity versus World Production for Various Materials (b)



a b

Source: Gutowski T.G., Sahni S., Allwood J.M., Ashby M.F., Worrell E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. PhilTrans R Soc A 371: 20120003.http://dx.doi.org/10.1098/rsta.2012.0003

Thus, ***for further reduction of anthropogenic effects on climate and for reduction of GHG emissions from production of materials, it is necessary to improve efficiency of use of materials proper or, which is the same, to reduce material intensity by half*** (Gutowski et al., 2013). Liu et al. came to the conclusion that reduction of emissions from aluminium smelting by 50% could not be achieved by 2050 unless saturation of aluminium accumulated in products and structures was reached[2] (2013).

Mankind should learn to make use of materials exploiting half as much of the physical volume of such materials. The search for such solutions has just begun. Possible focus areas include: design solutions that provide for lightweighting; reduction of waste in process flows; use of industrial waste to produce other products; product life extension; more intensive use of materials (Allwood et al., 2013). However, implementation of these opportunities reduces the possibility of using other opportunities. For example, lightweighting reduces the possibility of materials recycling, waste reduction and product life extension reduce the possibility of scrap usage; in addition, product life extension delays implementation of new technologies. One of the possible innovative solutions for enhancing the efficiency of materials use which has not been considered yet is modifying materials' properties with the use of CNT.

The range of basic materials considered in this paper is limited to: (a) materials the annual output of which exceeds 5 Mt; (b) materials making the main contribution to energy consumption and GHG emissions generation; and (c) materials demand for which has changed due to changes in their properties as a result of their modification with CNT.

The final list of materials to be studied includes:

[2] Liu G., C.E. Bangs and D.B. Müller. 2013. Stock dynamics and emission pathways of the global aluminium cycle. NATURE CLIMATE CHANGE. VOL. 3. APRIL 2013.

- Primary aluminium
- Processed aluminium
- Primary copper
- Processed copper
- Synthetic rubber
- Timber
- Wood-based panels, including:
  - plywood
  - chipboard
  - wood-based panels
  - MDF
  - veneer
- Plastics, including:
  - Thermoplasts, including:
    - polyethylene
    - polypropylene
    - polycarbonate
    - polyamide
    - ABS resins
  - Thermosetting plastics, including:
    - epoxy resins
    - polyester resins
    - polyurethane
    - carbon fibre
    - glass fibre
- Cement
- Concrete
- Clay
- Ceramics
- Construction composites
  - including glass-reinforced plastics
- Insulation materials
- Mineral wool
- Fibreglass wool
- Steel

Annual production outputs of three items out of this list (epoxy resins, carbon fibre, and polycarbonate) are below 5 Mt.

2.2 Long-Term Trends

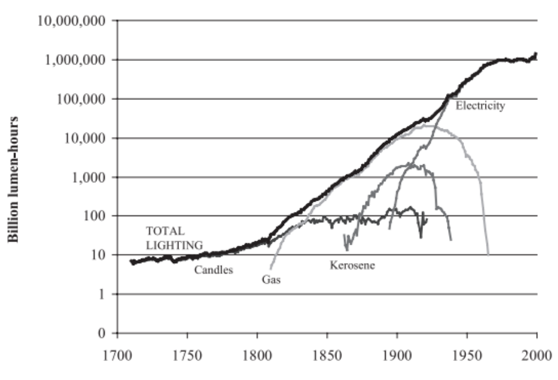
Development of human society requires constant consumption of materials and energy for life necessities, production of new material wealth elements and replacement of previously accumulated ones. Many specialists (Baccini and Brunner, 1991; Fisher-Kowalsky and Nunter, 1998; Ayres and Simonis, 1994; Krausmann et al., 2011) introduced and developed the concept of social and industrial metabolism by analogy with human body. Such metabolism involves processes of development support and economic growth maintenance through the use of extracted natural products, such as biological resources, mineral materials, and energy resources. All these materials undergo the processes of extraction, processing, transportation, and consumption. These processes generate useful products, as well as wastes and emissions. Despite the fairly long life cycle of certain materials embodied in products (centuries and even thousands years in case of ancient pyramids), all of them eventually turn into wastes or emissions. The higher the share of materials reuse (recycling), the slower this transformation. Eventually, social and industrial metabolism (substance exchange between human society and nature for development of the former) exerts such a great pressure on human environment and aggravates the wide range of environmental problems so much that it becomes unstable. Therefore, apart from being an apt metaphor, social metabolism serves as an analytical concept of sustained growth theory (Krausmann et al., 2011).

It is important to distinguish between materials flow (annual production and use of materials) and materials stock(accumulated amount of materials contained in durable products and performing various functions to meet the public needs). Like waste, the stock is a source of reuse of materials when their service life expires. The statistics do not give any estimates of the accumulated stock of materials. Analysts obtain such estimates when developing models of material needs forecasting (Pauliuk et al., 2015; Liu et al., 2013).

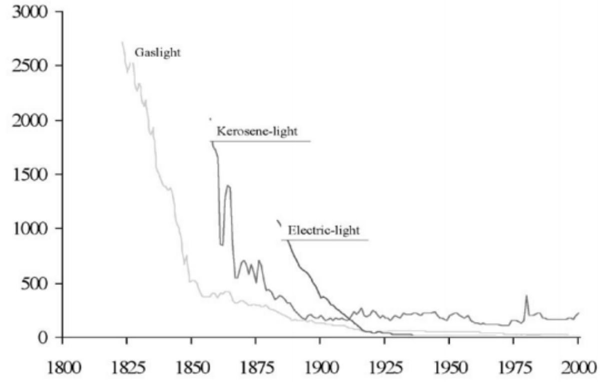
Materials flow is the governing factor for energy resources, because they (unless the stock changes) are used (fuel is combusted) within a limited period after production. As for materials, it is the stock rather than the flow that supports end services for economic agents: strength of load bearing structures or roadway, hardness, elasticity, shock resistance, fire resistance, plasticity, transparency, electrical or heat conductivity, heat expansion, frost resistance, hygroscopicity, sound insulation, etc. The recent 100 years are marked with transition from “flow materials”—such as biomass, the main part of which was consumed the year it was produced, to “stock materials” that can perform their functions for many years (Krausmann et al., 2009).

Technical progress makes it possible to obtain more services per unit of material used through improvement of material properties, as well as through replacement of certain materials with other materials. For example, use of artificial lighting in Great Britain increased 256 thousand times in 1700–2000. Moreover, efficiency of use of the relevant energy resources (the structure of which had undergone fundamental changes several times) increased almost 1,000 times, while the price per unit of lighting energy decreased 8 times, and per unit of light—7,676 times (Fig. 2.4). In other words, consumption of artificial lighting services grew almost 1,000 times faster than consumption of energy resources utilised to produce such artificial lighting. Introduction of contemporary materials is aimed at supporting demand for services from materials while minimising the physical volume of their use and volume of natural raw stock extraction for their production.

Figure 2.4 History of Light in United Kingdom



Consumption of Lighting from Candles, Gas, Kerosene and Electricity in the United Kingdom (in billion lumen-hours), 1700–2000



Price of Lighting from Gas, Kerosene and Electricity in the United Kingdom (per million lumen-hours), 1800–2000

Source: R. Fouquet and P.J.G. Pearson. Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300–2000). The Energy Journal, Vol. 27, No. 1. 2006.

There are various models of social and industrial metabolism that depend on availability of stocks of mineral resources in different countries and on prices for such resources. Two polar examples are the USA and Japan (Krausmann et al., 2011). Japan demonstrates capabilities of absolute dematerialisation of its economy—economic growth accompanied by reduced consumption of materials. Many OECD member countries have also demonstrated similar model with regard to consumption of primary energy and mineral materials during 10–15 years. Their GDP grows (though relatively slowly) along with stabilisation of energy and materials consumption and reduction in organic fuel consumption. They have come to the level of saturation with ferrous metals accumulated in buildings, plant, and equipment (stock)—11 to 16 tonnes per person; they do not need any further expansion of their use and increasingly rely on scrap using in production (Pauliuk et al., 2013; Pauliuk et al., 2015). As for other materials, such as aluminium, even developed countries have not reached saturation yet (Liu et al., 2013). Developing countries, including China and India, are far from the stage of economy dematerialisation. Since their role in the global economy is growing, the latter starts to develop under the growing pressure on natural systems caused by the growing use of biological and mineral materials.

To better understand the prospects of basic materials consumption growth for development of the global economy until 2050 and until 2100, it is important to determine the process of metabolism evolution over the recent one and a half century. Long-term trends (from 1870 on) were estimated for the world as a whole on the basis of materials from Krausmann et al. (2011) for industrial socio-metabolitic mode, as well as on the basis of other materials.[3] Changes for the period from 1980 on are shown in detail in Sections 2.3 and 2.4.

Development of human society is accompanied by changes in the scale and structure of materials used—metabolism evolution—with gradual replacement of biomaterials for mineral materials and fossil fuel along with enhancement of their use efficiency, but with absolute growth in their consumption and associated growth in wastes and emissions. Fig. 2.5 shows the material history of time taken from M. Ashby's work.

Past epochs were named after the new breakthrough materials and marked with development of technologies for production and use of the existing and new materials accompanied by gradual

[3] It should be noted that the main part of research studies focuses on analysis of energy resources use. The world science pays significantly less attention to analysis of materials use. Nevertheless, there are several schools that focus on analysis of materials use.

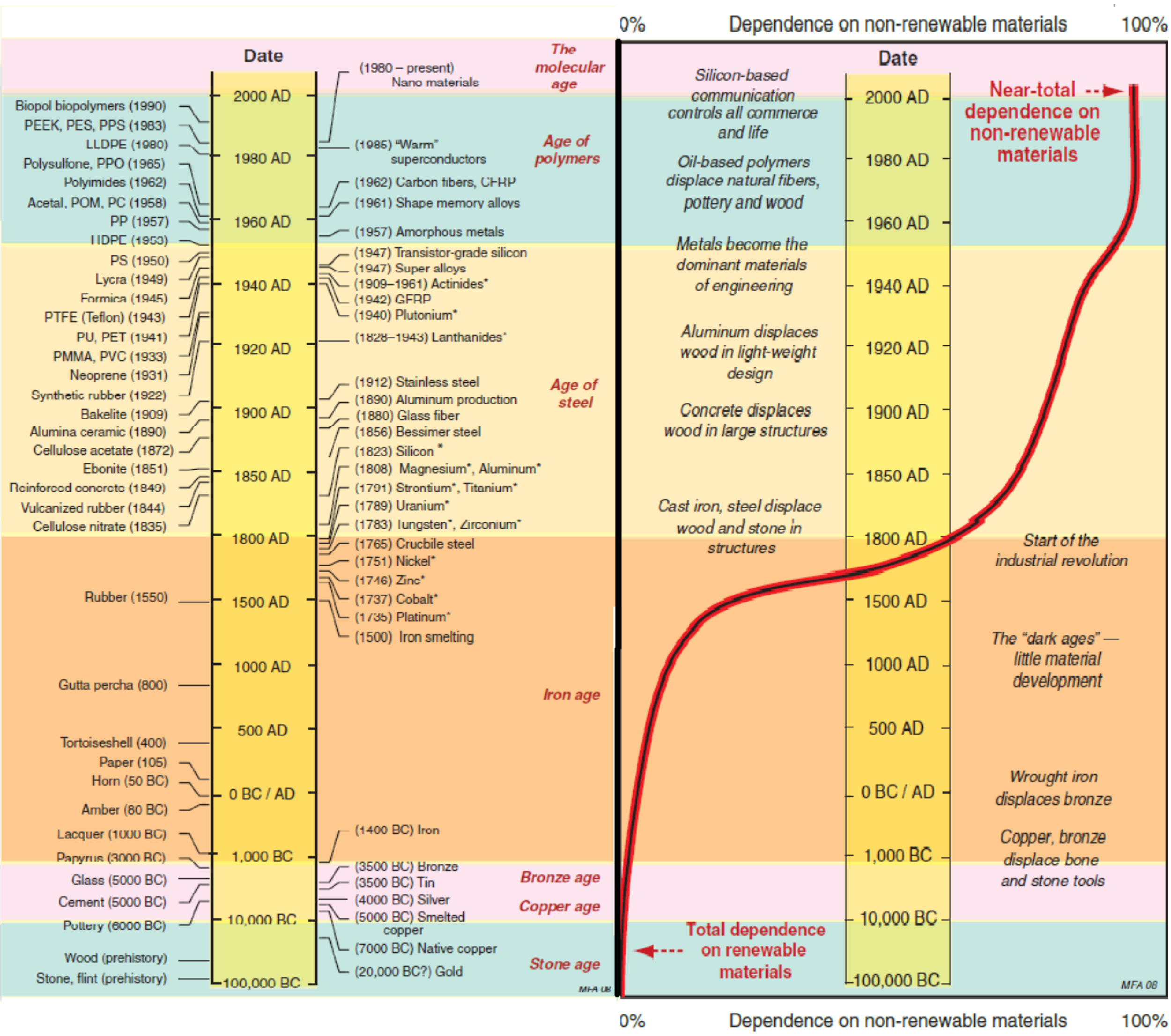
transition from organic (prevalence of agricultural) to industrial economy built upon the use of fossil resources.

Before coal, photosynthesis was the only source of energy that could be stored in “organic economy.” Biomass in various forms was the main source of food, fodder, fuel, and materials. Metal fabrication was limited due to very high fuel (charcoal) demand and shortage of land and woods. Population growth was limited by overall land productivity (Allwood et al., 2013; Wrigley, 2013). Transition to economy of fossil materials removed that limitation and significantly expanded the limits to growth. Industrial revolution was based on transition from biomass-related limitations to opportunities opened up by the use of fossil fuel:

- multifold increase in power flow density from 0.1–1 W/m^2 for biomass to 1,000–10,000 W/m^2 for organic fuel;
- removal of limitations to annual utilisation volumes of grown biomass and transition to utilisation of large stocks of fossil fuel suitable for building-up annual volumes of its utilisation and unrestricted by annual reproductive capabilities of biosystems; and
- provision of economic growth with cheaper energy resources.

According to Fouquet (2011), prices for coal were many-fold lower than prices for wood fuel in England of 1300–1900. But in Sweden, coal became cheaper than fire wood only in 1850 (Kadner, 2002). For that reason, industrialisation started there markedly later.

Figure 2.5 The materials timeline



The materials timeline. The scale is nonlinear, with big steps at the bottom, small ones at the top. A star (*) indicates the date at which an element was first identified. Unstarred labels give the date at which the material became of practical importance.

The increasing dependence on nonrenewable materials over time, unimportant when they are plentiful but an emerging problem as they become scarce.

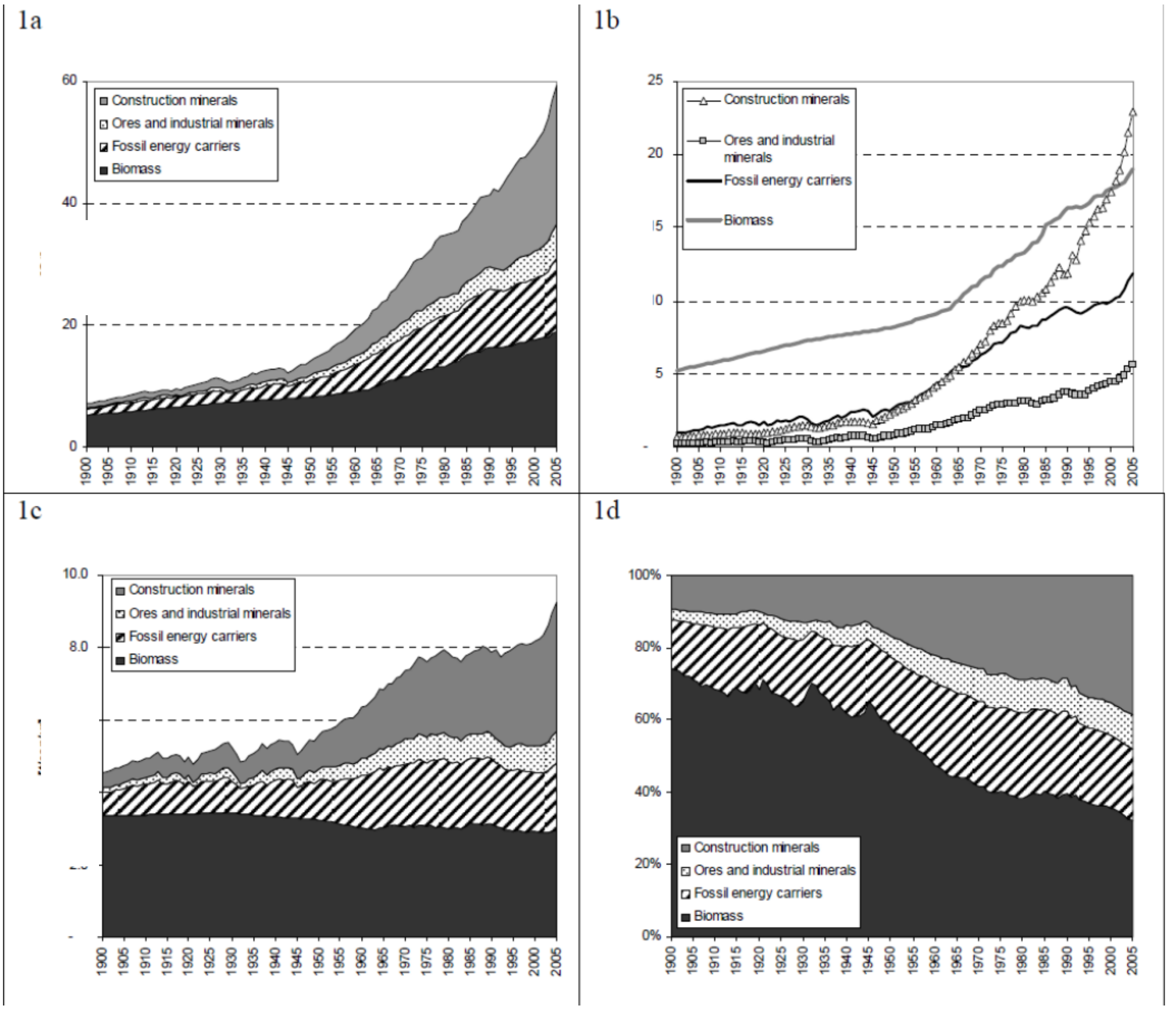
Source: Ashby MF. 2012 Materials and the environment: eco-informed material choice, 2nd edn. Oxford, UK: Butterworth-Heinemann

Transition to fossil fuel made it possible to overcome "limits to growth" of agrarian economy, to concentrate production and population in large towns, and to ensure efficient long-distance transportation of large volumes of goods. As a result, limitation to economic growth related to availability of productive land was removed, while rates of growth in global utilisation of energy and materials rapidly increased (Fig. 2.6). The share of biomass in the structure of materials use gradually decreased through the growth in the share of fossil fuel followed by growth in use of industrial minerals and ores and, finally, construction materials. Utilisation of construction materials has been growing especially fast for the recent half a century. In 2005, annual consumption of materials, including biomass, reached 65 bt, in 2011—77 bt, which was 15–16 times higher than the 1850 level.

The 20th century was unprecedented in the history of mankind: the population increased 4-fold, global GDP increased 24-fold, consumption of all materials increased 8-fold, while consumption of biomass increased 3.6-fold, consumption of metal ores increased 27-fold, and

consumption of construction materials increased 37-fold. Annual growth in consumption of materials ranged from 1 to 4%. Fossil metals and mineral construction materials (concrete, brick, glass, etc.) replaced biomass in many applications. The share of biomass in the structure of materials used dropped from 74% in 1900 to 32% in 2005, while the share of construction materials increased from 9 to 39%. In 1900, renewable sources of materials accounted for three-quarters, but at the beginning of the 21st century, they accounted only for 30%. In 1900–2005, the share of wood in the structure of biomass used decreased from 15 to 11%. The share of iron ore in the structure of metallic ores use decreased from 95% to 85%, that of alumina increased from 0.1% to 6.6%. The share of mineral resources for cement production in the structure of mineral construction materials increased from 15 to 74% (Krausmann et al., 2009).

Figure 2.6 Materials Use (DMC=DE) by Material Types in the Period 1900 to 2005



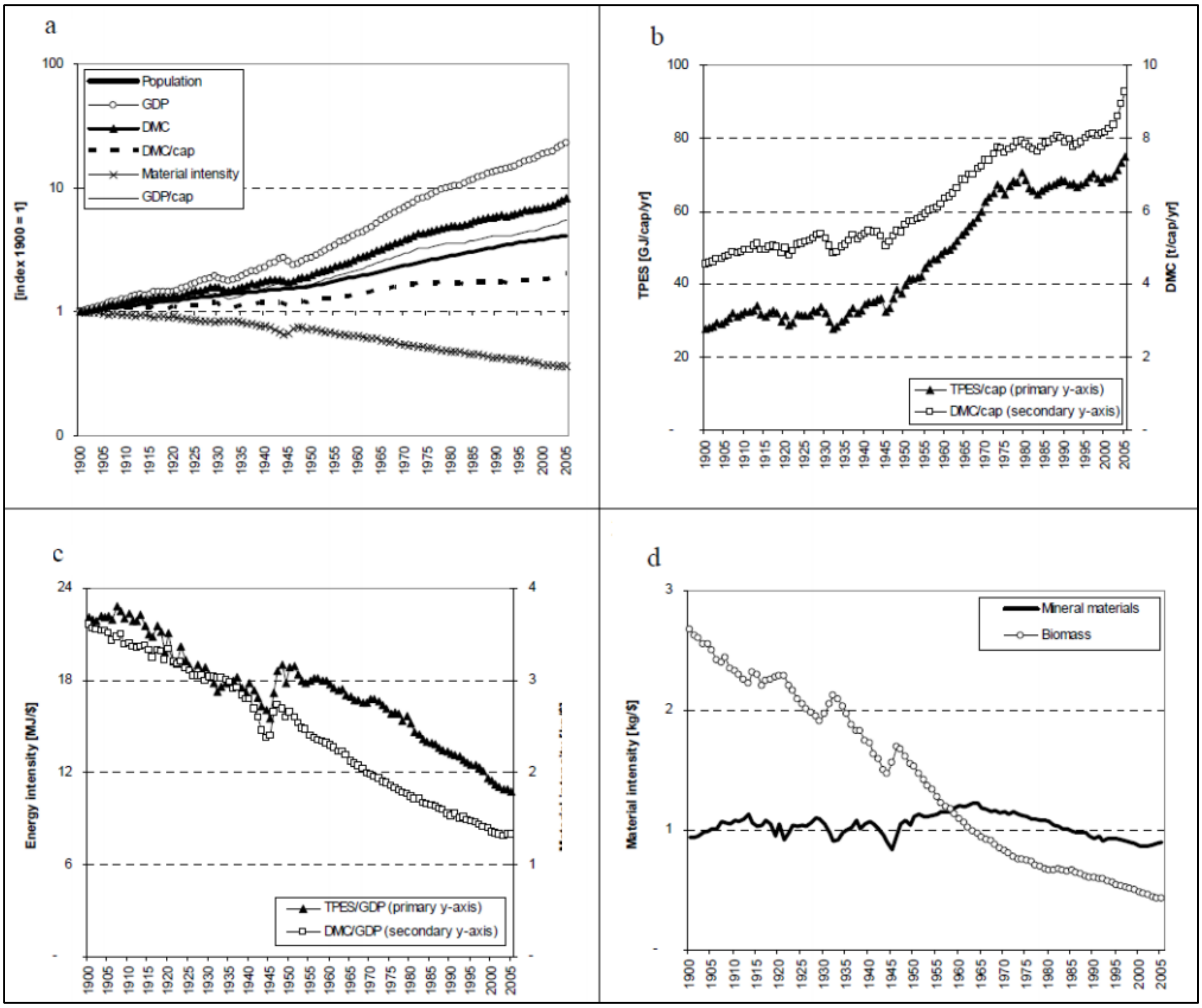
a) and b) - total materials use in Giga tons (Gt) per year; c) metabolic rate (materials use in t/cap/year); d) share of material types of total materials use.

Source: Krausmann et al., 2009.

While the growth in the use of biomass was close to the population growth rate, the growth of fossil resources extraction was close to the global GDP growth rates. Therefore, specific per capita use of fuel and materials followed the common trend for growth which markedly increased in the post-war period (1945–1975). After that, both indicators temporarily stabilised until 2000 when a new growth wave started (Fig. 2.7). Four periods of different changes in per capita consumption of materials can be noted: 1900–1945: average annual growth only by 0.23%; 1945–1973: annual growth by 1.55%; 1973–2000: annual growth approx. by 2%; 2000–

2015: annual growth approx. by 2.6%. Therefore, ***2000 was followed by a new wave of growth in the global per capita consumption of materials***.

Figure 2.7 Material Consumption Growth Drivers and Specific Characteristics of Material Consumption in 1900–2005



(a) Development of materials use (DMC), total primary energy supply (TPES), population and GDP; (b) Metabolic rates (materials use and TPES per capita and year); (c) material and energy intensity; (d) material intensity for biomass and mineral materials

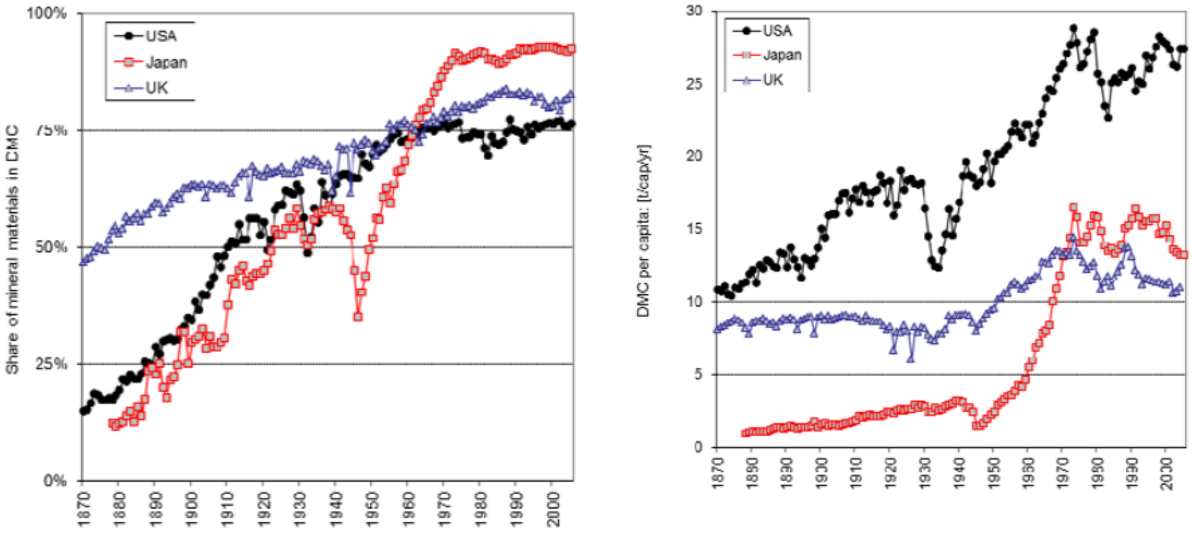
Source: Krausmann et al., 2009.

In the last few decades, materials utilisation rate (per capita) in developed countries has stabilised or even started to decrease (Fig. 2.8). Coupled with the growing share of countries with comparably low level of per capita consumption of basic materials, this fact caused temporary stabilisation of the global indicator. However, due to growth in specific consumption of materials in developing countries and growth in their share in the global economy, per capita consumption of materials worldwide resumed to grow.

Despite considerable differences, the processes of growth in the share of fossil resources in the total utilisation of materials and growth of specific per capita consumption had many similar features in certain developed countries. The main features include saturation of total per capita consumption of mineral materials and fuel after 1975 (Fig. 2.8).

In 1900–2005, specific materials use per unit of global GDP decreased almost 2.5-fold. However, this decrease was primarily caused by reduced demand for biomass owing to the properties (including structural properties) of new materials (all cement and about 50% of steel are used in construction). Their share in the structure of materials used was rapidly growing in 1870–1970 (Fig. 2.6). Changes in this share for the world as a whole reflected with slight lag the changes that took place in developed countries (Fig. 2.8). This means that characteristics of the global industrial metabolism in developed countries outline the future trends for the world as a whole.

Figure 2.8 Share of Mineral Materials in Domestic Material Consumption and Material use per Capita in USA, Japan and UK in 1870–2005



Share of mineral materials in domestic material consumption

Material use per capita

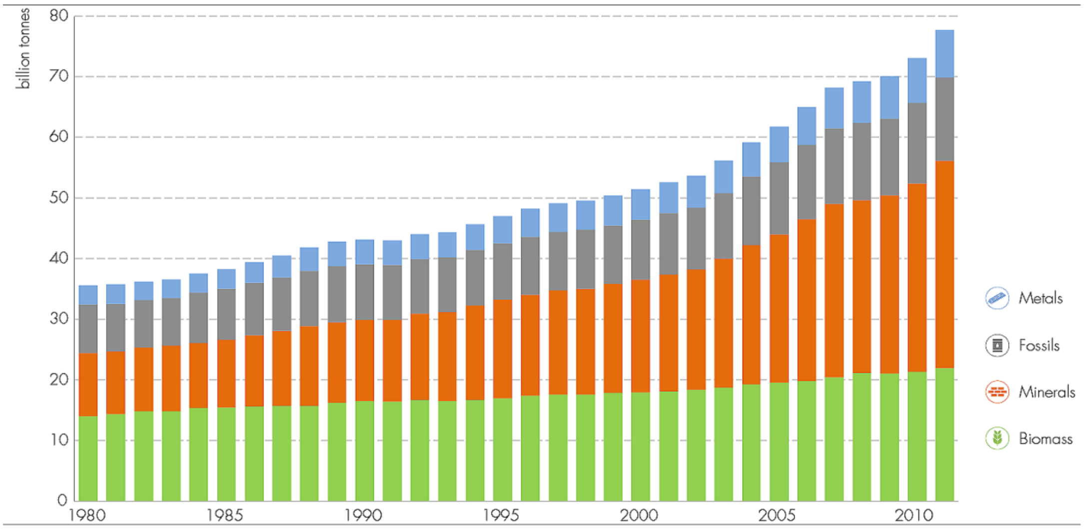
Source: Krausmann et al., 2011.

During the recent 100 years, specific mineral materials use per unit of GDP has varied under the influence of long waves in economy, with the centre of oscillations about a fairly stable level (Fig. 2.8). In the USA, it increased in 1870–1920 and decreased thereafter (Gierlinger and Krausmann, 2011). In Japan, the growth phase started in 1870 and took almost 100 years (Krausmann et al., 2011).

2.3 Recent Trends

As already mentioned, after some slowdown at the beginning of the 21st century, consumption of basic materials accelerated: in 2000–2011 alone, it increased almost by half, i.e.,was annually growing by 3.7% on the average (Fig. 2.9). ***After extrapolation of these rates to 2015, consumption of basic materials can be estimated almost at 90 bt.*** Production of construction and industrial minerals demonstrated outstripping growth rate. Use of biomass demonstrated the slowest growth. Extraction of industrial and construction minerals in 1980–2011 increased by 228%, extraction of metal ores increased by 147%, extraction of fossil fuels increased by 73%, and extraction of biomass increased only by 56%. Share of renewable sources in extraction of resources decreased from 39% in 1980 to 28% in 2011.

Figure 2.9 Global Resource Extraction by Material Category 1980–2011

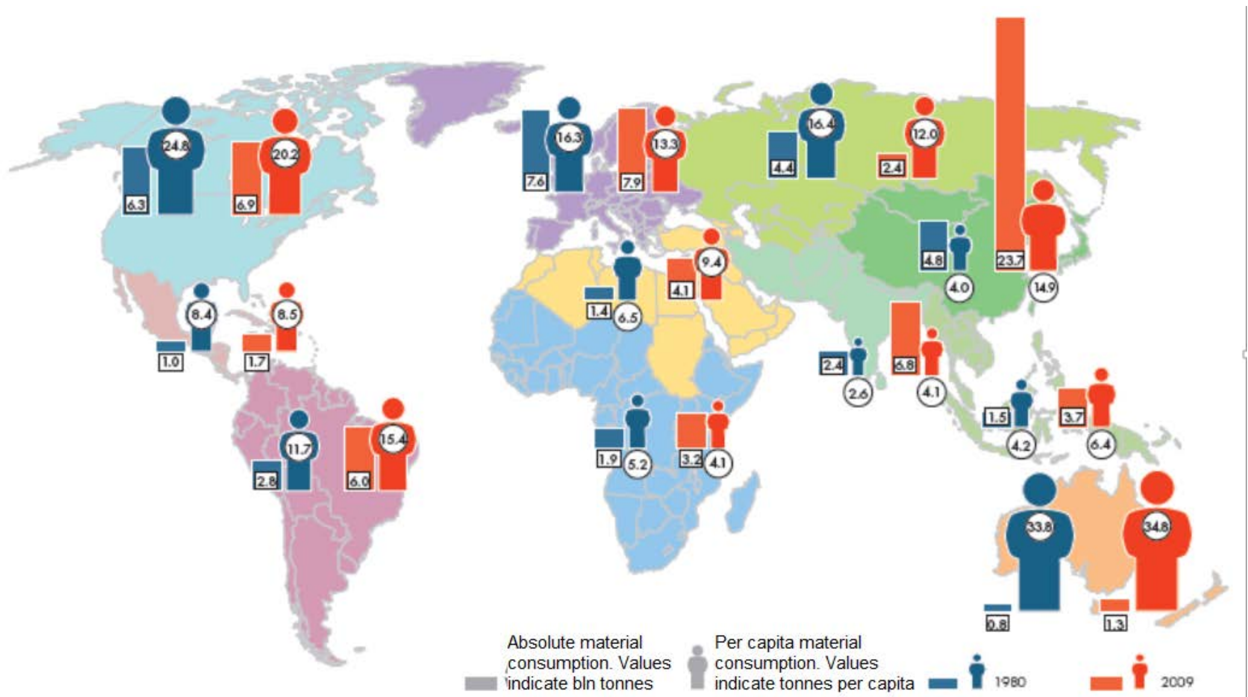


Source: SERI (2014). Global Material Flows Database. www.materialflows.net.

In 2011, Asia accounted for 46 bt, or 60%, out of 78 bt. Latin America ranked second (9 bt) and was followed by Western Europe and the USA that accounted for about 7.5 bt each. In 1980–2011, China increased extraction of fossil fuel, metal ores and biomass by 383%, 771% and 122% respectively and extraction of industrial and construction minerals—more than by 3,007%. Extraction of materials from earth's crust increased by 758% in total against 204% in India.

Per capita production of basic materials continued to grow but varied from region to region of the world (Fig. 2.10). Annual per capita consumption of resources in the USA is close to 20 tonnes, in Latin America—15 tonnes, in Europe—13 tonnes, in the former USSR republics—12 tonnes, in Africa—only 4 tonnes. On account of international trade in materials, volumes of their production and consumption differ. However, high share of biomass and construction materials, which are normally utilised not far from places of production, makes such differences less significant than in case of fossil fuel. The USA and Western Europe are major importers of materials, China has a balance of production and consumption, while Australia, Canada, Latin America, and Africa are net exporters of materials.

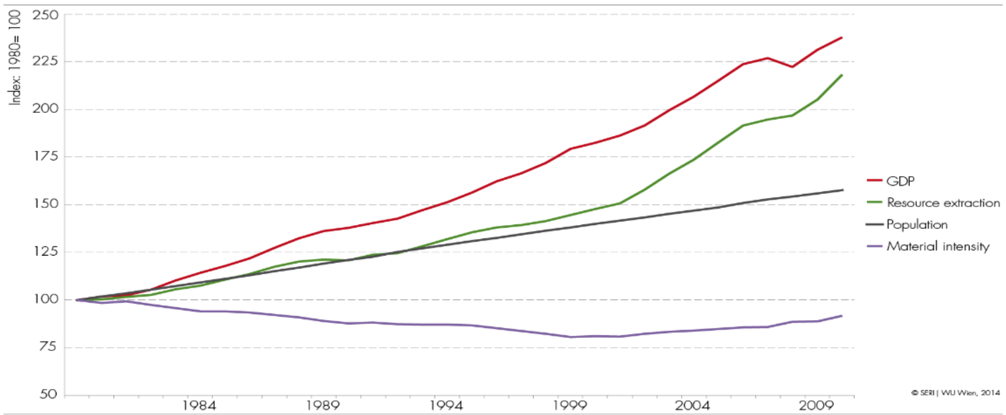
Figure 2.10 Material Consumption per Capita and Day in 1980 and 2009



). Global Material Flows Database. www.materialflows.net.

The growth in population and global GDP are the main drivers of demand for materials (Fig. 2.11). This figure does not show any prices, because it is difficult to aggregate them for basic materials. Planetary boundaries have recently narrowed, and prices for resources have started to grow. If we exclude biomass from material balance, trends towards growth in per capita consumption of materials and trend towards stabilisation of material intensity of the global GDP will become clearer.

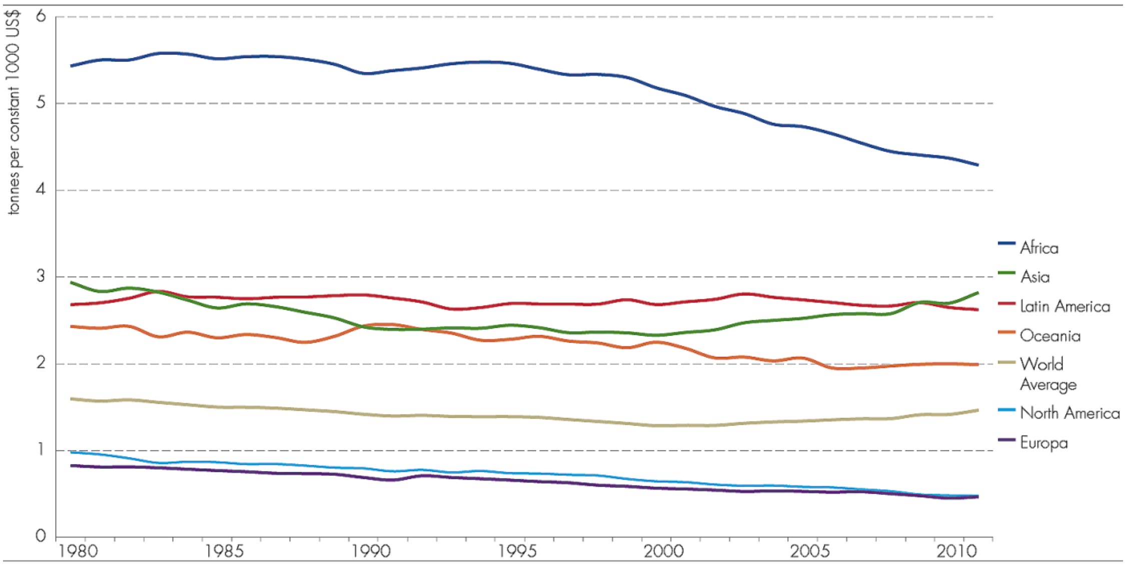
Figure 2.11 Basic Materials Consumption Growth Drivers



Source: SERI (2014). Global Material Flows Database. www.materialflows.net.

Worldwide average per capita consumption of materials remained practically stable in 1980–2000 and then started to rapidly grow up to 11 t/person/year in 2011. Material intensity of GDP slightly decreased, but mainly on account of biomass. It did not decrease for mineral resources. It decreased in developed countries; in developing countries, it either remained comparably stable or also decreased. In Asia, it decreased in 1980–2000 and started to grow thereafter. Coupled with rapid growth in GDP of the region, this blocked decrease in global material intensity (Fig. 2.12).

Figure 2.12 GDP Material Intensity by Region

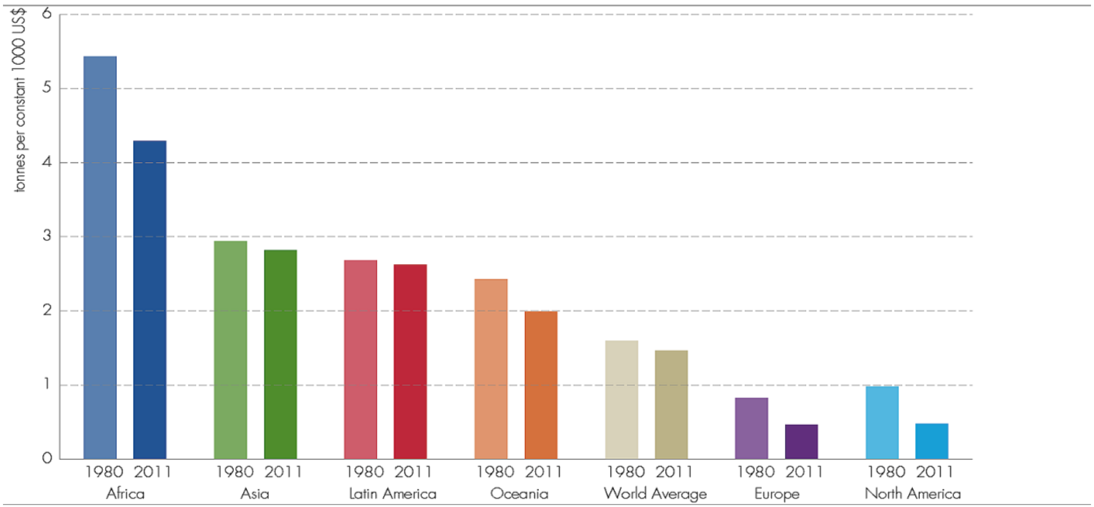


Note: GDP in 2000 prices.

Source: SERI (2014). Global Material Flows Database. www.materialflows.net.

There is clear dependence of material intensity of GDP on the level of economic development (Fig. 2.13). This dependence is greater in developing countries as compared to developed economies. The same dependence exists for energy intensity. Therefore, if we exclude fossil fuel from the total volume of materials used, we can obtain similar dependence for materials only. Another fact is that ***rates of material intensity reduction at comparably low income levels have been fairly limited over the period of 31 years. They increase as the level of economic development grows.***

Figure 2.13 GDP Material Intensity by Region (2007)



Source: SERI (2014). Global Material Flows Database. www.materialflows.net.

Relative stability of global material intensity (net of biomass) over almost 100 years means that given the assumed material intensity gap, reduction of material intensity in certain regions was made up for by the growth in the share of regions with relatively higher material intensity in aggregate consumption of materials. Transition of developing countries to higher levels of development and significant growth of their share in the utilisation of materials can create a global trend towards reduction of material intensity.

Defining the concept of material intensity in the multi-material world (when products are made of a large number of materials) becomes challenging. Summing materials up on the basis of their weight may be inappropriate for determining the aggregate indicator of materials utilisation. Summing up can be weighted by prices, specific energy consumption, or environmental impact. Each option poses challenges. Moreover, it is important to take into account the product life cycle, energy consumption at the stage of product operation, possibilities of materials recycling, which become complicated in case of composite materials. There are different approaches to estimating the aggregate indicator of materials utilisation, but the common solution has not been found yet (see Lifset and Eckelman, 2013).

Changes in consumption of various materials, changes in population, GDP and material intensity in 1900–2015 are summarised in Table 2.1.

Table 2.1 Specific Use of Materials (DMC) and Energy (DEC) per Capita and per Unit of GDP (in USD of 1990) in 1870–2005

	Biomass	Fossil fuels	Metal ores	Raw stock for construction materials	Total materials	Total materials per capita	Population	GDP	Per capita GDP	Primary energy consumption
1900–1945	0.92%	1.70%	2.30%	1.98%	1.21%	0.23%	0.98%	2.13%	1.13%	1.33%
1945–1973	1.52%	4.48%	5.74%	6.05%	3.30%	1.55%	1.72%	4.18%	2.42%	4.39%
1973–2005	1.42%	1.63%	2.21%	3.22%	2.13%	0.56%	1.56%	3.27%	1.69%	1.90%
1900–2005	1.23%	2.41%	3.18%	3.43%	2.04%	0.68%	1.35%	3.02%	1.64%	2.31%
1900–2005 (-fold)	**3.6**	**12.2**	**26.7**	**34.4**	**8.4**	**2.0**	**4.1**	**22.8**	**5.5**	**11.0**
1980–2011	1.47%	1.78%	2.86%	3.91%	2.55%	1.07%	1.46%	3.25%	1.76%	1.95%
2000–2011	1.94%	3.08%	4.19%	5.56%	3.81%	2.57%	1.21%	3.82%	2.57%	2.43%
1900–2011 (-fold)	**4.1**	**14.3**	**36.7**	**47.7**	**10.5**	**2.4**	**4.4**	**28.5**	**6.4**	**12.5**
1900–2015 (-fold)	**4.4**	**16.1**	**43.2**	**59.2**	**12.2**	**2.6**	**4.6**	**33.1**	**7.1**	**13.8**

Source: Data for 1900–2005: Krausmann et al., 2009. Data for 1980–2011: SERI (2014). Global Material Flows Database. www.materialflows.net. Extrapolation to 2015: CENEf-XXI on the basis of average annual rates for 2000–2011.

Very-long-term (over 115 years) and current trends of recent 40 years can be summarised as follows:

- ✓ In 1900–2015, the global population increased 4.4-fold.
- ✓ The global GDP increased 33-fold.
- ✓ In the 20th and the 21st centuries, the consumption of basic materials markedly accelerated largely because of the transformation of the economic development energy base.
- ✓ As predicted by the Club of Rome in its report *The Limits to Growth* (1972), consumption of materials grew almost exponentially and increased 12-fold over 115 years.
- ✓ In 2015, the aggregate consumption of all basic materials can be estimated at approx. 90 bt.
- ✓ Consumption of inorganic (fossil) materials grew much faster than the use of biomass, the share of which decreased almost 2.5-fold. This caused a fundamental shift in the structure of materials employed from domination of biomass to domination of fossil materials.
- ✓ The use of construction materials grew especially fast.

- ✓ Per capita consumption of basic materials continued to grow with long cycles of acceleration and deceleration and grew 2.8-fold.
- ✓ Per capita consumption of materials net of biomass grew 7.5-fold.
- ✓ Material intensity of GDP increased 2.7-fold.
- ✓ Material intensity of basic materials net of biomass changed cyclically around the constant level over the horizon period of 115 years.
- ✓ As the level of economic development grew, specific consumption of materials per unit of GDP and per capita becomes saturated, and then dematerialisation of economic growth starts.
- ✓ Developed countries have already reached this stage.
- ✓ The gap between the economic development levels of developed and developing countries is relatively large, as is the time distance to be covered by the latter to reach the dematerialisation stage.
- ✓ Since the share of developing countries in the global economy is growing,
  - ➢ the global specific material use per capita is still a long way from saturation level.
  - ➢ Material intensity of global GDP may cyclically change around a relatively stable value for decades.

Continuation of these trends in the long term will increase pressure on the resource base so far as population increases up to 9–10 bn and middle-class population increases from the current 1 bn to 4 bn (Baptist and Hepburn, 2013). This pressure may exceed the “load bearing capacity” of the planet. Decoupling of economic growth and materials consumption growth requires significant improvement of materials utilisation efficiency and decarbonisation of social metabolism (Krausmann et al., 2011). According to Baptist and Hepburn (2013), apart from environmental advantages, reduction of material intensity and energy intensity produces positive effect on multi-factor performance and, therefore, on economic growth rates.

2.4 Volume and Changes in Production of Certain Basic Materials

Aluminium. Aluminium is the most abundant metal on Earth and accounts for up to 8.8% in the earth's crust. It does not occur in the free state because of its chemical activity. Only some of minerals and mine rocks containing aluminium are suitable for industrial production. The process of aluminium smelting involves bauxite mining, conversion of bauxites into alumina and subsequent aluminium smelting.

The key areas of aluminium application are construction and transport sector. In developed countries, the main consumption of aluminium takes place in transport engineering. Aluminium is widely used in car industry reducing car weight, increasing its cost effectiveness, and minimising air emissions. Developing countries are actively expanding the infrastructure in response to mass migration of growing population to big cities. Therefore, the main consumption of aluminium in this group of countries falls on construction.

Transport engineering accounts for 27% of all aluminium consumption,[4] Over the last 30 year, average aluminium content in all cars of the world has increased from 3% of gross car weight in 1977 to 9.7% in 2012.[5] A mid-sized car contains 120 kg of aluminium where 35% is accounted for by the engine that requires high strength and wear resistance, 15% is accounted for by the

[4] Sustainable Materials: with both eyes open. http://www.withbotheyesopen.com/read.php
[5] RUSAL (http://www.rusal.ru)

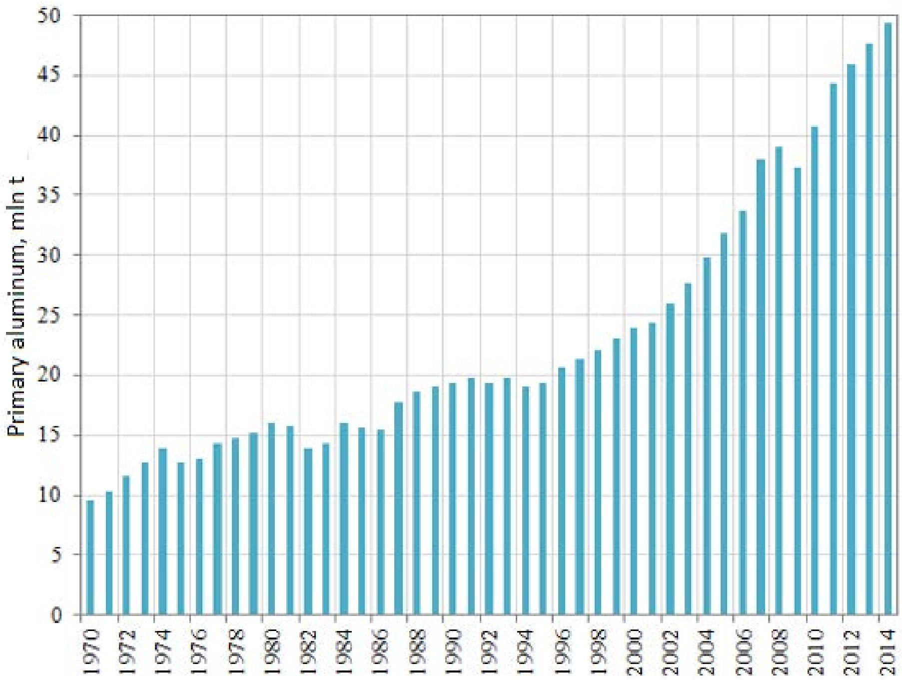
gear-box casing that requires rigidity for teeth alignment and heat conductivity for friction heat transfer, and 15% is accounted for by cast wheel disks. The rest of aluminium volume is used in cooling radiators and in pressed parts of chassis and suspension. Aluminium is also widely used in aerospace industry and accounts for up to 80% of airframe structure.

Industrial equipment accounts for 49% aluminium consumption. Aluminium is widely used in electrical equipment (20% of consumption), including wires (about 60% of copper conductivity, but aluminium is cheaper and lighter), protective covering for electric wiring, buswork in switchgears. In addition, aluminium is widely used in heat-exchange equipment thanks to its high heat conductivity, good corrosion resistance, and low cost. Another 13% of aluminium is used in packaging materials and containers, 9% in powder metallurgy, ink and pigment industry. In addition, 7% of aluminium consumption is accounted for by manufacture of household appliances, mainly washing machines, refrigerators, and freezers.

Construction accounts only for 24% of total aluminium consumption. Manufacturing of windows, doors, and building face elements accounts for 45% of aluminium used in construction. Another 40% of aluminium is used in corrosion-resistant roof and facing structures.

In 2014, the global aluminium smelting amounted to 49.3 Mt.[6] The global aluminium smelting has currently increased 5-fold versus 1970 (Fig. 2.14).

Figure 2.14 World Primary Aluminum production



Source: U.S. Geological Survey—MINERAL COMMODITY. http://minerals.usgs.gov/minerals/pubs/mcs.

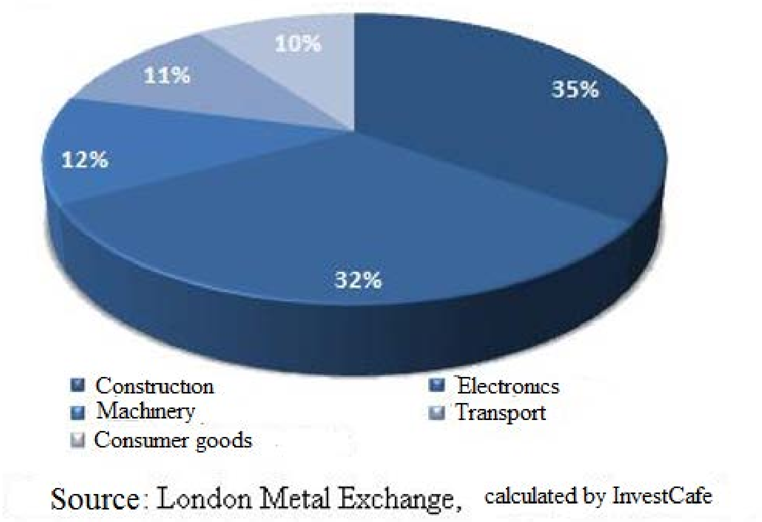
Copper. Copper occurs in nature both in compounds and in native state. Chalcopyrite (also known as copper pyrite), chalcosine, and bornite have industrial value. Sometimes, copper occurs in native state; individual accumulations can weigh 400 tonnes. The major part of copper ore is mined by the open pit. Copper content in ore ranges from 0.3 to 1.0%. Copper has high heat and electric conductivity (it ranks second after silver in terms of electric conductivity among metals). Copper is obtained from copper ores and minerals. The main methods for obtaining copper are pyrometallurgy, hydrometallurgy, and electrolysis. There are many copper alloys: brass (copper-zinc alloy), bronze (alloy of copper, tin, and other metals), cupronickel (copper-nickel alloy), etc.

[6] U.S. Geological Survey – MINERAL COMMODITY. http://minerals.usgs.gov/minerals/pubs/mcs

Thanks to its low specific resistance, copper is widely used in electric engineering for making power and other cables, wires or other conductors, e.g., for printed wiring. Copper wires are also used in coils of electric drivers and power transformers. Thanks to its high heat conductivity, copper is also applied in various heat-removing devices, such as cooling, air conditioning and heating radiators, computer coolers, and heat pipes.

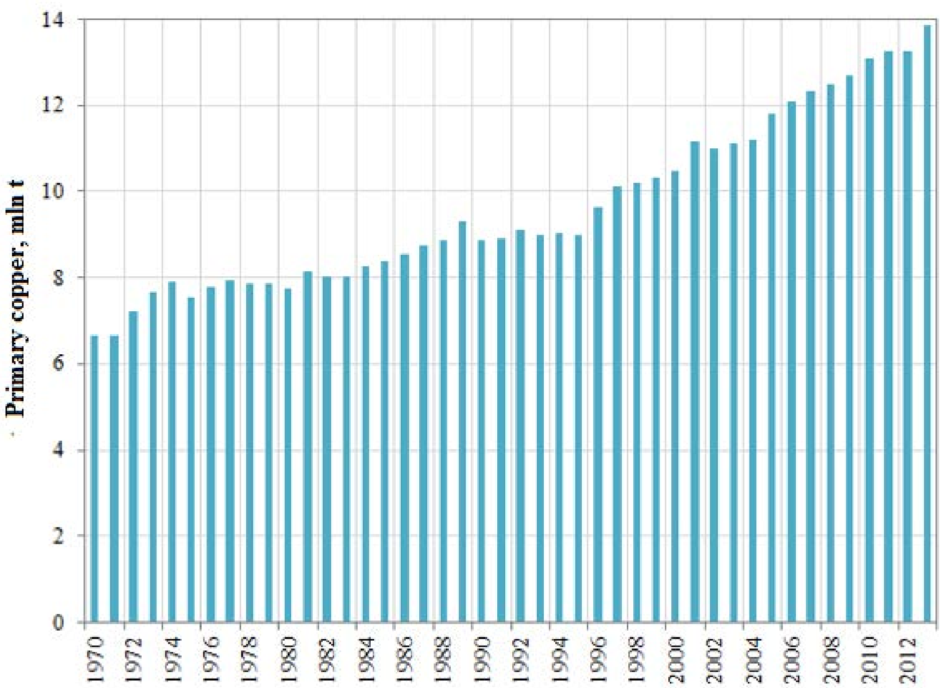
The structure of copper consumption by branches is shown in Fig. 2.15. The main copper consumers are construction (35%) and electronic (32%) industries.

Figure 2.15 Copper Consumption by Sector



In 2013, global output of primary copper amounted to 13.8 Mt. The global copper output has currently increased 3-fold versus 1970 (Fig. 2.16).

Figure 2.16 World Copper Production



Source: World mineral statistics data. https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method= searchWMS.

Cement and concrete. Cement, concrete, and reinforced concrete made of cement are currently the main construction materials that find application in various construction areas. Upon interaction with water, aqueous solutions of salts, or other liquids, cement forms plastic mass that hardens with time and becomes a rocklike body. It is mainly used to make concrete and mortars. Cement is obtained by fine grinding of clinker and gypsum. Clinker is homogeneous sintered raw mix obtained by uniform burning and consisting of limestone and clay of fixed composition that ensures prevalence of calcium silicates. Cement is graded according to strength. The grades are determined mainly by ultimate compression strength of half sections of prismatic test samples 40 × 40 × 160 mm in size made of cement-silica sand mixture (1:3). Grades range from M100 to M600 (in 100 or 50 increments), where the figures indicate compression strength of 100 to 600 kg/cm^2 (10–60 MPa) respectively.

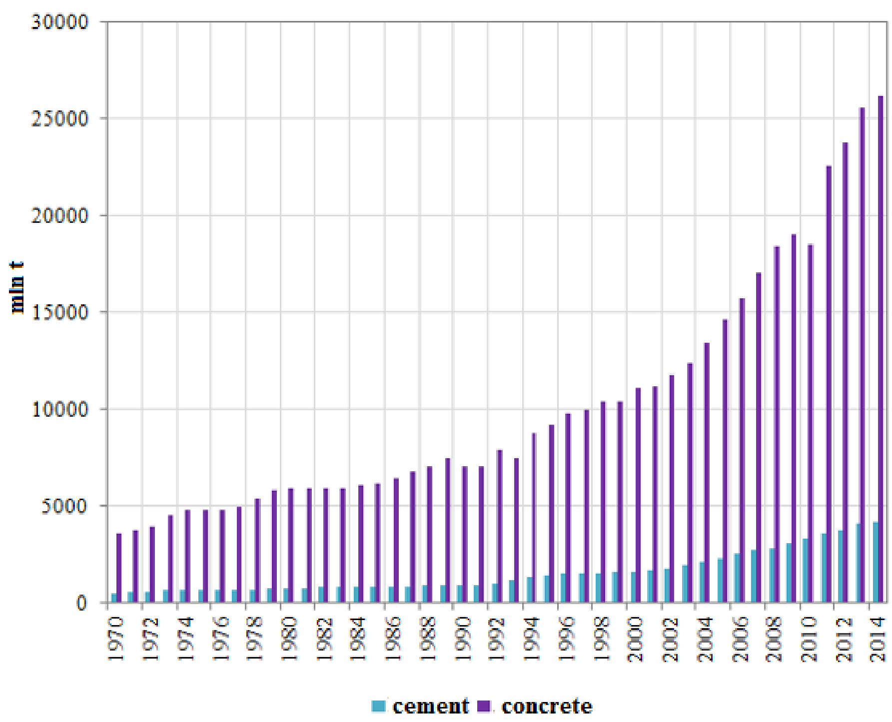
Concrete is artificial rock construction material obtained by mixing cement, sand, gravel, and water (their ratio depends on cement grade, fraction, and moisture of sand and gravel), as well as small amounts of additives (plasticisers, hydrophobisators, etc.). Reinforced concrete is composite construction material consisting of concrete and steel.

The main cement consumers in Russia are producers of asbestos-cement products (20%), households (6%), producers of reinforced concrete products (53%), and construction and installation work (21%).[7]

In the current production structure of prefabricated concrete, flat and linear units (slabs and blocks) account for 80%, while foundation blocks, piles, cross-ties, pipes, etc. account for the remaining 20%. Application areas of cast reinforced concrete are: transport construction and water engineering, underground development, construction of administrative and public buildings, luxury residential houses.

In 2014, global output of cement and concrete amounted to 4,180 and 26,000[8] Mt respectively. Since 1970, the global outputs of cement and concrete production have increased 8.4 and 7.3 times respectively (Fig. 2.17).

Figure 2.17 World Cement and Concrete Production

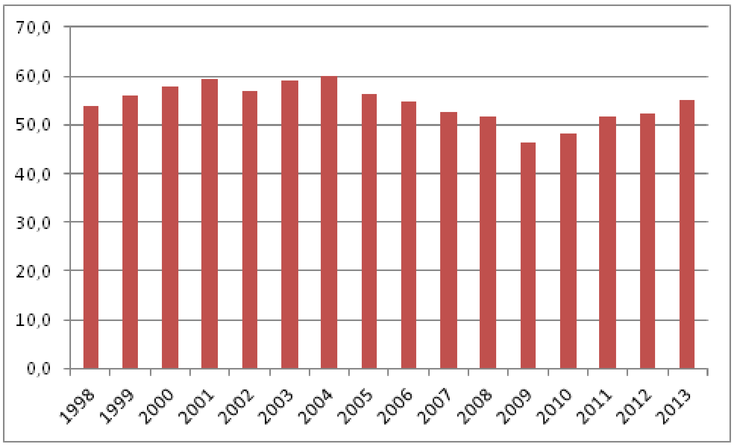


Source: U.S. Geological Survey—MINERAL COMMODITY. http://minerals.usgs.gov/minerals/pubs/mcs; Climate Change. http://www.tececo.com/sustainability.climate_change.php.

[7] As reported by Eurocement.
[8] U.S. Geological Survey – MINERAL COMMODITY. http://minerals.usgs.gov/minerals/pubs/mcs

Brick. In 1998–2013, global outputs of brick remained relatively stable, with cyclical oscillations within 46–59 Mt (Fig. 2.18). In 2013, the output amounted to 55 Mt.

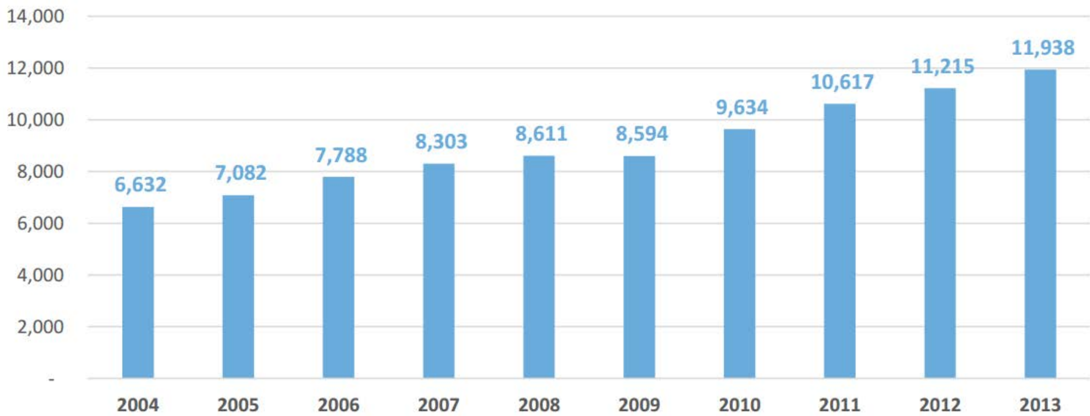
Figure 2.18 World Brick Production (mln t)



Source: U.S. Geological Survey—MINERAL COMMODITY. http://minerals.usgs.gov/minerals/pubs/mcs; http://www.ecobrick.in/.

Ceramics are articles and materials obtained by sintering clays and clay mixtures with mineral additions as well as oxides and other inorganic compounds. Ceramic objects are widely used in all areas of life: everyday life (various wares), construction (brick, roof tile, pipes, plates, glazed tiles, sculptural details), engineering, transport, sculpture and applied art. The main technological types of ceramics are terra-cotta, majolica, faience, stoneware, and porcelain. The main types of ceramic products and materials are brick, concrete, stone, and alumina.

Figure 2.19 World Ceramics Production (mln m^2)



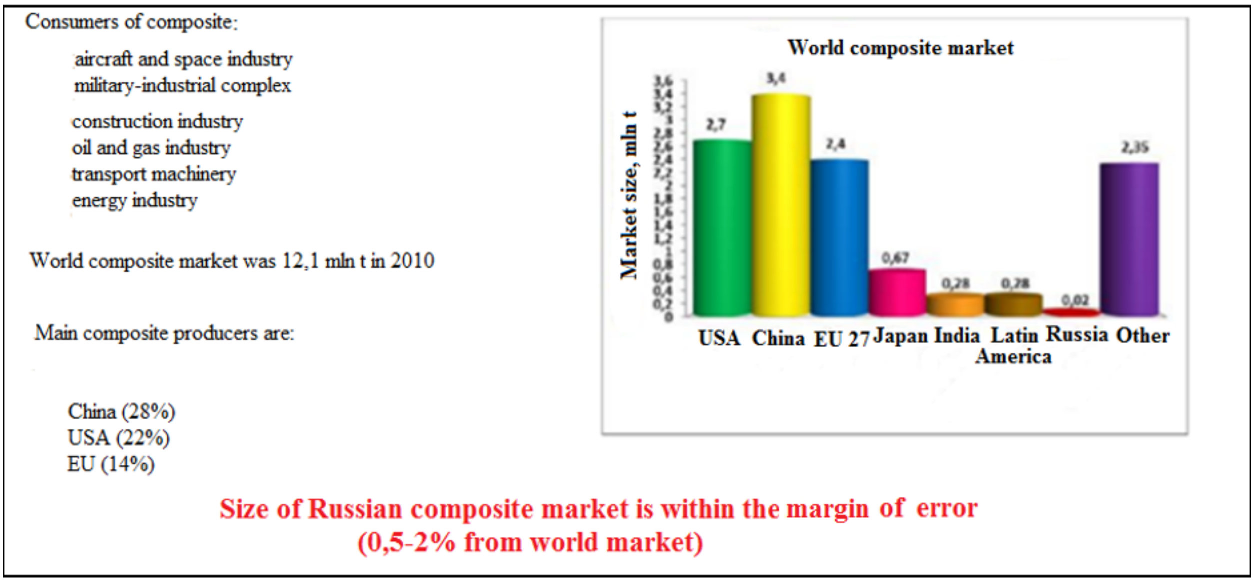
Source: World production and consumption of ceramic tiles - II edition. http://www.acimac.it/documenti/settore%20in%20cifre%20free/produzione-consumo/2015/schede_esempio_ENG.pdf

Over the period from 2004 to 2013, the output increased from 6.6 million m^2 to 11.9 million m^2 (Fig. 2.19), the average annual growth was 9%. After conversion at average density for each type of ceramic tiles, the weight of ceramic products produced in 2013 can be estimated at 131–251 Mt = 11.938 million m^2 * (11–21) kg/m^2.

Construction composites are artificial nonuniform construction materials consisting of several components that can be clearly distinguished. A composite normally consists of two types of components: a reinforcing agent and a matrix. The global market of composite materials is dominated by glass-reinforced plastics and carbon plastics. Total global output of all the other construction composites does not exceed several thousand tonnes per year.

In 2010, the volume of global market of composite materials achieved 12.1 Mt. According to estimates of JECmagazine, the leading media outlet in the area of composite materials, the average annual growth of this market will reach 4%.

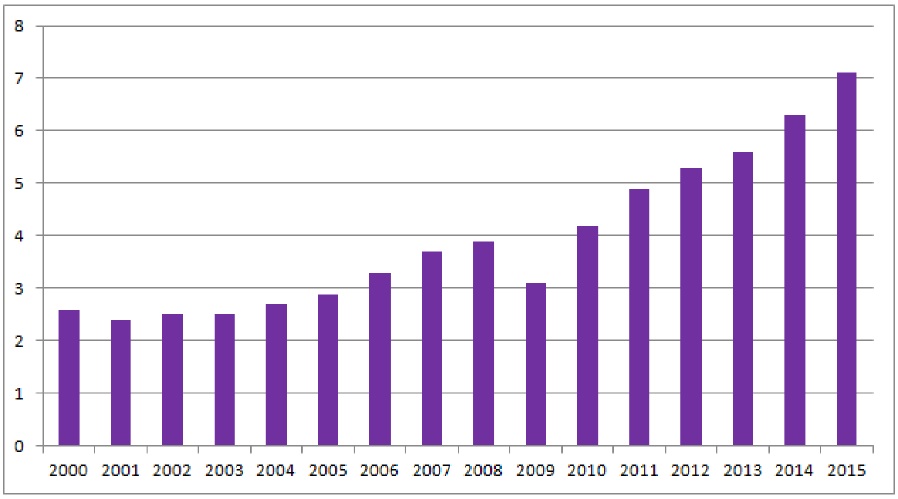
Figure 2.20 World Composite Market



Source: JECmagazine, No. 67, August–September, 2011 p. 19.
www.congressnano.ru/images/materials/KS2_Vetohin.pdf

Glass-reinforced plastics. In 2014, global outputs of glass-reinforced plastics amounted to 6.2 Mt, and in 2015, they are supposed to exceed 7.1 Mt (Fig. 2.21). The outputs have increased 2.8-fold since 2000.

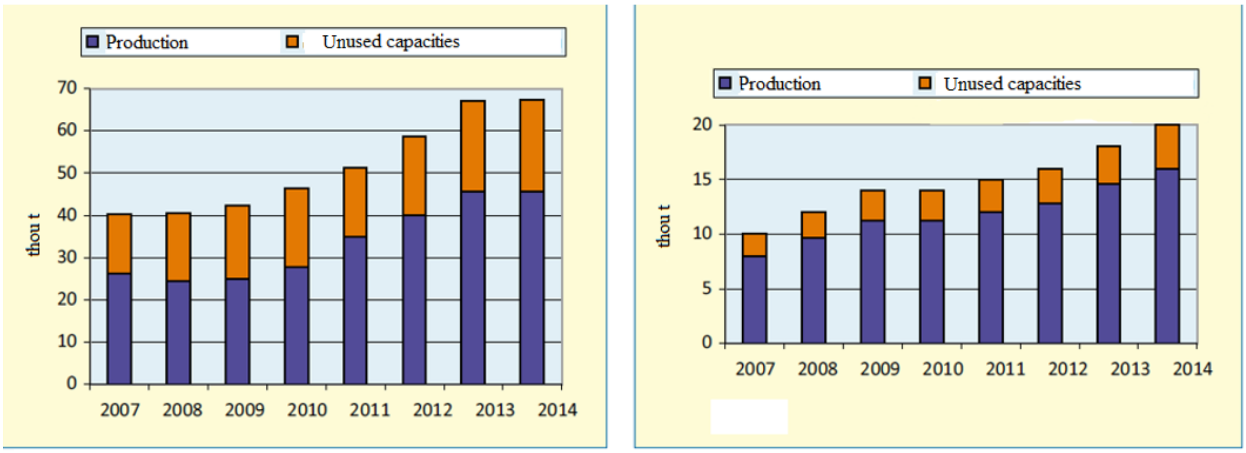
Figure 2.21 World Glass Fiber Plastics Production (mln t)



Source:http://investor.owenscorning.com/files/doc_events/2012/2-Composite%20Solutions%20Business.pdf.
http://www.reportlinker.com/p0694459/Global-and-China-Glass-Fiber-Industry-Report.html
(http://www.prweb.com/releases/glass_fibers_fiberglass/glass_wool_insulation/prweb4596424.htm).

In 2013, global outputs of **carbon plastics** did not exceed 88 kt (Fig. 2.22). The price for carbon plastics is 10–30 times higher than that for glass-reinforced plastics, but the latter dominate in terms of outputs of polymer composites.

Figure 2.22 Carbon Plastics Production



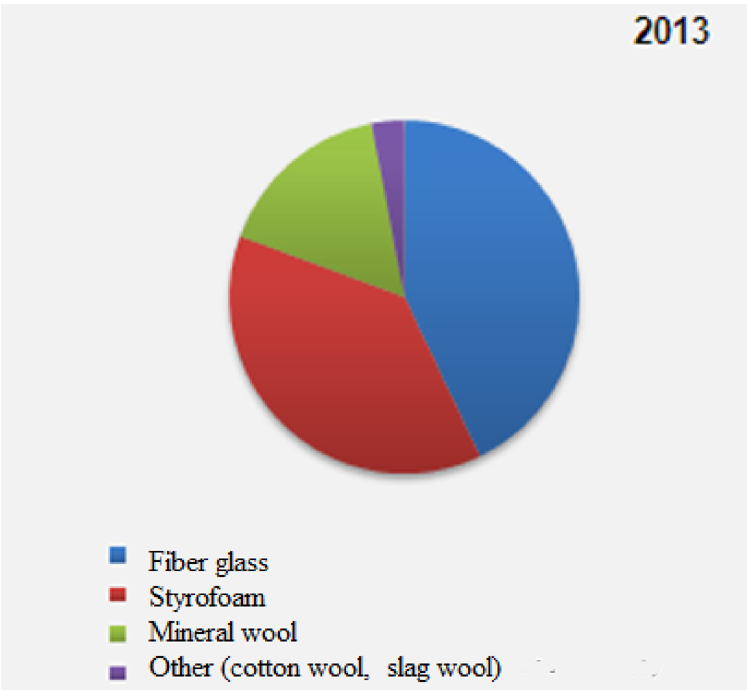
World thin carbon fibers production and unused capacities in 2007-2014 (2011-2014 - projection) (source - Higher School of Economics)

World thick carbon fibers production and unused capacities in 2007-2014 (2011-2014 - projection) (source - Higher School of Economics)

Source:http://www.polymerbranch.com/ebb71045453f38676c40deb9864f811d/80832b858dd51e67a79581ac270912e9/magazineclause.pdf.

Insulation materials. Classification of insulation materials can range from mineral fibres to foam plastics. The main commercially available insulation materials (Fig. 2.23): mineral wool, fibreglass wool, foamed polyurethane, foamed polystyrene, foamed concrete, and foamed glass. As shown earlier, global outputs of fibreglass wool on the basis of glass-reinforced plastics amounted to 6.2 Mt in 2014.

Figure 2.23 World Isolation Materials Market in 2013



Source: Transparency market research *http://www.ceeconstruction.com/news/96353/changing-structure-of-the-thermal-insulation-material-market-in-russia*, http://www.transparencymarketresearch.com/insulation-market.html

In 2011, outputs of mineral wool in Europe amounted to 2.4 Mt.[9] Considering the annual output of mineral wool in the USA (550 kt) and in Canada (60 kt), the global output can be estimated at 3.1 Mt.

Timber and wood-based panels. Timber is parts of trunk of particular size and quality, produced as a result of lumbering operations or used as semi-finished products for further mechanical or chemical processing. Wood-based panels are composite materials made of wood fibres, chips, and veneer and fixed by some means or other. In general, they are made according to international and national standards.

Outputs of timber and wood-based panels correlate with a large number of variables, such as:

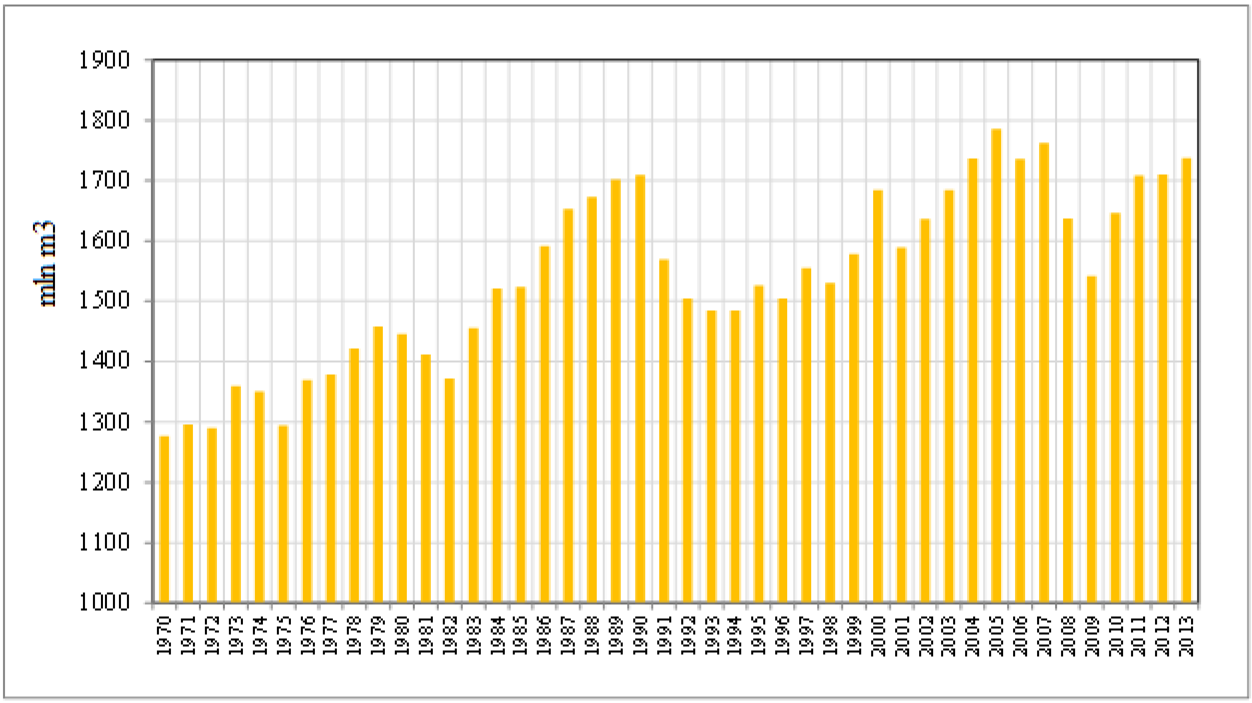
- Population size. Under otherwise equal conditions, growth of population results in growth of demand for wood and wood products. However, this dependence has been decreasing in recent years due to progressive expansion of digital technologies.
- International trade. Under otherwise equal conditions, growth of international trade results in growth of demand for wood and wood products due to additional demand for packaging materials.
- Share of waste recycling. Under otherwise equal conditions, growing share of waste recycling reduces the demand for wood.
- Welfare of the population. Under otherwise equal conditions, improved welfare of the population increases the demand for wood-based panels and alters the structure of their production: cheap panels (plywood) are replaced with better analogues (medium density fibreboards and chipboards).
- Prices, standardisation and certification. Under otherwise equal conditions and in comparable values, price escalation, including escalation caused by the need to standardise and certify products, results in reduced demand for wood and wood products.

Global outputs of timber are shown in cubic metres. In 1970–2013, the outputs increased from 1,276 million cubic metres to 1,737 million cubic metres (see Fig. 2.24); the average annual growth was 0.8%. Density of commercial wood species ranges from 450 to 900 kg/m^3. Therefore, if we take 650 kg/m^3 as an average value, the weight of timber produced can be estimated at 1,129 Mt as of the last reporting date.

Global outputs of wood-based panels are shown in cubic metres. Figures are given for the most commonly used types of wood-based panels: plywood, chipboard (CB), insulation wood-based panel (IWP), fibreboard (FB), medium-density fibreboard (MDF), and veneer panels (VP). In 1970–2013, the outputs increased from 77.8 million cubic metres to 382.8 million cubic metres (see Fig. 2.25); the average annual growth was 3.9%. After conversion at average density for each type of wood-based panels, the weight of wood-based panels produced in 2013 can be estimated at 252 Mt.

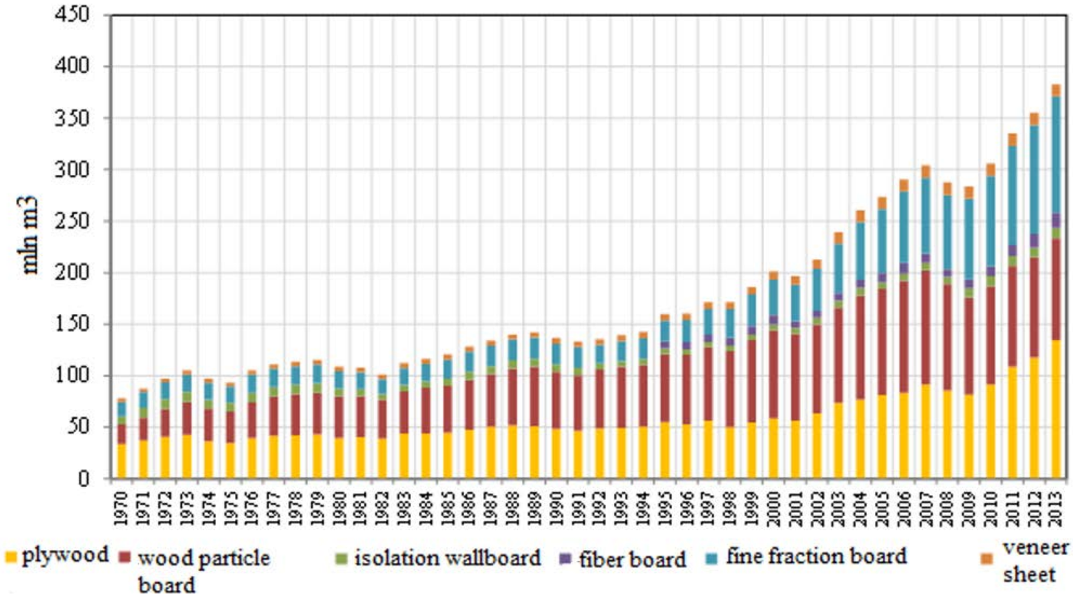
[9] http://www.atsdr.cdc.gov/toxprofiles/tp161-c5.pdf

Figure 2.24 World Timber Production



Source: http://www.factfish.com/statistic/industrial%20roundwood,%20total,%20production%20volume

Figure 2.25 World Wood-Based Panels Production

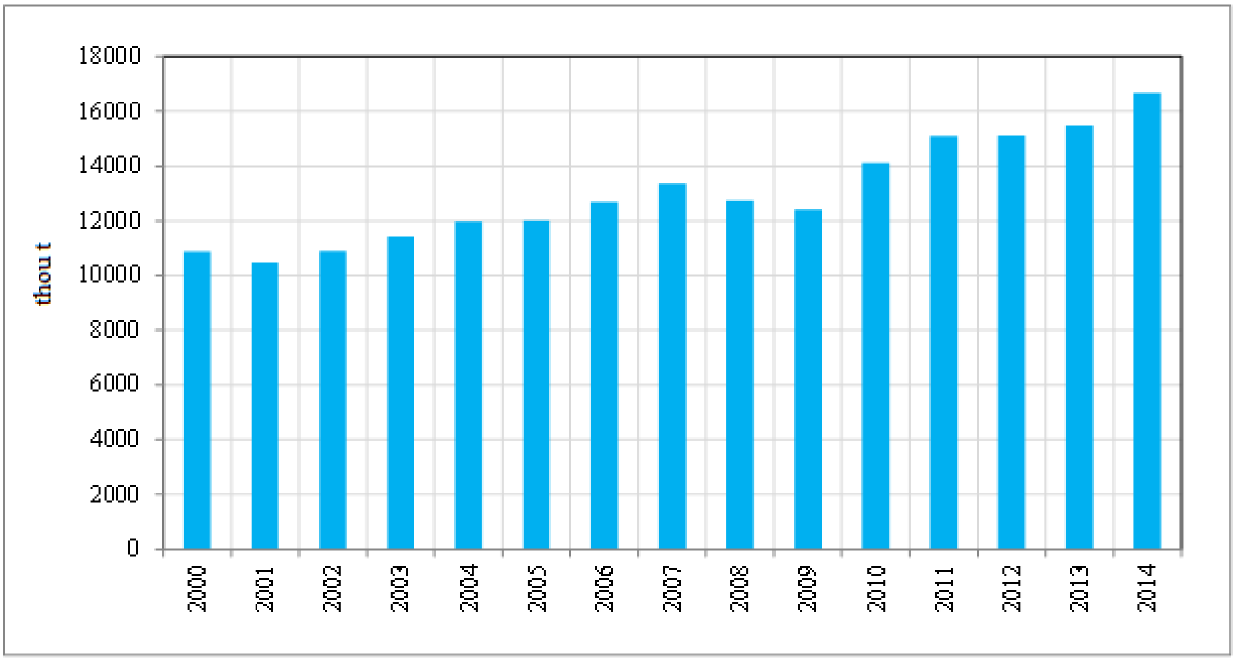


Source: estimated based on http://www.factfish.com/catalog/geography%20and%20agriculture.

Synthetic rubber. Synthetic rubber is elastomer obtained through polymerisation of two or more petroleum-based monomers. Butadiene and styrene butadiene rubbers are the most common types for making a wide range of products (apart from tire manufacturing, synthetic rubber is used in aviation, ship building, and for construction of high-speed trains). The key drivers of synthetic rubber output expansion are the growth of car industry, technological progress, and significant reduction of price for synthetic rubber raw stock. The major market development trends include: growth of demand for materials with enhanced process performance; price reduction; severe competition; and increase in supply. However, production of synthetic rubber is suppressed by environmental problems and depletion of fossil fuels.

Global outputs of synthetic rubber increased from 10.9 Mt in 2000 to 16.7 Mt in 2014 (see Fig. 2.26); the average annual growth was 3.8%. As of 2014, the maximum amount of synthetic rubber was produced in the Asia-Pacific Region (9.8 Mt); Europe, Africa, and Middle East produced 4.0 Mt; America produced 2.9 Mt.

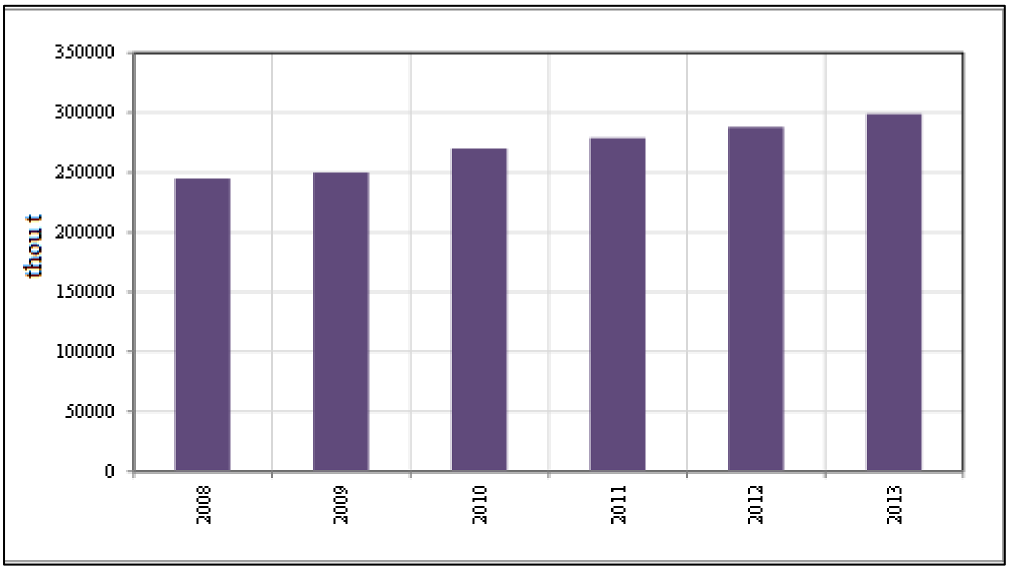
Figure 2.26 World Synthetic Rubber Production



Source: 2000–2013—http://www.statista.com/statistics/280536/global-natural-rubber-production/; 2014 - http://www.rubberstudy.com/documents/WebSiteData.pdf

Plastics. Plastics are organic materials based on synthetic or natural high-molecular compounds (polymers). Plastics are used in many spheres and branches of economy. Outputs of certain plastics are driven by the development of branches where they find the widest application. Global outputs of plastics increased from 245 Mt in 2008 to 299 Mt in 2013 (see Fig. 2.27); the average annual growth was 4.1%.

Figure 2.27 World Plastics Production

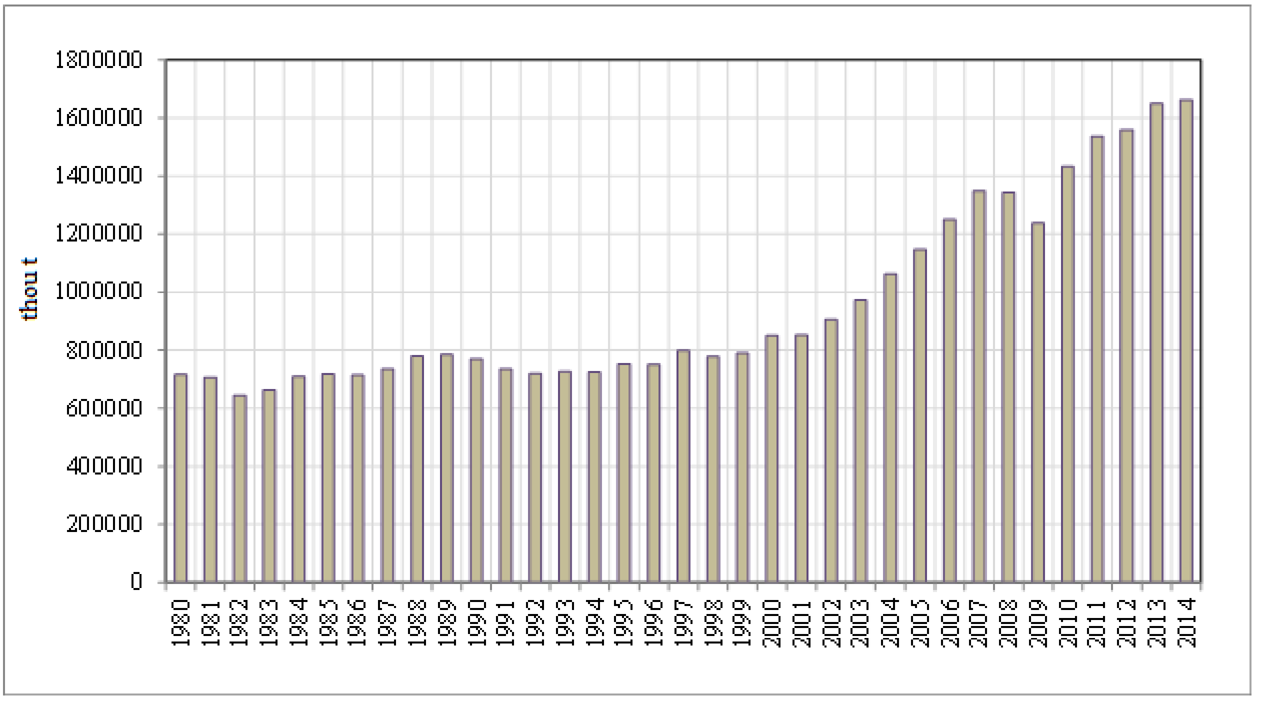


Source: Plastics—the Facts 2014/2015. An analysis of European plastics production, demand and waste data. Plastics in Europe. http://www.plasticseurope.org/plastics-industry/market-and-economics.aspx

The details for generation of time series for production of various plastics are limited. The main part of plastics (39.4%) is used as packaging material, another 20.4% are used in construction, 8.2% in car industry, 5.5% in electronics manufacturing, 4.2% in agriculture, the remaining portion is used in manufacture of household appliances, medical and other equipment, sports goods, furniture, etc.

Ferrous metals. Steel is alloy (solid solution) of iron and carbon (and other elements), where carbon content does not exceed 2.14%. Considering that alloying agents can be added to steel, it is common practice to call steel any alloy containing at least 45% of iron. Steel is widely used in engineering and construction. Studies show[10] that outputs of steel are closely related to changes in GDP. Global outputs of crude steel increased from 716.4 Mt in 1980 to 1,662 Mt in 2014 (see Fig. 2.28).

Figure 2.28 World Crude Steel Production



Source: 1980–2013—http://www.worldsteel.org/dms/internetDocumentList/statistics-archive/production-archive/steel-archive/steel-annually/steel-annually-1980-2013/document/steel%20annually%201980-2013.pdf; 2014 – https://www.worldsteel.org/media-centre/press-releases/2015/World-crude-steel-output-increases-by-1.2--in-2014.html

Global volumes of iron ore extraction increased from 896 Mt in 1980 to 3,220 Mt in 2014.[11] Global outputs of pig iron increased from 506 Mt in 1980 to 1,181 Mt in 2014.[12]

[10] For example: http://marketrealist.com/2014/07/key-drivers-steel-consumption-must-know-overview/.

[11] 1980–2012: World Mineral Statistics, British Geological Survey; 2013–2014: Mineral Commodity Summaries; 2015: US Geological Survey.

[12] 1980–2013: http://www.worldsteel.org/dms/internetDocumentList/statistics-archive/production-archive/iron-archive/iron-annually/DRI_yearly_1980-2012/document/DRI%20annual%201980-2013.pdf; 2014: https://www.worldsteel.org/statistics/DRI-production.html

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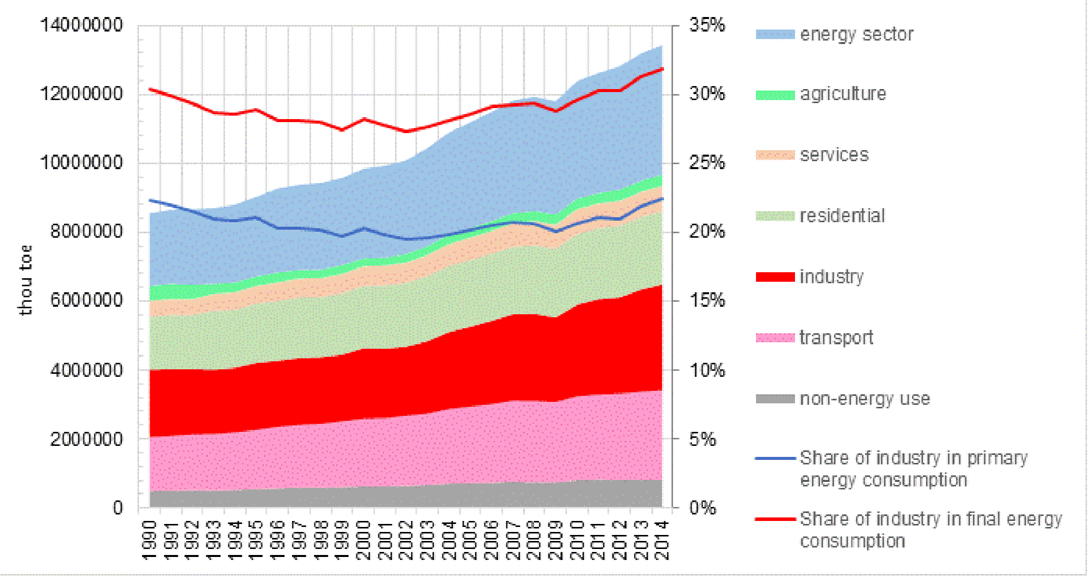
3 Role of Energy Consumed for Production and Transport of Materials in the World Energy Balance

3.1 Direct Energy Consumption in Basic Materials Production

Energy consumption in the production sector as well as energy inputs in production and transportation of basic materials can be measured based on international statistics on global energy consumption. Moreover, indirect energy consumption volumes associated with production of basic materials can be derived from the estimates of energy inputs in electric power and heat generation as well as in provision of other types of energy to end users.

Direct energy consumption in the global production sector in 2014 is estimated at 3.07 bn TOE. It has grown by 57% since 1990. In 1990–2002, the share of the production sector in primary energy consumption was decreasing. Growth resumed in 2002, and by 2014 the share of industrial production in the world energy balance went back up to its historical level: it accounted for 22% of primary energy consumption and for 32% of final energy consumption (Fig. 3.1).

Figure 3.1 Global Primary Energy Use in 1990–2014



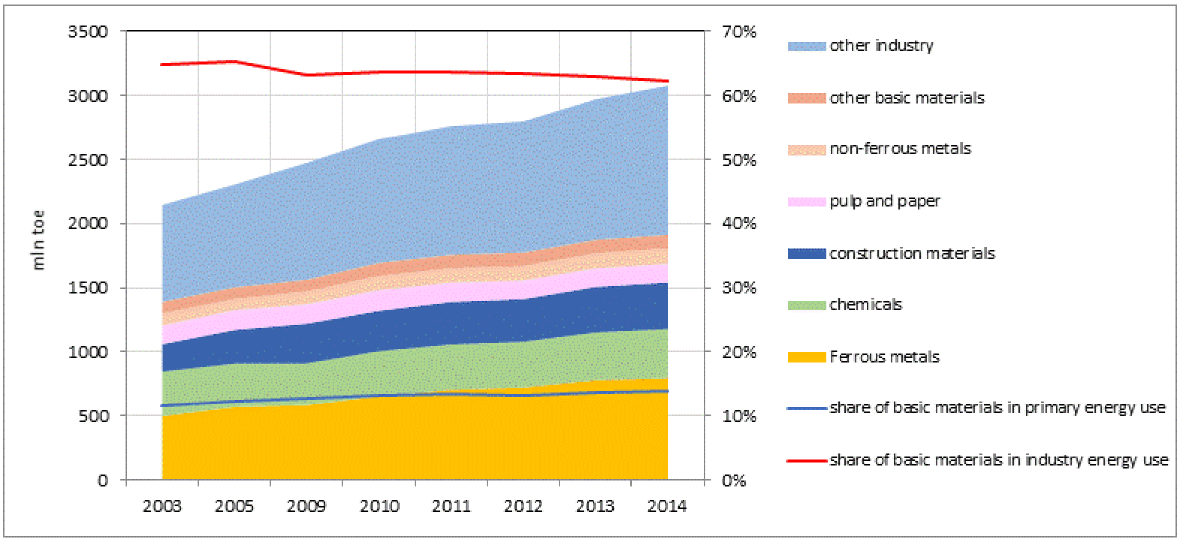
Source: IEA (2014).

Based on IEA statistics, industrial energy consumption can be broken down into segments such as basic materials production, including ferrous and non-ferrous metals, chemicals, pulp and paper, construction materials, and other types of basic materials, as well as ore mining and woodworking. In 2014, 1.66 bn TOE was consumed in basic materials production. This value should be topped off with 70.5 Mtoe consumed in coke production and 187 Mtoe corresponding to coal and coke consumption in blast furnace processes, or the total of 257.5 Mtoe, i.e., another 1.9% of primary energy consumption. IEA includes these energy inputs into ferrous metals production in the energy sector's figures. Therefore:

- ***The volume of energy consumption for production of basic materials amounted to 1.91 bn TOE, while the share of energy consumption for production of basic materials increased from 11% in 2003 to 14% in 2004.***

- ***As high technology and engineering industry developed, the share of basic materials in the aggregate energy consumption in the production sector decreased: in 2014, it was estimated at 62% versus 65% in 2003 (Fig. 3.2).***

Figure 3.2 Global Industrial Energy Use in 20032014



Source: IEA (2014).

3.2 Indirect Energy Consumption in Basic Materials Production

The estimated values of final energy consumption and associated GHG emissions fail to fully reflect the energy consumption in basic materials production along the energy chain. These estimates sum up energy savings related to energy carriers of different quality, exergetic potential, and cost, which is not exactly appropriate. Delivering one unit of energy to the end user requires additional energy consumption at different stages of the energy chain: energy losses in electric grids and heat and gas supply networks; energy consumption in transportation, beneficiation, processing, and mining of energy resources; fuel consumption in electric power and heat generation; electric power consumption in production of the relevant fuel, etc. Such indirect consumption can add up to significant volumes.

As a rule, indirect effects taken into consideration are limited to energy losses in generation and transmission of electric power and heat. In this case, electric power savings by end users equal to 1 tce translate into primary energy savings of 2.6–3 tce, taking into account the effects in the electric power sector (thermodynamic losses in electric power generation, auxiliary power consumption by power plants, and grid losses). Heat savings equal to 1 tce translate into primary energy savings of 1.2–1.3 tce (thermodynamic losses in heat generation and losses in heat supply networks). This simplified approach ignores the fact that fuel production and delivery to consumers also require electric power and heat, which in turns requires fuel, etc.

To cover the full range of indirect effects, back in 1992 it was proposed to present the energy efficiency improvement potential in an energy balance table and assess indirect effects using a method similar to the one applied by input-output models.[13] The calculation is based on the following relation between final and primary energy consumption: $PE = AE * PE + FE$, or $PE = (E - AE)^{-1} * FE$, where PE is the primary energy consumption (generation) vector by type

[13] Bashmakov I. Energy conservation: costs and benefits for Russia and the former USSR. Battelle Memorial Institute. PNL. Washington D.C. April 1992. See also: Bashmakov I. Costs and benefits of CO2 emission reduction in Russia / In Costs, Impacts, and Benefits of CO2 Mitigation [Editors: Y. Kaya, N. Nakichenovich, W. Nordhouse, F. Toth]. IIASA. Laxenburg. 1993. P. 453–474.

of energy carrier,[14] *AE* is the square matrix of consumption coefficients for primary resource *i* in generation and delivery of energy carrier *j* to consumers, and *FE* is the final energy consumption vector (including the net export of energy carriers). Each coefficient ae_{ij} shows how much coal, petroleum products, gas, electric power, and heat is required to provide, for example, one unit of coal to consumers. Any technology changes lead to adjustments in matrix *AE*. Matrix $(E\text{-}AE)^{-1}$ with coefficients based on global energy consumption in 2012 is available in Table 3.1.

Table 3.1 Matrix of Total Energy Consumption Coefficients per Unit of Energy Delivered to End Users

	Coal	Oil and oil products	Natural gas	Other solid fuels	NPPs	Renewable sources	Electric power	Heat
Coal	1.102	0.029	0.005	0.000	0.000	0.000	1.420	0.008
Oil and oil products	0.002	1.072	0.002	0.000	0.000	0.000	0.176	0.080
Natural gas	0.003	0.024	1.119	0.000	0.000	0.000	0.613	0.827
Other solid fuels	0.000	0.021	0.000	1.009	0.000	0.000	0.069	0.110
NPPs	0.001	0.006	0.001	0.000	1.000	0.000	0.378	0.006
Renewable sources	0.001	0.004	0.000	0.000	0.000	1.000	0.253	0.004
Electrical energy	0.004	0.019	0.002	0.000	0.000	0.000	1.150	0.004
Heat	0.001	0.010	0.001	0.000	0.000	0.000	0.004	1.063
Total	**1.114**	**1.187**	**1.130**	**1.009**	**1.000**	**1.000**	**4.064**	**2.101**
Total, including fuel transportation via pipeline or rail	**1.116**	**1.237**	**1.178**	**1.009**	**1.000**	**1.000**	**4.095**	**2.101**

Source: Calculated by the authors based on the world energy balance (IEA) for 2012.

To fill out matrix *AE,* statistical data must be regrouped, and certain values need to be estimated. In the input-output table, all consumption values are positive. In the energy balance, fuel inputs in energy conversion processes are negative, and energy outputs in relevant processes are positive. This approach helps avoid double counting, yet it results in an overestimation of the primary energy consumption in 2012 by approximately 11.6%. The double counting can be eliminated by subtracting the volumes embodied into electric power and heat from the fuel inputs in electric power and heat generation; however, in such case, the consumption balance of the relevant type of fuel is distorted by the same amount. Therefore, the values in the columns of matrix *A* specifying consumption of energy resources in electric power and heat generation shall be adjusted to reflect only thermodynamic losses during electric power and heat generation. Moreover, coal consumption in coke production and in blast furnace processes is reallocated to the final energy consumption in the ferrous metals sector. As a result, we have a new modified matrix of total energy consumption per unit of energy delivered to end users.

Table 3.2 Modified Matrix of Total Energy Consumption Coefficients per Unit of Energy Delivered to End Users

	Coal	Oil and oil products	Natural gas	Other solid fuels	NPPs	Renewable sources	Electric power	Heat
Coal	1.026	0.019	0.004	0.000	0.000	0.000	0.845	0.002
Oil and oil products	0.001	1.071	0.002	0.000	0.000	0.000	0.112	0.022
Natural gas	0.001	0.014	1.117	0.000	0.000	0.000	0.320	0.274
Other solid fuels	0.000	0.021	0.000	1.009	0.000	0.000	0.055	0.046
NPPs	0.001	0.004	0.000	0.000	1.000	0.000	0.252	0.005
Renewable sources	0.001	0.004	0.000	0.000	0.000	1.000	0.252	0.004
Electrical energy	0.004	0.019	0.002	0.000	0.000	0.000	1.146	0.002
Heat	0.001	0.010	0.001	0.000	0.000	0.000	0.003	1.062

[14] Adjusted to changes in available resources.

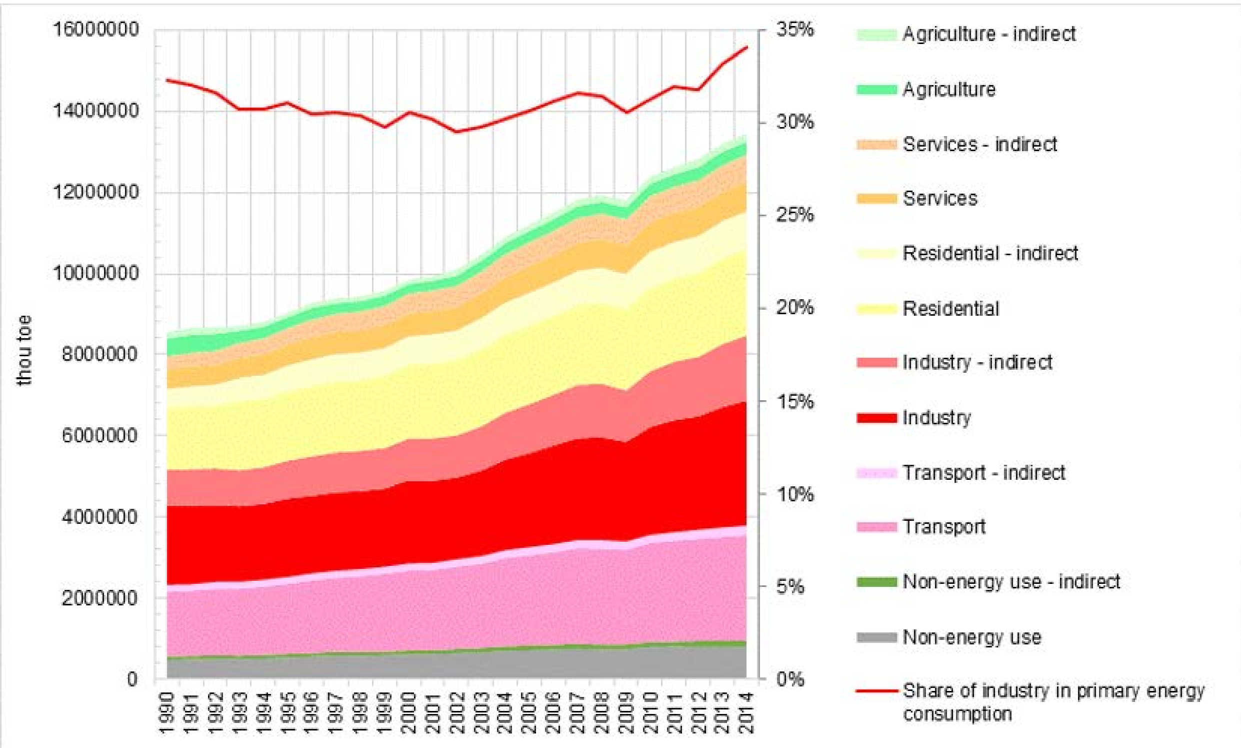
Total	**1.035**	**1.162**	**1.127**	**1.009**	**1.000**	**1.000**	**2.986**	**1.417**
Total, including fuel transportation via pipeline or rail	**1.037**	**1.211**	**1.175**	**1.009**	**1.000**	**1.000**	**3.008**	**1.417**

Source: Calculated by the authors based on the world energy balance (IEA) for 2012.

If the amount of oil products delivered to end users is equal to 1 tce, the total energy demand in the energy sector is increased by 0.16 tce, or by 0.21 tce if we add consumption in energy transportation. Electric power and heat have the maximum indirect effects. They exceed the coefficients traditionally used in indirect effect calculations.[15] Having taken all the indirect effects into account, we see that 1 tce of electric power savings by end users translates into total savings of 2.99 tce across the entire energy chain, while 1 tce of heat savings translates into 1.42 tce saved. According to this method, the direct and indirect energy consumption in the production sector in 2014 equals to 4.73 bn TOE, **or** 34.4% of primary energy consumption. One unit of direct energy consumption in the production sector is accounted for by 0.54 units of indirect consumption.

Another way to assess indirect effects is to distribute all the energy sector losses among end user sectors, proportionally to the relevant consumption volumes of individual energy carrier types. If we distribute energy consumption volumes of the energy sector among end user sectors according to the logic applied by IPCC, one unit of direct energy consumption in the production sector will translate into 0.52 units of indirect consumption (versus 0.45 units in 1990). ***In 2014, direct and indirect energy consumption in the industrial sector amounted to 4.68 bn TOE, i.e., 34% of the aggregate consumption of primary energy*** (Fig. 3.3). Thus, the industrial sector accounts for over one third of the global energy consumption.

Figure 3.3 Global Direct and Indirect Energy Use by Sectors in 1990–2014



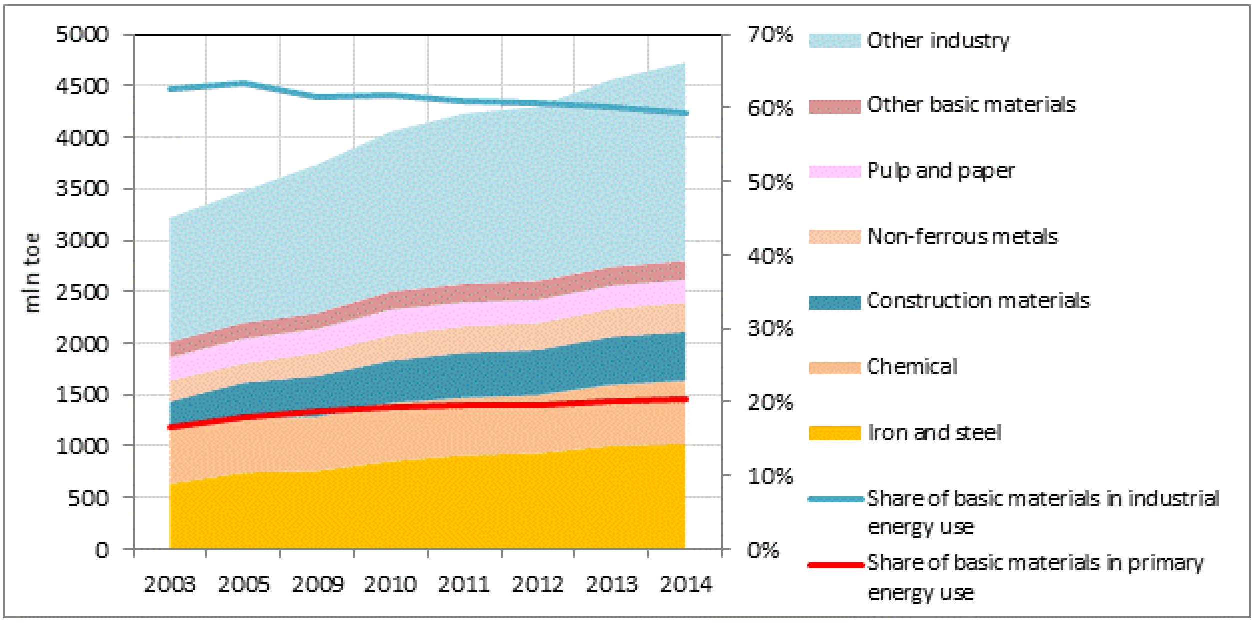
Source: authors' estimations based on IEA (2014).

[15] Worrell E., Neelis M., Price L., Galitsky C., Zhou N. World Best Practice Energy Intensity Values for Selected Industrial Sectors, 2007. // Lawrence Berkeley National Laboratory. – Berkeley, CA. 2007. - 44 p.

The difference in the results between the two above mentioned methods is merely 1%. However, the second method is more time-consuming when estimating indirect effects in specific sectors. Therefore, the first method was applied in this context. To estimate the indirect energy consumption in basic materials production, coefficients from the *Total* line of Table 3.2 were used for each material type. ***Consequently, the direct and indirect energy consumption in basic materials production in 2014 amounted to 2.8 bn TOE, or 59% of the total direct and indirect consumption in the production sector and 20% of the total primary energy consumption*** (Fig. 3.4). The former share has decreased since 2003, whereas the latter has grown.

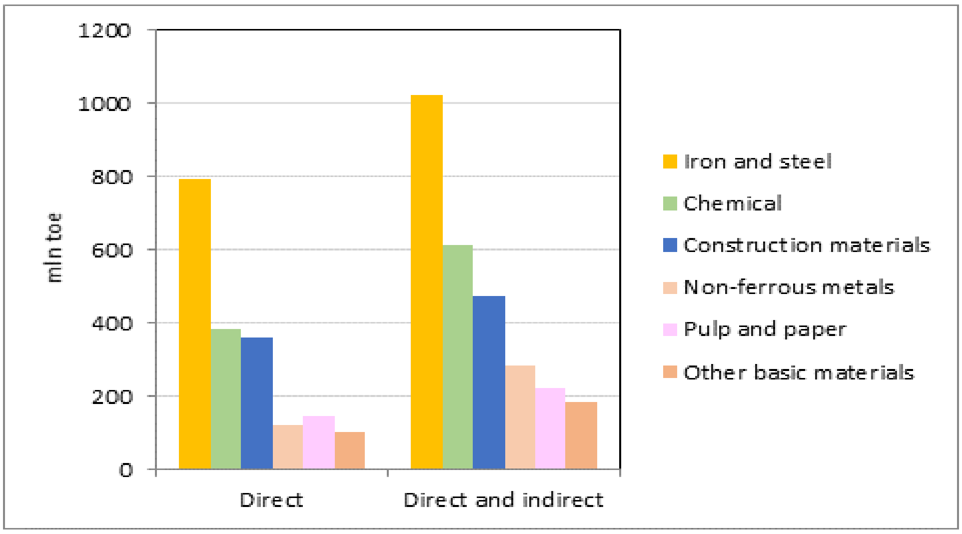
The ferrous metals sector is No. 1 in terms of both direct energy consumption and the total of direct and direct volumes: 795 and 1,025 Mtoe respectively (Fig. 3.5). Next comes the chemical sector with 384 and 613 Mtoe respectively. The construction materials sector is No. 3 with 363 and 474 Mtoe. The pulp and paper sector is the fourth in terms of direct emissions (145 Mtoe), yet only the fifth in terms of the total volume (222 Mtoe). And vice versa, the non-ferrous metals sector is No. 5 in terms of direct emissions (121 Mtoe) and No. 4 in terms of the total volume (283 Mtoe). The *Other Basic Materials* category comes last on the list.

Figure 3.4 Direct and Indirect Global Industrial Energy Use in 2003–2014



Source: authors' estimations based on IEA (2014) and table 3.1.

Figure 3.5 Direct and Indirect Energy Use by Key Basic Materials Industries in 2014



Source: authors' estimations based on IEA (2014) and table 3.1.

The coefficients in Table 3.2 reflect both indirect energy consumption ratios and the multiplicative effect of energy savings. The primary energy savings potential was calculated by summing up the final energy savings and the reduction in primary energy consumption within the energy sector, enabled either by increasing the efficiency of energy conversion technologies or by reducing the demand for feedstock conversion:

$$TEEP = \Delta FE + (AE-AE_{nt})*(PE-\Delta FE) \quad (3.1),$$

where AE_{nt} is matrix AE with new technology coefficients.

During potential assessment, the authors also considered the fact that base values of the primary energy vector must be adjusted to the reduction in final energy consumption volumes (ΔFE). That is, the more electric power is saved by end users, for instance, the less electric power has to be generated; therefore, the impact of a power plant upgrade will be somewhat lower than that of preserving the same generation volumes as in the base year. Thus, the increasing final energy savings somewhat reduce the savings in electric power and heat generation and transmission versus the base levels (Equation 1.2).

By taking indirect energy savings into account, we make energy savings and specific energy-saving inputs more commensurable. Three sets of coefficients can be applied when estimating indirect energy-saving effects: in the first case, the values from the last line of Table 3.2; in the second case, the values from the pre-last line of Table 3.2; in the third case (the simplest option), only electric power and heat coefficients are applied to estimate the indirect effects.

3.3 Values and Growth Rates of Specific Energy Consumption in Production of Selected Basic Materials

3.3.1 Concepts of Specific Energy Consumption

There are several concepts defining specific energy consumption in production of goods and services. The key difference between them is concerned with the scope of operations to produce a good or provide a service, included in the calculation:

- direct energy consumption at specific stages of the process involving production of specific goods or provision of services (specific energy consumption in iron ore mining, aluminium smelting, ethylene production, etc.; see Table 3.3);

- direct and indirect energy consumption at specific stages of the production process, including energy losses in generation of electric power or heat used to produce goods or provide services;
- direct energy consumption per unit of end-use product (steel, concrete), including the process mass balance and energy consumption at each one of the earlier process stages for both the end-use product and the raw materials and semi-finished goods used for its production;
- direct and indirect energy consumption per unit of end-use product at each process stage, including the losses in the course of electric power and heat generation for the purposes of its production;
- specific consumption of embodied energy, which means the energy input over the life cycle of the product at all the stages of its production process, production of its components, energy consumption in the course of their transportation to the location of final use, and the energy input embodied in the process equipment, industrial buildings and structures; in certain cases, it also includes the energy input in the course of product use throughout its lifetime.

The wider the limits of the system under analysis, the higher the specific energy consumption;

Table 3.3 Specific Energy Consumption in Production of Selected Industrial Goods

	Measurement units	BAT worldwide	Prevailing level worldwide	Comments
Oil refining	kgce/t	53.9	71–75	Global practice
Iron ore	kgce/t	8.5	10.0	Global practice
Iron ore concentrate	kgce/t	50.9	58.0	Global practice
Iron ore pellets	kgce/t	21.4		Karelsky Okatysh
Coke	kgce/t	119.0	143.0	Global practice
Pig iron	kgce/t	355.0	461.0	Global practice
BOF steel	kgce/t	-15.0	34.0	Global practice
EAF steel	kgce/t	50.0	80.6	Global practice
Rolled ferrous metal products	kgce/t	31	68	Global practice
EAF ferroalloys	kgce/t	700	700	Sverdlovsk Region
Aluminium	kgce/t	1,599	1,763–1,906	Global practice
Alumina	kgce/t	252–324	410–546	Global practice
Copper	kgce/t	215	471–490	
Synthetic ammonia	kgce/t	892–956	1,120–1,400	Global practice
Fertilisers	kgce/t	109	131	Global practice
Ethylene	kgce/t	458	683	Global practice
Polyethylene	kgce/t	65–68		Global practice
Polypropylene	kgce/t	34		Global practice
Polystyrene	kgce/t	31		Global practice
Polyvinylchloride	kgce/t	78		Global practice
Synthetic rubber	kgce/t	765		Global practice
Pulp	kgce/t	404	485	Global practice
Paper	kgce/t	241	320	Global practice
Cardboard	kgce/t	237	266	Global practice
Glass	kgce/t	116–132	222–250	Global practice
Bricks	kgce/t	51	68–137	Global practice
Cement	kgce/t	7–11	13	Global practice
Clinker	kgce/t	99	120–145	Global practice

Source: Calculated by CENEf based on the data available in Appendix 3.1.

IEA points out that in 2012, the global average specific direct energy consumption was 706 kgce/t and the specific direct emissions level was 1.8 t of CO_2eq per 1 t of steel. These figures include all the energy consumption along the multi-stage process chain within the current technological framework in the ferrous metals sector; however, they do not include emissions related to electric power and heat generation. In EAF steel production, direct emissions are either zero or negligible. However, taking into account energy consumption during this process, the coefficient will be equal to 349 kg of CO_2/t = 655 kW·h/t * 533 g of CO_2/kW·h. This value cannot be directly compared to the volume of emissions per tonne specified above (1.8 t of CO_2eq/t).

In addition to estimating specific energy consumption per unit of good, it is also essential to measure consumption per unit of service involving use of a certain product: strength, conductivity, movement, cooling, etc. As it was demonstrated in Chapter 2, the specific energy consumption associated with artificial lighting has decreased more than 7,600-fold since 1700. This decrease was to a large extent prompted by the substitution of one product (tallow candles) with another (gas lanterns and later electric light bulbs, from incandescent to fluorescent to LED).

Embodied energy* is *the total energy consumption needed to support the entire product life cycle, including energy consumption in processes such as feedstock mining and transportation, production of materials and goods, assembly, installation, and dismantling of buildings and machinery, breakup and demolition, disposal and burial. The methods of life cycle energy consumption assessment have been joined into a group called Life Cycle Analysis, and they are regulated by a series of standards ISO 14040–14044.

The database maintained by the University of Bath (UK)[16] provides estimates of embodied energy volumes in steel produced from primary materials (35.4 MJ/kg, or 1.2 tce/t) and estimates of associated embodied emissions (2.89 t of CO_2eq/t). For steel made from metal scrap, the latter coefficient is equal to 0.47 t CO_2eq/t. Possible steel coefficients vary greatly depending on the scope of energy consumption in energy generation taken into account.

Thus, it is important to use comparable metrics and select suitable specific energy consumption indicators per relevant output units, optimal for achievement of assigned objectives. This also refers to summing up the effects. It is wrong to add up embodied energy inputs for pig iron, steel, and rolled products because they represent different stages of the same production process, with rolled metal as the end-use product.

To achieve the objective of this study, it is essential to assess the complex effect from integration of nanotubes into traditional materials; for that reason, the concept of embodied (materialised) energy consumption is selected for further effect assessment. On the other hand, the concept of direct and indirect energy consumption and emissions was applied to estimate the share of basic materials production in the overall energy consumption and total anthropogenic emissions.

3.3.2 Concept of Embodied Energy Use

In the context of this study, values of specific embodied energy use and specific embodied GHG emissions are taken predominantly from the ICE database (Inventory of Carbon & Energy. V2.0) of the University of Bath. Therefore, below we provide a brief overview of the development concept and parameters of this database.

The scope of analysis is determined using the approach "from cradle to grave", or "from quarry to landfill." Even within the defined scope, there are multiple options, affecting the final value of specific emissions, including the degree of recovery and use of recycled materials, the

[16] University of Bath. 2011 ICE (Inventory of Carbon & Energy). V2.0. www.bath.ac.uk/mech-eng/sert/embodied.

applied technology framework, transportation methods, etc. The ideal scope of life cycle analysis is presented in Table 3.4.

Table 3.4 Scope of Embodied (Materialised) Energy and Emissions Analysis

Indicator	Scope of analysis
Input energy	Converted to primary energy equivalent
Primary energy	Measured from the point of fossil fuel extraction
Primary electricity	Included. Estimated based on energy content of electric power, not substituted fuel
Renewable energy, including electric power	Included.
Heat capacity	Estimated according to maximum heat capacity. For many fuel types, the value will be higher than the result of the fuel consumption calculation method based on minimum heat capacity, widely applied in Russia and Europe
Calorific ratios for organic fuels	Included when the resource is used as fuel and excluded when it is used as feedstock
Fuel used for non-energy needs	Included in the estimate but considered separately
Carbon capture and disposal, biological carbon storage	Not included
GHG emissions associated with fuel consumption	Including all CO_2 emissions in the course of production
GHG emissions from industrial processes	Included
Other GHG emissions	Included
Transport sector	Included according to the scope “from quarry to landfill (dump site).”

Source: University of Bath. 2011 ICE (Inventory of Carbon & Energy). V2.0 - Update Notes.

ICE database 2.0 provides emission values both for CO_2 alone and for all gases converted to CO_2 eq; biogenic carbon storage and capture are not included but tracked separately. The embodied energy and GHG emissions database of the University of Bath covers almost 200 types of materials. Specific energy consumption and emissions (carbon footprint) are estimated based on input data from multiple reviewed sources (over 250) using a special methodology and five criteria: compliance with the methodology prescribed by ISO; scope of analysis; source of data or country of origin; time elapsed since data publication; embodied carbon estimates depending on the energy mix used in production. The great variance among the estimates is due to the discrepancies in approaches applied by different researchers. Feedback from professional users was an important factor in selecting best values of specific parameters in the “quarry to landfill” chain. The discrepancies between estimates in different sources can be attributed to the differences in the definition of the scope of analysis, estimated composition and specific materials use and energy consumption at each stage, which can vary depending on the country, granularity, and analysis methods, as well as the degree of metal scrap recycling.[17]

General view of the embodied energy *Eemb* estimation process based on the mass balance method:

$$Eemb = (1-m)*(\sum_i X_i * a_i + Pe) + Te \tag{3.2}$$

where m is the share of production losses (%); X_i is the mass (kg) of materials used in production; a_i is the specific consumption of embodied energy per unit of raw material i consumed; Pe is the energy consumed to produce the end-use product from raw materials; and T is the energy consumed to deliver the end-use product. To estimate the energy embodied in one product item, we need to know specific embodied energy values for other product items. Thus,

[17] Hammond, G.P. and Jones, C.I. 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers – Energy, 161 (2). pp. 87–98. ISSN 1751-4223.

this method can be used only for approximate estimation of embodied energy, with the accuracy depending on the number of iterations.

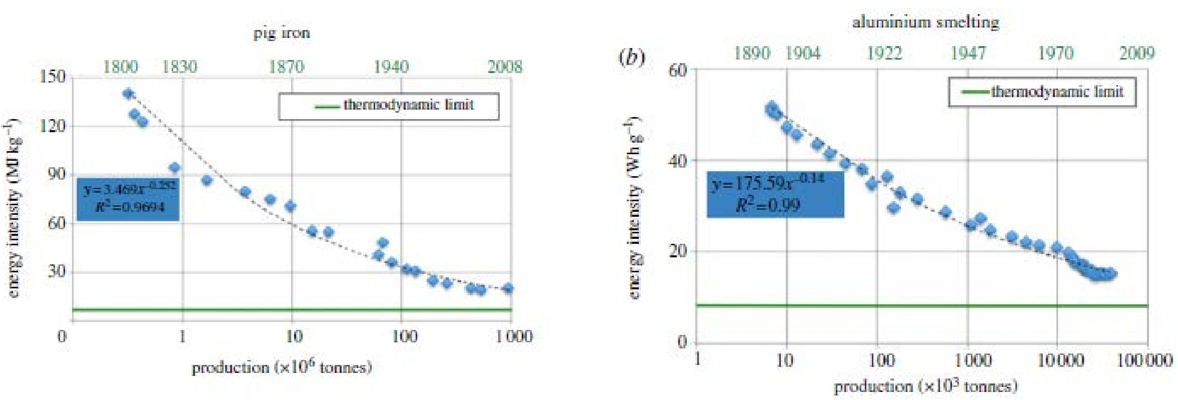
On the other hand, the input-output method applied to estimate indirect energy consumption is free from this drawback. Normally, input-output tables are expressed in money terms and aggregate data to a certain degree which might be too high to estimate embodied energy. However, the input-output method also has its shortcomings. Building an input-output table with values expressed in physical terms is a time-consuming task; for this reason, statistical offices usually refrain from drawing up such tables, while expert estimates are published quite seldom and too late.[18]

After drawing up an input-output table in physical terms, embodied energy can be estimated using the following formula: $e_{emb} = e*(I - A)^{-1}$, where e is the vector of direct specific energy consumption per unit of product of each type, I is a unit matrix, and A is the input-output matrix with values expressed in physical terms. The results obtained by applying the input-output method can be different from the values calculated using the mass balance method, which is based on tree-like stage-by-stage flow charts of material production processes, including estimated material inputs and outputs in each node of the chart.

3.3.3 Changes in Specific Energy Consumption over Time

In 2000–2012, energy intensity of industrial production decreased by 12%, i.e., it annually decreased by slightly less than 1%. The value decreased by 13% in the USA, whereas in China it grew by 4%. Specific energy consumption decreases along with technology advancement and scale-up of material production. There is a concept of learning curves (or experience curves) that demonstrates how the specific energy consumption declines as the production scale grows. Fig. 3.6 shows retrospective dependencies for the downward trend in specific consumption in pig iron and aluminium production. The progress ratio is calculated using the formula: $PR = [P_0 * 2^{-a}] / [P_0 * 2^{-a}] = 2^{-a}$, where a is an empirical estimate of the specific consumption reduction ratio (see Fig. 3.6). According to the correlation shown in Fig. 3.6, a two-fold growth of material output resulted in a reduction of specific consumption by 16% in pig iron production and by 9% in aluminium production. All in all, over the entire history of production of these materials, the specific energy consumption has decreased almost 10-fold for pig iron and 3.3-fold for aluminium. The annual average rate of decrease was 1–1.5%.

Figure 3.6 Learning Curves—Specific Energy Use Reduction Trend Driven by Scaled Up Materials Production



Pig iron production   Aluminium production (electricity)

[18] Hannon B. 2013. Energy and materials conservation: applying pioneering research and techniques to current non-energy material conservation issues. PhilTrans R Soc A 371: 20120005.http://dx.doi.org/10.1098/rsta.2012.0005.

Source: Gutowski TG, Sahni S, Allwood JM, Ashby MF, Worrell E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. PhilTrans R Soc A 371: 20120003.http://dx.doi.org/10.1098/rsta.2012.0003

As the values approach the thermodynamic (theoretical) minimum, the rate at which specific energy consumption decreases becomes lower. In 2000–2012, worldwide average specific energy consumption for steel production decreased only by 5%, that for production of primary aluminium remained almost on the same level (since 1980, it had been decreasing only by 0.4% every year).[19]

3.4 Reduction Potential for Specific Energy Consumption

As specific consumption values approach the theoretical minimum (standard Gibbs energy input to convert one type of material to another), the potential for further reduction is shrinking (Fig. 3.6). Nevertheless, according to Table 3.1, for many types of materials, the gap between the specific values achieved by most popular technologies and the BAT worldwide is still significant. ***Thus, the potential for energy saving in materials production is not yet exhausted. According to the estimates made by IPCC, the energy intensity of the industrial sector can be further reduced by 25% if all the currently applied technologies are replaced with BAT. UNIDO estimates the potential at 26% and points out that two thirds of that volume belongs to energy intensive industrial production; however, the relative savings potential of such facilities is below the average level in the production sector.[20] The estimate made by IEA equals to 20%.***[21] These are global average values.[22] UNIDO estimates the potential at 15–20% in developed countries and 30–35% in developing economies. In countries with obsolete technologies, such as Russia and Ukraine, the reduction potential for specific consumption is 43%.[23]

The gap versus the theoretical minimum can be further narrowed by means of innovations and improvement of BAT. According to the estimates made by IPCC, such efforts will provide an opportunity to reduce the specific energy consumption by another 20%.

In its 2009, 2012, and 2015 Energy Technology Perspectives reports, IEA estimates the potential of reducing the specific energy consumption at 19% in steel production, 30% in cement production, 15% in chemicals and petrochemicals (or 36% taking into account use of petroleum and natural gas for chemical applications), and 15% in pulp and paper production. In steel production, no major reduction of specific energy consumption is expected until 2025. As for cement production, the relevant indicator is supposed to decline by 9%.[24] In IIASA's forecast of specific energy consumption in production of basic materials, no significant reduction is envisaged until 2030, either (GEA, 2012). By 2050, the following decrease of specific energy

[19] IEA. 2015. Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action. IEA/OECD. Paris. 2015.
[20] Global Industrial Energy Efficiency Benchmarking. An Energy Policy Tool. Working paper. UNIDO. November 2010.
[21] IEA. 2012. Energy technology perspectives 2012. Pathway to a clean energy system. IEA/OECD. Paris. 2012.
[22] Fischedick M., J. Roy, A. Abdel-Aziz, A. Acquaye, J. M. Allwood, J.-P. Ceron, Y. Geng, H. Kheshgi, A. Lanza, D. Perczyk, L. Price, E. Santalla, C. Sheinbaum, and K. Tanaka, 2014: Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlцmer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[23] I. A. Bashmakov. Energy Efficiency Improvement in the Russian Production Sector. Moscow, March 2013. www.cenef.ru
[24] IEA. 2015. Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action. IEA/OECD. Paris. 2015.

consumption is possible: for steel—by 24–36%, for cement—by 28%, for aluminium—by 20–27%.[25]

3.5 Specific Energy Consumption in Transportation of Basic Materials

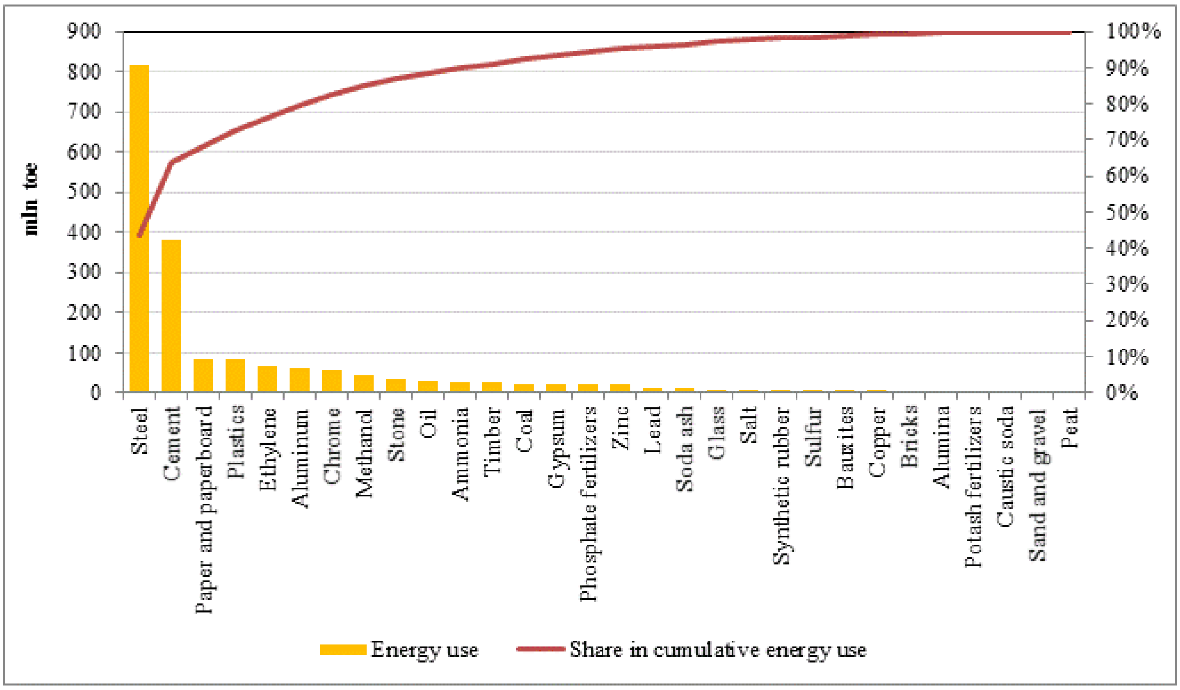
In the freight turnover of basic materials, approximately 60% belongs to water-borne shipments, 18% to railway, and 22% to trucks. As for transportation of basic materials, the share of ships (mostly sea) is higher—up to 90%; the share of railway is around 6%, and that of trucks is approximately 4%. Specific energy consumption per unit of transportation effort varies greatly depending on the type of transport: 0.04–0.18 MJ/tkm for sea shipments (bulk carriers), 0.24–0.34 MJ/tkm for railway, and 3.6–6.6 MJ/tkm for trucks (GEA, 2012; IPCC, 2014; IEA, 2009). Over the last 20 years, these values have decreased, but not significantly—approximately by 10%.[26] There is a potential for further reduction of specific energy consumption. For instance, new hybrid trucks consume 2.4–3.6 MJ/tkm. The share of air in the freight turnover is small; particularly, in case with basic materials, it is close to zero.

3.6 Estimated Energy Consumption in Production of the Key Types of Basic Materials

To estimate energy consumption in the production of key types of basic materials, the authors referred to reported production volumes in 2013–2014 and global average specific energy consumption data, partly available in Table 3.5. In addition, specific consumption and types of basic materials were selected to avoid double counting. That is, the energy consumption in steel production already includes the energy inputs in production of iron ore, pellets, concentrate, pig iron, and coke; therefore, these materials are not listed in the table. Also, the specific energy consumption in brick production already includes the energy inputs in production of clay, so there are no separate data for clay production. To the contrary, the specific energy consumption in aluminium production does not include the energy inputs in bauxite mining and alumina production. The estimates are available in Fig. 3.7.

[25] Ibid.
[26] IEA. 2009. Transport energy and CO2. Moving towards sustainability. IEA/OECD. Paris. 2012.

Figure 3.7 Energy Use for Key Basic Materials Production



Source: authors

Accordingly, 30 types of basic materials account for 1.87 bn TOE of energy consumption. This figure is higher than the above mentioned energy consumption volume in the sectors producing basic materials (metals, ore, chemicals and petrochemicals, woodworking, pulp and paper, and construction materials)—1.6 bn TOE; the reason is that in certain cases (petrochemical products), specific energy consumption includes the feedstock and/or the data on average global specific energy consumption are not sufficiently reliable. Fig. 3.7 shows that ***the majority of energy consumption (80%) belongs to a small group of materials: steel, cement, paper and cardboard, plastics, ethylene, and aluminium.*** The consumption volumes are the following: 814 Mtoe for steel, 380 Mtoe for cement, 85 Mtoe for paper and cardboard, 83 Mtoe for plastics, 67 Mtoe for ethylene, and 62 Mtoe for aluminium. The remaining 24 types of basic materials consume 382 Mtoe altogether. These figures are close, yet somewhat different from the values specified above for the relevant production sectors.

3.7 Embodied Energy Use

Estimation of energy consumption in basic materials production based on the concept of embodied energy use yields different results and a different order of materials in the consumption ranking (Fig. 3.8).

Figure 3.8 Embodied Energy Use for Key Basic Materials Production

Source: authors

The total embodied energy consumption in production of 32 types of basic materials (materials used as feedstock for their production are not included in the calculation to avoid double counting) amounted to 3,815 Mtoe. This value constitutes 27.8% in the global primary energy consumption in 2014,[27] and it is more than four times greater than the direct energy consumption in production of such materials (see Fig. 3.8).

The calculation is based on the information from the database of the University of Bath,[28] data by M. Ashby (2009)[29] and Low Tech Magazine data.[30] The total also includes the energy inputs into transportation of materials. In addition to this year's data, the total includes historical data on embodied energy consumption, although the share of the latter is small.

The majority of embodied energy consumption belongs to steel (33.3%), plastics (19.8%), cement (13.6%), paper and cardboard (7.6%), timber (6.7%), aluminium (4.8%), ammonia (3.2%), and ethylene (2.3%). These eight groups of basic materials account for 90% of the total embodied energy consumption in the production of all the 32 types of basic materials.

The embodied energy consumption data for the key types of basic materials reviewed in this study are available in Table 3.5. Not all the energy consumption volumes specified in the table can be summed up. For the avoidance of double counting, do not add the energy consumed for

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[27] IEA measures primary energy consumption based on minimum heat capacity whereas embodied energy use values are estimated based on maximum heat capacity; therefore, the share can be somewhat lower—around 26.6%.

[28] University of Bath. 2011 ICE (Inventory of Carbon & Energy). V2.0. www.bath.ac.uk/mech-eng/sert/embodied.

[29] Ashby M.F. 2009. Materials and the Environment: Eco-Informed Material Choice Materials and the Environment. Butterworth-Heinemann is an imprint of Elsevier 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA. Linacre House, Jordan Hill, Oxford OX2 8DP, UK.

[30] http://www.lowtechmagazine.com/what-is-the-embodied-energy-of-materials.html

product production to the energy consumed for production of raw stock and semi-finished products of which the product is made when estimating the total consumption of embodied energy. The summed up lines of Table 3.5 are highlighted in bold.

Table 3.5 Embodied (Materialised) Energy Consumption in Production of Basic Materials Selected for Analysis

Material	Production volumes in 2013–2014	Embodied energy consumption	Specific embodied energy consumption		
			value used	minimum value	maximum value
	kt (thousand m^3)	ktoe	GJ/t (GJ/m^3)	GJ/t	GJ/t
Steel	**1,662,000**	**1,231.4**	**31.25**	**29.0**	**32.0**
Primary aluminium	**49,300**	**256.3**	**217.70**		
Processed aluminium	**40,000**	**27.7**	**29.00**		
Primary copper	**13,800**	**18.8**	**57.00**		
Recycled copper	**7,100**	**2.8**	**16.50**		
Synthetic rubber	**16,683**	**39.8**	**99.88**	**64.4**	**147.6**
Timber	**(1,737,400)**	**265.8**	**(153.00)**		
Wood-based panels, including:					
Plywood	87,300[1]	31.3	15.00	7.58	27.60
Chipboard	64,500[1]	22.4	14.50	2.00	36.29
Wood-based panels	13,300[1]	5.1	16.00	3.43	61.26
MDF	79,000[1]	20.8	11.00	8.96	11.90
veneer	5,300[1]	2.9	23.00		
Plastics, incl.:	**299,000**	**752.0**	**105.30**	**45.70**	**162.00**
Thermoplasts, incl.:					
ABS resins	5,800[2]	10.8	77.83	1.24	114.20
polyamide, incl.:	7,700	23.7	137.60		
polyamide 6	4,300	12.4	120.50		
polyamide 6.6	3,400	11.3	138.60		
polyvinylchloride	43,000	72.5	70.61	15.10	120.00
polypropylene	52,200	117.2	93.97	40.20	171.00
polystyrene	14,600	33.2	95.07[3]		
polyester, incl.:[4]	53,300	112.7	88.50		
polyethylene terephthalate	28,000[5]	60.5	90.45	21.90	153.30
polyethylene, incl.:	56,200	120.4	89.72	59.04	188.59
low-density	23,300	43.3	77.72	51.00	103.00
linear low-density	7,400	28.7	162.14		
high-density	25,500	48.5	79.67	18.60	103.00
polycarbonate	3,300	8.9	112.90	80.30	158.51

Material	Production volumes in 2013–2014	Embodied energy consumption	Specific embodied energy consumption		
			value used	minimum value	maximum value
	kt (thousand m^3)	ktoe	GJ/t (GJ/m^3)	GJ/t	GJ/t
Thermosetting plastics, incl.:					
polyurethane	11,700	22.4	80.10	65.20	110.00
epoxy resin	2,410[6]	6.8	117.50	105.00	130.00
Cement	**4,180,000**	**549.1**	**5.50**		
Concrete	26,158,000	468.6	0.75		
Clay	56,500	8.8	6.50		
Ceramics	**191,000**	**45.6**	**10.00**	**2.50**	**29.07**
Construction composites, incl.:	**6,288**	**17.2**			
fibreglass plastic	6,200	16.7	112.50	107.00	118.00
carbon fibre-reinforced plastic	88	0.5	259.00	183.00	286.00
Insulation materials	**38,106**	**3.6**			
mineral wool	3,100	1.3	17.00		
fibreglass wool	3,500[7]	2.3	28.00		
Total (without double counting)					

1: calculated based on cubic metres data for average density
2: 2006 data
3: the average of specific embodied energy use for foam polystyrene, high-impact polystyrene, and thermal polystyrene
4: usually thermoplasts, may be thermosetting plastic
5: 2012 data
6: 2012 data
7: fibreglass wool defined for fibreglass plastics class

The conclusion is that ***the energy consumption associated with production of specific basic materials covered by this study is equal to 3,227 Mtoe, or 24% of the total global consumption of primary energy in 2014.***

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4 Greenhouse Gas Emissions from Production, Transport and Use of Basic Materials

4.1 Changes in Global Anthropogenic GHG Emissions in 1970–2014

4.1.1 All Greenhouse Gases

Estimates of changes in global emissions by the main sectors of the global economy over 1970–2010 are based on EDGAR/IEA database created by IPCC Working Group III when preparing the Fifth Assessment Report.[31] It contains an array of sectors and subsectors: Agriculture, Forestry and Other Land Use (AFOLU) sector, residential buildings, public buildings, various means of transportation, energy sector, and production sector. The production sector includes the most carbon intensive branches and products: ferrous industry, non-ferrous industry, cement, limestone and other non-metallic minerals, chemical products, pulp and paper products.

Statistical series of EDGAR base end on 2010. CENEf has extended these series to 2014 using various auxiliary indicators (Fig. 4.1). Emissions from production of materials (cement, aluminium, steel, pig iron, and limestone) were estimated using the data on their outputs or production growth rates in 2011–2014 on the basis of USGS data for 2012–2014[32] and with account for changes in energy intensity and carbon intensity, as reported by Enerdata.[33] Information on paper output in 2010–2011 was taken from Japan Paper Association,[34] information for 2012–2013 was taken from the website of Swedish Forest Industries Federation;[35] the 2014 production was assumed to be equal to the level of 2013. Emissions from the chemicals sector were estimated on the basis of the industrial production index of the chemical industry, as reported by UNIDO.[36] The changes in emissions from other production branches were estimated in proportion to the worldwide production index of the processing industry and with account for energy intensity and carbon intensity reduction, as reported by Enerdata. GHG emissions from transport and residential buildings for 2011–2012 were estimated on the basis of IEA data on CO_2 emissions from these sectors,[37] and then—according to the changes in energy consumption by these sectors, also on the basis of IEA data[38] extrapolated to 2013–2014. Emissions from residential buildings were estimated in proportion to energy consumed by this sector in 2011–2012 according to IEA data,[39] and then—according to the constant correlation with the volume of emissions from residential buildings.

[31] JRC / PBL (2013). Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2 FT2010. European Commission, Joint Research Centre (JRC) / PBL Netherlands Environmental Assessment Agency. Available at: http://edgar.jrc.ec.europa.eu; IEA (2012). CO2 Emissions from Fuel Combustion. Beyond 2020 Online Database. IEA, Paris, France. Available at: http://data.iea.org; IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[32] U.S. Geological Survey, 2012-2015, Mineral commodity summaries 2012-2015: U.S. Geological Survey.

[33] Global Energy Statistical Yearbook 2015, Enerdata.

[34] Japan in the World (according to the figure in Annual Review of Global Pulp and Paper Statistics by RISI). (In Japanese). Japan Paper Association. Retrieved Dec.17, 2011 and Nov.15, 2012.

[35] http://www.forestindustries.se/

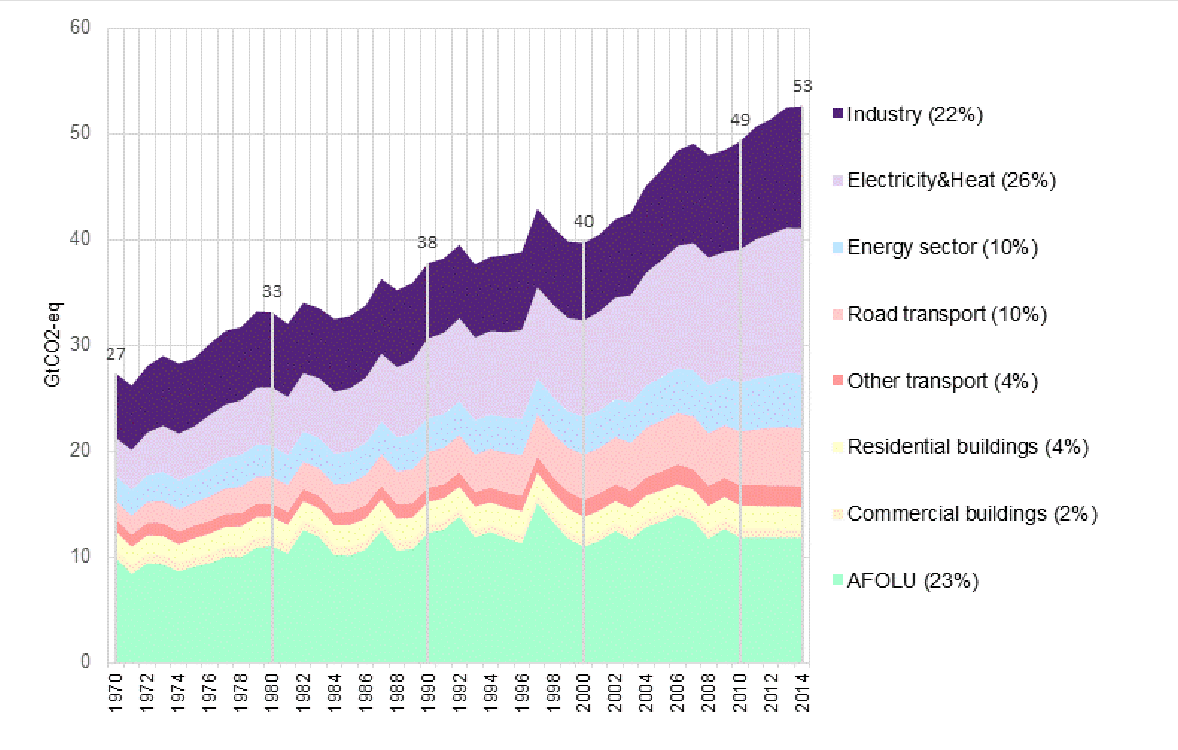
[36] Quarterly publications of World Manufacturing Production, available at https://www.unido.org/en/resources/publications/cross-cutting-issues/world-manufacturing-production-reports.html.

[37] CO2 Emission from Fuel Combustion. International Energy Agency. OECD, Paris, France.

[38] Energy Balances Of Non-OECD Countries (2014 Edition). OECD/IEA, 2014.

[39] Energy Balances Of Non-OECD Countries (2014 Edition). OECD/IEA, 2014.

Figure 4.1 GHG Emissions Dynamics by Sector in 1970–2014



	Average annual growth rates				
	1971-1980	**1981-1990**	**1991-2000**	**2001-2010**	**2011-2014**
Total	**1.94%**	**1.33%**	**0.51%**	**2.19%**	**1.56%**
AFOLU	1.07%	1.08%	-1.14%	0.76%	0.00%
Residential buildings	0.62%	1.54%	-0.21%	0.47%	-1.43%
Public buildings	1.43%	-1.91%	-0.65%	1.53%	-1.23%
Energy sector	3.53%	2.43%	1.68%	3.10%	2.24%
Industry	**1.49%**	**0.04%**	**0.31%**	**3.37%**	**3.17%**
Transport	3.05%	2.25%	2.22%	1.69%	1.75%

Notes: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use.

Source: 1970-2010—EDGAR/IEA database, 2011-2014—estimated by CENEf-XXI.

Emissions from the AFOLU sector were recorded at the level of 2010, because this sector has not shown any trend in the GHG emission changes since 1980. Emissions from the energy sector in 2011–2012 were estimated in proportion to IEA data[40] on CO_2 emissions from this sector; emissions for 2013–2014 were estimated by establishing the functional connection between growth rates of emissions from the energy sector and the growth rates of the global GDP. The global GDP for 2000–2013 was taken according to the World Bank data.[41] In 2014, the preliminary estimate of GDP growth was taken according to the IMF data.[42]

Fig. 4.1 shows the concluding picture of changes in direct GHG emissions (CO_2, CH_4, N_2O, etc.) by the main sectors of the global economy in 1970–2014.

In 2011–2014, global anthropogenic GHG emission was growing slightly slower than in 2001–2010; by 2014, it approached 52 billion tonnes (bt) of CO_2eq.

[40] CO_2 Emission from Fuel Combustion. International Energy Agency. OECD, Paris, France.
[41] http://databank.worldbank.org/data/views/reports/tableview.aspx.
[42] Online database of the International Monetary Fund http://www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx.

In 1970–2000, transport emissions demonstrated the fastest growth, but after 2000, production sector took the lead. In 2000–2014, GHG emissions from production sector grew by 64% and increased half or twice as fast as total emissions.

In 2014, production sector directly contributed 11.6 bt of CO_2eq to the total GHG emission, i.e., it accounted for 22% of anthropogenic emission. Production sector ranks second in terms of global GHG emissions after generation of electric and thermal energy (26%). Production sector, net of AFOLU sector, accounts for 28%.[43]

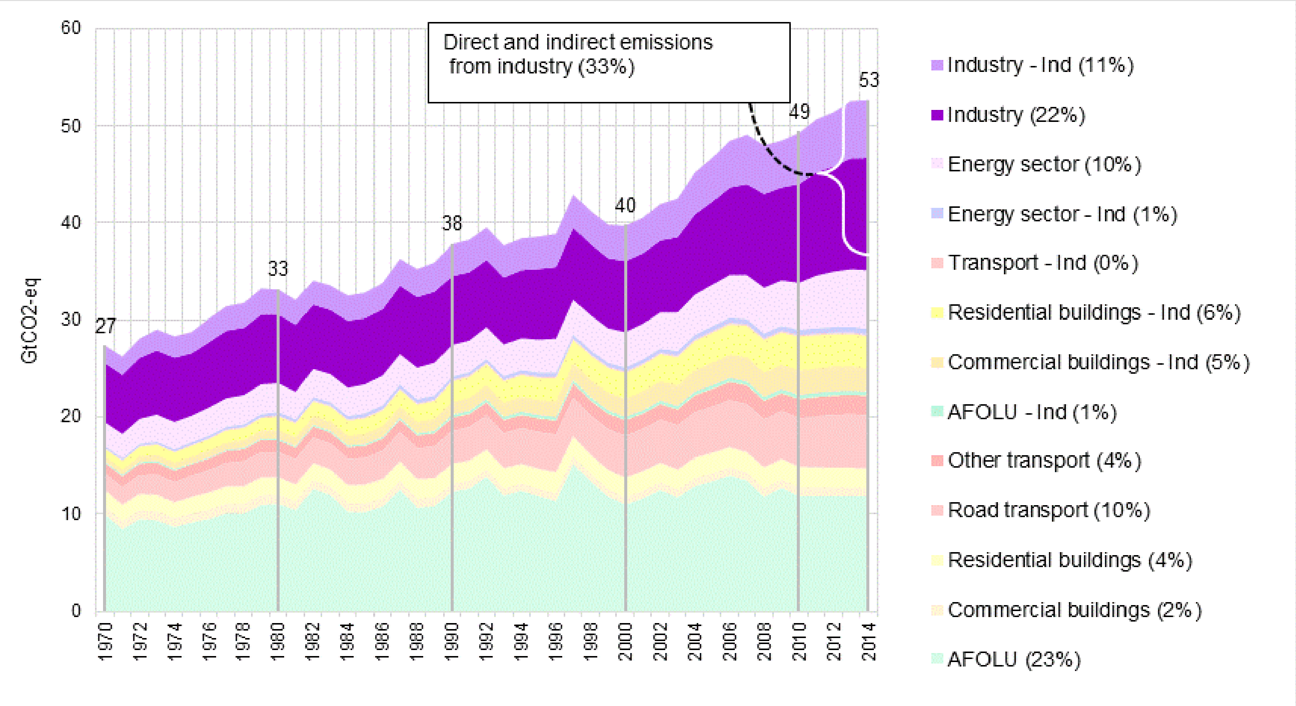
The alternative approach to estimating the sectors' contribution to emission distributes emissions from fuel combustion in the course of heat and electric energy generation among end sectors (indirect emissions) in proportion to their consumption volumes (Fig. 4.2).

Indirect emissions for 1970–2010 were determined on the basis of EDGAR/IEA database; CENEf has extended the values to 2011–2014 in proportion to changes in direct emissions from certain sectors and BP estimates of energy generation in 2013–2014.[44] After such allocation, the energy sector accounts only for emissions from use of fuel for own needs and emissions in the course of extraction, treatment and transportation of fuel resources.[45]

Indirect GHG emissions from production sector account for 11% of all emissions, and the production sector's share in total emissions reaches 33%, or 43% net of AFOLU.

In 2014, total direct and indirect GHG emissions from production sector were estimated at 17.5 bt of CO_2eq. Since 2000, they have grown by 60%.

Figure 4.2 Evolution of GHG Emissions from Key Sectors and Distribution of Emissions from Heat and Electricity Generation by Sectors (Indirect Emissions) in 1970–2014



[43] IEA gives a lower estimate for 2012: 8,389 million tonnes (Mt) of CO_2. This estimate does not include other GHG. IEA. 2015. Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action. IEA/OECD. Paris. 2015.
[44] BP Statistical Review of World Energy. June 2015.
[45] Broadly speaking, in the global economy, which is a closed economy, these emissions should also be allocated among end consumption sectors.

	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Total	**1.94%**	**1.33%**	**0.51%**	**2.19%**	**1.56%**
AFOLU	1.07%	1.19%	-1.08%	0.81%	0.00%
Residential buildings	2.64%	2.61%	1.09%	1.87%	-1.43%
Public buildings	3.35%	1.51%	2.23%	2.57%	-1.23%
Energy sector	2.21%	0.78%	1.06%	2.79%	2.16%
Industry	**2.01%**	**0.73%**	**0.55%**	**3.49%**	**3.17%**
Transport	3.04%	2.27%	2.14%	1.70%	1.75%

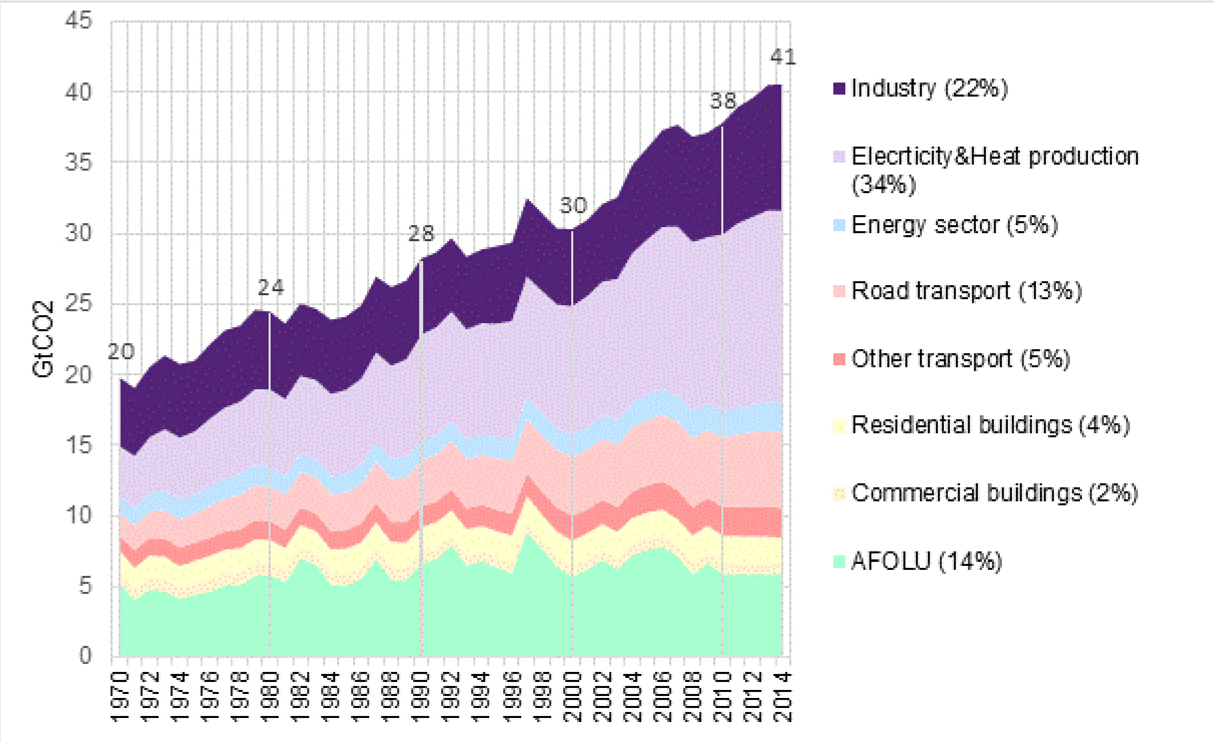
Note: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use. Energy sector does not include emissions from heat and electricity production, as they are related to end-use sectors.

Source: 1970–2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

4.1.2 CO_2

EDGAR/IEA database highlights carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Using the procedure described above, CENEf has estimated the changes in CO_2 emissions for 2011–2014 (Fig. 4.3). Similar procedures were used to estimate CH_4 and N_2O emissions in 2011–2014.

Figure 4.3 CO_2 Emissions Dynamics by Sector in 1970–2014



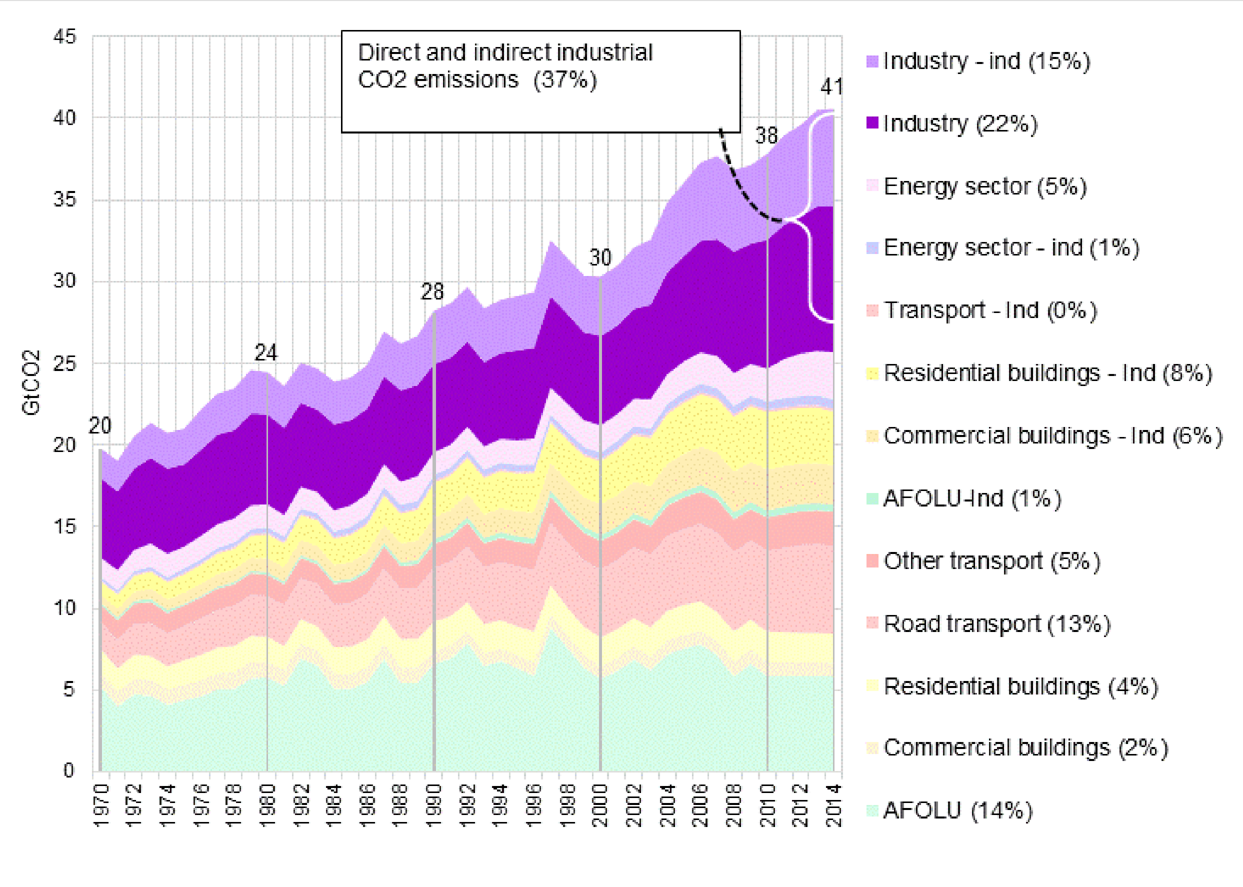
	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Total	**2.08%**	**1.45%**	**0.70%**	**2.24%**	**1.92%**
AFOLU	1.00%	1.38%	-1.48%	0.28%	0.00%
Residential buildings	0.59%	1.52%	-0.08%	0.39%	-1.43%
Public buildings	1.43%	-1.91%	-0.64%	1.53%	-1.23%
Energy sector	3.86%	2.60%	1.89%	2.98%	2.24%
Industry	**1.28%**	**-0.22%**	**0.14%**	**3.73%**	**3.17%**
Transport	3.44%	2.25%	2.22%	1.69%	1.75%

Notes: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use.

Source: 1970–2010—EDGAR/IEA database, 2011-2014 – estimated by CENEf-XXI.

These calculations show that CO_2 emissions accounted for 77% of all GHG emissions in 2014. Changes and structure of direct (Fig. 4.3) and indirect (Fig. 4.4) global emissions of CO_2 are close to the results obtained for GHG as a whole. However, the contribution of AFOLU significantly decreases, since this sector mainly produces significant emissions of methane and nitrous oxide.

Figure 4.4 Evolution of CO_2 Emissions from Key Sectors and Distribution of Emissions from Heat and Electricity Generation by Sectors (Indirect Emissions) in 1970-2014



	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Total	**2.08%**	**1.45%**	**0.70%**	**2.24%**	**2.32%**
AFOLU	0.99%	1.57%	-1.35%	0.41%	0.00%
Residential buildings	2.82%	2.69%	1.24%	1.93%	-0.18%
Public buildings	3.36%	1.52%	2.24%	2.57%	0.03%
Energy sector	2.23%	-0.01%	1.57%	1.88%	2.00%
Industry	**1.95%**	**0.69%**	**0.50%**	**3.73%**	**4.07%**
Transport	3.42%	2.27%	2.14%	1.70%	2.52%

Note: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use. Energy sector does not include emissions from heat and electricity production, as they are related to end-use sectors.

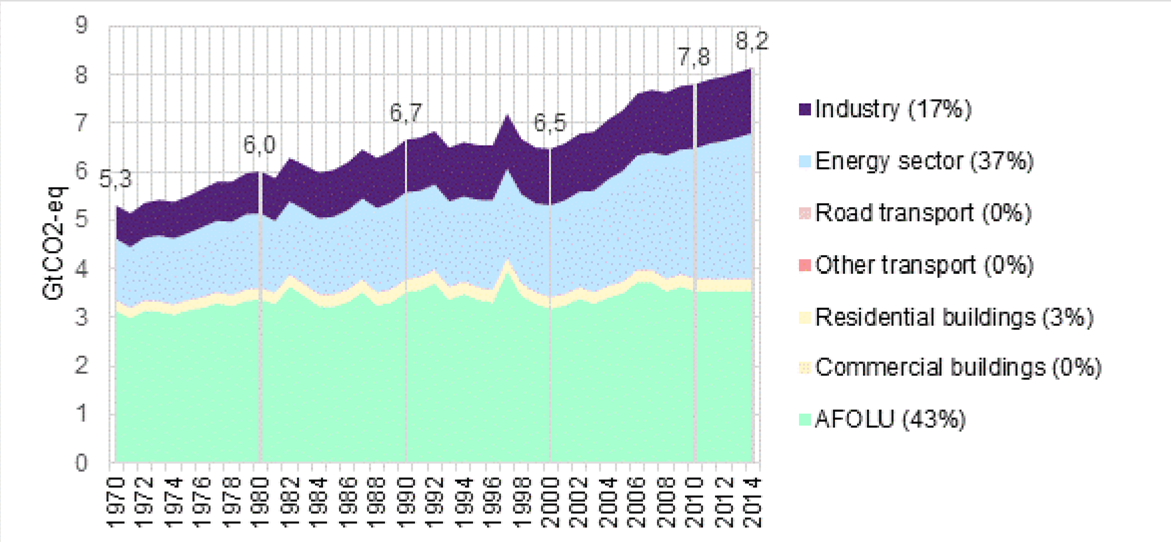
Source: 1970–2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

In 2014, direct and indirect CO_2 emissions from production sector were estimated at 8.9 and 5.9 bt of CO_2 respectively, or 14.9 bt of CO_2 in total. In 2000–2014, emissions increased by 63%. Contribution of production sector to CO_2 emissions, including direct and indirect emissions, increases up to 37%; net of AFOLU, it remains at the level of 43%.

4.1.3 CH_4 and N_2O

Methane and nitrous oxide rank second and third after CO_2 in terms of GHG emissions (when brought to CO_2 equivalent). They account for 15% and 6% in the total GHG emission respectively. EDGAR/IEA base does not contain any data on indirect emissions of methane and nitrous oxide, because such emissions are insignificant in the course of heat and electric energy generation. Therefore, only changes in direct emissions are quoted for these GHGs (Figs. 4.5 and 4.6).

Figure 4.5 CH_4 Emissions in 1970-2014



	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Total	**1.26%**	**1.04%**	**-0.29%**	**1.89%**	**1.09%**
AFOLU	0.72%	0.41%	-1.00%	1.07%	0.00%
Residential buildings	0.77%	1.75%	-1.31%	0.97%	-0.18%
Public buildings	1.03%	-2.19%	0.28%	1.89%	0.03%
Energy sector	2.04%	1.54%	0.60%	3.58%	2.89%
Industry	**2.37%**	**2.30%**	**0.69%**	**1.30%**	**0.47%**
Transport	-1.46%	1.32%	-1.50%	-0.64%	1.65%

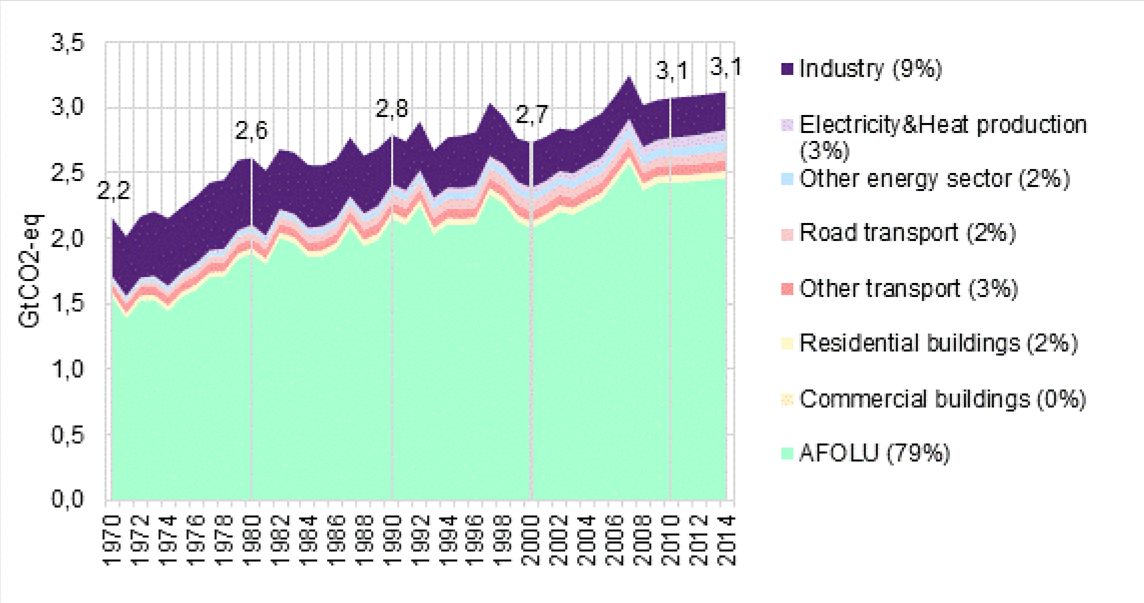
Notes: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use.

Source: 1970–2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

The procedure for estimating emissions of CH_4 and N_2O in 2011–2014 is practically identical to the procedure for estimating CO_2 and GHG emissions as a whole. Emissions of CH_4 and N_2O from transport and residential buildings were estimated in proportion to energy consumed by these sectors until 2012, as reported by IEA,[46] with the consumption extrapolated to 2013–2014. Emissions of nitrous oxide from the chemicals sector and other production sectors in 2011–2014 were estimated using time trend, since the industrial production index overestimates the growth of emissions. The same trend was used to extrapolate the volume of N_2O emissions from the AFOLU sector.

[46] Energy Balances Of Non-OECD Countries (2014 Edition). OECD/IEA, 2014

Figure 4.6 N_2O Emissions in 1970-2014



	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Total	**1.95%**	**0.66%**	**-0.21%**	**1.18%**	**0.31%**
AFOLU	1.99%	1.34%	-0.34%	1.56%	0.35%
Residential buildings	0.92%	1.31%	0.56%	0.91%	-0.18%
Public buildings	0.85%	-4.13%	-3.47%	1.81%	0.03%
Energy sector	4.24%	3.34%	2.88%	3.71%	2.89%
Industry	**1.33%**	**-2.99%**	**-0.86%**	**-1.28%**	**-1.11%**
Transport	3.70%	1.32%	1.27%	-0.94%	1.65%

Notes: Shares of sectors in total 2014 emissions are shown in the legend. Vertical lines show total emission volumes. AFOLU is agriculture, forestry and other land use.

Source: 1970–2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

The main emissions of methane are concentrated in three sectors (Fig. 4.6): production sector, energy sector (mainly volatile emissions from production and transportation of fuel), and AFOLU. The share of AFOLU in emissions of methane and nitrous oxide is significantly higher than in CO_2 emission. AFOLU accounts for the major part in emissions of nitrous oxide (79%): N_2O emissions from this sector grow over the whole analysis horizon. Emissions from production sector, on the contrary, decrease at an average annual rate of about 1%.

In 2014, methane emissions from production sector reached 1.35 bt of CO_2eq, but production of materials accounted only for 26 Mt of that volume. Methane emissions from production of materials have grown by 97% since 2000, while emissions from production sector have grown only by 16% since 2000.

In 2014, total emissions of nitrous oxide from production sector reached 0.3 bt of CO_2eq, and production of materials accounted for about one-third (120 Mt) of that volume (half as much since 2000).

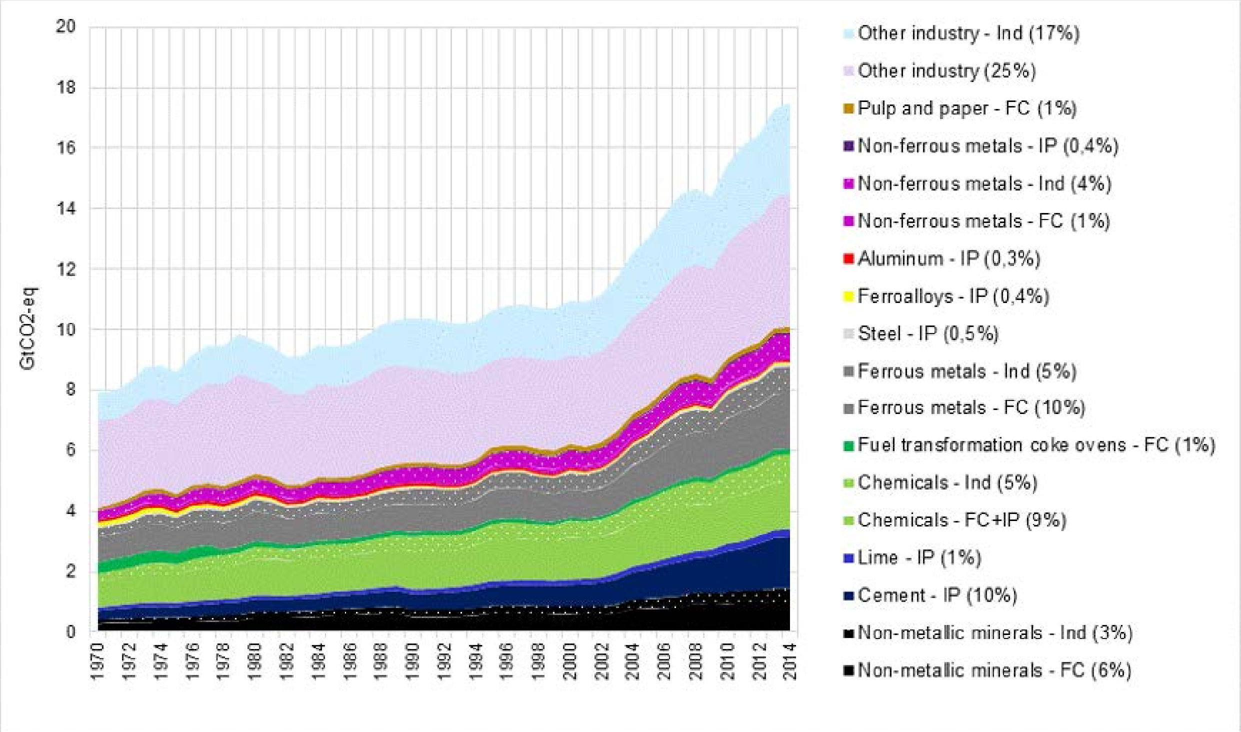
Production sector accounts only for 17% in methane emissions (materials account for 0.3%) and for 9% in nitrous oxide emissions (materials account for 3%). Methane emissions from production sector grow slower than total emissions, while nitrous oxide emissions have been decreasing during recent 35 years.

4.2 Contribution of Basic Materials to Volume and Changes in Anthropogenic GHG Emissions

4.2.1 All Greenhouse Gases

According to the IPCC guidelines, production of materials generates emissions from two components: energy generation (fuel combustion and volatile emissions from fuel) and industrial processes. For example, CO_2 is generated in cement production during heating and calcination of limestone to produce clinker. Production of pig iron and steel can be accompanied by emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). EDGAR/IEA database highlights emissions from industrial processes, as well as emissions from fuel combustion for industrial production. In order to estimate the contribution of basic materials production to the total volume of GHG emissions, it is important to estimate emissions from both of the aforesaid components. EDGAR/IEA database makes it possible to identify the contribution of the main basic materials or groups of basic materials (Fig. 4.7).

Figure 4.7 Evolution of Direct and Indirect GHG Emissions from Key Industries



	Average annual growth rates				
	1971-1980	**1981-1990**	**1991-2000**	**2001-2010**	**2011-2014**
Industry	**2.01%**	**0.73%**	**0.55%**	**3.49%**	**3.17%**
Non-metallic minerals	4.03%	1.56%	2.11%	5.28%	3.93%
Chemicals	3.90%	0.82%	1.08%	1.79%	1.65%
Ferrous metals	-0.10%	-0.20%	-0.04%	5.13%	2.65%
Non-ferrous metals	3.73%	1.15%	0.81%	2.59%	2.67%
Other industry	2.07%	0.64%	0.25%	2.52%	3.12%

Note: proportions in the legend are shares of sectors in 2014 total industrial emission. Vertical lines show total emission volumes. IP—Industrial processes, FC—fuel combustion, Ind—indirect emissions.

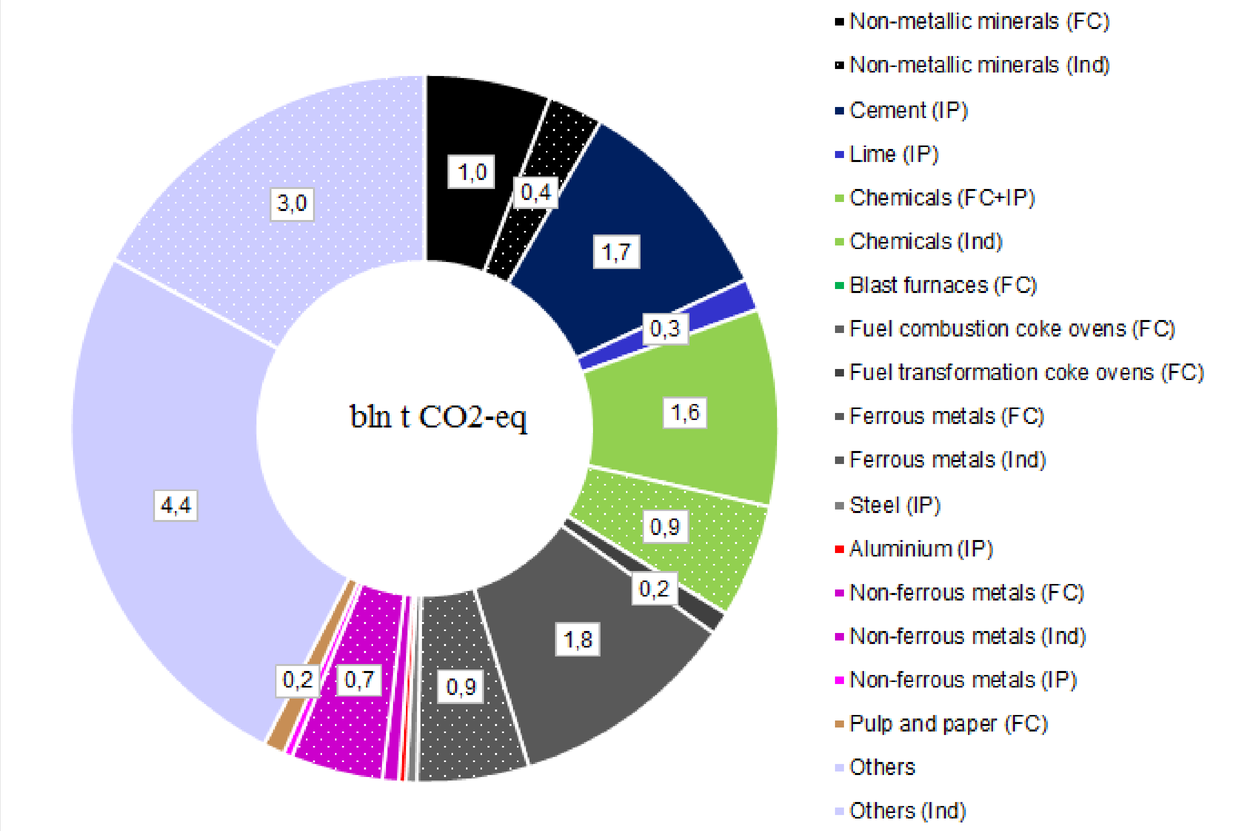
Source: before 2010—EDGAR/IEA database, 2011–2014—estimated by CENEf-XXI.

In general, basic materials account for 7.1 bt of CO_2eq of direct emissions and 3.0 bt of CO_2eq of indirect emissions in 2014, or for the total of 10.1 bt. This is equivalent to 58% of GHG emissions from production sector and 19% of all anthropogenic GHG emissions.

While in 1970–2000, GHG emissions from production sector grew by 3 bt of CO_2eq in total, over the twice shorter period (2000–2014), they grew by 6.5 bt of CO_2eq. Emissions from production of materials grew by 2.1 and 3.9 bt of CO_2eq respectively. I.e., the average annual growth increased 4-fold.

As shown in Chapter 2, the bulk volume of energy consumption is actually accounted for by five groups of materials (*the "Big Five"*): steel, cement, paper (and cardboard), aluminium, and plastics (as an aggregate group). The most carbon intensive basic materials in terms of direct and indirect emissions from combustion and industrial processes are non-metallic minerals (20%), ferrous metals (16%), and chemical products (14%) (Fig. 4.8). The circular diagram shows in detail the allocation of direct and indirect emissions among production branches. Production of cement and ferrous metals are the sectors with the fastest growing emissions.

Figure 4.8 Direct and Indirect Industrial GHG Emissions in 2014 by Product



Note: (Ind)—indirect emissions, (IP)—industrial processes, (FC)—fuel combustion. Indirect emissions are allocated to sectors proportional to electricity consumption in 2012 according IEA[47].

Source: CENEf-XXI

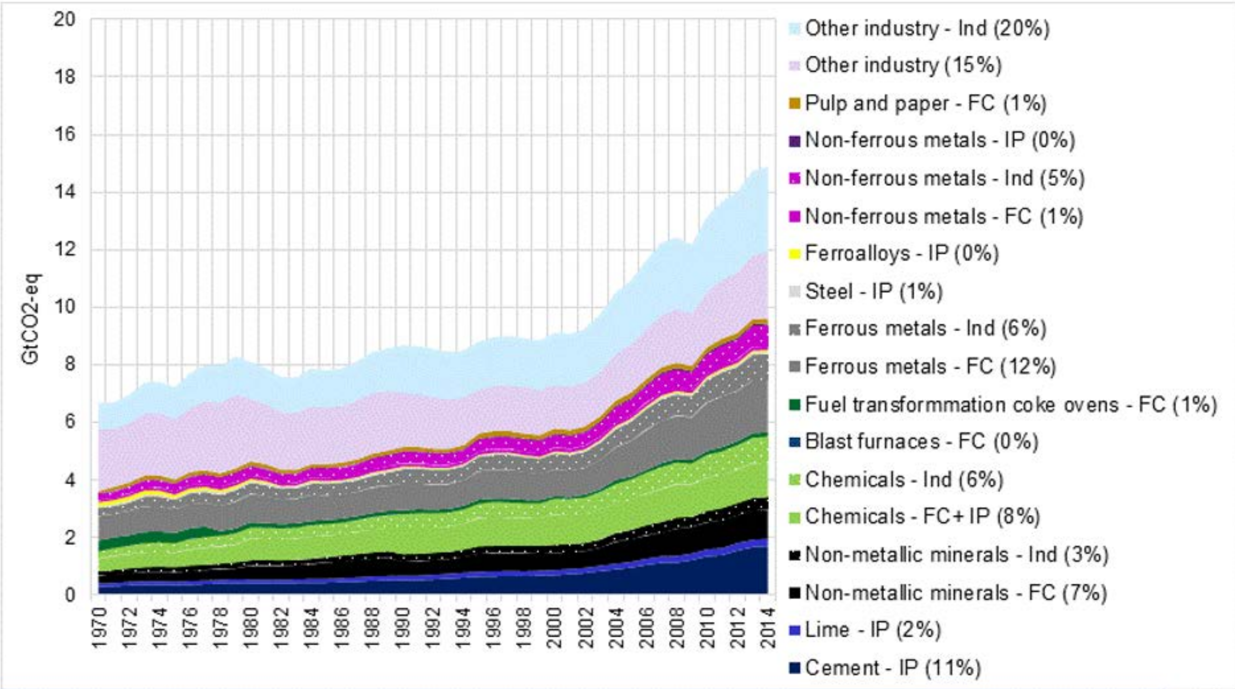
4.2.2 CO_2

Direct and indirect CO_2 emissions account for 85% of all GHG emissions from production sector. Direct and indirect emissions from production of materials account for 66% (10.1 bt) of the above mentioned volume. The most carbon intensive materials in terms of direct emissions are products of ferrous industry, chemical products, and cement. The circular diagram shows in

[47] Energy Balances Of Non-OECD Countries (2014 Edition). OECD/IEA, 2014

detail the allocation of direct and indirect emissions among production branches. The fastest growing branches are the production of cement and ferrous metals. Indirect emissions from production sector are allocated among the branches in proportion to energy consumed by such branches in 2012, as reported by IEA.[48]

Figure 4.9 Evolution of Direct and Indirect CO_2 Emissions from Key Industries



	Average annual growth rates				
	1971-1980	**1981-1990**	**1991-2000**	**2001-2010**	**2011-2014**
Industry	**1.95%**	**0.69%**	**0.50%**	**3.73%**	**3.17%**
Non-metallic minerals	3.91%	1.13%	1.70%	2.89%	2.29%
Chemicals	4.93%	2.06%	1.37%	2.01%	1.80%
Ferrous metals	-0.12%	-0.20%	-0.03%	5.13%	2.53%
Non-ferrous metals	3.88%	1.56%	1.43%	2.96%	2.91%
Other industry	2.02%	0.52%	-0.05%	2.58%	3.16%

Note: (Ind)—indirect emissions, (IP)—industrial processes, (FC)—fuel combustion. Proportions in the legend are shares of sectors in 2014 total industrial emission.

Source: before 2010—EDGAR/IEA database, 2011-2014—estimated by CENEf-XXI.

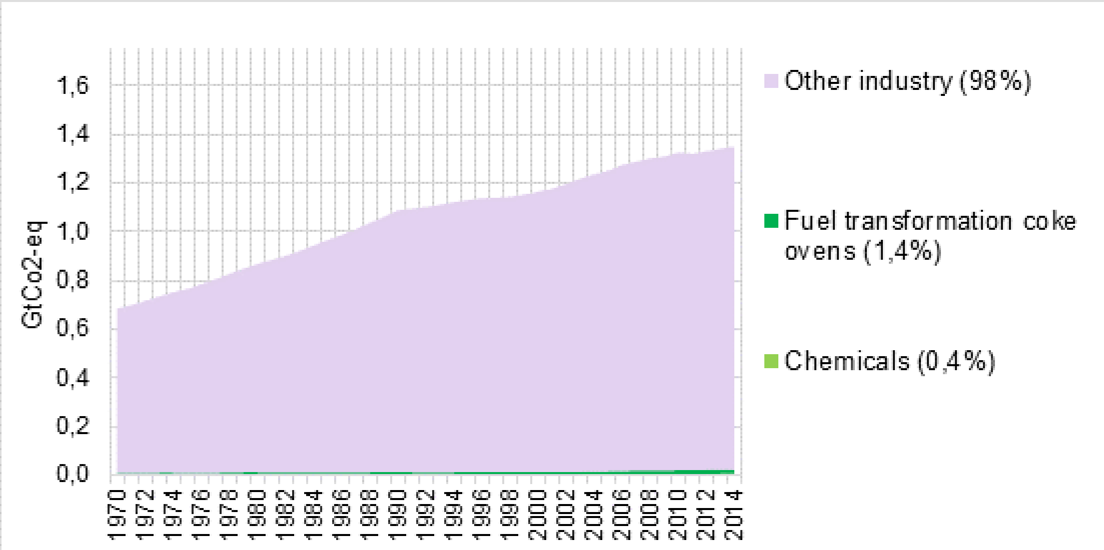
According to estimates of IIASA (2012),[49] in 2005, direct emissions of CO_2 in production sector reached 6.66 bt of CO_2eq, direct and indirect emissions reached 9.86 bt of CO_2eq, which is a little lower than the estimate shown in Fig. 4.9.

4.2.3 CH_4 and N_2O

In 2014, emissions of methane and nitrous oxide account for 7.7% and 1.6% of GHG emissions in production sector respectively. The share of basic materials in methane emissions is minimal (Fig. 4.10), since they occur mainly in the course of extraction and treatment of fuel and to a lesser extent at the stage of fuel use. The chemicals sector accounts for a large volume of nitrous oxide emissions (Fig. 4.11).

[48] Energy Balances Of Non-OECD Countries (2014 Edition). OECD/IEA, 2014
[49] Global energy assessment. Toward a sustainable future. IIASA. 2012.

Figure 4.10 Industrial CH_4 Emissions Dynamics

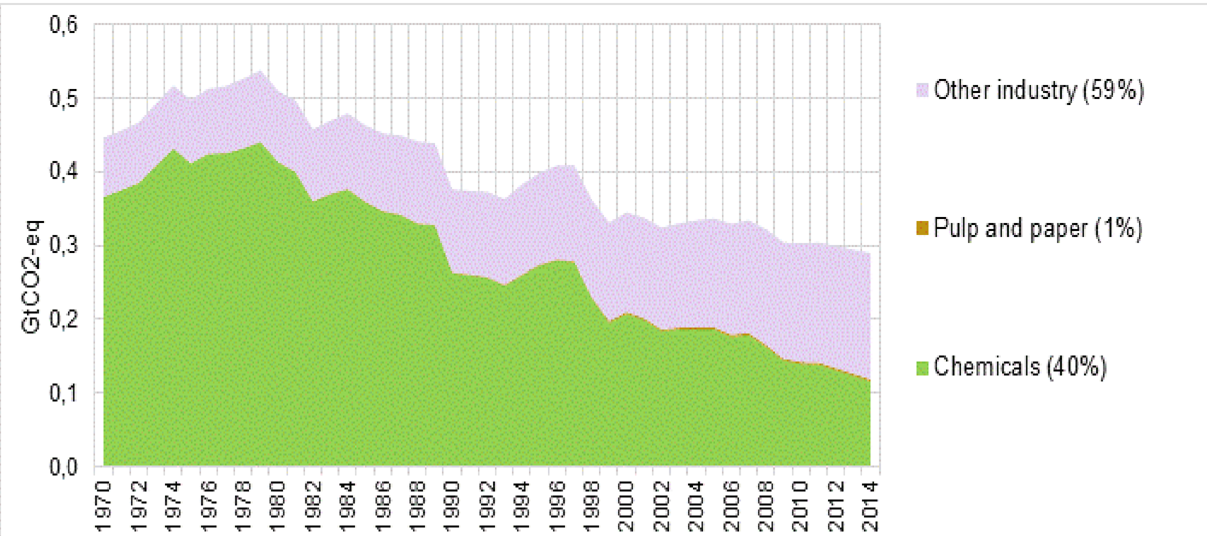


	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Industry	**2,37%**	**2,30%**	**0,69%**	**1,30%**	**0,47%**
Fuel transformation coke ovens	2,15%	0,08%	-1,02%	5,73%	4,76%
Chemicals	4,15%	2,54%	3,20%	3,83%	2,87%
Ferrous metals	4,33%	-1,77%	-0,06%	6,11%	4,19%
Other industry	2,37%	2,33%	0,70%	1,25%	0,40%

Note: percent values represent the share of the sector in overall industrial emission in 2014

Source: before 2010—EDGAR/IEA database, 2011-2014—estimated by CENEf-XXI.

Figure 4.11 Industrial N_2O Emissions Dynamics



	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Industry	1.33%	-2.99%	-0.86%	-1.28%	-1.11%
Chemicals	1.22%	-4.41%	-2.33%	-3.90%	-4.48%
Pulp and paper	5.51%	4.93%	10.87%	0.35%	0.57%
Other industry	1.79%	1.59%	1.96%	1.78%	1.52%

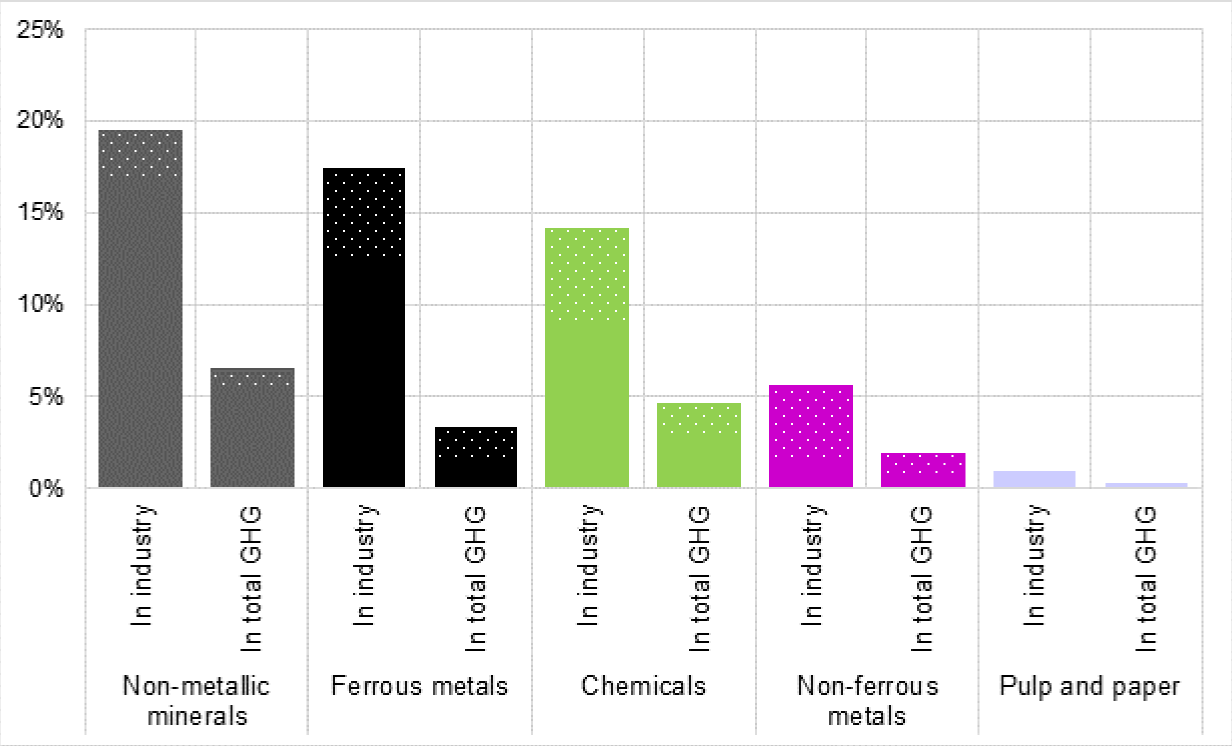
Note: percent values represent the share of the sector in overall industrial emission in 2014

Source: before 2010—EDGAR/IEA database, 2011-2014—estimated by CENEf-XXI.

4.3 Ranking of Basic Materials According to Their Contribution to Changes in Global Anthropogenic GHG Emissions

Basic materials can be ranked according to their contribution to the volume and changes in the global anthropogenic GHG emissions in different ways: with account for production of one material at the final technical process stage; with account for energy consumption at all production stages of the end-use product; with account for, or net of, indirect emissions. Estimates of GHG emissions contribution for production of certain materials can markedly very depending on the way selected. For example, aluminium smelting does not generate any emissions. However, there are indirect emissions that occur in the course of electric energy generation and anode consumption. If we take into account energy consumption at the stage of bauxite mining, alumina production, aluminium rolling, industrial and consumer scrap picking, emissions per unit of smelt aluminium for the whole process flow will significantly exceed emissions from aluminium smelting.

Figure 4.12 Basic Materials Ranged by Their Contribution to 2014 Anthropogenic GHG Emissions



Note: Left columns depict shares in industrial emissions. Right columns depict shares in total anthropogenic emissions. Dotted areas represent indirect emissions.

Source: CENEF-XXI

Certain authors give estimates of the contribution made by some basic materials to the total emission. According to the estimates of Pauliuk et al. (2013), steel (at all stages of production, which is practically equivalent to ferrous industry) accounts for 25% of GHG emissions from production sector and for 9% of total anthropogenic emission.[50] Apparently, this share does not include AFOLU. EDGAR/IEA estimates contribution of ferrous industry at 7.8%, i.e., even net

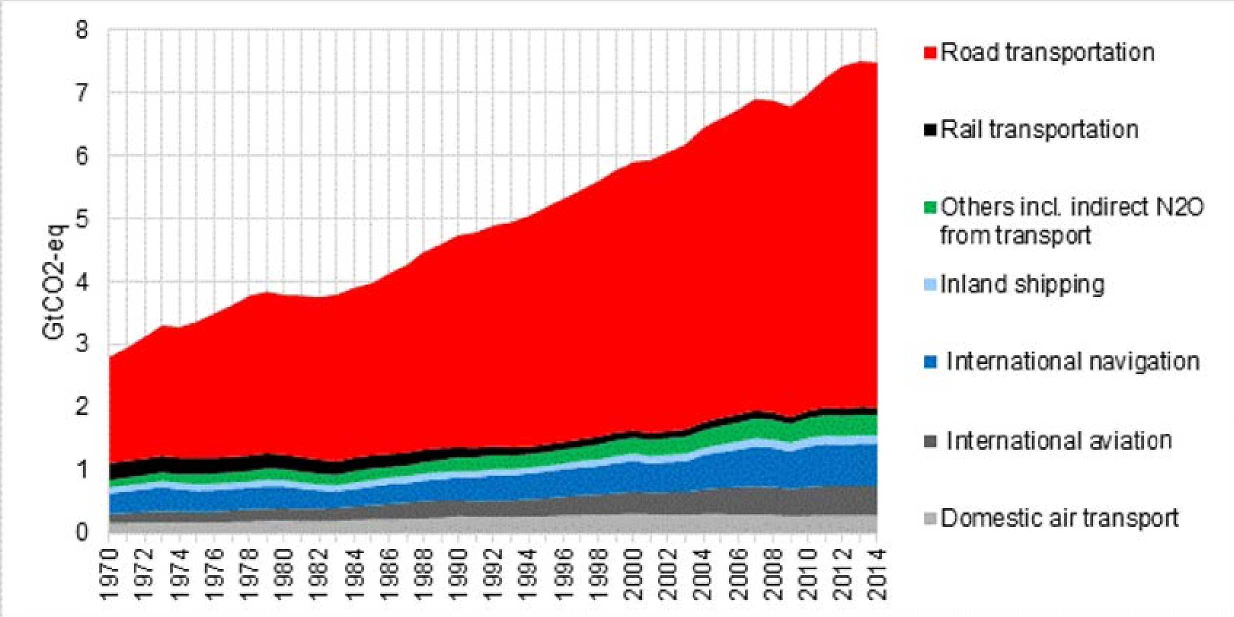
[50] Pauliuk S., T. Wang, D.B. Müller. 2013. Steel all over the world: Estimating in-use stocks of iron for 200 countries. Volume 71, February 2013, pages 22–30; Pauliuk S., R.L. Milford, D.B. Müller, and J.M. Allwood. 2013. The Steel Scrap Age Environmental Science & Technology.

of AFOLU, the estimates differ. According to estimates of Liu et al., aluminium accounts for 1% at all stages of its production.[51] EDGAR/IEA database gives the same estimate.

4.4 GHG Emissions from Transport

Greenhouse gas emissions from fuel combustion in transport grew very rapidly from 2.8 bt of CO_2eq in 1970 to 7.5 bt of CO_2eq in 2014 (Fig. 4.13). They account for 14% of all anthropogenic emissions, or 18% of emissions net of AFOLU, and 23% of emissions from fuel combustion.

Figure 4.13 GHG Emission from Transport Dynamics



	Average annual growth rates				
	1971-1980	1981-1990	1991-2000	2001-2010	2011-2014
Transportation-direct	**3.05%**	**2.25%**	**2.22%**	**1.69%**	**1.75%**
Motor	4.20%	2.86%	2.40%	1.67%	2.15%
Railway	-1.76%	-3.66%	-3.10%	-0.36%	0.68%
Domestic air	2.42%	3.29%	1.28%	-1.11%	0.68%
International aviation	2.49%	2.51%	3.18%	2.68%	0.68%
International navigation	0.56%	0.48%	3.05%	2.80%	0.68%
Inland shipping	1.37%	-0.61%	1.31%	1.72%	0.68%
Other	3.78%	2.42%	1.43%	2.41%	0.68%
Indirect	2.82%	2.93%	-1.21%	2.19%	2.52%
Total	**3.04%**	**2.27%**	**2.14%**	**1.70%**	**1.75%**

Source: before 2010—EDGAR/IEA database, 2011-2014—estimated by CENEf-XXI.

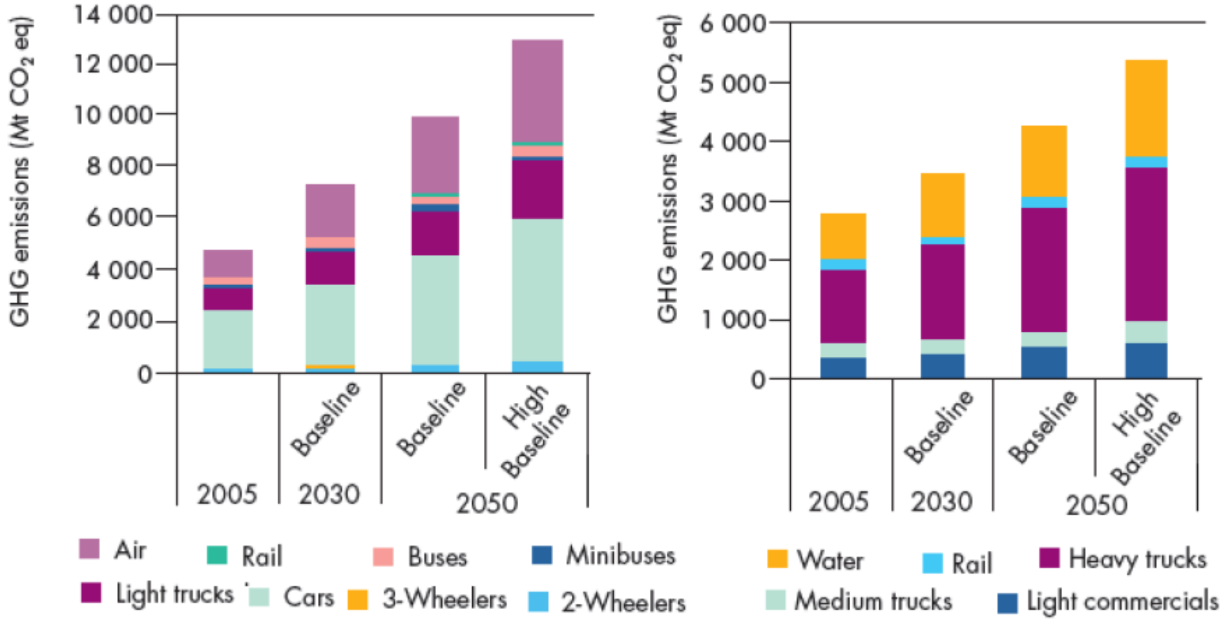
The share of indirect emissions from transport is very limited—less than 1.5%. Motor transport demonstrates the highest growth. In 1970, it accounted for 60% of emissions from transport, while in 2014, it accounted for more than 72%. The share of railway transport decreased from 10% to 1.6%; the share of pipeline transport decreased from 2.8% to 2.4%; the share of water transport decreased form 15% to 11.3%; the share of air transport decreased from 11.2% to 10.6% (Sims et al., 2014).

Volumes of freight traffic have increased almost fourfold over the last 30 years (GEA, 2012). In 1985–2005, the freight turnover of international freight traffic increased 4-fold and reached 118.5 bn tkm, that of domestic freight traffic increased 2.3-fold and reached 24 bn tkm. In 2005,

[51] Liu G., C.E. Bangs and D.B. Müller. 2013. Stock dynamics and emission pathways of the global aluminium cycle. NATURE CLIMATE CHANGE. VOL. 3. APRIL 2013.

GHG emissions from freight transport were below 3 bt of CO_2eq (Fig. 4.14). By 2014, they exceeded 3 bt of CO_2eq.

Figure 4.14 GHG Emissions from Passenger and Freight Transport



Source: Global Energy Assessment. Towards a sustainable future. 2012. IIASA. Module 9.

Basic materials account for almost two-thirds of freight turnover and, according to estimates, for slightly more than a half of GHG emissions (Table 4.1). Net of oil and gas, this share is 34%.

Table 4.1 Share of Basic Materials in Freight Turnover and GHG Emissions

	Share in freight turnover (%)	Share in CO_2 emissions (%)
Minerals	26.53	11.73
Oil	23.69	4.78
Gas	3.52	8.8
Wood products	1.21	1.30
Paper and cardboard	1.97	8.91
Chemical products	8.15	0.86
Other minerals	1.95	9.78
Ferrous metals	4.74	2.82
Other metals	1.31	1.08
Metal products	1.21	0.7
Total	**74.28**	**50.76**

Source: Cristea A., D. Hummels, L. Puzzello, M. Avetisyan. 2012. Trade and the greenhouse gas emissions from international freight transport. Journal of Environmental Economics and Management 2012. http://dx.doi.org/10.1016/j.jeem.2012.06.002

The reason is that a large share of basic materials is transported by sea transport. Specific energy consumption per unit of sea transport work is many-fold lower as compared to motor transport that carries mainly finished industrial products. A large part of goods transported by sea transport is accounted for by dry freight (38%), oil and oil products (36%), while container freight accounts only for 15%. The main freights carried by sea transport: crude oil (15.3 bn tkm), iron ore (6.6 bn tkm); coal (5.4 bn tkm); oil products (4.2 bn tkm); grain and groats (2.3 bn tkm).

While sea transport accounts for 80% of international freight traffic, trucks produce the highest volume of total emissions. In 2005, they produced 1.2 bt of CO_2eq and acted as the main growth driver of freight transport emissions, as reported by IEA. Total emissions from sea freight transport reached almost 1 bt of CO_2eq. According to IPCC, specific emissions per useful distance produced by new medium-duty trucks reach 270–490 g of CO_2eq per tkm, by new heavy-duty trucks—76–180 g of CO_2eq per tkm, by water transport—only 10–40 g of CO_2eq per tkm.

Transport adds about 10–14% to direct and indirect GHG emissions from production of basic materials. Thus, GHG emissions from freight transport can be estimated at 3 bt of CO_2eq, materials account for about 50% of freight turnover, which means that transportation of materials produces approximately 1.5 bt of CO_2eq. Net of oil and natural gas transport, this will make 1 bt.

4.5 Concepts and Factors of Specific GHG Emissions

The concept of materialised GHG emissions is based on the concept of specific embodied energy use described in Chapter 3. Further calculations of GHG emissions are based mainly on the values from ICE database (Inventory of Carbon & Energy. V2.0) of the University of Bath.

The *GHGemb* scheme for calculation of embodied emissions with the use of the material balance method looks as follows:

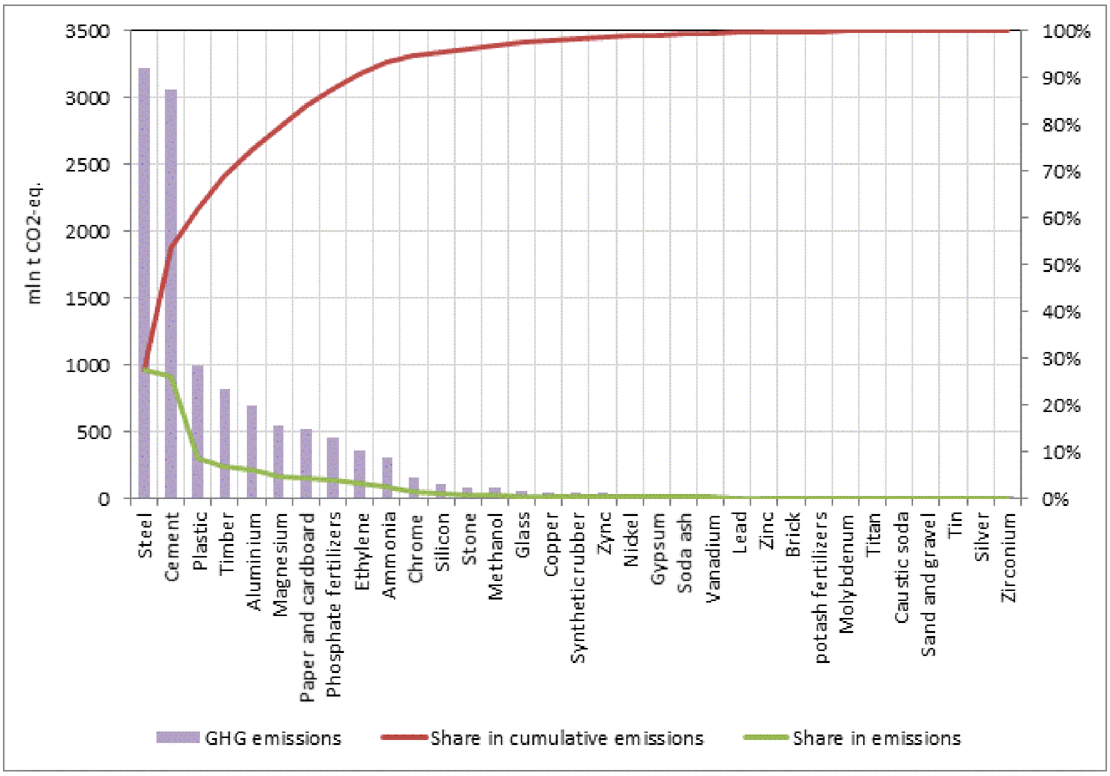
$$GHGemb = (1-m)*(\sum_i X_i * a_i * ghg_i + GHGe + GHGi) + Te * ghg_t \quad (3.2)$$

where *m* is the share of production losses (%); X_i is the weight (kg) of materials used to make a product; a_i is specific use of embodied energy per unit of raw stock of *i* type; ghg_i is GHG emission per unit of embodied energy (depends on the structure of energy carriers being used); *GHGe are* emissions from fuel combustion as part of embodied energy in the course product making out of raw stock; *GHGi* are emissions from industrial processes (e.g., from calcination of limestone for cement production); *Te* is energy consumption for transport of the end-use product; ghg_i are specific GHG emissions per unit of energy consumed to transport the product. As with energy, to estimate GHG embodied in one product, we need to know specific indicators of embodied energy for other products. Thus this method can provide the approximate estimations of embodied energy estimations only depending of iteration number during the define stage. Moreover, specific emissions per unit of energy may vary through the growth in the share of low-carbon sources of energy at each production stage of product or semi-finished products of which the product is made. As shown in Chapter 3, the calculations take into account GHG emissions from fuel use and from industrial processes. Other GHGs, apart from CO_2, are also taken into account.

Estimates of GHG emissions from production of the main basic materials on the basis of the specific embodied emissions concept were made in such a way as to avoid double counting. In other words, emissions from production of raw stock for making the 33 main basic materials are not shown in Fig. 4.15. The calculation was based on the information on specific emissions from the University of Bath database[52] and data of M. Ashby (2009).[53] The final total also includes the emissions from transport of materials.

[52] University of Bath. 2011 ICE (Inventory of Carbon & Energy). V2.0. www.bath.ac.uk/mech-eng/sert/embodied.
[53] Ashby M.F. 2009. Materials and the Environment: Eco-Informed Material Choice Materials and the Environment. Butterworth-Heinemann is an imprint of Elsevier 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA. Linacre House, Jordan Hill, Oxford OX2 8DP, UK.

Figure 4.15 Embodied GHG Emissions from Key Basic Materials Production



Source: authors

Total embodied GHG emissions for production of 32 basic materials amounted to 11,448 Mt of CO_2eq. This accounts for 21.5% of global anthropogenic GHG emissions in 2014, or 27% net of AFOLU sector.

The main part of embodied emissions is accounted for (in billion tonnes of CO_2eq) by production of steel (3.2); cement (3.1); plastics (1); timber (0.8); aluminium (0.68); magnesium (0.55); paper and cardboard (0.52); phosphatic fertilisers (0.45); ethylene (0.36); ammonia (0.3). These 10 groups of basic materials account for 93% of all embodied GHG emissions in 32 basic materials.

Table 4.2 shows embodied GHG emissions from production of materials covered by this study. Not all of the table lines may be summed up (cement may not be summed up with concrete). Accordingly, ***emissions from production of the basic materials covered by this paper amount to 8,295 Mt of CO_2eq in total.***

Table 4.2 Embodied GHG Emissions from Production of Materials Under Analysis

Material	Production output in 2013–2014	Embodied emissions CO_2eq	Specific embodied GHG emissions	
	kt (thousand m^3)	Mt	kg of CO_2/kg	kg of CO_2e/kg (kg of CO_2eq/m^3)
Steel	**1,650,000**	**3,217.5**	**1.95**	
Primary aluminium	**49,300**	**630.5**	**11.46**	**12.79**
Processed aluminium	**40,000**	**58.0**	**1.35**	**1.45**
Primary copper	**13,800**	**52.6**	**3.65**	**3.81**
Processed copper	**7,100**	**5.9**	**0.80**	**0.84**
Synthetic rubber	**16,683**	**47.6**	**2.66**	**2.85**
Timber	**1,129,300**[1]	**813.0**		**0.72**
Wood-based panels, incl.:				
plywood	87,300[1]	96.0	1.07[2]	1.10[2]
chipboard	64,500[1]	55.5	0.84[2]	0.86[2]
wood-based panels	13,300[1]	14.5	1.01[2]	1.09[2]
MDF	79,000[1]	58.4	0.72[2]	0.74[2]
Plastics, incl.:	**299,000**	**989.7**	**2.73**	**3.31**
thermoplasts, incl.:				
ABS resins	5,800[3]	21.8	3.05	3.76
polyamide, incl.:	7,700	66.2		
polyamide 6	4,300	39.3	5.47	9.14
polyamide 6.6	3,400	26.9	6.54	7.92
polyvinylchloride	43,000	133.3	2.61	3.10
polypropylene	52,200	179.1	2.97	3.43
polystyrene	14,600	54.0	2.92[4]	3.70[4]
polyester, incl.:[5]	53,300	151.9	2.85	
polyethylene terephthalate	28,000[6]	58.2	2.08	
polyethylene, incl.:	56,200	114.7		
low-density	23,300	48.5	1.69	2.08
linear low-density	7,400	17.0[7]		
high-density	25,500	49.2	1.57	1.93
polycarbonate	3,300	19.9	6.03	7.62
thermosetting plastics, incl.:				
polyurethane	11,700	38.6		3.30
epoxy resin	2,410[8]	11.0	4.22	4.56
Cement	**4,180,000**	**3,093.2**	**0.73**	**0.74**
Concrete	26,158,000	2,798.9	0.10	0.107
Clay	56,500	27.1	0.45	0.48
Ceramics	191,000	1,26.1	0.66	0.70
Construction composites, incl.:	**6,288**	**50.2**		
fiberglass plastic	6,200	48.8		7.87
carbon fibre-reinforced plastic	88	1.4		16.1
Insulation materials	**38,108**	**8.7**		
Mineral wool	3,100	3.7		1.2
Fibreglass wool	3,500[9]	5.0		1.44

1: calculated based on cubic metres data for average density
2: carbon intensity consists of two components: emissions from fuel and energy resources and biological component.
3: 2006 data
4: the average of specific embodied GHG emissions for foam polystyrene, high-impact polystyrene, and thermal polystyrene.
5: usually thermoplasts, may be thermosetting plastic
6: 2012 data
7: the value is obtained by subtracting values for low-density and high-density polyethylene from total emissions of CO_2eq.
8: 2012 data

9: fibreglass wool defined for fiber-glass plastics class

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5 Long-Term Projections for Global Anthropogenic GHG Emissions

5.1 Forecasting Tools

In view of the need to consider a vast number of interrelated variables within very large and complex systems, integrating resources, technologies, economy, energy sector, environment, and society and distributed in space and time, this kind of analysis is normally performed using large and complex mathematical models designed for simulation experiments involving scenario-based forecasting.

The key objective of the IPCC Fifth Assessment Report was to measure the dynamic emission reduction potential using large-scale integrated global models. These models simulate the key correlations between major systems: demographics, economy, energy sector, environment, and climate. The essence of the integrated model is a simplified and formalised approach, capable of reflecting the evolution of very complex physical and social systems in the long run (in most cases, until 2100). Scenario calculations are based on a number of assumptions outlined in the initial data. The output is an assessment of changes concerned with economy, energy balance, land use, and climate. The major GHG emissions growth drivers are population and economic growth. Growth is constrained primarily by availability of natural resources, and opportunities for overcoming such constraints depend on technological advances in resource efficiency improvement. Models simulating the impact of government policy measures for emissions reduction help assess associated costs and benefits.

Integrated models vary in terms of granularity and interrelations between individual sectors of economy, which explains the discrepancies between estimates made for similar scenarios. In addition, there are differences in how these models reflect global trade, etc. General equilibrium models cover all the sectors of economy, facilitating assessment of the cumulative effect of policy measures. Partial equilibrium models predetermine the economic growth rate. In this case, it is assumed that the economy does not react to policy measures or any other changes, such as technological advances. Such models are focused on detailed representation of the selected economic system (e.g., energy sector). All other things being equal, general equilibrium models yield higher aggregate costs than partial equilibrium models do. The reason is that general equilibrium models take into account the impact in all the sectors. On the other hand, general equilibrium models offer more substitution opportunities in the sectors left beyond the scope of partial equilibrium models, which reduces costs.

Perfect foresight models (e.g., intertemporal optimisation models) are based on the assumption that potential future decisions affect current decisions. To the contrary, in recursive models, decisions made at any point in time can be based solely on the information available at that moment. In general, perfect foresight models often distribute emissions reduction over time more efficiently than recursive models do.

Model framework may change depending on the combination of decisions: for example, how fast capital is redistributed among sectors; how flexible the economy can be in adopting new energy technologies; whether there are any constraints on available natural resources; and how much it costs to extract those resources. More flexible models yield a lower value of aggregate emissions reduction costs.

Models vary greatly in terms of their granularity in defining key sectors and systems. These differences affect the parameters of low-carbon development pathways for the global economy. Some models consider CO_2 emissions only. Many models overlook emissions associated with land use, changes in land use, and forestry. In addition, many models are missing the part with carbon cycle modelling (necessary to measure atmospheric concentration of carbon). Models segmenting the global economy into regions help assess the response of regional economies to the emissions mitigation policy.

In some models, the rate of technical advancements is determined exogenously, independent of policy measures and investment decisions. Such models fail to reflect the impact of emissions mitigation measures on technology advancement. Other models set the rate of technological advancements endogenously, including assessment of dependence on investments in R&D and accumulated experience from application of such technologies. Such models help to understand how much technology development depends on GHG emissions mitigation policy measures. Usually, these aggregate models fail to reflect the changes in the behaviour of economic systems with the degree of granularity that dedicated sectoral models offer.

Moreover, engineering sectoral models provide a detailed description of technological frameworks in individual sectors or branches of economy without considering macroeconomic effects. Integrated models yield somewhat lower estimates of emissions reduction potential compared to sectoral models. Nevertheless, the engineering and macroeconomic approaches produce similar estimates of emissions reduction potential. The results converge as integrated models (top down analysis) expand the scope of technologies they take into account, whereas sectoral models (bottom up analysis) include more macroeconomic and market responses and consider emissions reduction obstacles. The bottom up approach is especially useful in assessing the impact of specific policy measures at the sector level (such as energy efficiency improvement efforts), whereas the top down method is more efficient in evaluating the policy impact on the economy in general (for example, carbon taxes).

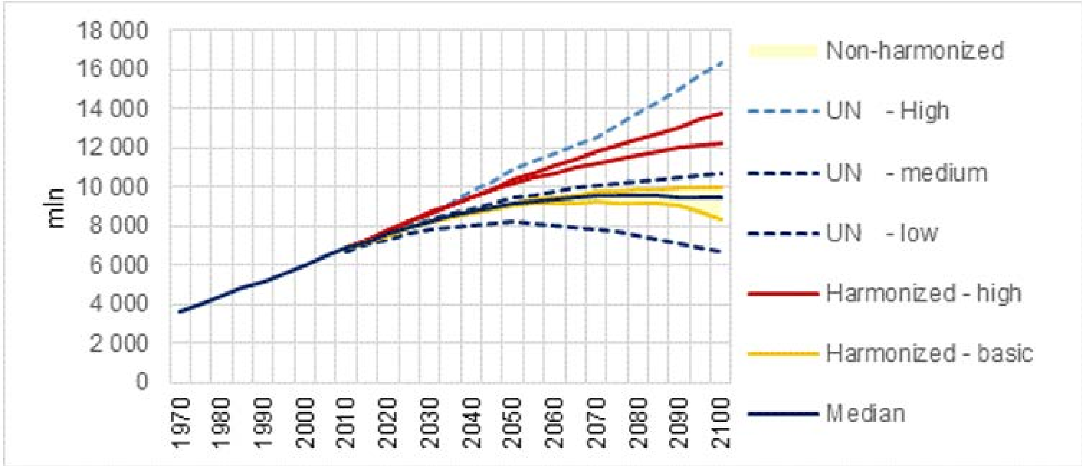
5.2 Key Scenario Parameters

Key factors determining GHG emissions trends are covered by the Kaya identity: population, GDP per capita, energy use per unit of GDP, and carbon emissions per unit of primary energy. Chapter 6 of the Third Working Group contribution to the IPCC Fifth Assessment Report contains several forecast versions for these four factors until 2100, summarising outcomes of hundreds of forecast scenarios.[54]

The global population has increased twofold over the recent 45 years, while in historic retrospective, the time of population doubling reduced 2- to 3-fold, but over the horizon up to 2100, there may be no doubling at all (Fig. 5.1). That is, demographic analysts are convinced that the exponential growth trend with an ever increasing rate observed in the 20th century is no longer valid— still further, the planet's population may plateau and stabilise or even start declining. This is a radical change from the demographic trends of the post-industrial era. However, the global population growth may not stop until 2050. There is a rather wide range of projections; however, according to the median value of the forecasts reviewed by IPCC, the world's population will reach 8.5 bn people by 2035 (plus 24% versus 2010), then increase to 9 bn people (plus 34% versus 2010) by 2050 and 9.4 bn (plus 37%) by the end of the century. UN offers three forecast scenarios, with the growth by 2100 ranging from 0 to 138%. Hereafter, we will refer to the median forecast as the base scenario.

[54] Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Loschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlцmer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Figure 5.1 Global Population Growth Projections until 2100

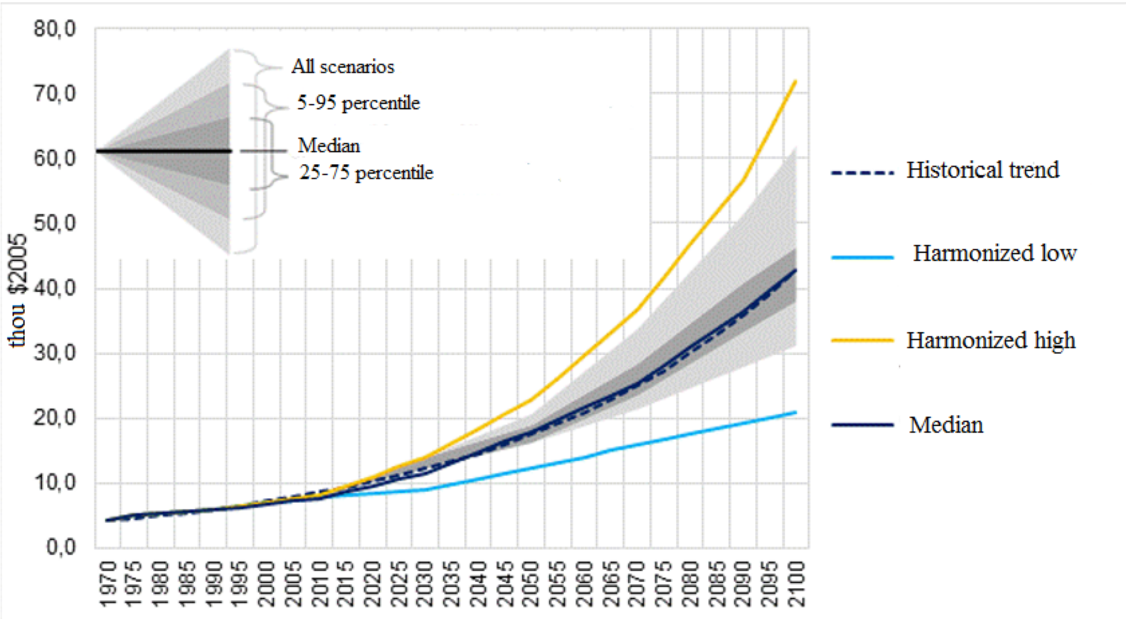


Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened. Scenarios are normalized using IEA 2010 data.

Sources: IPCC (2015), IEA (2014).

The spread of forecasts for the global per capita GDP is even wider (Fig. 5.2). It may grow 3–3.5 times by 2035, 3.8–4.9 times by 2050, and 7.5–14.7 times by 2100 (versus 2010). According to the median scenario, it will exceed USD 13,000 in 2035 (in 2005 prices), USD 18,000 in 2050, and USD 43,000 in 2100. The growth rate throughout the period 2010–2100 will be stable at 1.8% per annum.

Figure 5.2 Global GDP per Capita Projections until 2100 (2005 Exchange Rates)



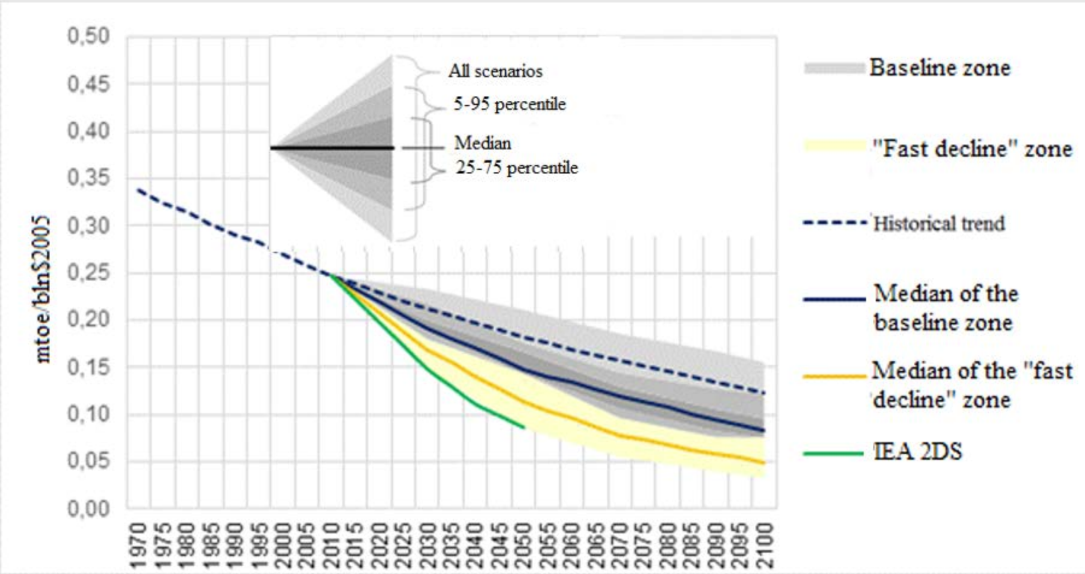
Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest) and full range (lightest). Scenarios are normalized using IEA 2010 data.

Sources: IPCC (2015), IEA (2014).

According to the median forecast, the global GDP may increase almost 8-fold by 2100 due to population and per capita income growth. The median scenario envisages GDP growth from USD 51,855 bn in 2010 (in 2005 prices) to USD 111,378 bn in 2035, USD 164,587 bn in 2050, and USD 404,771 bn in 2100. As the growth rate of the world's population slows down, average annual growth rate of GDP will gradually diminish as well: from 3% in 2010–2035 to 2.5% in 2035–2050, and to 1.8% in 2050–2100.

According to the median scenario, energy intensity of GDP will drop 27% by 2035, 40% by 2050, and 67% by 2100 versus 2010. That is, it will be decreasing by 1.2% per annum on average, like it did historically. In the base scenario, energy intensity of GDP decreases annually by 1.2% in 2010–2035, by 1.3% in 2035–2050, and by 1.16% in 2050–2100. In the group of fast reduction scenarios, energy consumption per unit of GDP drops 37%, 54%, and 80%, respectively, and the GDP decreases annually by 1.9%, 2.0%, and 1.6%. The projected reduction of energy intensity of GDP by 2050 in IEA's 2DS scenario actually matches the lower boundary of the fast reduction scenario by IPCC in Fig. 5.3.

Figure 5.3 Global GDP Energy Intensity Dynamics

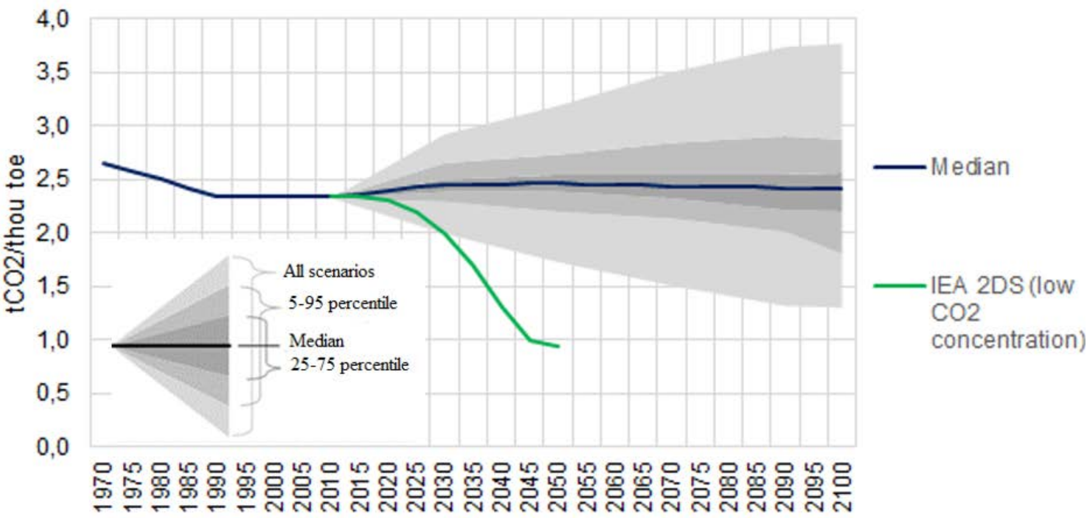


Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th — 95th percentile range (lighter), and full range (lightest). Scenarios are normalized using IEA 2010 data.

Sources: IPCC (2015), IEA (2014)

IPCC median scenario for carbon emissions per unit of primary energy assumes no major reduction. The results of the forecasts analysed by IPCC vary greatly (Fig. 5.4): from significant 54% reduction to 60% growth by 2100. However, the most likely scenario is that in 2100, carbon emissions will be equal to 94–109% of the 2010 value. This is the range left after cutting off 25% most optimistic and 25% most pessimistic scenarios.

Figure 5.4 Carbon Intensity of Primary Energy



Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th — 95th percentile range (lighter), and full range (lightest). Scenarios are normalized using IEA 2010 data.

Sources: IPCC (2014), IEA (2014), IEA (2015)

The projected carbon emissions reduction per unit of primary energy by 2050 in IEA's 2DS scenario is far beyond the range of values in forecasts analysed by IPCC. In this scenario, carbon emissions per unit of primary energy drop 60% by 2050; that is, the reduction rate is below the lower boundary of the projected range in IPCC scenario (Fig. 5.4).

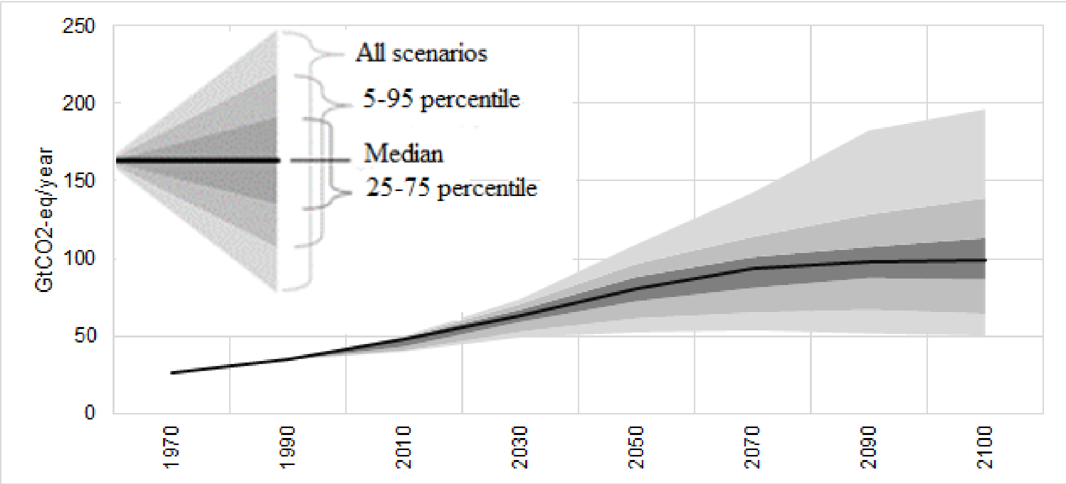
5.3 Long-Term Forecasts for Anthropogenic Greenhouse Gas Emissions

The trends in anthropogenic GHG emissions depend on the combination of factors reviewed above. ***Under IPCC's median scenario of the baseline band, all anthropogenic GHG emissions may stabilise in 2090 at a level close to 100 Gt of CO_2eq (which is 2 times higher than the current level).*** In 2035, the volume of emissions under the base scenario can achieve 67 Gt of CO_2eq, and in 2050, it can achieve 81 Gt of CO_2eq (Fig. 5.5). In the median (base) scenario, the average annual growth rate of GHG emissions amounts to 1.4% in 2010–2035, 1.2% in 2035–2050, and 0.4% in 2050–2100.

The range of scenarios analysed by IPCC is quite wide: taking all the possible scenarios into account, by 2100, the growth rate versus 2010 may range from 25 to 300%. However, if we cut off 25% most optimistic and 25% most pessimistic scenarios, the most likely trend is gradual stabilisation of emission volumes.

If we limit the analysis to projected CO_2 emissions from fuel combustion and industrial processes, emissions in the base scenario will grow to 52 Gt of CO_2 in 2035, 64 Gt of CO_2 in 2050, and 84 Gt of CO_2 in 2100, which is 2.6 times above the 2010 level (Fig. 5.6). In the fast reduction group of scenarios, the growth rate of emissions is significantly lower: 43 Gt of CO_2 in 2035, 46 Gt of CO_2 in 2050, and 52 Gt of CO_2 in 2100; still, this is 70% above the 2010 level. The growth of CO_2 emissions from fuel combustion and industrial processes will slow down from 2% in 2010–2035 to 1.3% in 2035–2050 and 0.8% in 2050–2100.

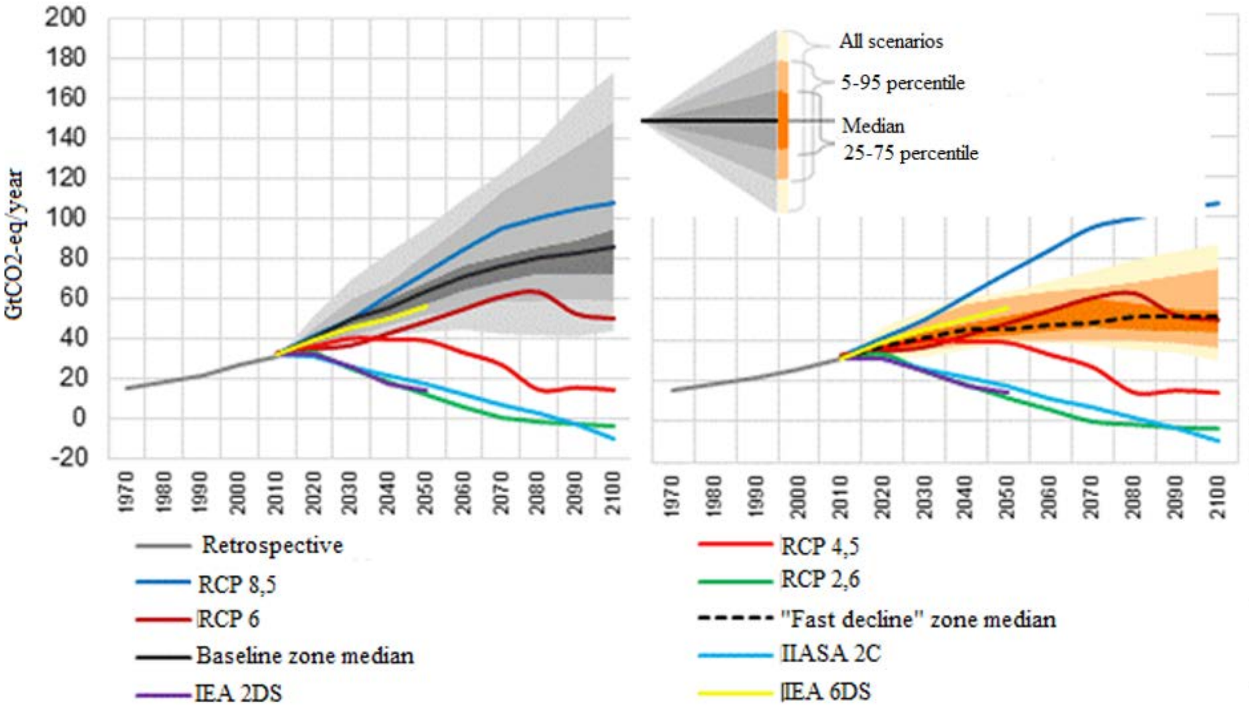
Figure 5.5 Evolution of global anthropogenic GHG emissions to 2100



Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th — 95th percentile range (lighter), and full range (lightest). Scenarios are normalized using IEA 2010 data.

Source: IPCC (2014).

Figure 5.6 Global Fuel Combustion and Industrial Processes CO_2 Emissions in Scenarios with Default Growth Assumptions and Fast Energy Intensity Decline until 2100



Note: The figures show world CO2 emissions from fuel combustion and industrial processes dividing all scenarios into two groups: baseline (left) and “fast decline” (right). Scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th — 95th percentile range (lighter), and full range (lightest). Scenarios are normalized using IEA 2010 data. For representative concentration pathways (RCP), developed by IPCC, are defined by a corrensponding value of radiative forcing in 2100 compared to 1750: 2,6 W/m2 for RCP 2,6, etc. RTC’s are depicted on both left and right figure for comparison with the medians. IEA and IIASA scenarios are also depicted for comparison.

Sources: IPCC (2014), IEA (2015), IIASA (2012).

The 2DS developed by IEA (Energy Technology Perspectives) matches IPCC's RCP 2.6 scenario, and so does IIASA's 2DS. IEA's 6DS is close to the median of IPCC base scenario.

According to IPCC estimates, in the group of scenarios involving growth of atmospheric GHG concentration above 650 ppm (70% growth versus 2010), direct and indirect GHG emissions from industrial processes will exceed 26 Gt of CO_2eq by 2100. This group of scenarios consists mostly of base forecast pathways of different groups, assuming no additional emissions reduction measures. Groups of scenarios resulting in a low atmospheric GHG concentration assume implementation of various policy measures targeted at climate change mitigation.

Figure 5.7 Industry GHG Emissions from Fuel Combustion and Industrial Processes, Including Indirect Emissions

Industry sector scenarios over the 21st century that lead to low (430–530 ppm CO2eq), medium (530–650 ppm CO2eq) and high (> 650 ppm CO2eq) atmospheric CO2eq concentrations in 2100. Median values are depicted with black dots. Shading reflects interquartile range (darkest), 5^{th}–95^{th} percentile range (lighter), and full range (lightest). White dots depict IEA scenarios (only CO2).

Source: IPCC (2015), EDGAR/IEA (base year 2010 value).

According to the median values in the base scenario, emissions will amount to 19.4 Gt of CO_2eq in 2035 (26% growth versus 2010) and 21 Gt of CO_2eq in 2050 (36% growth versus 2010). The most probable range of emission volumes is 19–25 Gt of CO_2eq in 2050 and 18–30 Gt of CO_2eq in 2100. Average annual growth rates will reach 0.9% in 2010–2035, 0.6% in 2035–2050, and 0.4% in 2050–2100.

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6 Projected Basic Materials Production until 2100

Forecasting Methods

Unlike the case with the energy sector, materials demand forecasting methods and practices are relatively underdeveloped. This especially concerns long-term forecasts. In a major part of integrated global models estimating the impact of anthropogenic emissions on climate, basic materials production forecasts are either not referred to or not disclosed. In certain cases performance indicators are available only for aggregate sectors (ferrous metals, chemicals, etc.). When models do include variables representing basic materials production volumes, these are generally projected as a function of population, GDP or trends in specific consumption of materials per capita or per GDP unit. The first approach was applied by IEA (2012), and the second approach is used, for example, in the global POLES model (2003).

In some cases forecasts based on specific indicators are adjusted to factor in sufficiency of available exhaustible natural resources to ensure the feasibility of their cumulative extraction volumes within the forecast period. For instance, in the report delivered by Klimenko (2010) a projection of basic materials production volumes until 2100 based on a forecast for specific consumption is further tested against the hypothesis involving possible saturation of demand for the relevant material, and against potential resource constraints, i.e. the volume of proven recoverable reserves. In such case, production first peaks (according to Klimenko, the peak in steel output will be reached in 2075), and then decreases. However, the possibility of resource recycling (for example, using scrap metal) was left out of scope, which can lead to wrong conclusions regarding the impact of resource constraints. This aspect was discussed in detail by Mathews (2012), using steel as an example. The possibility of scrap metal recycling being neglected, the peak is projected as early as 2025–2030. However, active scrap metal use lifts the above resource constraint.

Due to the absence of reliable data on material consumption breakdown by sector (construction, transport equipment, machinery, and other products), models hardly ever include functions measuring material demand in specific sectors of economy. Nevertheless, there are some examples of detailed product volumes distribution among sectors. Such breakdown for steel and aluminium is provided by Liu et al. (2012), Pauliuk et al. (2013), Allwood (2012), Ashby (2009), Allwood et al. (2011). However, different authors provide different data. Moreover, economic indicators—resource extraction cost and its price—are rarely used in long-term models. Such parameters as price elasticity of demand for various material applications, price elasticity of material substitution, and the impact of scientific and technological advances on demand are understudied as well.

When developing forecasts for associated groups of basic materials, material flow (mass balance) models are employed, which entails analysis of all production stages in their interdependence: from base ore mining to production of finished goods, including losses at every processing stage and recycling of process and consumer scrap (recovered materials).

A new forecasting tool has been developed in the recent years, based on the concept of material as a service and the distinction between accumulated stock and materials flow. The flow is the annual production and consumption of a resource, while the stock is the resource volume embodied in the accumulated material wealth used by the humankind. In other words, it is the volume of steel, cement or aluminium embodied in the available structures, buildings, machinery, equipment, packaging, etc. accumulated over the whole lifetime of the relevant material. It is annually replenished by new production volumes, both from fresh feedstock and recycled materials (less the changes in stocks), and reduced due to corrosion and irretrievable losses of materials (due to the limited share of recycled resources) after their lifetime is over. Liu et al. (2012) have plotted a generalised logistic curve, which is a synthesis of the regular logistic curve and the Gompertz function, which are generally used for saturation phenomena modelling:

$$S(t) = \frac{\hat{S}}{1 + \left(\frac{\hat{S}}{S_0} - 1\right)\cdot\exp(c\cdot(1 - \exp(d\cdot(t - t_0))))}$$

Parameters: t is the time, $\hat{S}$ is the saturation level, S_0 is the accumulated stock of a material at the given point in time t_0, c and d are the two parameters defining the shape of the curve, which are selected so that the following two boundary conditions are satisfied: (a) The modelled curve is tangential to the historical data curve at t_0 = 2008; and (b) the accumulated stock reaches 99% of the saturation level at t_s.

The Gompertz function is used to describe the trajectory of the curves in Fig. 6.1. It is expressed by the following equation:

$$S_{PC} = S_{PC}^{L} + (S_{PC}^{U} - S_{PC}^{L})e^{-e^{-b(g-g_0)}}$$

where S^L_{pc} is the minimum stock of the relevant material per capita (can be equal to 0); S^U_{pc} is the saturation level for the material per capita; b is a constant; g is GDP per capita; g_0 is the value of GDP per capita at which the level of accumulated stock of the relevant material reaches per capita saturation.

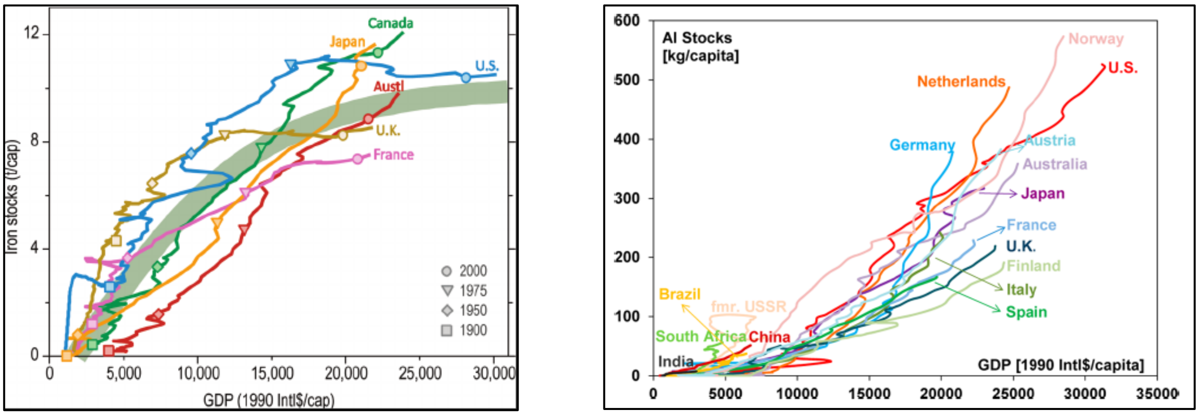
Fujitsuka et al. (2013) also estimate the stock of materials in the material flow model, but their model is different:

$$S_t = \frac{S_{sat}}{1 + \exp\,(\alpha - \beta \times GDP_t)}$$

where S_t is the stock of the relevant material per capita in year t, S_{sat} is the saturation level, GDP_t is the value of GDP per capita in year t, α and β are the parameters defining the shape of the logistic curve.

To apply the stock saturation approach, it is necessary to know the average lifetime of the material in various applications or sectors of economy and consumption breakdown by sector. Since there is rather little information of such kind in statistical data, it has to be logically reconstructed (using steel and aluminium as examples, see details in Pauliuk et al., 2013; Liu and Müller, 2013). The main idea is that services provided by a certain kind of material depend on its stock level rather than on its annual flow. If there is a certain saturation level for the service, annual production volumes can be quite irregular and depend greatly on the possibility of material recycling. ***As it was shown by Pauliuk et al. (2013), many developed countries have already reached saturation for steel at the level of 14±2 t per capita. However, no country has reached saturation for aluminium, and its specific stock per capita continues to grow as per capita income increases (Liu and Müller, 2013).*** The accumulated stock of aluminium is 0.6 bt, or 90 kg per capita, and it keeps growing by 5–10 kg/capita annually. At the same time, it reaches 100–600 kg/capita in developed countries (Liu and Müller, 2013). However, even in the richest countries the current level of accumulated stock of aluminium per capita is more than 20 times lower than the saturation level reached by steel.

Figure 6.1 Dynamics of Steel Stocks (a) and Aluminium stocks (b) in World Countries (per capita)



(a) Per capita iron stocks in use versus per capita GDP PPP (1990 international dollars).

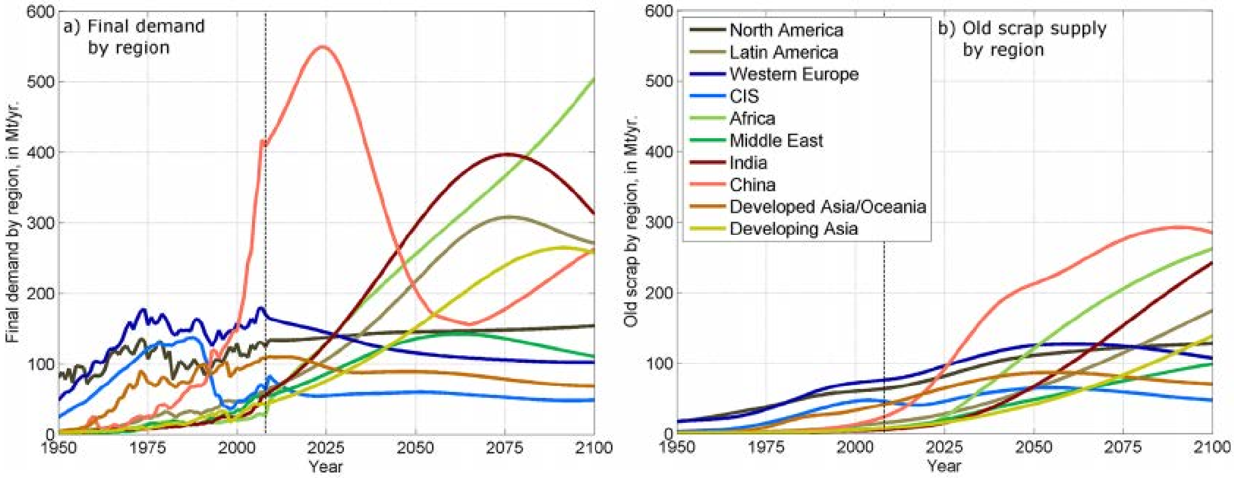
(b) Per-capita aluminium stocks in use relative to per-capita GDP PPP for selected countries. The GDP data are measured based on purchasing power parity (PPP) in 1990. The stock data are shown only until 2008 because of GDP data availability.

Sources: Liu and Muller (2013); Muller et al. (2011).

A high level of material saturation makes it possible to use recycle resources more actively as they become recycled at the end of the service life of various facilities. Accumulated stock saturation is not equivalent to annual flow saturation. Unlike the approach described by Klimenko (2010) who takes into consideration potential saturation of the annual material demand flow, the present approach focuses on the saturation of the stock of material. Its projection on annual production volumes can vary significantly depending on the level, saturation time, and degree of material recycling (Fig. 6.2). As for steel, only in North America does the production pathway resemble flow saturation (annual steel output).

This approach has certain limitations: it is applicable only when data on the accumulated stock of the relevant material are available, and when the saturation time and level of the accumulated stock of this material per capita are known. Assessing the accumulated stock is a really time-consuming task and it requires enormous volumes of information on production, international trade, material consumption and recycling (see details in Liu and Müller, 2013; Pauliuk et al., 2013). Therefore this approach has been applied on a global scale (to the world economy) only to forecast steel and aluminium production volumes. At present G. Liu is performing this kind of analysis for cement. The key driver in this approach is population.

Figure 6.2 Final Steel Demand (a) and Old Scrap Supply (b) by Region



a b

Note. Old scrap does not include scrap received during steel production

Source: Pauliuk S. et al. (2013).

Before we move on to projections for selected types of basic materials, it is important to note that even retrospective estimates of selected materials' production and consumption volumes vary significantly. It is important to distinguish final consumption of a resource from its production. For instance, production of crude steel exceeds the volume of its final consumption by approximately 10%. According to IEA estimates (2012), crude steel production in 2010 was 1,232 Mt; other sources say it was 1,390 Mt (Mathews A., 2012). It is important to take into consideration the difference in production and consumption of materials due to changes in stocks. It is also essential to distinguish production of fresh materials (for example primary aluminium) from scrap metal recovery or waste recycling.

Below are the global output projections for the key types of basic materials that this study focuses on. They were collected from various publications and calculated using different methodologies. ***Out of the whole range of forecasts, baseline projections were selected for the purposes of the present study, i.e. such forecasts until 2035, 2050, and 2100 that are based on the most probable trends in production, provided no special policy measures are taken and no technological breakthroughs are achieved to improve the efficiency of material use, as well as on the most probable future trends in population size or GDP*** (see Chapter 5).

For some types of materials (primarily the “Big Five”), quite a lot of forecasts are available, while for other types there are hardly any projections at all. In case with the latter, the authors had to generate their own forecasts based on future trends for similar materials and historical trends in their specific use per capita or per unit of GDP.

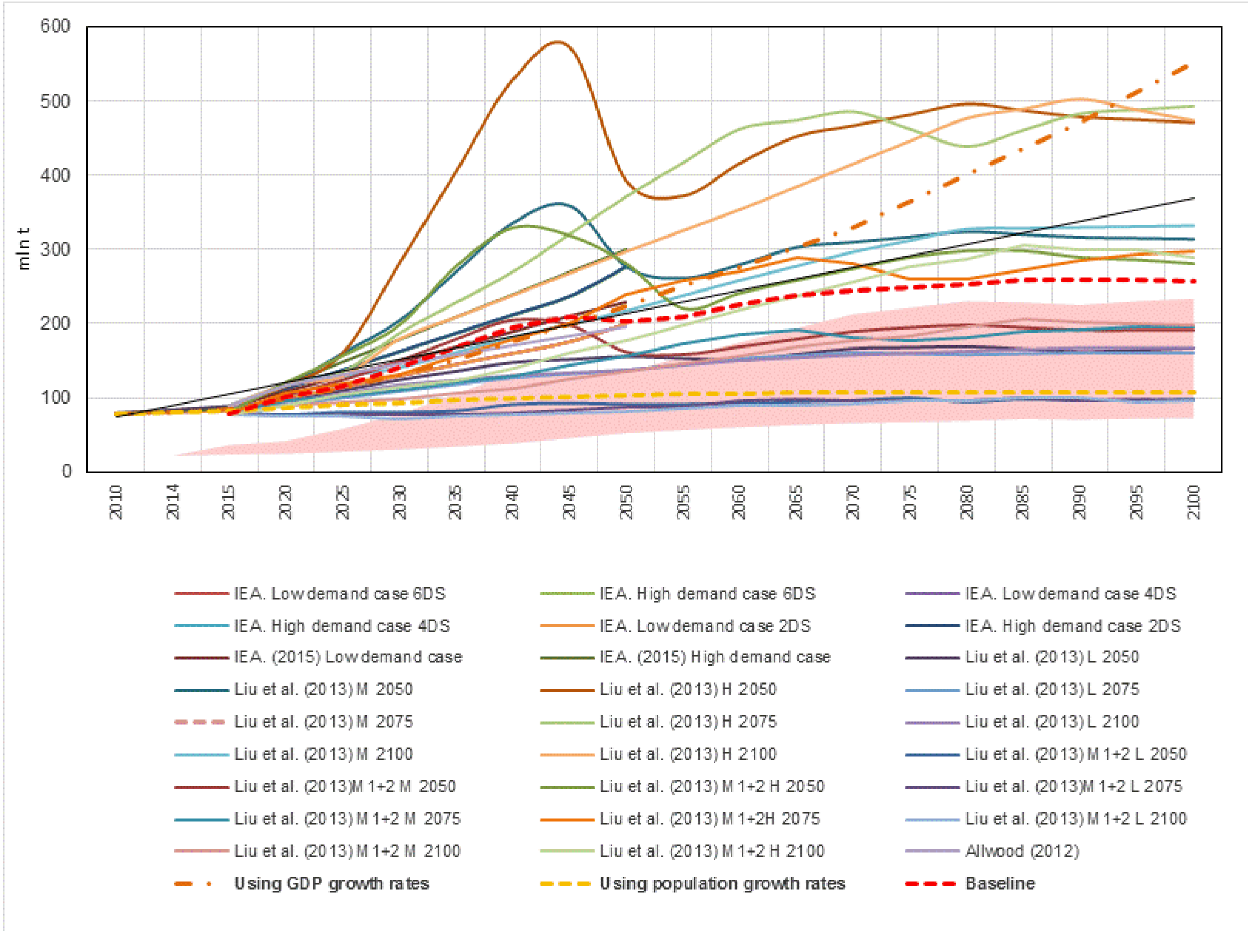
6.1 Aluminium

Long-term aluminium production forecasts were taken from the studies of IEA (2012 and 2015), Liu at al. (2013), Allwood (2012), and Klimenko (2010).[55] When developing their forecasts, Liu et al. (2013) used the stock saturation approach.

[55] The forecasts by Klimenko (2010) apply exclusively to primary aluminium. The expected range in 2100 is 14–76 Mt, which is narrower than in other projections. For example, IEA (2012) projects a range of 94–135 Mt in 2050, while Liu et al. (2013) forecast a range of 20–117 Mt in 2100.

The forecasts shown in Fig. 6.3 reflect the estimated production volumes of both primary and secondary aluminium. Secondary aluminium becomes more important as the stocks of aluminium grow and its recycling rate (which is already rather high) increases even further, and as the volume of waste (process scrap) at different stages of aluminium goods production decreases.

Figure 6.3 Primary and Secondary Aluminium Production Dynamics until 2100



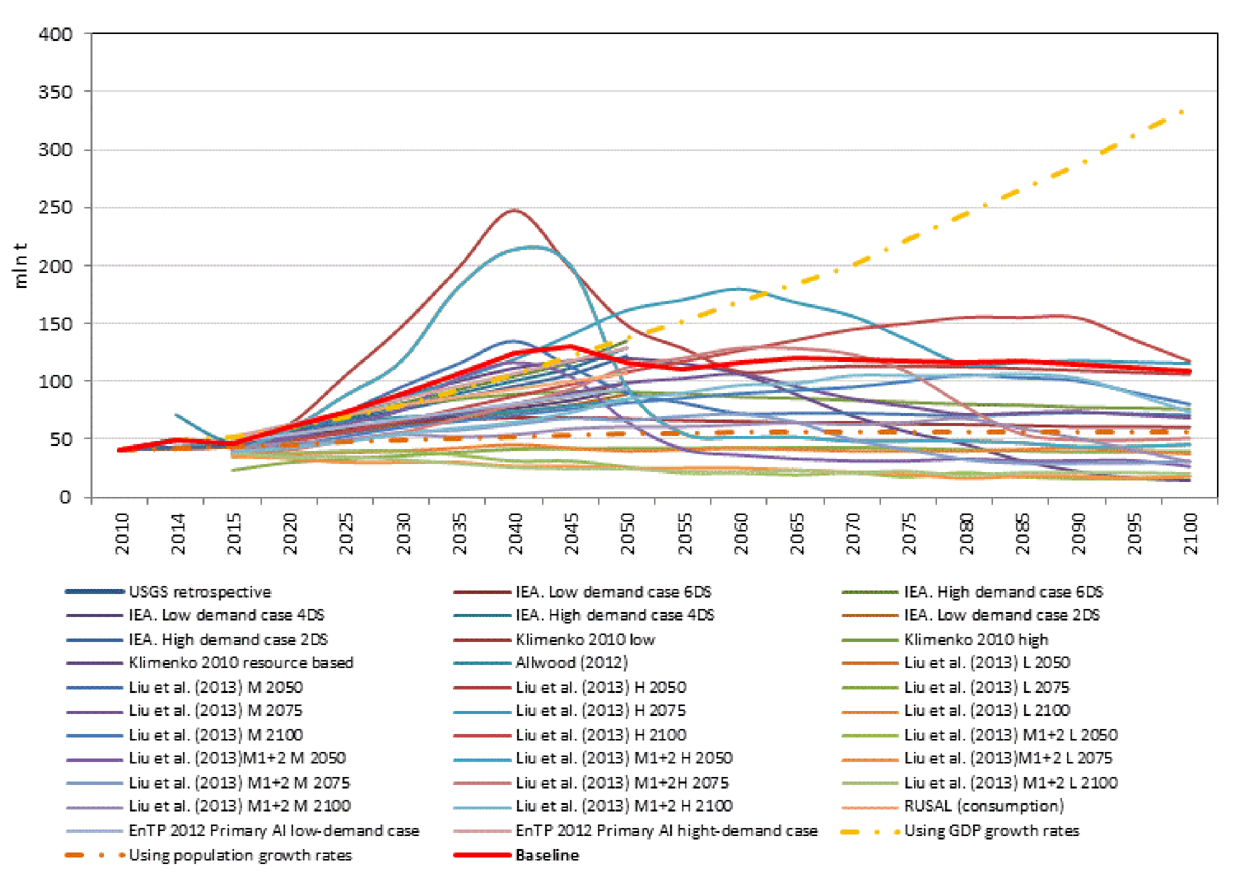
Sources: IEA (2012); IEA (2015); Allwood (2012); Liu et al. (2013).

In their scenario forecasts, Liu et al. (2013) consider various time frames and levels with respect to accumulated aluminium stock saturation (2050, 2075, and 2100), as well as various saturation levels for the global aluminium stocks (L—low, M—medium, H—high). Moreover, a number of scenarios allow for more efficient use of aluminium thanks to active technological advancement towards lower waste volumes at different processing stages and the relevant decrease in process scrap along with the dramatic increase in old (consumer) scrap recycling.

Fig. 6.3 also demonstrates the trends in aluminium production, provided it grows at the pace equal to the growth rate of the planet's population or the global GDP. The baseline projection is the average of the forecasts developed by Liu et al. (2013) and by other authors. In this scenario, aluminium production grows at a faster rate than GDP until 2045. In other words, the trend of the previous decades is sustained during this period. Afterwards, production volumes stabilise at the baseline level and grow approximately at the same rate as the population. The 2050 value projected in this scenario (258 Mt) is approximately in the middle of the range specified in the latest aluminium production forecast by IEA (2015), 230–300 Mt. It means that this scenario can be regarded as the baseline projection. Fig. 6.3 shows that it is rather representative of the scenario group with average aluminium output growth rates until 2100. This scenario is the average among all the aluminium production projections.

Trends in production of primary aluminium depend quite heavily on the hypotheses regarding scrap metal use. The estimated scrap use curve is based on the average values among 15 different projections, outlining the filled area in Fig. 6.4. By 2100 the volume will reach 150 Mt. By subtracting this figure from the baseline aluminium production, we calculate the baseline projection for aluminium output (Fig. 6.4).

Figure 6.4 Primary Aluminium Production Dynamics until 2100



Sources: IEA (2012); IEA (2015); Allwood (2012); Liu et al. (2013).

Similar to total aluminium volumes, primary aluminium production grows at a higher rate than GDP until 2045 and then gradually diminishes to 108 Mt per annum by 2100. In many forecasts, projected primary aluminium production volumes are below this level. However, there are no reasons to use higher values in primary aluminium production assumptions.

6.2 Copper

Long-term copper production forecasts were taken from the reports of MarketReportsStore.com, Freedonia group, Science Magazine[56], Ayres et al. (2002)[57].

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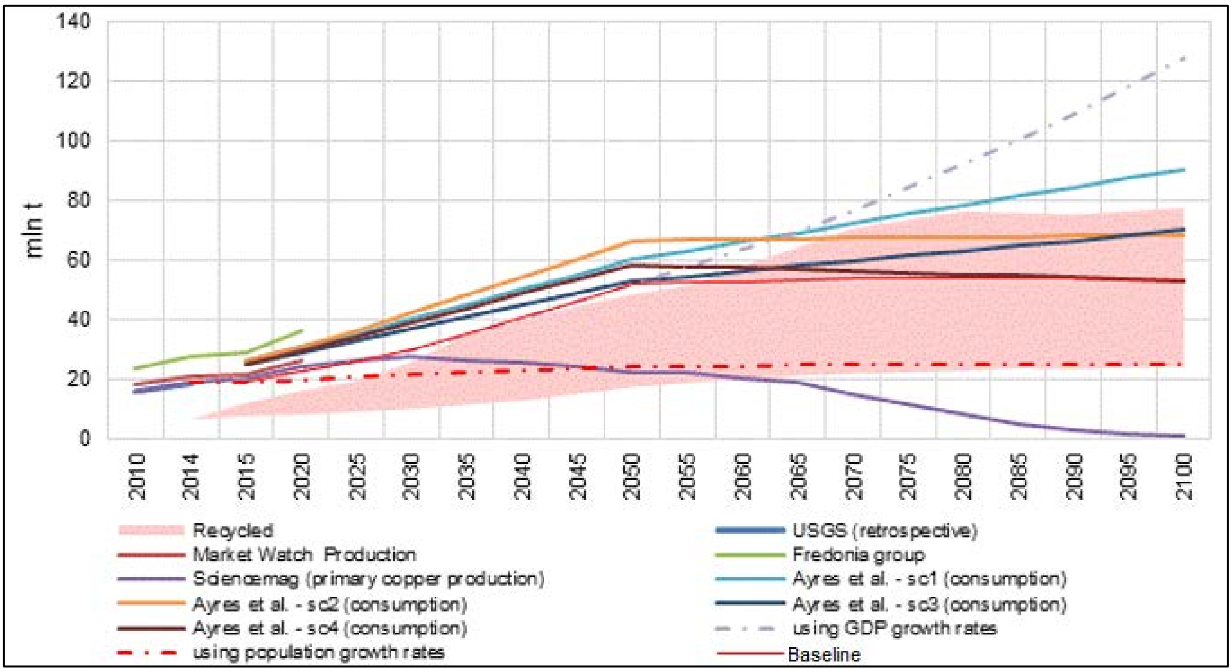
[56] R. Kerr, 2014. The Coming Copper Peak. VOL 343 SCIENCE www.sciencemag.org.
[57] 2002. R.U. Ayres et al. The life cycle of copper, its co-products and byproducts.

Figure 6.5 Copper Production and Consumption Dynamics until 2100



Sources: MarketReportsStore.com, Freedonia group, sciencemag.org, Ayres et al. (2002).

The majority of the forecasts assume copper consumption saturation, peak and subsequent decrease by the end of the century. In Science Magazine 2014, R. Kerr (referring to Northey et al. (2014))[58] projects a peak before 2030 and a drop in copper production almost to zero by 2100. In addition, the article mentions similar results obtained by several scholars when experimenting with accumulated stock models, i.e. an increase in primary copper production inevitably followed by a sharp decline within the next two decades.

An older forecast by Ayres includes four different scenarios for copper demand development, depending on the population and global economy growth rates. All those scenarios assume that growth continues until 2050, followed by deceleration or even stagnation of consumption volumes until the end of the century.

The range of secondary copper consumption volumes was calculated based on the assumption that copper processing will be developing at the same pace as aluminium processing.

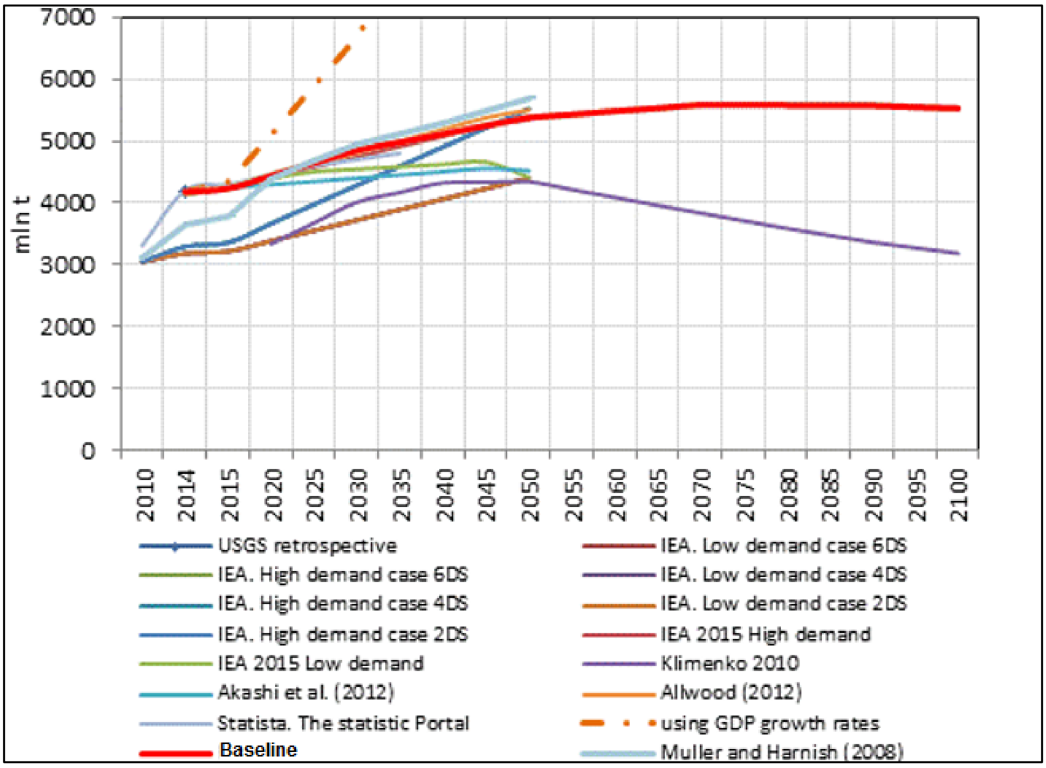
58 S. Northey et al. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resources, Conservation And Recycling 83 (February 2014).

6.3 Cement

Long-term cement production forecasts were taken from the studies of IEA (2012 and 2015), Allwood (2012), Klimenko (2010)[59], Akashi (2012) and Statista (2015). Most forecasts are based on estimated per capita cement consumption and population growth trends.

Referring to the stagnation or even decrease in per capita cement consumption in developed countries, as well as the extrapolation of this situation to the whole world with a time lag, Klimenko (2010) concludes that the global cement production will reach a peak and subsequently decrease by 2100 (Fig. 6.6). Such an assumption is reasonable, since it is expected that even in China with its highest development rate cement consumption will reach a peak before 2040 and then start to gradually diminish (Huang et al., 2013).

Figure 6.6 Cement Production Dynamics until 2100



Sources: IEA (2012); IEA (2015); Allwood (2012); Akashi (2013); Statista (2015); Klimenko (2010).

The consumption decrease in developed countries and in China can be neutralized by the growing per capita cement consumption in India and other developing countries (Müller N., and J. Harnish, 2008). As to Klimenko's hypothesis regarding the peak around 2040, other forecasts do not predict any peaks until 2050 (Fig. 6.6). In IEA forecast (2012), the estimates for 2015 were obviously understated; therefore in the new IEA forecast (2015) these were corrected upwards.

The main growth driver in cement consumption forecasts is the population. Therefore the baseline projection is almost identical to the forecast generated by indexing production volumes to the population size.

[59] The forecasts by Klimenko (2010) apply exclusively to primary aluminium. The expected range in 2100 is 14–76 Mt, which is narrower than in other projections. For example, IEA (2012) projects a range of 94–135 Mt in 2050, while Liu et al. (2013) forecast a range of 20–117 Mt in 2100.

6.4 Concrete

According to USGS estimates, in 2014 the world consumption of concrete amounted to 26.3 bt, which is 6.3 times more than its total output. There are no long-term estimates for the global concrete production. In addition to cement, concrete mix normally includes construction aggregates such as sand and gravel, and water. The proportion of components in concrete depends on the concrete grade: the higher the grade, the higher is the cement content. On average, cement accounts for 12–14% in the total weight of cement, sand, and gravel mix. The University of Bath uses the 12% value in its database. The average estimates for Chinese buildings are also close to 12% (Huang et al., 2013).

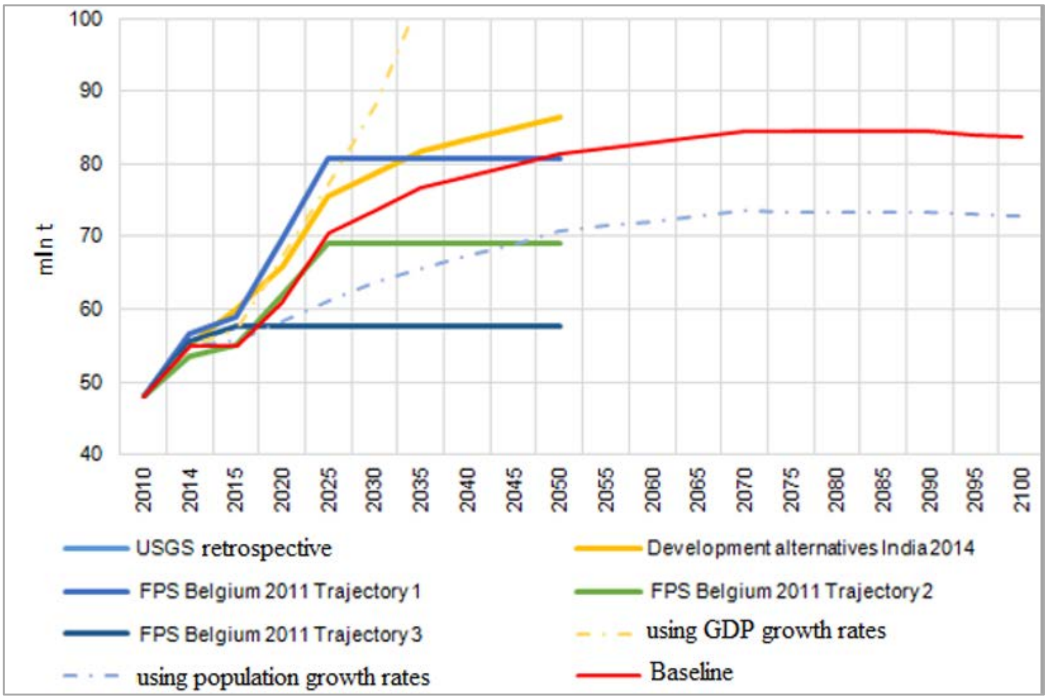
In other words, to project concrete production volumes, the above cement output values must be multiplied by 7÷8.5. Since cement is used not only for concrete production but for mortars and asbestos-cement items as well, the actual multiplier is assumed equal to the average ratio in the last 20 years, which is 6.2. That is, the baseline projection for concrete consumption is equal to the baseline projection for cement (see Fig. 6.6), multiplied by the factor of 6.2. Thus, in the base scenario concrete production reaches 34 bt and stabilises at that level.

6.5 Brick

There are no forecasts for brick production until 2100. In the available projections, the forecasting time frame is limited to 2050. A group of Indian specialists (Development alternatives India 2014) predicts saturation in brick production due to substitution of bricks by cheaper and lighter modern construction materials (Fig. 6.7). A Belgian consulting group VITO suggested three different scenarios for brick and ceramics in the framework of its low-carbon map of Belgium, ordered by Federal Public Service Health, Food Chain Safety and Environment[60]. According to its projections, the production of brick and ceramics will grow by 68 and 44%, respectively, by 2025, and then reach saturation either by 2050 (scenarios 1 and 2, accordingly) or as early as 2015 (scenario 3). The saturation effect is primarily caused by demand saturation in residential construction, as well as by changes in brick production processes.

[60] http://www.klimaat.be/2050/files/9813/8323/7398/3_Industry_-_Ceramic.pdf.

Figure 6.7 Brick Production Dynamics until 2100



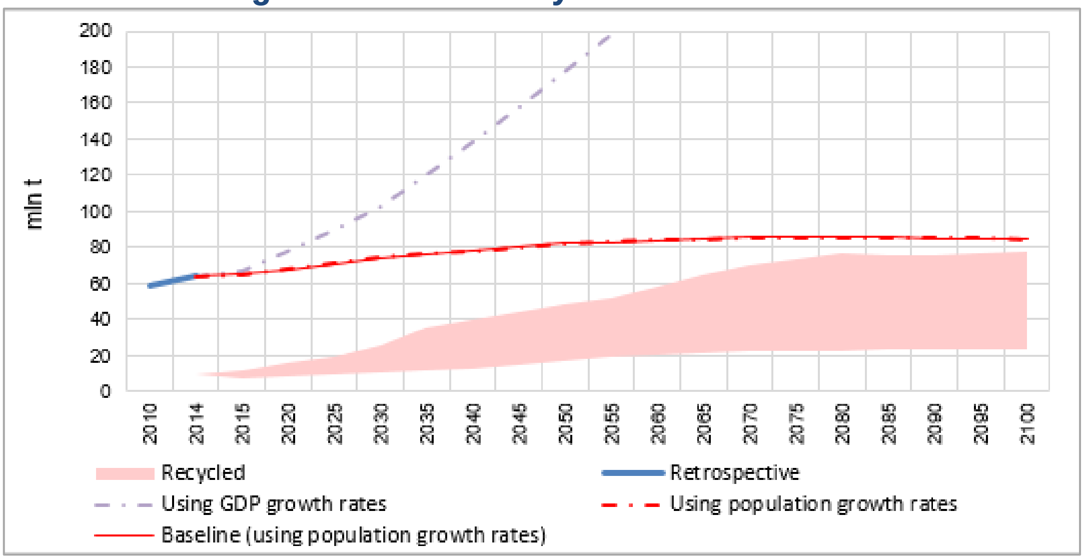
Sources: CENEF-XXI, Federal public service health food chain safety and environment 2011, USGS 2013, Development alternatives India 2014.

FPS Belgium's 2011 moderate growth scenario (Trajectory 2) was chosen as the baseline scenario for brick production until 2020; in 2020–2050, the baseline scenario is identical to the forecast provided in Development alternatives India 2014; and after 2050, the projection is proportional to the predicted population growth rate.

6.6 Flat Glass

No long-term forecasts for flat glass production until 2100 are available, either. The trends in glazing glass production are assumed to be the same as in cement demand: according to the results of retrospective analysis, specific consumption of both materials per 1 sq. m of housing is virtually constant (Huang et al., 2013). By 2100 glass consumption will have stabilised (Fig. 6.8).

Figure 6.8 Flat glass Production Dynamics until 2100

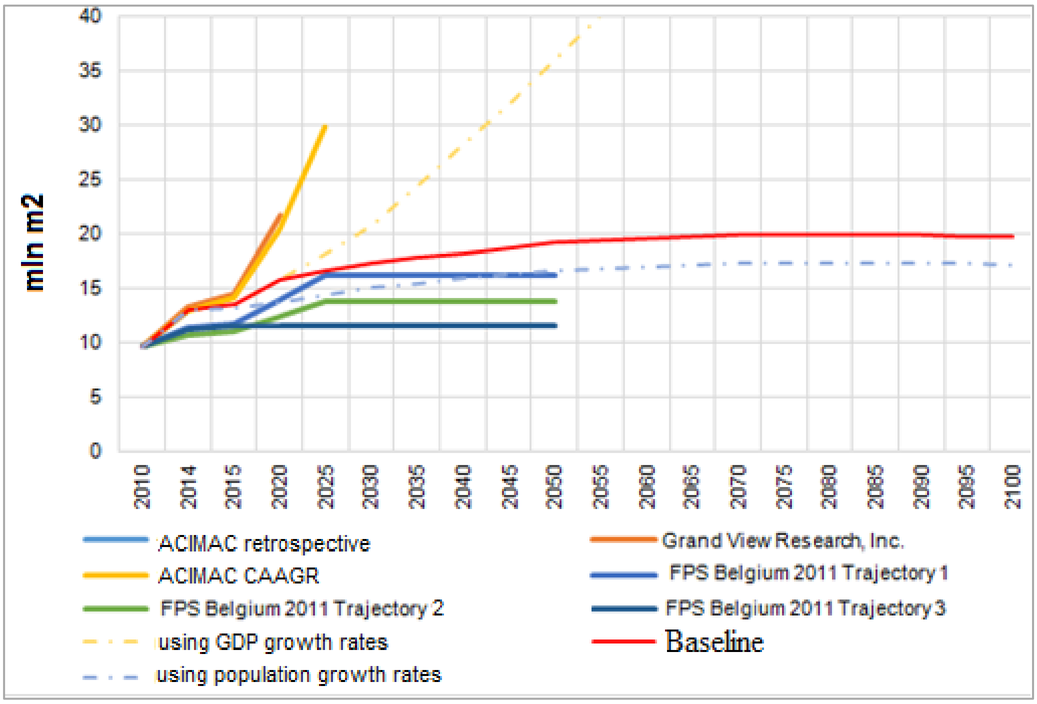


Sources: CENEF-XXI, Pilkington and the Flat Glass Industry 2010.

6.7 Ceramics

No very-long-term forecasts for ceramics production until 2100 are available. However, there are certain projections until 2020 and until 2050. The baseline projection was developed based on the above-mentioned forecasts and relevant trends involving changes in main factors affecting ceramics production (Fig. 6.9). As projected, substitution of hardwood floors and other flooring materials with floor tiles thanks to such properties as high strength or frost and heat resistance will have a positive impact on the ceramic tiles market in the short run.

Figure 6.9 Ceramics Production Dynamics until 2100



Sources: CENEF-XXI, Federal public service health food chain safety and environment 2011, ACIMAC 2015, Grand View Research, Inc. 2012.

Trends in the available scenarios are quite varied. The scenario based on the forecast by Grand View Research, Inc.[61] predicts that the world demand for ceramics will reach 21.8 mln sq. m in 2020, increasing on average by 8.5% per annum in 2014–2020. In the later years until 2100, the projection is proportional to the population size. In the scenario based on the forecast made by ACIMAC[62], the compound annual growth rate of the demand for ceramics until 2020 is 9%. In the three scenarios of the above-mentioned Belgian consulting group VITO,[63] the production level increases by 68 and 44% until 2025, reaching saturation after that. A similar production decrease is projected in the European Ceramic Industry Roadmap until 2050.[64]

ACIMAC growth scenario was chosen as the baseline projection for ceramics production until 2020, and after 2020 the projection is based on population growth.

[61] http://www.ceramicindustry.com/articles/94710-construction-growth-expected-to-drive-ceramic-tile-market.

[62] http://www.acimac.it/documenti/settore%20in%20cifre%20free/produzione-consumo/2015/schede_esempio_ENG.pdf.

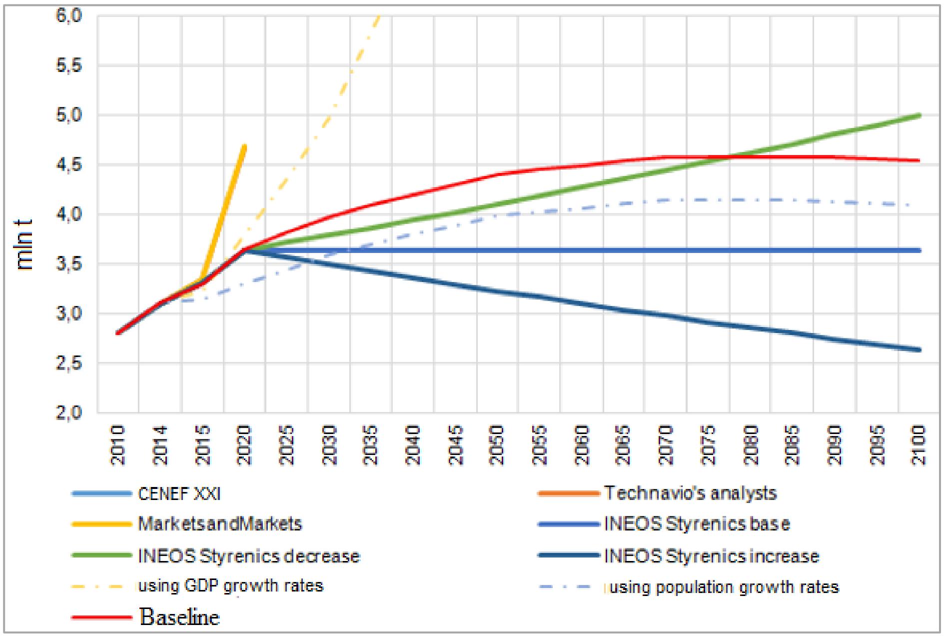
[63] http://www.klimaat.be/2050/files/9813/8323/7398/3_Industry_-_Ceramic.pdf.

[64] Source: Paving the way to 2050, The ceramic industry roadmap, The European ceramic industry association, 2013.

6.8 Insulation materials

In the forecast by TechNavio (Infiniti Research Ltd)[65], the global demand for thermal insulation materials increases by 8% per annum in 2015–2020. This forecast includes projections for Asia, Europe, North America and the rest of the world. It also takes into account the changes in the markets of mineral wool, fibreglass wool, expanded polystyrene, polyurethane, and other insulation materials. In the scenario by Markets and Markets , the compound annual growth rate for the whole range of insulation materials up until 2020 is also 8%. INEOS Styrenics presented its three scenarios until 2100[66]. According to them, insulation materials production will be growing until 2020. From that point and until 2100, the output of insulation materials will either drop by up to 30% (scenario with a slow rate of building commissioning), or be moderate (scenario with a moderate rate of building commissioning, especially for the low-energy segment), or increase by up to 30% (fast rate of building commissioning scenario), depending on the overall housing commissioning rate and the rate of commissioning for housing with next-to-zero energy consumption.

Figure 6.10 Mineral Wool Production Dynamics until 2100



Sources: CENEF-XXI; TechNavio, 2011; Markets and Markets 2013; INEOS Styrenics 2012.

The baseline projection for the output of thermal insulation materials until 2020 is based on the average annual production growth rate equal to 8% (which is confirmed by several above-mentioned expert judgements), and after 2020 the projection is based on the population growth.

6.9 Construction composites

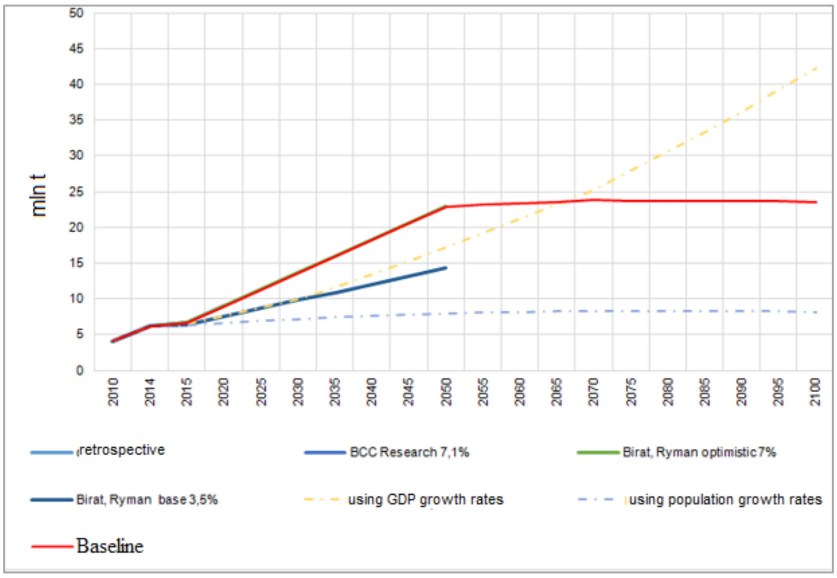
Glass-Reinforced Plastics. The market for glass-reinforced plastics is one of the fastest-growing markets, alongside with carbon plastics. In the scenario forecast by ReportsnReports.com[67], the global demand for glass-reinforced plastics is growing by 7.2% per annum until 2020. The authors estimated the relevant growth rate after researching the market for various glass-reinforced plastics applications, including transportation, construction and infrastructure, electric and electronic goods, consumer goods, etc., broken down by their application geography. In the forecast by BCC Research, the global demand for glass-reinforced plastics is growing by 7.1%

[65] http://www.giiresearch.com/report/infi301380-global-insulation-market.html.
[66] http://www.slideshare.net/netplusz/stephen-long-eu-legislation-and-insulation.
[67] http://www.ceramicindustry.com/articles/94710-construction-growth-expected-to-drive-ceramic-tile-market.

until 2020. In the scenarios proposed by Birat, Ryman et al.[68], the global demand for glass-reinforced plastics is rising at the average annual rate of 3.5 and 7% until 2020. However, the said scenarios cover not only glass-reinforced plastics, but other glass items as well, including flat and industrial glass.

The moderate scenario by BCC Research was chosen as the baseline projection for glass-reinforced plastics production until 2020, and in 2020–2050 the baseline projection is based on the scenario developed by Birat, Ryman, et al. with the annual growth of 7% (due to the anticipated substitution of traditional materials with glass-reinforced plastics in the medium run). Beyond 2050, the projection is based on the population growth because of the expected saturation after most of the substitution potential of traditional materials has been exhausted (Fig. 6.11).

Figure 6.11 Glass-Reinforced Plastics Production Dynamics until 2100

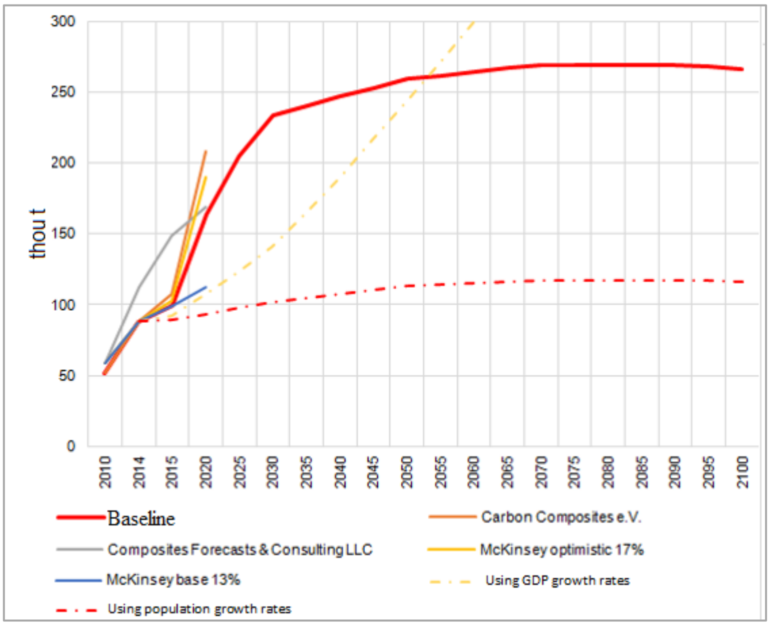


Sources: CENEF-XXI, Federal BCC Research 2013, Birat, Ryman 2011.

Carbon plastics. No forecasts are available for carbon plastics production after 2020; therefore, Fig. 6.12 displays the forecasts until 2020 only. The market for carbon plastics is one of the fastest-growing industrial markets. In the scenario proposed by Carbon Composites e.V., the projected demand for carbon plastics covers three key consumption segments: wind farms, aerospace and automotive industry, and sports. In the scenarios proposed by McKinsey, the global demand for carbon plastics is growing at the average annual rate of 13 and 17% until 2020. However, these scenarios were presented in December 2012, and already in 2013 and 2014 it became obvious that those were overestimated. In the scenario proposed by Composites Forecasts & Consulting LLC, the forecast takes into account the potential capacity expansion and the opportunities for application of certain types of carbon plastics in the automotive and aerospace industry as well as in some other sectors.

[68] Technology offer for production of goods and services. Quantitative description of the links between social services and technologies in a post-carbon society and data for energy and CO2 intensity of materials. Birat, Chiappini, Ryman, Riesbeck, 2011.

Figure 6.12 Carbon Plastics Production Dynamics until 2100



Sources: CENEF-XXI, Carbon Composites e.V. 2013, Composites Forecasts & Consulting LLC 2013, McKinsey 2011.

The scenario developed by Composites Forecasts & Consulting LLC with the average annual production growth rate of 13% was chosen as the baseline projection for carbon plastics production until 2020, whereas the projection for the later years involves gradually subsiding rates of production capacity expansion, dropping to 5% by 2050. After 2050, the forecast is based on the rate from the scenario modelling population growth.

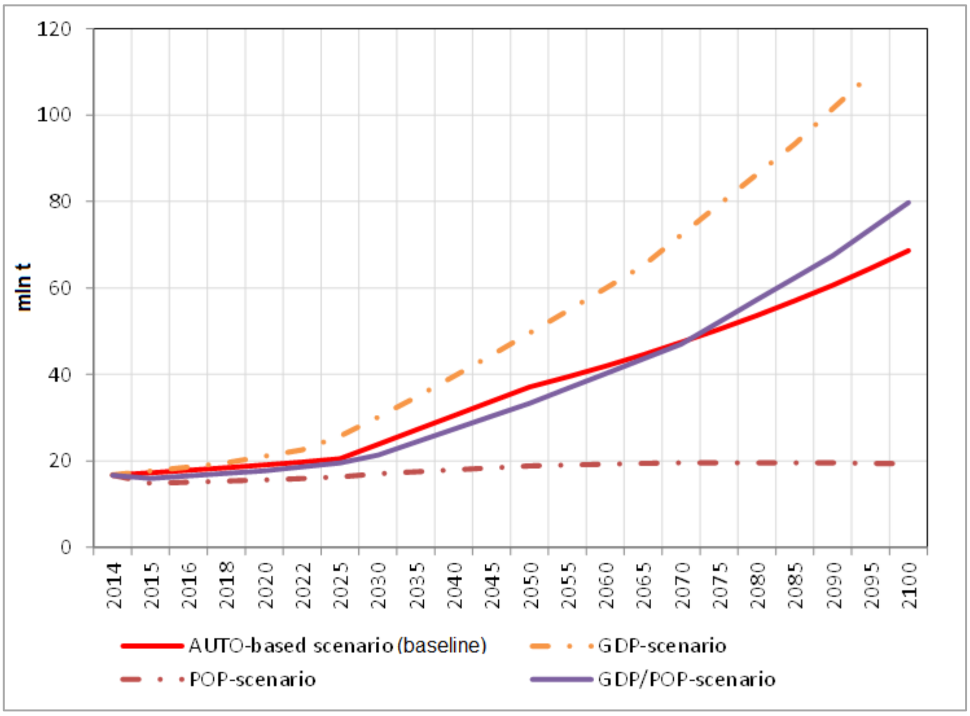
6.10 Synthetic Rubber

There are no long-term scenarios for synthetic rubber production growth; therefore the authors developed their own projections based on the three key demand drivers: GDP growth, car fleet, and population. The scenario based on the world GDP growth (GDP scenario) involves adjustment of the actual synthetic rubber output in the base year to the global GDP index. The scenario based on the population size (POP scenario) is linked to the population growth rate. The growth figures in these scenarios vary greatly (Fig. 6.13), but they fail to factor in some important drivers.

More than half of the produced synthetic rubber is used as feedstock for car tyres and inner tubes; accordingly, this segment depends heavily on car manufacturing volumes. In the past years, the average annual production growth rates of both groups were almost identical—3.2 and 3.4%, respectively, for synthetic rubber and cars. The scenario based on car production volumes (AUTO-based scenario) involves adjustment of the actual volume of synthetic rubber output in the base year to the car production index. The latter is based on extrapolation of IEA projections for cars[69]. This scenario is regarded as the baseline. Its results are close to the projections based on production indexing to per capita GDP.

[69] http://www.iea.org/aboutus/faqs/transport/

Figure 6.13 Synthetic Rubber Production Dynamics until 2100



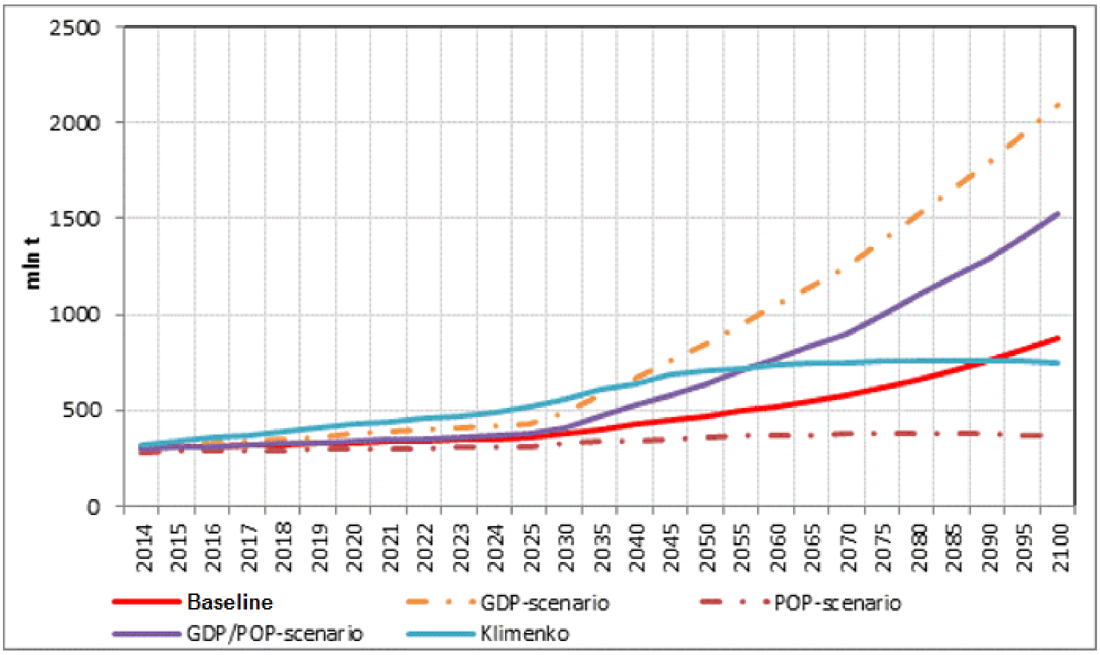
Sources: CENEF-XXI

6.11 Plastics

There is a long-term forecast for the total volume of plastics until 2050 developed by Allwood (2012); however, there are no production volume forecasts for individual types of plastics, except a mid-term projection for polyethylene until 2024. Moreover, IEA (2012) developed its forecasts for two monomers (ethylene and propylene) until 2050. They can serve as the basis to develop forecasts for relevant polymerization products (polyethylene and polypropylene). In this section, aggregate plastics and thermoplasts production forecasts will be discussed.

There are four different scenarios with projected output volumes: GDP growth rate scenario, population growth scenario, per capita GDP growth scenario, and total plastics production scenario. In the latter case, the forecast was based on projected plastics output volumes in 2050 according to Allwood (2012) and extrapolation of the trend to the whole period under consideration, with shares of different types of plastics in the total volume assumed constant. This scenario will be regarded as the baseline for thermoplasts. The reason why the global plastics production scenario available in the study by Klimenko (2010) was rejected as the baseline is that it assumes rather early saturation of the global plastics market (before 2050), which is hardly possible due to multiple constraints related to finance, resources, and legislation. Forecast results are presented in Figs. 6.14–6.15.

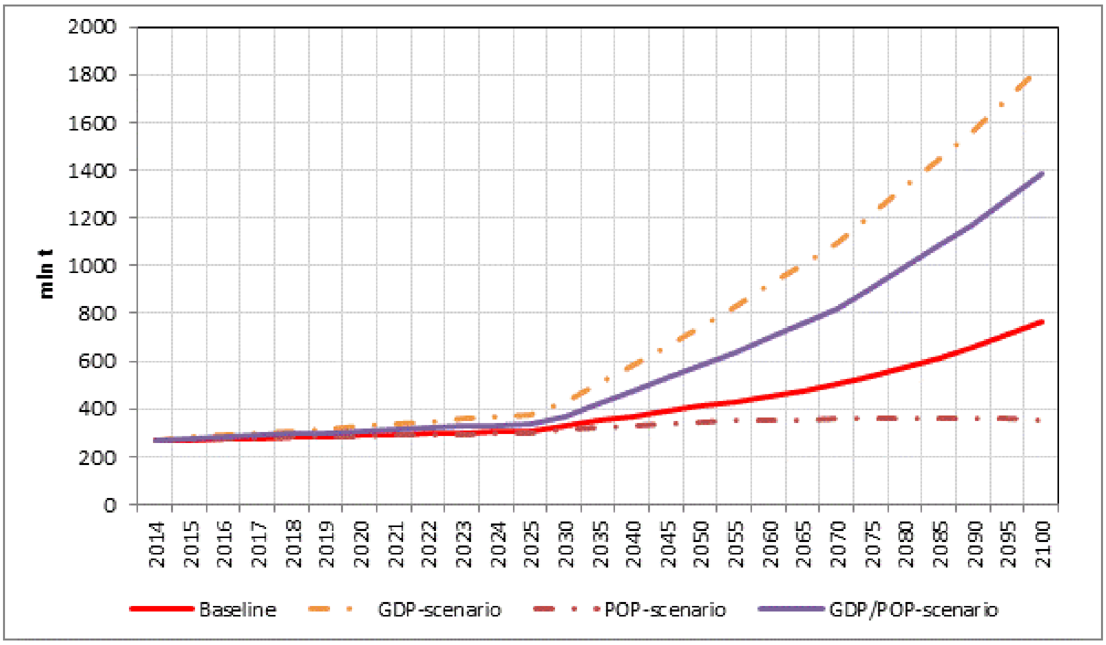
Figure 6.14 Plastics Production Dynamics until 2100



Note: baseline scenario is formed using annual growth rates of total platics production until 2050 by Allwood (2012).

Source: CENEF-XXI

Figure 6.15 Thermoplasts Production Dynamics until 2100



Note: baseline scenario is formed using annual growth rates of total platics production until 2050 by Allwood (2012).

Source: CENEF-XXI.

6.12 Timber and Wood-Based Panels

There are just a few long-term timber production forecasts: Klimenko (2010) and State of the World's Forests (2009), FAO UN[70]. The former covers the period until 2100 and the latter, until 2030. The low scenario developed by Klimenko assumes that timber consumption will continue to decrease by 0.25 m^3/capita per annum; the high scenario was generated by extrapolating the trends from the forecast by Food and Agriculture Organization of the United Nations beyond 2030. The UN forecast assumes expansion of man-made forest areas.

Moreover, timber consumption forecasts are presented in the studies Outlook to 2060 for World Forests and Forest Industries (2012) and Key Global Supply Trends and North America Impact Look: Impacts on BC Lumber Industry by Russel Taylor (2013). In the first case, the forecast includes four different scenarios until 2060, based on the Global Forest Products Model (GFPM) that takes into account a great number of factors: forest area trends, timber consumed for power generating purposes, prices for wooden products, etc. Consumption and production volumes of any product cannot be equated to each other because of product stocks. However, both have similar growth trends. Therefore timber demand projections can be used to forecast timber production volumes, provided they are adjusted to accumulated stocks (assuming the latter remain at a constant level until 2100). This is exactly how the following models were developed: Outlook-2060-based scenario A1, Outlook-2060-based scenario A2, Outlook-2060-based scenario B1 and Outlook-2060-based scenario A1-Low Fuelwood. The GDP-scenario and the POP-scenario involve adjustment of the baseline timber production scenario to GDP and population growth rates, respectively. Outlook-2060-based scenario A1-Low Fuelwood was selected as the baseline scenario for timber production.

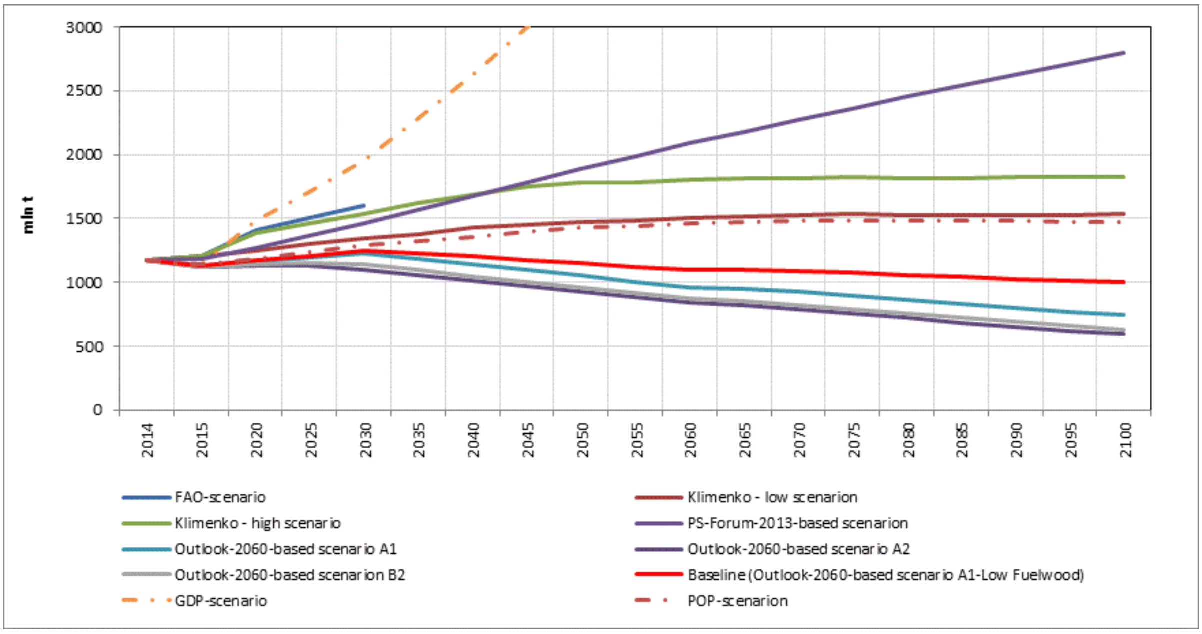
Wood-based panels production forecasts are provided in State of the World's Forests 2009 (2009) and Outlook to 2060 for World Forests and Forest Industries (2012). The former covers the period until 2030 and the latter, until 2060. However, the latter forecast is not applicable as it includes only selected types of wood-based panels.

There is a certain correlation between the wood-based panels output and timber production, expressed as the share of wood-based panels in the total production volume of timber. This share has been steadily increasing over the recent decades; this trend has become especially notable since 1990. Based on the above correlation, the authors made an assumption that the share of wood-based panels increases each year (but at a lower rate), which served as the basis for the new scenarios: Klimenko—based on low scenario), Klimenko—(based on high scenario).

Depending on the scenario, the growth rate of the share of wood-based panels in the total timber production ranges from 22% in 2013 to 27–29% in 2100. The GDP-scenario and the POP-scenario involve adjustment of the baseline wood-based panels production scenario to GDP and population growth rates, respectively. Forecast results are presented in Figs. 6.16–6.17.

[70] Food and Agriculture Organization of the United Nations.

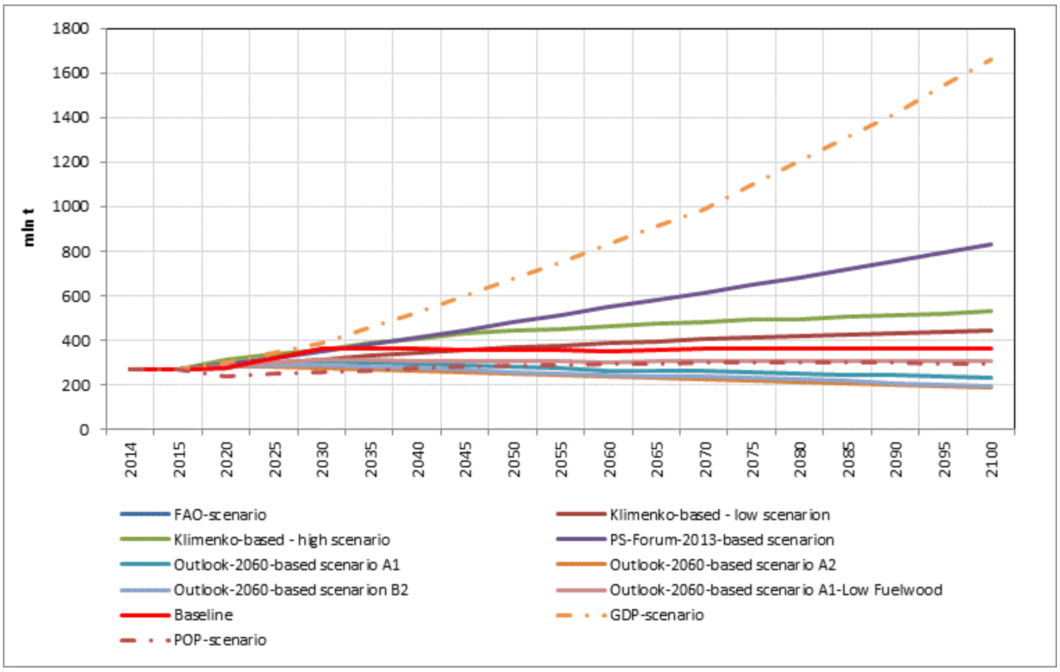
Figure 6.16 Timber Production Dynamics until 2100



Note: baseline scenario is formed using annual growth rates from scenario A1-Low Fuelwood Outlook "Outlook to 2060 for World Forests and Forest Industries" (2012).

Sources: Power Smart Forum - 2013 Collaborating for Change and Impact: Key Global Supply Trends and North America Impact Look: Impacts on BC Lumber Industry, Russel Taylor, p. 6. State of the World's Forests, p. 64. Outlook to 2060 for World Forests and Forest Industries, Joseph Buongiorno et al., p. 80; CENEF-XXI.

Figure 6.17 Wood-Based Panels Production Dynamics until 2100



Sources: Power Smart Forum - 2013 Collaborating for Change and Impact: Key Global Supply Trends and North America Impact Look: Impacts on BC Lumber Industry, Russel Taylor, p. 6. State of the World's Forests, p. 64. Outlook to 2060 for World Forests and Forest Industries, Joseph Buongiorno et al., p. 80; CENEF-XXI.

6.13 Steel

Long-term steel production forecasts were taken from the studies of IEA (2012 and 2015), Pauliuk et al. (2013), Klimenko (2010), World Steel (2011), Mathews (2012), Akashi et al.

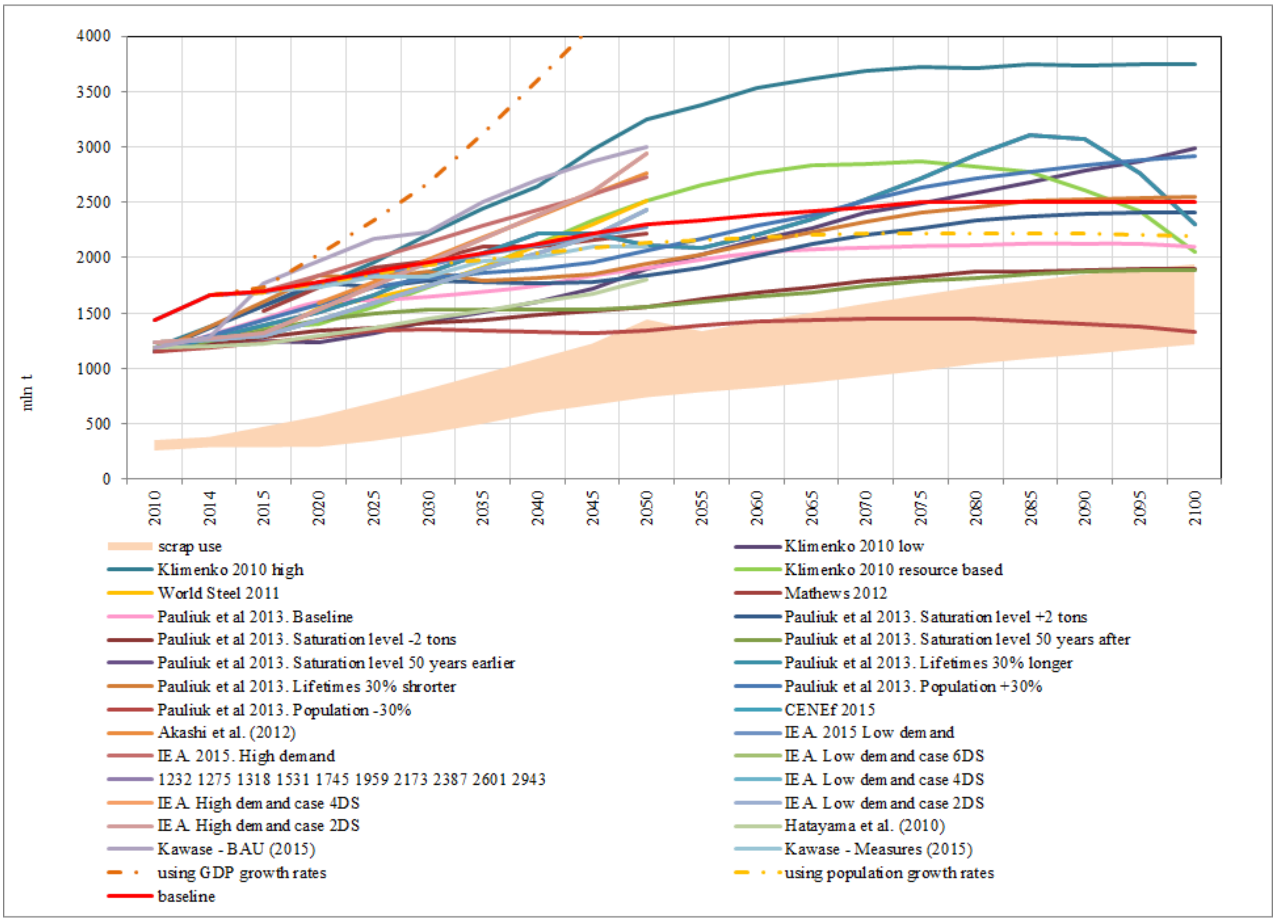
(2012) and Kawase (2015). The forecasts by Pauliuk et al (2013), Mathews (2012), Akashi et al. (2012) are based on the stock saturation approach. Fujitsuka et al. (2013) provide no estimates for annual steel production, and only project accumulated steel stocks just a little over 50 bt in 2050, which is close to the estimates provided by Pauliuk et al.(2013).

The stock saturation effect leads to a production peak and subsequent decrease or stabilisation of volumes, not only in developed economies but in developing countries as well. This effect also results in a considerable increase of the scrap metal share in steel smelting volumes, which in turns leads to a higher share of arc-furnace steel-making (Fig. 6.18).

The scenario forecasts by Pauliuk et al (2013) include a range of different time frames and saturation levels for accumulated steel stocks at the global scale (expressed in tonnes per capita). In most of the scenarios, global saturation occurs no sooner than 2050, which means steel production continues to grow. The saturation point can occur later than 2050 (Fig. 6.18). Apparently, long-term steel production projections are more correlated to population growth than to GDP growth. The stock saturation concept itself implies saturation per capita. Therefore, steel production will stabilise after 2050, following the stabilisation of population growth and market saturation. This trend is reflected in the baseline projection, which assumes that steel production will grow at first and then flatten out at the level of 2.5 bt per annum.

Both before 2050 and after, the baseline projection is very close to the median forecast based on a set of scenario trajectories until 2050 and until 2100. If we consider the median forecast for scrap metal use, involving growth approximately up to 1.5 bt in 2100 (see Fig. 6.18), it becomes obvious that the share and even the volume of primary steel will be decreasing from the present 1.25–1.3 to 1 bt per annum, which is a natural outcome according to the stock saturation concept. The slow steel production growth and the relevant saturation effect both result from steel substitution with new and lighter materials that have high strength and other advantages.

Figure 6.18 Primary and Secondary Steel Production until 2100



Sources: IEA (2012); IEA (2015); Pauliuk et al. (2013), Klimenko (2010), World Steel (2011), Mathews (2012), Akashi et al. (2012), and Kawase (2015).

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7 Effect of Basic Materials Modification Using CNT on the Demand for Basic Materials

7.1 Assessing the Energy Intensity of CNT Production

As per the data of OC[6]SiAl, the production of 1 kg of carbon nanotubes (SWCNT) requires 800 kW·h. The rest of energy consumption is insignificant. It is equivalent to the direct energy consumption in the amount of 800,000 kW h/t or 98.4 TCE/t as well as to direct CO_2 emissions in the amount of 426 t CO_2 per 1 t of SWCNT (calculated on the basis of the world average GHG carbon intensity per 1 kW·h (533 g CO_2 per kW·h for 2012)). In Russia, the carbon intensity value for generating electric power was equal to 429 g CO_2 per kW·h in 2012, therefore, for the Russian conditions, the carbon intensity of direct CO_2 emissions equals 343 t CO_2 per 1 t of SWCNT.

To assess the embodied emissions caused by SWCNT production, the rates from the Electric Power column of Table 3.1 (see Chapter 3) were used. To generate electric power at NPPs and through renewable energy sources, the parameters of embodied GHG emissions as per IPCC (2014) were used, which amounted to 12 g CO_2eq per kW_e and 24 g CO_2eq per kW_e (for hydraulic power), respectively. As per other assessments, the above values were 60 g CO_2eq per kW_e and 15 g CO_2eq per kW_e, respectively (Lenzen, 2008). The said amounts comprise energy consumption for the entire nuclear fuel cycle, including nuclear-waste storage as well as the energy consumption for erecting power assets. The average emission rates for GHG (CO_2, CH_4, and N_2O) have been determined as per the IPCC (2014) and IEA (2014a and 2014b) data for 2012.

There are no specific embodied emissions for carbon nanotubes (SWCNT) assessments specified in the references. As per the CENEf-XXI assessments, the said emissions are equal to 567 t CO_2eq per tonne of SWCNT. These assessments include no energy consumption values for producing feedstock for SWCNT manufacturing. With the increase in the share of low-carbon generation, the carbon intensity per kW·h will decrease to 280–400 g CO_2 per kW·h by 2050 (IEA, 2012; Akashi, 2012) and then will become even lower. This will allow to ***reduce the carbon intensity value to 405 t CO_2 per 1 t of SWCNT by 2050, presumably with a subsequent further decrease to 220 t CO_2 per 1 t of SWCNT by 2100.*** What is more, it is possible that the technology will continue to develop, and the specific energy consumption for producing CNT will further decrease. However, for the time being, the said amounts are 43 times larger than the embodied emissions for primary aluminium. Therefore, ***the low-carbon effect from using SWCNT can only be achieved provided that augmentation the basic materials with SWCNT requires small proportions: from percent fractions to several percent with a significant reduction in the demand for basic materials per unit of function performed by them. This becomes possible since SWCNT has an absolutely outstanding strength-to-weight ratio, which is 462 times higher than the similar parameter for steel*** (Table 7.1).

The addition of small amounts of SWCNT is required to change the properties of basic materials. ***Due to the high carbon intensity of SWCNT production, there are upper limits imposed on maximum allowable augmentation shares for SWCNT basic materials, which allows to facilitate the total reduction of emissions per unit of useful function of the applied material. The higher is the ratio of reduction in the demand for basic materials per effect unit due to increased consumer properties of the augmented material, the larger is the said share*** (Table 7.2).

Table 7.1 Comparison of Properties for Certain Materials

	Young's modulus (hPa)	Strain (%)	Tensile strength (hPa)	Density (g/cm^3)	Normalised strength-to-

					weight ratio
Single-wall carbon nanotubes	542–1054	12	150	1.4	462
Multi-wall carbon nanotubes	400–1200	1.5	150	1.8–2.6	15
Steel	208	9	0.4	7.8	1
Titanium	103	15		4.5	2
Epoxy resin	3.5		0.05	1.25	
Wood	16		0.08	0.6	

Source: Lekas, D. (2005). Analysis of Nanotechnology from an Industrial Ecology Perspective Part II: Substance Flow Analysis Study of Carbon Nanotubes. Yale School of Forestry & Environmental Studies. Revised Draft - November 2005.

Table 7.2 Maximum Allowable Augmentation Shares for SWCNT Basic Materials Allowing to Facilitate an Emission Reduction per Unit of Useful Function of the Applied Material

Material	Specific embodied GHG emissions	Maximum allowable augmentation shares for SWCNT basic materials for different ratios of reduction in the material demand due to the improvement of their properties		
	(t CO2eq/t)	1	2	3
SWCNT	**567.00**			
Steel	1.95	0.34%	0.69%	2.06%
Primary aluminium	13.10	2.31%	4.62%	13.86%
Processed aluminium	1.45	0.26%	0.51%	1.53%
Primary copper	3.81	0.67%	1.34%	4.03%
Processed copper	0.84	0.15%	0.30%	0.89%
Synthetic rubber	2.85	0.50%	1.01%	3.02%
Timber	0.72	0.13%	0.25%	0.76%
Plywood	1.10	0.19%	0.39%	1.17%
Chipboard	0.86	0.15%	0.30%	0.91%
Wood-based panels	1.09	0.19%	0.39%	1.16%
MDF	0.74	0.13%	0.26%	0.79%
Plastics	3.31	0.58%	1.17%	3.50%
ABS resins	3.76	0.66%	1.33%	3.98%
polyamide 6	9.14	1.61%	3.22%	9.67%
polyamide 6.6	7.92	1.40%	2.79%	8.38%
polyvinyl chloride	3.10	0.55%	1.09%	3.28%
polypropylene	3.43	0.60%	1.21%	3.63%
polystyrene	3.70	0.65%	1.31%	3.92%
polyester	2.08	0.37%	0.73%	2.20%
polyethylene	2.08	0.37%	0.73%	2.20%
polycarbonate	7.62	1.34%	2.69%	8.06%
polyurethane	3.30	0.58%	1.16%	3.49%
Epoxy resin	4.56	0.80%	1.61%	4.83%
Cement	0.74	0.13%	0.26%	0.78%
Concrete	0.11	0.02%	0.04%	0.11%
Clay	0.48	0.08%	0.17%	0.51%
Ceramics	0.70	0.12%	0.25%	0.74%
Brick	0.24	0.04%	0.08%	0.25%
Glass-fibre plastic	7.87	1.39%	2.78%	8.33%
Carbon fibre-reinforced plastic	16.10	2.84%	5.68%	17.04%
Mineral wool	1.20	0.21%	0.42%	1.27%
Fibreglass wool	1.44	0.25%	0.51%	1.52%

Source: CENEf-XXI; Hammond G. and Jones C. 2011. Inventory of Carbon & Energy (ICE). Version 2.0. Sustainable Energy Research Team (SERT). Department of Mechanical Engineering. University of Bath, UK

OCSiAl obtained the data on the reduction in the demand for basic materials when modifying the said materials with CNT on the basis of the analysis of a large number of literary sources. Since the expert assessments vary considerably, specific pointwise values were obtained through processing these assessments and further used in the present paper. In each case, two key parameters are defined: a fraction of SWCNT added to a basic material and reduced requirement for it due to its improved consumer properties (strength, elasticity, etc.). These parameters are subject to change, which allows to analyse the sensitivity of the results obtained to the hypotheses adopted with regard to their specific values. In this paper, no consideration is given to the materials for which the augmentation share for basic materials requires larger proportions than those specified in Table 7.2, since this provides no advantage in terms of the total reduction of GHG emissions.

A pattern for calculating the reduction of net emissions is as follows. When adding SWCNT, the volume of augmented material is determined as follows: $V_i = V_{swcnt} / d_i$, where V_{swcnt} is the volume of applied SWCNT, d_i - the share of SWCNT added when augmenting the basic material *i*; V_i is the volume of the doped material *i*. This allows to replace the traditional basic material in the volume k_i*V_i, where k_i is the ratio of increase in consumer properties of the basic material. In this case, the reduction in the demand for basic materials will be equal to $V_i*(k_i - 1)$.

The net reduction of GHG emissions (less the emissions from SWCNT production) equals $em_i*V_i*(k_i - 1) – V_i*d_i*em_{swcnt}$, where em_i and em_{swcnt} are embodied GHG emissions from the production of the basic material *i* and SWCNT. The replacement produces an effect in terms of reducing GHG emissions, provided that the condition $(k_i - 1)/d_i > em_{swcnt}/em_i$ or $(k_i - 1)/d_i* em_i/em_{swcnt} > 1$ is met. The higher is the last ratio, the higher is the augmentation effect. The abatement limit for GHG emissions caused by the production of basic material *i* can be achieved provided that all the volume of the basic material has been reviewed in terms of increasing its consumer functions, has been augmented with SWCNT and equals $em_i*V_{iforecast}*(1-1/k_i)$, where $V_{iforecast}$ is the forecasted volume of production of the traditional base material *i*.

7.2 Reduction in the Demand for Basic Materials when Modifying Them with CNT

7.2.1 Aluminium

There are 10 expert assessments for aluminium (Table 7.3 and Fig. 7.1). With the exception of one assessment (see Source 1), other expert assessments correlate well and are rather close to the trend. Two dependence approximations were plotted: with and without the assessment of Source (1).

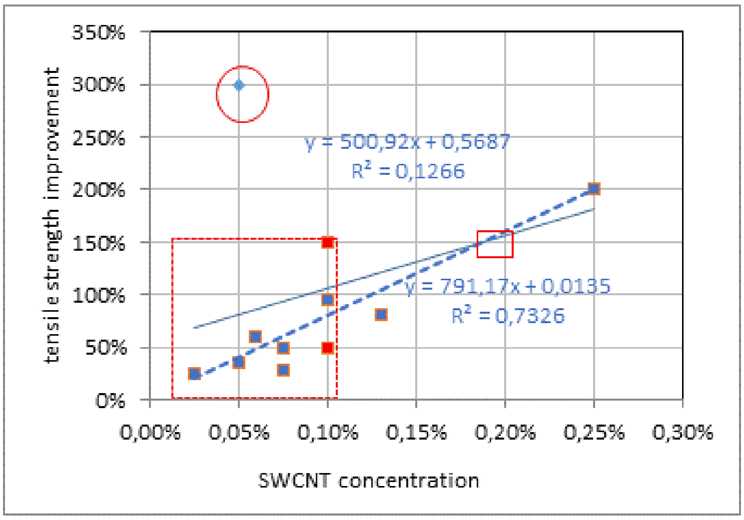
They display similar values within the area close to the value of 0.2%: adding such volume of SWCNT per mass unit of aluminium allows to increase the ultimate tensile strength by 150% or reduce the demand for aluminium by 2.5 times. When augmenting with the proportion of 0.1%, the ultimate tensile strength increases by 100%. This corresponds to the average ratio in the articles and to the middle of the OCSiAl assessment range. These are the ratios that were used for calculations. As to the increase of the tensile modulus, an inverse dependence on the SWCNT addition share is observed as per the data of the provided expert assessments, which is why the OC[6]SiAl assessment provided in Table 7.3 was used.

Table 7.3 Parameters of Changes in Aluminium Properties when Augmenting It with SWCNT

Item No.	Sources	Concentration in terms of SWCNT	Ultimate tensile strength (% of strength increase)	Tensile modulus (% of elasticity increase)
1	Hansang Kwon, Dae Hoon Park, Jean Francois Silvain, Akira Kawasaki. Investigation of carbon nanotube reinforced aluminum matrix composite materials // Composites Science and Technology, Volume 70, Issue 3, March 2010, Pages 546–550	0.05%	300%	---
2	H.J. Choi, J.H. Shin, D.H. Bae. Grain size effect on the strengthening behavior of aluminum-based composites containing multi-walled carbon nanotubes. // Composites Science and Technology 71 (2011) 1699–1705	0.25%	200%	---
3	A.M.K. Esawi, K. Morsi, A. Sayed, M. Taher, S. Lanka. The influence of carbon nanotube (CNT) morphology and diameter on the processing and properties of CNT-reinforced aluminium composites. // Composites Part A: Applied Science and Manufacturing, Volume 42, Issue 3, March 2011, Pages 234–243	0.10%	96%	33%
4	Dong H. Nam, Seung I. Cha, Byung K. Lim, Hoon M. Park, Do S. Han, Soon H. Hong. Synergistic strengthening by load transfer mechanism and grain refinement of CNT/Al–Cu composites. // Carbon, Volume 50, Issue 7, June 2012, Pages 2417–2423	0.13%	81%	27%
5	Lin Jiang, Zhiqiang Li, Genlian Fan, Linlin Cao, Di Zhang. The use of flake powder metallurgy to produce carbon nanotube (CNT)/aluminum composites with a homogenous CNT distribution. // Carbon, Volume 50, Issue 5, April 2012, Pages 1993–1998	0.06%	60%	27%
6	C.F. Deng, D.Z. Wang, X.X. Zhang, A.B. Li. Processing and properties of carbon nanotubes reinforced aluminum composites. // Materials Science and Engineering A 444 (2007) 138–145	0.05%	36%	41%
7	Abou Bakr Elshalakany, T.A. Osman, A. Khattab, B. Azzam and M. Zaki. Microstructure and Mechanical Properties of MWCNTs Reinforced A356 Aluminum Alloys Cast Nanocomposites Fabricated by Using a Combination of Rheocasting and Squeeze Casting Techniques. // Hindawi Publishing Corporation Journal of Nanomaterials Volume 2014, Article ID 386370, 14 pages	0.075%	50%	
8	R.M. Rashad, O.M. Awadallah, A.S. Wifi. Effect of MWCNTs content on the characteristics of A356 nanocomposite. // Journal of Achievements in Materials and Manufacturing Engineering, Volume 58, Issue 2, June 2013	0.075%	29%	
9	Jinzhi Liao, Ming-Jen Tan. Mixing of carbon nanotubes (CNTs) and aluminum powder for powder metallurgy use. // Powder Technology, Volume 208, Issue 1, 10 March 2011, Pages 42–48	0.025%	25%	
	Average values in the articles	*0.091%*	*97.44%*	
10	Expert assessment of OCSiAl	0.01–0.1%	up to 150% (pure aluminium), up to 50% (aluminium alloys)	up to 30%

Source: Developed by OCSiAl

Figure 7.1 Impact of SWCNT Augmentation on Aluminium Tensile Strength



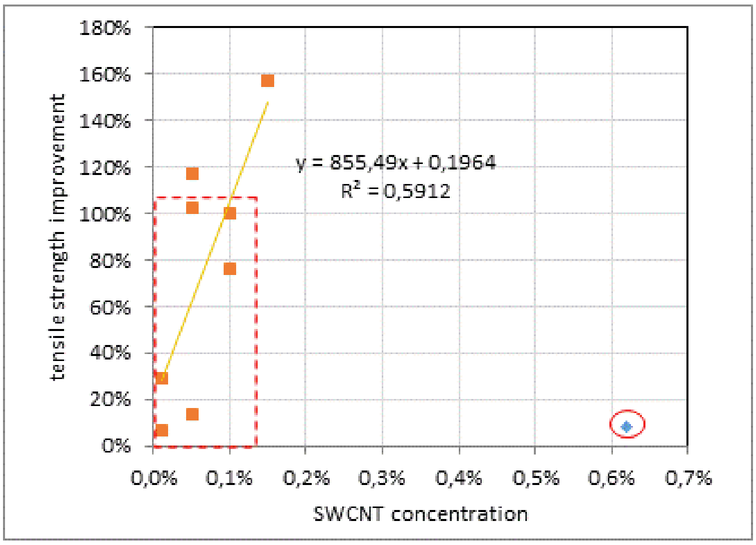
Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.1.

7.2.2 Copper

There are 10 expert assessments available for copper as well (see Fig. 7.2 and 7.3, Table 7.4). With the exception of one assessment (see Source 5), other expert assessments correlate rather well. Within the area close to the value of 0.1%, it appears that adding such volume of SWCNT per mass unit of copper allows to increase the ultimate tensile strength by 100% or reduce the demand for copper by 2 times. This corresponds to the upper limit of the OCSiAl assessment range. These are the ratios that were used for further calculations. As per the data of the above-mentioned expert assessments, the increase of tensile modulus is also directly dependent on the SWCNT addition share and correlates well with the OCSiAl assessments (see Fig. 7.3).

Figure 7.2 Impact of SWCNT Augmentation on Copper Tensile Strength



Dotted rectangle shows OCSiAl estimations range.

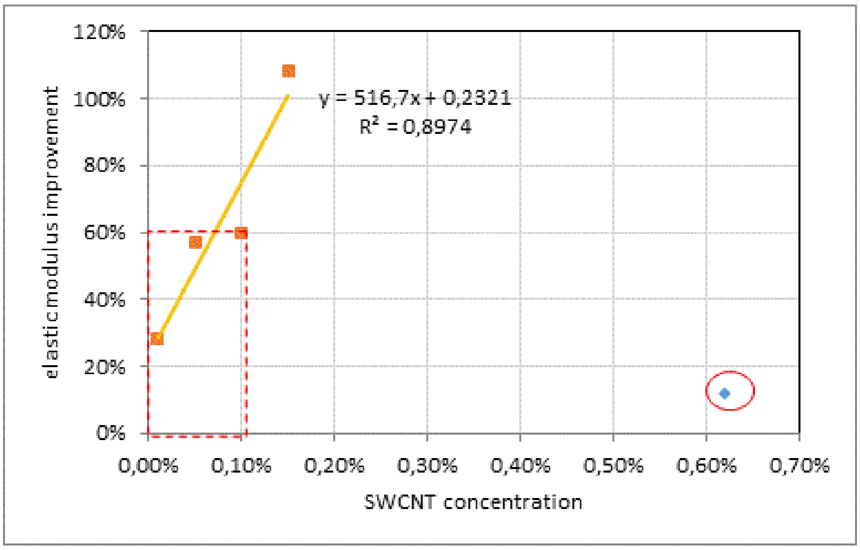
Source: CENEF-XXI based on table 7.2.

Table 7.4 Parameters of Changes in Copper Properties when Augmenting It with SWCNT

Item No.	Source		Ultimate tensile strength (% of strength increase)	Tensile modulus (% of elasticity increase)
1	Walid M. Daoushb, Byung K. Lima, Chan B. Moa, Dong H. Nama, Soon H. Electrical and mechanical properties of carbon nanotube reinforced copper nanocomposites fabricated by electroless deposition process. // Materials Science and Engineering A 513–514 (2009) 247–253	0.15%	157%	108%
2	Nie Junhui, Jia Chengchang, JIA Xian, Zhang Yafeng, Shi Na, and LI Yi. Fabrication, microstructures, and properties of copper matrix composites reinforced by molybdenum-coated carbon nanotubes. //Rare Metals Vol. 30, No. 4, Aug 2011, p. 401	0.05%	102%	
3	C.H. Guo, Z.J. Zhan. Influence of different preparation processes on the mechanical properties of carbo nanotube-reinforced copper matrix composites. // Strength of Materials, Vol. 1, January, 2015	0.01%	29%	
4	Z.W. Xue, L.D. Wang, P.T. Zhao, S.C. Xu, J.L. Qi, W.D. Fei. Microstructures and tensile behavior of carbon nanotubes reinforced Cu matrix composites with molecular-level dispersion. // Materials and Design 34 (2012) 298–301	0.05%	117%	57%
5	Yan-Hui Li, William Housten, Yimin Zhao and Yan Qiu Zhu Cu. Single-walled carbon nanotube laminate composites fabricated by cold rolling and annealing. // Nanotechnology 18 (2007) 205607	0.62%	8%	12%
6	Ke Chu, Cheng-chang Jia, Li-kun Jiang, Wen-sheng Li Improvement of interface and mechanical properties in carbon nanotube reinforced Cu–Cr matrix composites.	0.10%	76%	
7	Seungchan Cho, Keiko Kikuchi, Akira Kawasaki, Hansang Kwon and Yangdo Kim. Effective load transfer by a chromium carbide nanostructure in a multi-walled carbon nanotube/copper matrix composit.	0.05%	14%	
8	Guangyu Chai, Ying Sun, Jianren ‘Jenny’ Sun and Quanfang Chen. Mechanical properties of carbon nanotube-copper nanocomposites. //J. Micromech. Microeng. 18 (2008) 035013		208%	
9	Hongqi Li, Amit Misra, Zenji Horita, Carl C. Koch, Nathan A. Mara, Patricia O. Dickerson, and Yuntian Zhu. Strong and ductile nanostructured Cu-carbon nanotube composite. // APPLIED PHYSICS LETTERS 95, 071907	0.01%	7%	28%
	Average values in the articles	*0.130%*	*79.78%*	
10	Expert assessment of OCSiAl		up to 100% (for pure copper)	up to 60% (for pure copper)

Source: Developed by OCSiAl

Figure 7.3 Impact of SWCNT Augmentation on Copper Tensile Strength



Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.2.

7.3 Construction Materials

7.3.1 Concrete and Cement

There are 10 expert assessments available for concrete as well (see Table 7.5 and Fig. 7.4). The expert assessments vary considerably and show no apparent dependence.

Table 7.5 Parameters of Changes in Concrete Properties when Augmenting It with SWCNT

Item No.	Source	Concentration in terms of SWCNT (in concrete)	Hardening compressive, %
1	A.M. Hunashyal, Sagar V. Tippa, S.S. Quadri, and N.R. Banapurmath. Experimental Investigation on Effect of Carbon Nanotubes and Carbon Fibres on the Behavior of Plain Cement Mortar Composite Round Bars under Direct Tension. ISRN Nanotechnology, Volume 2011 (2011), Article ID 856849, 6 pages.	0.04%	70
2	Shama Parveen, Sohel Rana, and Raul Fangueiro. A Review on Nanomaterial Dispersion, Microstructure, and Mechanical Properties of Carbon Nanotube and Nanofiber Reinforced Cementitious Composites. Journal of Nanomaterials. Volume 2013 (2013), Article ID 710175, 19 pages.	0.007%	50
3	María del Carmen Camacho, Oscar Galao, Francisco Javier Baeza, Emilio Zornoza and Pedro Garcés. Mechanical Properties and Durability of CNT Cement Composites. *Materials* **2014**, *7*(3), 1640–1651; doi:10.3390/ma7031640	0.04%	15
4	Nur Yazdani, Vinoth Mohanam. Carbon Nano-Tube and Nano-Fiber in Cement Mortar: Effect of Dosage Rate and Water-Cement Ratio. International Journal of Material Science (IJMSCI) Volume 4 Issue 2, June 2014.	0.005%	50

Item No.	Source	Concentration in terms of SWCNT (in concrete)	Hardening compressive, %
5	Simone Musso, Jean-Marc Tulliani, Giuseppe Ferro, Alberto Tagliaferro. Influence of carbon nanotubes structure on the mechanical behavior of cement composites. Composites Science and Technology, Volume 69, Issues 11–12, September 2009, Pages 1985–1990.	0.025%	34
6	S.J. Chen, F.G. Collins, A.J.N. Macleod, Z. Pan, W.H. Duan, C.M. Wang. Carbon nanotube-cement composites: A retrospect. The IES Journal Part A: Civil & Structural Engineering, Volume 4, Issue 4, 2011.	0.025%	50
7	Grigory Yakovlev, Grigory Pervushin, Irina Maeva, Jadvyga Keriene, Igor Pudov, Arina Shaybadullina, Alexander Buryanov, Alexander Korzhenko, Sergey Senkov. Modification of Construction Materials with Multi-Walled Carbon Nanotubes. Procedia Engineering. Volume 57, 2013, Pages 407–41.	0.005%	46
8	Khuzin, Airat. Concrete Composites with the Addition of Multi-Wall Carbon Nanotubes. Ph.D. Thesis in Engineering Science: 05.23.05 / Khuzin, Airat; [Defended at: Kazan State University of Architecture and Engineering]. Kazan, 2014. 182 pages.	0.0005%	70
9	Rashid K. Abu Al-Rub, Ahmad I. Ashour, Bryan M. Tyson. On the aspect ratio effect of multi-walled carbon nanotube reinforcements on the mechanical properties of cementitious nanocomposites. Construction and Building Materials. Volume 35, October 2012, Pages 647–655	0.005%	34
	Average values in the articles	*0.140%*	*46.56*
10	Expert assessment of OCSiAl	0.001%	70

Source: Developed by OCSiAl

The OCSiAl assessments are ones of the highest. According to them, adding mere 0.001% allows to increase the hardening compressive of concrete by 70%, which should result in reducing the concrete consumption by 1.7 times per unit of useful function. This is the assessment that was used for calculations (in spite of the fact that some of other studies provide a more conservative assessment: adding 0.005% allows to reduce the demand by 1.5 times). These assessments are encircled in an oval in Fig. 7.5. The set concentration in concrete is transferred in terms of cement based on the cement share in concrete being equal to 12% (see Chapter 6).

Figure 7.4 Impact of SWCNT Augmentation on Concrete Compressive Strength

Source: CENEF-XXI based on table 7.3.

7.3.2 Ceramics

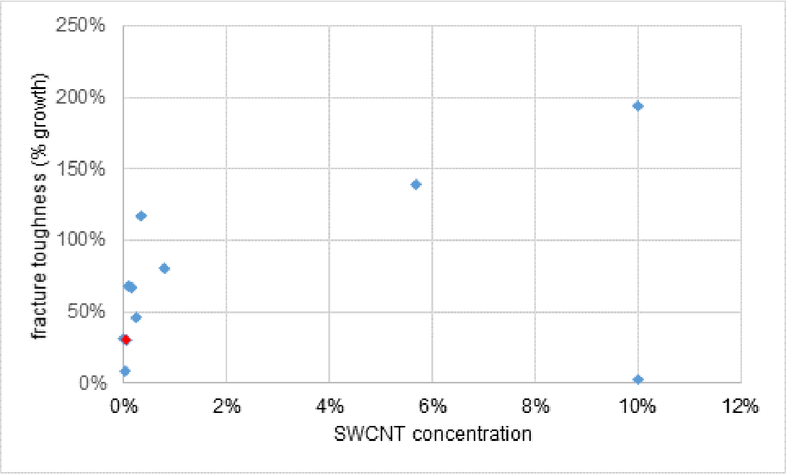
There are 10 expert assessments available for ceramics as well (see Table 7.6, Fig. 7.5 and 7.6). The expert assessments vary considerably and show no apparent dependence. Some of the assessments presuppose an augmenting material concentration exceeding the maximum allowable share ensuring a decrease in carbon intensity (Table 7.4).

Table 7.6 Parameters of Changes in Ceramics Properties when Augmenting It with SWCNT

Item No.	Source	Concentration in terms of SWCNT	Fracture viscosity (% of increase)	Hardness (% of increase)
1	Sun J., Gao L., Li W. Colloidal Processing of Carbon Nanotube/Alumina Composites. Chem. Mater. 2002, 14, 5169-72.	0.005%	31%	4%
2	Zhan G.-D., Kuntz J.D., Wan J., Mukherjee A.K. Single-wall carbon nanotubes as attractive toughening agents in alumina-based nanocomposites. Nat.	5.7% v/v vol% 10% v/v	139% 194%	–1.5% –20.7%
3	Wang X., Padture N.P., Tanaka H. Contact-damage-resistant ceramic/single-wall carbon nanotubes and ceramic/graphite composites.	10% v/v	3%	–52.6%
4	Fan J., Zhao D., Wu M., Xu Z., Song J. Preparation and Microstructure of Multi-Wall Carbon Nanotubes-Toughened Al2O3 Composite. J. Am. Ceram. Soc.	0.8% v/v	80%	–3.8% bending strength
5	Estili M., Kawasaki A., Sakamoto H., Mekuchi Y., Kuno M., Tsukada T. The homogeneous dispersion of surfactantless, slightly disordered, crystalline, multiwalled carbon nanotubes in α-alumina ceramics for structural reinforcement. Acta Mater.	0.175% v/v	67%	
6	Ahmad K., Pan W. Hybrid nanocomposites: A new route towards tougher alumina ceramics. Comp. Sci. Tech.	0.35%	117%	–7%
7	Lei S., Yue-Feng Z., Chan Z., Ji L. Heterocoagulation System Assisted Adsorption of Carbon Nanotubes on Alumina for Toughening Ceramics. Reinf. Plast. Compos.	0.1%	68%	9.6%
8	Zhang T., Kumari L., Du G.H., Li W.Z., Wang Q.W., Balani K., Agarwal A. Mechanical properties of carbon nanotube-alumina nanocomposites synthesized by chemical vapor deposition and spark plasma sintering. A 2009, 40, 86–93.	0.25%	46%	5.2%
9	Yamamoto G., Shirasu K., Hashida T., Takagi T., Suk J.W., An J., Piner R.D., Ruoff R.S. Nanotube fracture during the failure of carbon nanotube/alumina composites. Carbon 2011, 49, 3709-16.	0.045% v/v	8.5%	–1.7%
	Average values in the articles	*1.936%*	*68.278%*	
10	Expert assessment of OCSiAl	0.05%	30%	5%

Source: Developed by OCSiAl

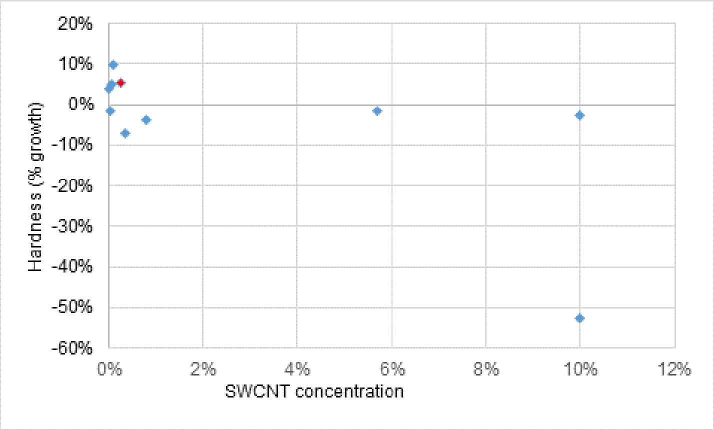
Figure 7.5 Impact of SWCNT Augmentation on Ceramics Fracture Toughness



Red dot depicts OCSiAl estimate.

Source: CENEF-XXI based on table 7.4.

Figure 7.6 Impact of SWCNT Augmentation on Ceramics Hardness



Red dot depicts OCSiAl estimate.

Source: CENEF-XXI based on table 7.4.

According to the OCSiAl assessments, adding 0.05% allows to increase ceramics fracture viscosity by 30% and its hardness by 5%, which should result in reducing the ceramics consumption by 1.3 times per unit of useful function. At that, a number of assessments claim that ceramics hardness, on the contrary, will decrease when CNT are added.

The following assessments were used for calculation: adding 0.05% allows to reduce the demand by 1.3 times.

7.3.3 Insulation Materials

As per the OCSiAl expert assessment, adding 0.1% of SWCNT allows to increase insulation material strength by 100%. No other expert assessments were obtained, therefore, this reinforcement value is used for calculation.

7.3.4 Construction Composites

The assessments which were used for construction composites are thoroughly examined below, in Section 7.3.3 Thermosetting Plastics. For these substances, the OCSiAl assessment parameters correlate to other parameters rather well. As per the said parameters, adding 0.05% of SWCNT allows to increase the strength of construction composites by 150% and their elastic modulus by 100%. Thus, adding 0.05% allows to reduce the demand for construction composites at least by half.

7.3.5 Glass

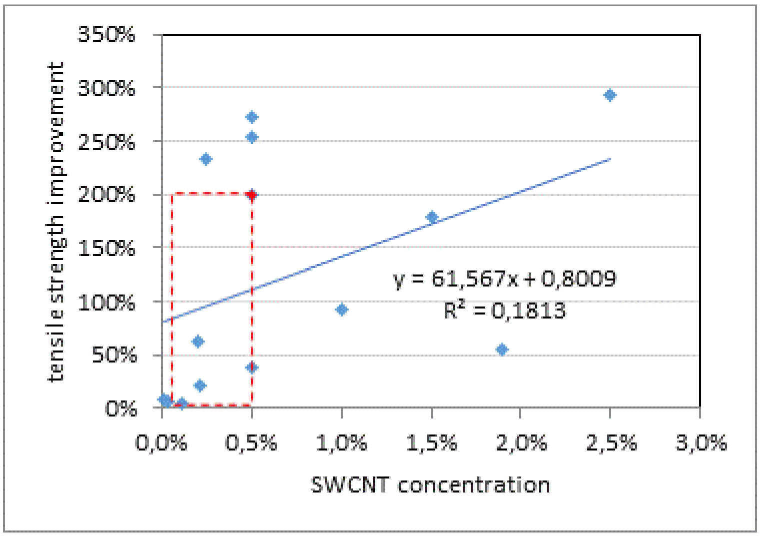
As per the OCSiAl expert assessment, adding 0.014% of SWCNT allows to increase glass strength by 50%. No other expert assessments were obtained, therefore, this reinforcement value is used for calculation.

7.4 Chemicals and Petrochemicals

7.4.1 Synthetic Rubber

There are 10 expert assessments available for synthetic rubber (see Table 7.7, Fig. 7.7–7.8). For the increase in the parameters of ultimate tensile strength and elastic modulus, there is a rather wide scatter in expert assessments showing weak dependence. The OCSiAl assessments assume an intermediate position for the above two parameters. According to these assessments, adding 0.5% of SWCNT allows to increase synthetic rubber strength and elastic modulus by 200% and reduce its consumption by 3 times. These are the assessments that were used for calculations.

Figure 7.7 Impact of SWCNT Augmentation on Synthetic Rubber Tensile Strength



Dotted rectangle shows OCSiAl estimations range.

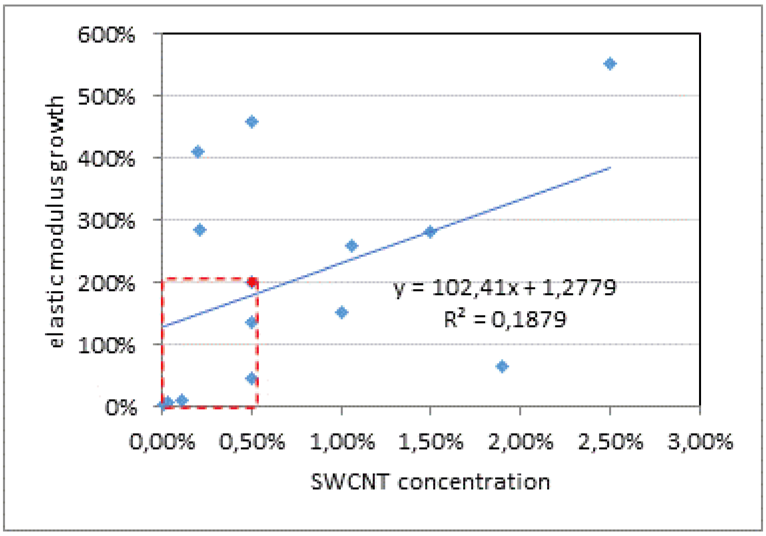
Source: CENEF-XXI based on table 7.5

Table 7.7 Parameters of Changes in Synthetic Rubber Properties when Augmenting It with SWCNT

Item No.	Source	Concentration in terms of SWCNT	Ultimate tensile strength (% of strength increase)	Tensile modulus (% of elasticity increase)
1	Endo M., Noguchi T., Ito M., Takeuchi K., Hayashi T., Kim Y.A., Wanibuchi T., Jinnai H., Terrones M., Dresselhaus M.S. Extreme-Performance Rubber Nanocomposites for Probing and Excavating Deep Oil Resources Using Multi-Walled Carbon Nanotubes. Adv. Funct.	0.05%		260%
2	Lu L., Zhai Y., Zhang Y., Ong C., Guo S. Reinforcement of hydrogenated carboxylated nitrile-butadiene rubber by multi-walled carbon nanotubes. Appl. Surf.	0.2%	62%	410%
3	Das A., Stöckelhuber K.W., Jurk R., Fritzsche J., Klüppel M., Heinrich G. Coupling activity of ionic liquids between diene elastomers and multi-walled carbon nanotubes.	0.25%	233%	
4	Fritzsche J., Lorenz H.,Klüppel M. CNT Based Elastomer-Hybrid-Nanocomposites with Promising Mechanical and Electrical Properties. Macromol. Eng.	0.21%	21%	286%
5	Anoop A.K., Sunil J.T., Rosamma A., Rani J. Natural Rubber-Carbon Nanotube Composites through Latex Compounding. Int. Polym.	1.9%	56%	64%
6	Kang I., Khaleque M.A., Yoo Y., Yoon P.J., Kim S.-Y., Lim K.T. Preparation and properties of ethylene propylene diene rubber/multi walled carbon nanotube composites for strain sensitive materials.	0.5%	38.6%	47%
		1.0%	92.5%	153%
		1.5%	178%	282%
		2.5%	293%	551%
7	Ismail H., Ramly A.F., Othman N. The Effect of Carbon Black/Multiwall Carbon Nanotube Hybrid Fillers on the Properties of Natural Rubber Nanocomposites. Polym.-Plast.	0.018%	7.6%	2.4%
		0.036%	5.8%	6.5%
		0.108%	5.3%	8.8%
8	Muataz A.A. Effect of Functionalized Carbon Nanotubes with Carboxylic Functional Group on the Mechanical and Thermal Properties of Styrene Butadiene Rubber. Fuller. Nanotub. Carb. Nanostruct.	0.5%	273%	460%
9	Peddini S.K., Bosnyak C.P., Henderson N.M., Ellison C.J., Paul D.R. Nanocomposites from styrene-butadiene rubber (SBR) and multiwall carbon nanotubes (MWCNT) part 2: Mechanical properties. Polymer 2015, 56, 443-51.	0.5%	254%	137%
	Average values obtained from the articles	*0.71%*	*116.91%*	*200.64%*
10	Expert assessment of OCSiAl	0.05–0.5%		

Source: Developed by OCSiAl

Figure 7.8 Impact of SWCNT Augmentation on Synthetic Rubber Elastic Modulus



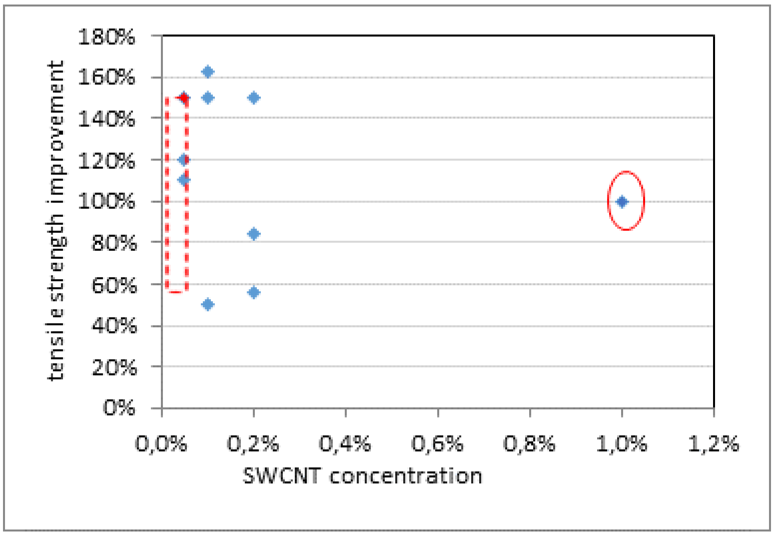
Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.5

7.4.2 Thermoplasts

There are 10 expert assessments available for thermoplasts. However, these are divided by separate types, so that no more than three of them are in one type (see Table 7.8, Figs. 7.9–7.10). The OCSiAl assessments are closer to the other ones, but for relatively lower concentrations, i.e. they deviate towards a more significant effect. According to them, adding 0.05% of SWCNT allows to increase thermoplasts strength and elastic modulus by 150% and reduce their consumption by 2.5 times. The additive level of 0.01% (the Customer's expert opinion) was used in the calculations for all thermoplasts to achieve the same elasticity values.

Figure 7.9 Impact of SWCNT Augmentation on Thermoplasts Tensile Strength



Dotted rectangle shows OCSiAl estimations range.

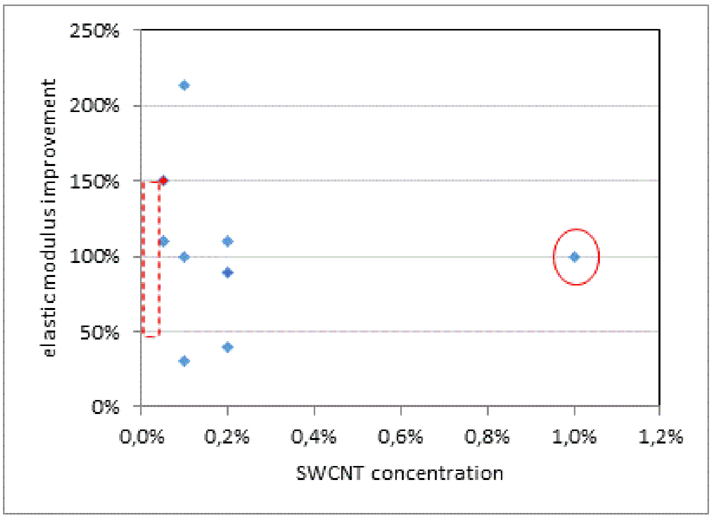
Source: CENEF-XXI based on table 7.6

Table 7.8 Parameters of Changes in the Properties of Thermoplasts when Augmenting Them with SWCNT

Item No.	Source	Concentration in terms of SWCNT	Ultimate tensile strength (% of strength increase)	Tensile modulus (% of elasticity increase)
1	**Polystyrene** Safadi B., Andrews R., Grulke E.A. Multiwalled carbon nanotube polymer composites: synthesis and characterization of thin films. J Appl Polym Sci 2002; 84: 2660–9.	0.1%	50%	100%
2	**Polystyrene** Blake R., Coleman J.N., Byrne M.T., McCarthy J.E., Perova T.S., Blau W.J., et al. Reinforcement of poly(vinyl chloride) and polystyrene using chlorinated polypropylene grafted carbon nanotubes. 2006; 16:	1.0%	100%	100%
3	**Polyethylene.** Xiao K.Q., Zhang L.C., Zarudi I. Mechanical and rheological properties of CNT-reinforced polyethylene composites. Compos Sci Technol 2007; 67:	0.2%	56%	89%
4	**Polyethylene.** Gorrasi J., Sarno M., Di Bartolomeo A., Sannino D., Ciambelli P., Vittoria V. Incorporation of carbon nanotubes into polyethylene by high energy ball milling: morphology and physical properties. J Polym Sci B 2007; 45: 597–606	0.1%	150%	30%
5	**Polypropylene.** McIntosh D., Khabashesku V.N., Barrera E.V. Nanocomposite fiber systems processed from fluorinated SWCNTs and a polypropylene matrix. Chem Mater 2006; 18:	0.2%	150%	110%
6	**PVC** Shi J.H., Yang B.X., Pramoda K.P., Goh S.H. Enhancement of the mechanical performance of poly(vinyl chloride) using poly(n-butyl methacrylate)-grafted multi-walled carbon nanotubes. Nanotechnology 2007; 18: 375704/1–8.	0.2%	84%	40%
7	**Polyamide.** Zhang W.D., Shen L., Phang I.Y., Liu T. CNT reinforced nylon-6 composite prepared by simple melt compounding. Macromolecules 2004; 37: 256-9	0.1%	120%	110%
8	**Polyamide.** Liu T., Phang I.Y., Shen L., Chow S.Y., Zhang Y.D. Morphology and mechanical properties of MWCNT reinforced nylon-6 composites. 7214–22	0.1%	162%	214%
9	**Polyamide.** Zhang W.D., Phang I.Y., Shen L., Chow S.Y., Liu T. Polymer nanocomposites using urchin-shaped CNT-silica hybrids as reinforcing fillers. Macromol Rapid Commun 2004; 25:	0.1%	110%	110%
	Average values obtained from the articles	*0.10%*	*109.11%*	*100.33%*
10	Expert assessment of OCSiAl			-150%

Source: Developed by OCSiAl

Figure 7.10 Impact of SWCNT Augmentation on Thermoplasts Elastic Modulus



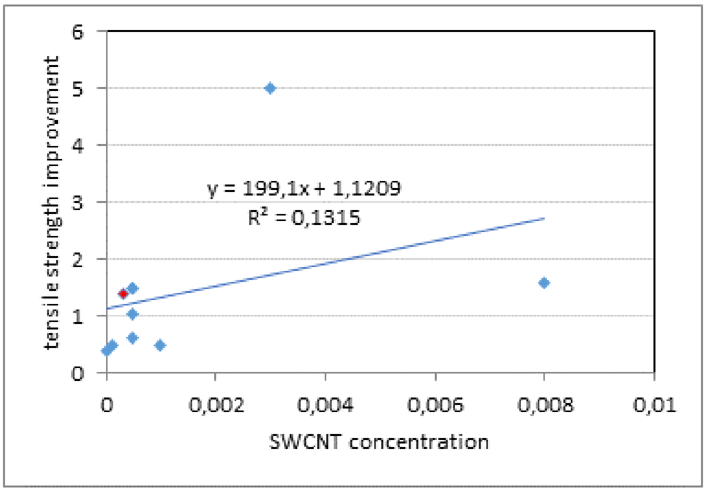
Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.6

7.4.3 Thermosetting Plastics

There are 10 expert assessments for thermosetting plastics (Table 7.9, Figs. 7.11 and 7.12). For the parameters of increasing ultimate tensile strength, there is a rather wide scatter in expert assessments showing weak dependence. On the contrary, the judgements in regards of increase of tensile modulus correlate rather well. For the given substances the OCSiAl estimation parameters also correlate to other parameters rather well. As per the said parameters, adding 0.05% of SWCNT makes it possible to increase thermosetting plastics strength by 150% and thermosetting plastics elastic modulus by 100%. Thus, adding 0.05% allows to reduce the demand for thermosetting plastics of at least by half. These are the very assessments that have been used for calculations.

Figure 7.11 Impact of SWCNT Augmentation on Thermosetting plastics Tensile STRENGTH



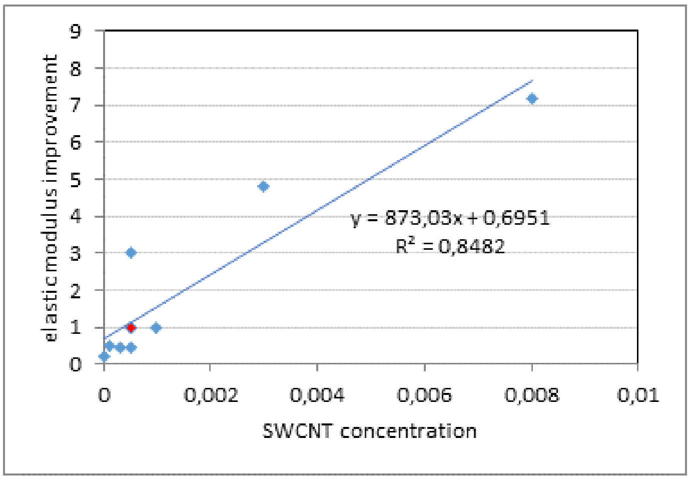
Source: CENEF-XXI based on table 7.7

Table 7.9 Parameters of Changes in Properties of Thermosetting Plastics When Augmenting Them With SWCNT

	Source	Concentration in terms of SWCNT	Ultimate tensile strength (% of strength increase)	Tensile modulus (% of elasticity increase)
1	Spitalsky Z. et al. Modification of carbon nanotubes and its effect on properties of carbon nanotube/epoxy nanocomposites. Polym Compos 2009; 30: 1378-87	0.05%	62%	45%
2	Qianqian Li et al. Mechanical properties and microstructure of single-wall carbon nanotube/elastomeric epoxy composites with block copolymers. Materials Letters Vol. 125, 116–119, 2014	0.03%	141%	43%
3	Bai J. Evidence of the reinforcement role of CVD multi-walled carbon nanotubes in a polymer matrix. Carbon 2003; 41: 1325-8	0.05%	105%	100%
4	Muthu J et al. Double-wall carbon nanotube-reinforced polyester nanocomposites: improved dispersion and mechanical properties. Polymer Composites 2012; 33, 6, 866–871	0.3%	500%	480%
5	Cheng Q.F. et al. Carbon nanotube/epoxy composites fabricated by resin transfer molding. 260–266	0.8%	160%	716%
6	Li Q et al. CNT/epoxy resin composites using a block copolymer as dispersing agent. Phys Stat Sol A 2004; 201: 89–91	0.01%	50%	50%
7	Martone A. et al. Reinforcement efficiency of multi-walled carbon nanotube/epoxy nano composites. Composites Science and Technology 2010; 70: 1154–1160	0.002%	40%	20%
8	Allaoui A. et al. Mechanical and electrical properties of a MWNT/epoxy composite. 1993-8	0.05%	150%	300%
9	Park J.M. et al. Nondestructive damage sensitivity and reinforcing effect of CNT/epoxy composites using electromicromechanical technique. Mater Sci Eng C 2003; 23: 971-5	0.1%	50%	100%
	Average values obtained from the articles	*0.07%*	*139.78%*	*206.00%*
10	Expert assessment of OCSiAl	0.05%	150%	100%

Source: Developed by OCSiAl

Figure 7.12 Impact of SWCNT Augmentation on Thermosetting Plastics Elastic Modulus



Source: CENEF-XXI based on table 7.7

7.5 Wooden and Plastics Composites

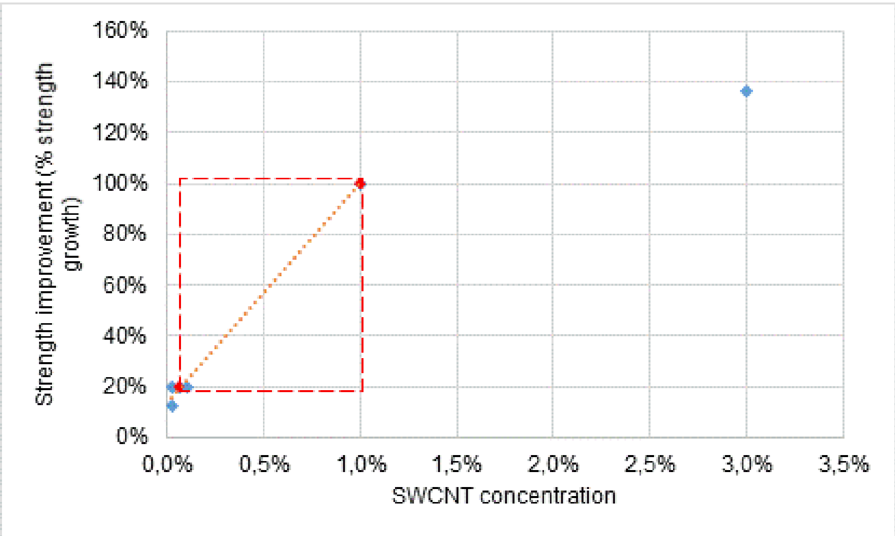
There are 4 expert judgements represented for wooden and plastics composites (see Table 7.10, Figs. 7.13–7.14). For the parameters of increasing ultimate tensile strength and elastic modulus there is a rather wide scatter of expert judgements showing weak dependence. The OCSiAl assessments assume an intermediate position for the above two parameters. According to them, adding 1% of SWCNT makes it possible to increase wooden and plastics composites strength and elastic modulus by 100% and reduce their consumption by 2 times. These are the assessments that were used for calculations.

Table 7.10 Parameters of Changes in Properties of Wooden and Plastics Composites when Augmenting them with SWCNT

Item No.	Source	Concentration in terms of SWCNT	Ultimate tensile strength (% of strength increase)	Elastic modulus (% of elasticity increase)
1	Fu S., Song P., Yang H., Jin Y., Lu F., Ye J., Wu Q. Effects of carbon nanotubes and its functionalization on the thermal and flammability properties of polypropylene/wood flour composites.	0.025%	12.5% - MWCNT, 19.9% - MWCNT–OH	
2	Farsheh A.T., Talaeipour M., Hemmasi A.H., Khademieslam H., Ghasemi I. Investigation on the mechanical and morphological properties of foamed nanocomposites based on wood flour/PVC/multi-walled carbon nanotube. BioResources 2011, 6, 841-52.	0.067%	20%	23%
3	Kordkheili H.Y., Farsi M., Rezazadeh Z. Physical, mechanical and morphological properties of polymer composites manufactured from carbon nanotubes and wood flour. B 2013, 44, 750-5.	3%	136%	145%
	Average values obtained from the articles	*1.03%*	*58.67%*	*84.00%*
4	Expert assessment of OCSiAl			

Source: Developed by OCSiAl

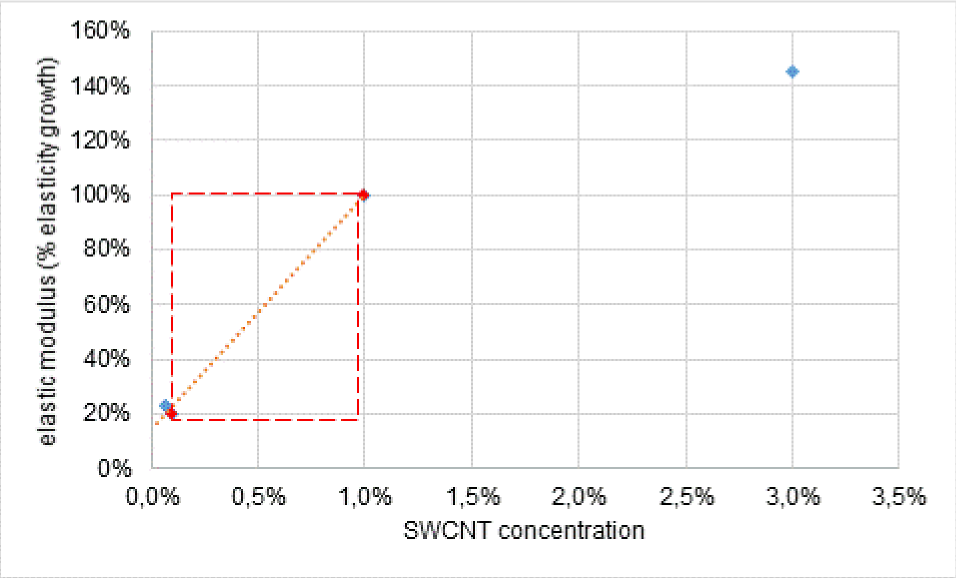
Figure 7.13 Impact of SWCNT Augmentation on Wooden Composites Strength



Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.8

Figure 7.14 Impact of SWCNT Augmentation on Wooden Composites Elastic Modulus



Dotted rectangle shows OCSiAl estimations range.

Source: CENEF-XXI based on table 7.8

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8 Assessment of Possibility of Reducing Global GHG Emissions in Some Basic Materials Production for Period until 2100

8.1 General

There is a wide range of methods to reduce GHG emissions from the production of the main basic materials. The main seven methods are:

- Reduce material intensity by reducing weight of products through the use of materials with higher strength and other characteristics (light-weighting). It is this method where SWCNT material augmentation is used.
- Reduce the proportion of process scrap and waste at all processing stages and during the production of end-use products from basic materials.
- Increase recyclability of materials.
- Increase the use of substitute additives (e.g. cement additives).
- Improve energy efficiency at all stages of production of basic materials and final products.
- Reduce the carbon intensity of the fuel and power consumed by improving the efficiency of generating plants, reducing transmission losses, changing the fuel balance in favour of less carbon-intensive types of fuel and renewable energy sources.
- Use the carbon capture and storage technology.

The combination of the possible contribution of these factors varies from material to material. However, it is not possible to reduce carbon emission by 40–70% of the 2010 level (IPCC, 2014) for any basic material using only one of the listed methods. This problem is of such a large scale that all the above-mentioned means, to some degree or another, have to be used to solve it. The optimum combination should be determined by the cost of the specific reduction of emissions. However, this issue is beyond the scope of this study.

The main issue is to determine the potential reduction level of GHG emissions by using the -above-listed factors, and, in particular, to assess the contribution of the material intensity reduction by SWCNT augmentation. The method of reducing material intensity by increasing the strength and other characteristics of the material has come to be known in literature as the *lightweight design*. This method has a great potential, but there are many restrictions for its use (Allwood et al., 2011; Carruth et al., 2011). In what follows, the possibility of reducing material intensity by increasing the strength and other characteristics of the materials is considered first. The other factors are considered as far as there is information for the assessment of their possible contribution.

Various methods can be used to decompose the contributions of major factors in the reduction of GHG emissions from the production and use of basic materials. In the first case, it is assumed that carbon intensity and energy consumption are reduced first, and savings from materials augmentation are calculated taking into account the reduced embodied carbon intensity, rather than the initial carbon intensity:

$$\begin{aligned}\Delta C &= M^0e^0c^0 - Mec = M^0e^0c^0 - M^0e^0c + M^0e^0c - M^0ec + M^0ec - Mec = \\ &= M^0e^0(c^0 - c) + M^0c(e^0 - e) + ec(M^0 - M)\end{aligned} \quad (8.1)$$

where:

ΔC is the reduction of the GHG emission;

M_0 and M are the amounts of materials needed (initially and after augmentation);

e^0 and e are the specific embodied energy consumption of the material (initial and after improving energy efficiency);

c^0 and c are the embodied carbon intensity per unit of embodied energy consumption (initial and after the increase in low-carbon energy generation and the transition to low-carbon fuels and renewable energy sources).

The contribution of the material intensity reduction in formula (8.1) is significantly underestimated.

In the second case, the emission reduction from lowering basic materials requirements is calculated using the basic embodied carbon intensity, and, then, the contribution made through the reduction of energy and carbon consumption is calculated taking into account the lower material requirements:

$$\Delta C = M^0 e^0 c^0 - Mec = M^0 e^0 c^0 - Me^0 c^0 + Me^0 c^0 - Me^0 c + Me^0 c - Mec = \\ = Me^0 (c^0 - c) + Mc(e^0 - e) + e^0 c^0 (M^0 - M) \quad (8.2)$$

The contribution of the material intensity reduction in formula (8.2), on the contrary, is greatly overestimated.

Since all three processes (improving the energy efficiency, switching to low-carbon energy, reduction of material intensity by the augmentation of the basic material) work simultaneously, to determine the exact contribution of each of the three factors mentioned above to the emission reduction one needs to use sophisticated methods of decomposition. In this study, to obtain better assessment of the contribution of each of the factors, we use the average value of those estimated by formulas (8.1) and (8.2). In this case, the contribution of each factor is estimated according to formulas (8.4)–(8.5):

$$DM = (M^0 - M) * (\frac{ec + e^0 c^0}{2}) \quad (8.3)$$

$$De = (e^0 - e) * (\frac{Mc + M^0 c}{2}) \quad (8.4)$$

$$Dc = (c^0 - c) * (\frac{Me^0 + M^0 e^0}{2}) \quad (8.5)$$

The first component reflects ***the contribution of reduction of the material intensity by augmentation provided that the processes of improving the energy efficiency, transition to low-carbon energy sources and reduction of material intensity occur in parallel.***

The assessment of contribution of energy efficiency improvement and carbon intensity reduction was carried out using the base case parameters, that is, on the assumption that no additional specific measures related to implementation of energy-efficient and low-carbon technologies will be taken.

Besides, ***the additional amount of GHG emissions from SWCNT production is also evaluated and taken into account in the calculation of the net reduction in GHG emissions from augmentation of basic material with SWCNT***.

Apart from the effects produced during basic material production, the operation of light-weight products can also bring about additional effects. For instance, reducing the weight of a car improves its fuel efficiency. These effects are also evaluated. The possibilities of using SWCNT are limited by both the potential rate of their production and the scale of the possible application, which is determined by the planned production volumes of basic materials and what percentage of it will be augmented with SWCNT.

8.2 Non-ferrous metals

8.2.1 Aluminium

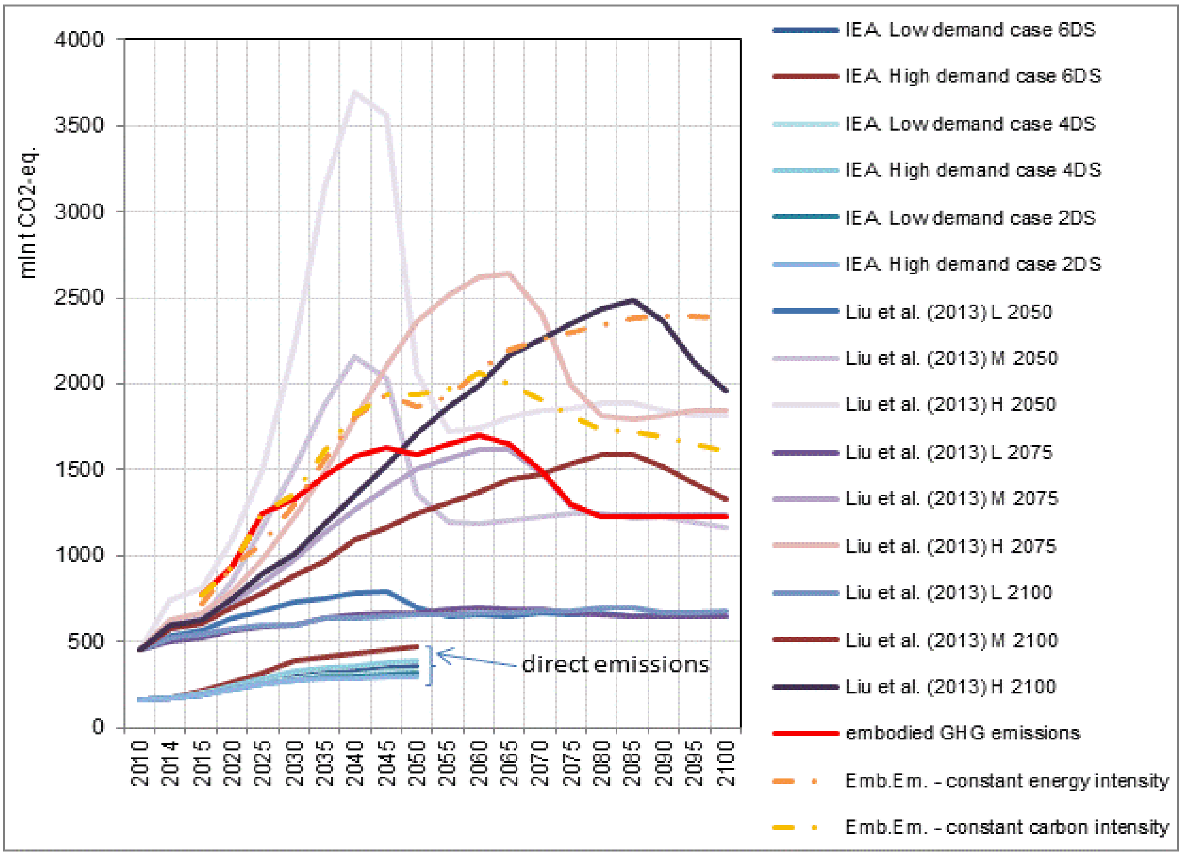
The embodied GHG emission in aluminium production in 2014 is estimated to be 700 Mt of CO_2eq. This accounts for 1.3% of total anthropogenic greenhouse gas emissions and 1.7% of GHG emission (not including the emissions from AFOLU) and 6.7% of industrial greenhouse emissions. Liu et al. (2012) estimated the direct and indirect global emissions at all stages of aluminium production in 2009 to be 446 Mt CO_2eq, of which 65% are the indirect GHG emissions associated with the use of electrical power for aluminium production.

The specific indicator of embodied emissions from aluminium production is one of the highest in the world: according to the in the University of Bath's database, it equals 12.79 t CO_2eq per tonne of primary aluminium and 1.8 t CO_2eq per 1 t of secondary aluminium (University of Bath, 2011). At an average specific power consumption of 14,540 kW/t (IEA, 2012) and the world average specific emissions of GHG per 1 kWh (533 g of CO_2 per 1 kWh in 2012, IEA, 2014), the amount of specific emissions from primary aluminium production alone is 7.75 t CO_2eq per tonne. This does not take into account carbon consumption in anodes. Other sources of emission include bauxite and alumina extraction, production and transportation, GHG emissions embodied in fuel, equipment, etc.

The ratio between primary and secondary aluminium production is a very important factor. Currently, about 40% of aluminium is production waste and is treated as process scrap (Allwood et al., 2011). In addition, a large volume of consumer scrap is collected. With the increase of aluminium reserves, the proportion of scrap in aluminium production will increase (see Chapter 6).

The projections of the rate of GHG emissions from the aluminium industry differ significantly (Fig. 8.1) and essentially depend on when and at what level the saturation of aluminium reserves per capita will take place, how the proportion of secondary aluminium and efficiency of primary aluminium production will increase, how the carbon intensity parameters of electrical power used in the production and the fuel balance of bauxite and alumina production will change. According to the IEA projection to the year 2050 (2012), the GHG emissions will be slowing down and gradually approaching the saturation point, but at a level that is 2–3 times higher than the current one. The saturation effect is shown more clearly in the forecasts made by Liu et al. (2013), but after the year 2050. Moreover, many scenarios suggest a possibility of reducing emissions after the peak is reached.

Figure 8.1 Evolution of GHG Emissions from Aluminium Production

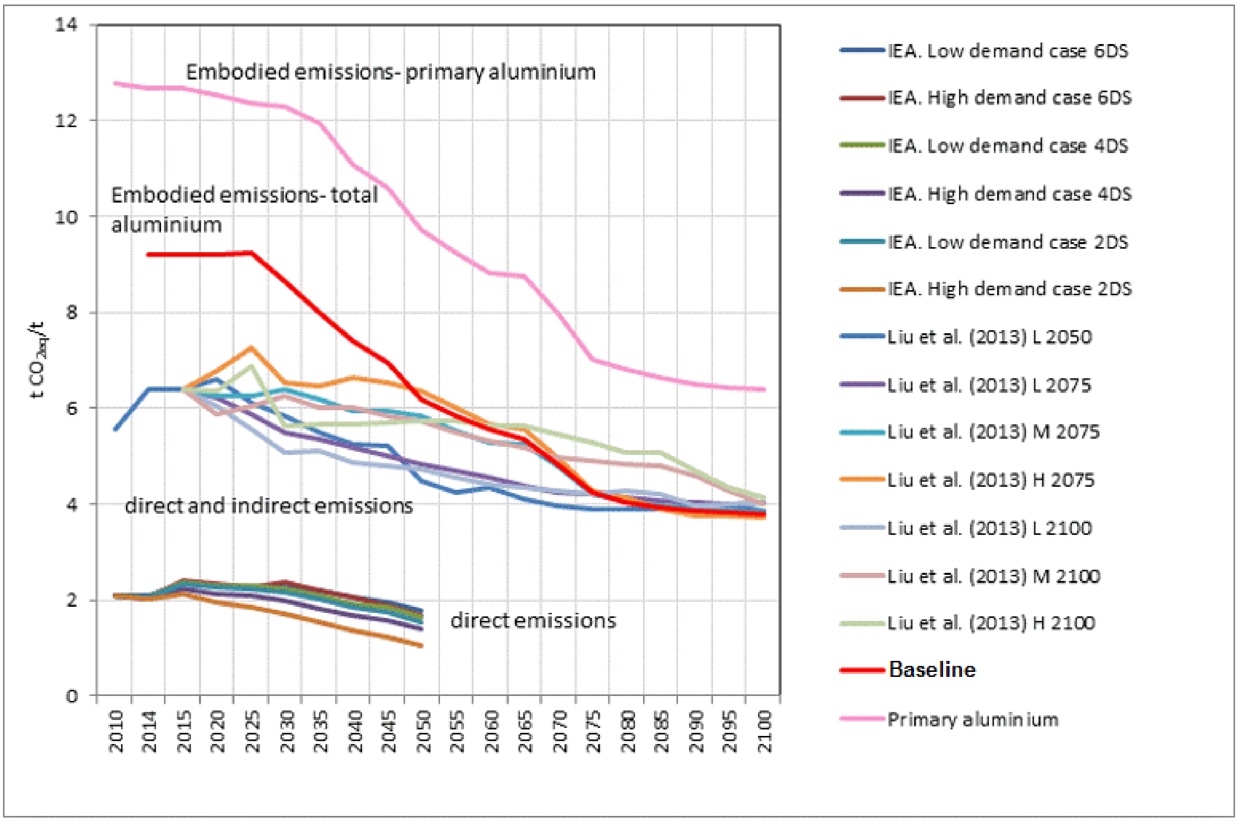


Sources: IEA (2012); Liu et al. (2013).

In addition to the possible stabilization of aluminium production or even slight decline after 2060 (Chapter 6), the possibility of reducing specific GHG emissions plays an important role (Fig. 8.2). However, significant reduction in specific GHG emission is not expected until 2030. This is due to slight increase in the carbon intensity of the energy used in the period to 2030, which is cause by the growing proportion of aluminium production in China and India, where the specific GHG emissions from electrical power production are high. Thus, this factor will have no restraining effect on emission dynamics until 2030. The theoretical minimum of power consumption for primary aluminium production is equal to 9,030 kW/t (Liu et al., 2013). The specific consumption has decreased from 35 to 15 thousand kW/t between 1900 and 2000. This figure has been declining by an average of 0.4% per year since 1980 (IEA, 2012). Therefore, the reduction of specific consumption is possible, but it will take place gradually and can come close to the theoretical minimum only by 2100 (Fig. 8.4).

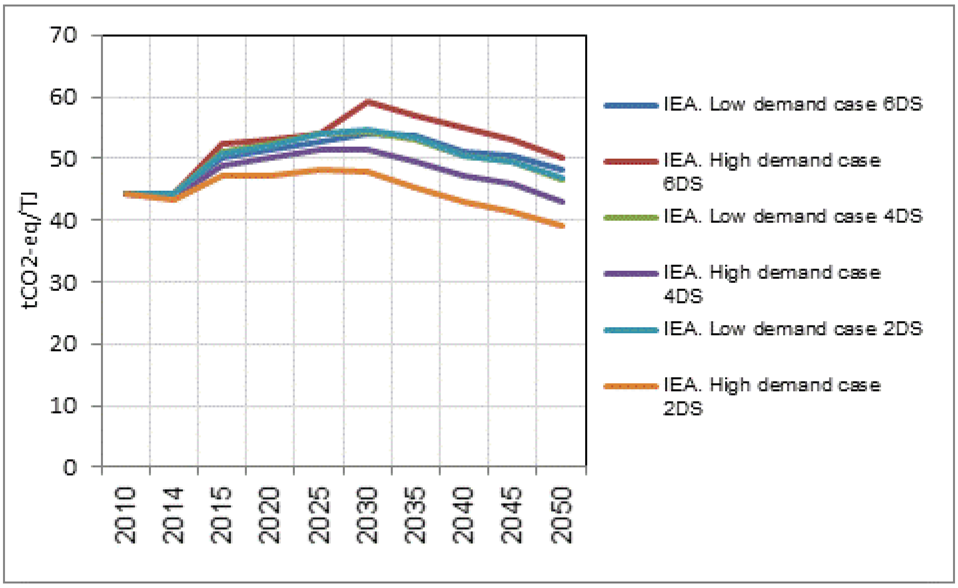
As a result, as noted by Liu et al. (2013), the reduction of GHG emissions from the aluminium industry by 50% from the level of 2000 is possible only under very optimistic assumptions about the proportion of aluminium recycling (scrap collection efficiency), new energy-efficient technologies emerging in the market and per capita aluminium stock saturating at a low level (not greater than 200 kg). Under other assumptions, this problem cannot be solved even by using the carbon capture and storage technology.

Figure 8.2 Evolution of Specific GHG Emissions from Aluminium Production



Sources: IEA (2012); Liu et al. (2013).

Figure 8.3 Evolution of Carbon Intensity of Energy Used for Aluminium Production



Source: IEA (2012)

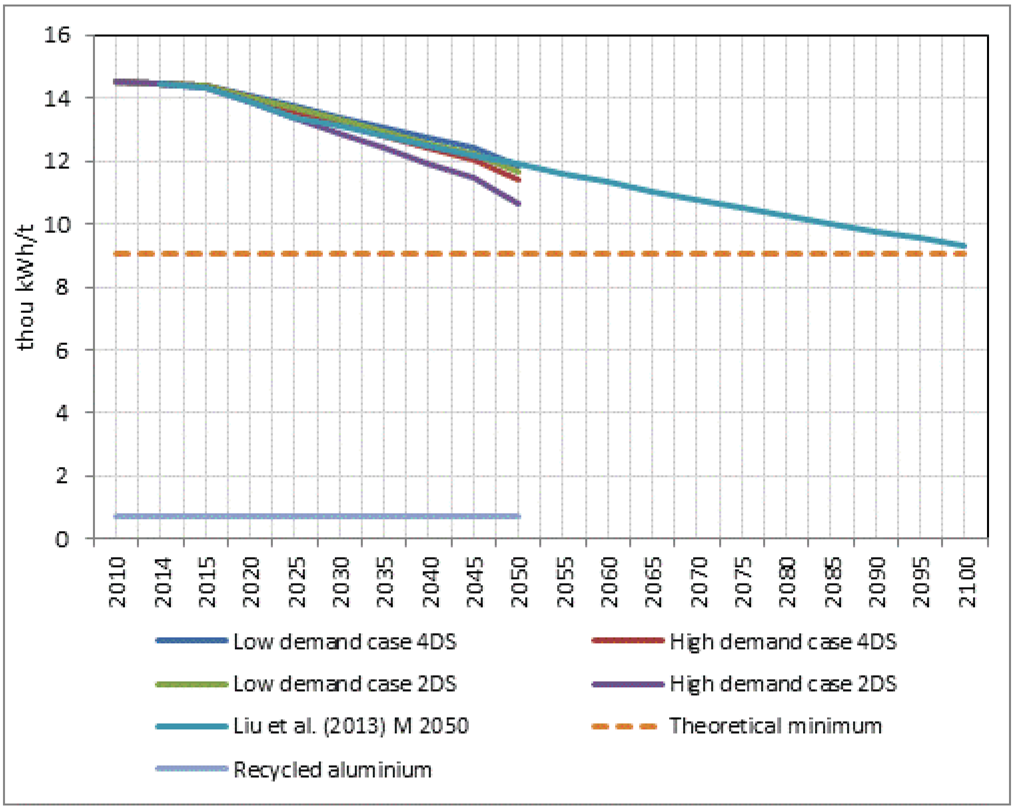
The main ways to reduce GHG emissions from aluminium production are as follows:

- **reduction of material intensity** by:
  - ✓ increasing the strength and other characteristics of aluminium by augmenting concrete with SWCNT;

- ✓ reducing the proportion of process scrap and waste in aluminium production. In 2009, 76 Mt of aluminium were produced, but only 45 Mt were used in the end-use products (Allwood et al., 2011);

- **increasing the amount of consumer scrap collection**, which could theoretically rise to 90% in 2050 and to 95% in 2100 (Liu et al., 2013);
- **improving the energy efficiency of aluminium and alumina** production by switching to inert baked anode and wet cathode technology, etc. The current global average of specific energy consumption in aluminium production is 14,500 kWh/t, and the energy consumption in alumina production is 17.2 GJ/t. There is a possibility of reducing energy consumption to the theoretical minimum; however, according to IEA (2012), switching to BAT parameters will reduce energy consumption only by 10%;
- **reduction of carbon intensity of the fuel and electrical power** by using fuel with lower specific emissions and reducing the carbon intensity of generated electrical power;
- **development of carbon capture and storage technology.** This technology should be mainly used at power plants, as the volumes of direct fuel combustion in the production chain of aluminium production are relatively small (about 80 Mt CO_2eq) and dispersed.

Figure 8.4 Evolution of Specific Energy Consumption for Aluminium Production



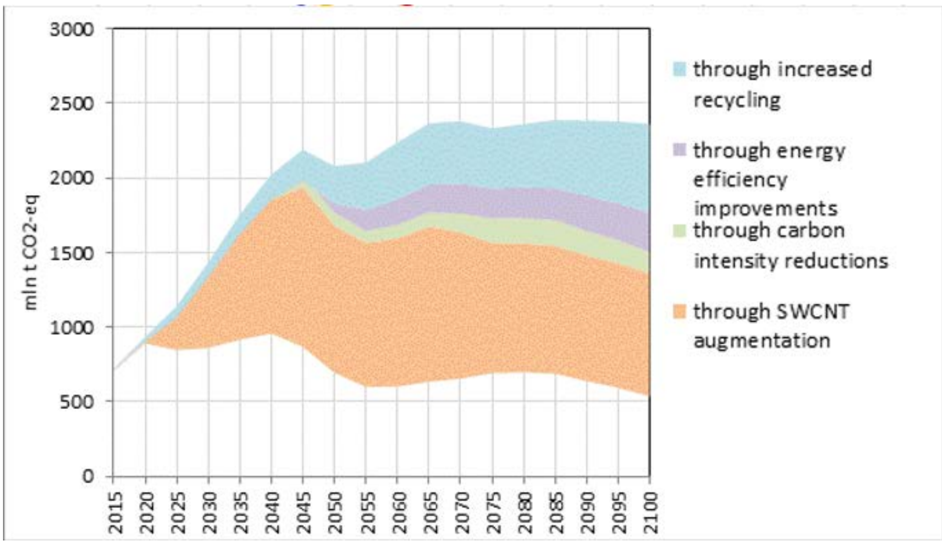
Sources: IEA (2012); Liu et al. (2013).

In the baseline scenario, the embodied GHG emissions from aluminium production increase in proportion to the production volumes as described in Chapter 6, and will reach 2.4 bt CO_2eq in 2090 and then stabilise at this level (Fig. 8.5). An increase in the use of secondary aluminium allows for considerable reduction of GHG emissions—by 250 Mt CO_2eq by 2050 and by 594 Mt CO_2eq by 2100. As already noted, energy efficiency can be increased, but in the baseline scenario only to a limited extent. Due to this factor, GHG emissions will be reduced by 65 Mt CO_2eq in 2050, and by 258 Mt CO_2eq in 2100. The contribution of fuel replacement and increase in the use of low-carbon electric energy is 60 Mt CO_2eq in 2050 and 264 Mt CO_2eq in 2100. All of these factors can substantially limit the growth of emissions until 2045, and stop it only after 2065 (Fig. 8.5). A further reduction is only possible by greater decarbonisation of the electric power industry, including widespread application of the carbon capture and storage technology.

However, there is another option. Adding SWCNT to aluminium in the proportion 0.1% per unit mass increases the ultimate tensile strength by 100%, i.e. reduces the need for aluminium by half (Chapter 7). Thus, if the entire volume of the aluminium produced is augmented, the demand for it can be halved by 2100. The rate of this reduction depends on the possible increase in the use of SWCNT for that purpose.

Assuming that in 2020 one tonne of SWCNT will be used for these purposes and the usage will increase by 10 t every 5 years, ***not only will this additional measure stop the growth of emissions by 2040 at a much lower level (Fig. 8.5), but it will also ensure that starting from 2085 the emission level will fall below the values of 2015. The contribution of this factor is 781 Mt CO_2eq in 2050 and 840 Mt CO_2eq in 2100. It is close to the total contribution of the increase in the use of secondary aluminium, increase in energy efficiency and reduction of carbon intensity of energy. If we subtract the emissions associated with SWCNT production, the net GHG emissions reduction is 738 Mt CO_2eq in 2050 and 811 Mt CO_2eq in 2100.***

Figure 8.5 GHG Emissions from Aluminium Production Dynamics



Source: CENEF-XXI

102 t of SWCNT are required in 2050 and 129 t in 2100, and a total of 73 kt during the period of 2015–2100 in order to reduce emissions by 42% from the baseline in 2050 and by 35% in 2100 due to this factor alone, and by 63% in 2050 and 77% in 2100 in combination with other factors.

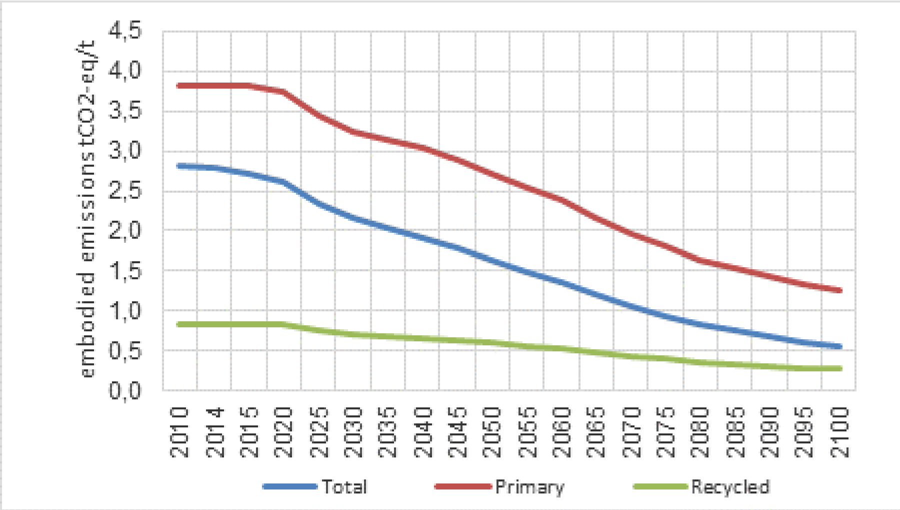
8.2.2 Copper

The embodied GHG emissions from copper production in 2014 are estimated to be about 50 Mt CO_2eq. This is less than 0.1% of total anthropogenic greenhouse gas emissions and accounts for 0.5% of industrial anthropogenic greenhouse gas emissions.

The ratio between primary and secondary copper production is a very important factor. Currently, the share of scrap is about 33%. The specific embodied emission from copper production is estimated at 3.81 t CO_2eq per 1 t of primary copper and 0.84 t CO_2eq per 1 t of secondary copper (University of Bath, 2011). There are no projections of GHG emissions from copper production.

In addition to a possible stabilization of copper consumption after 2050, an opportunity to reduce the specific GHG emissions can be very important (Fig. 8.6). The specific emissions from copper production are reduced as the energy efficiency of the production increases (the dynamics is assumed to equal the dynamics of the energy efficiency growth in the aluminium industry) and the specific GHG emissions from electric power and fuel production decreases, and as the use of secondary copper grows.

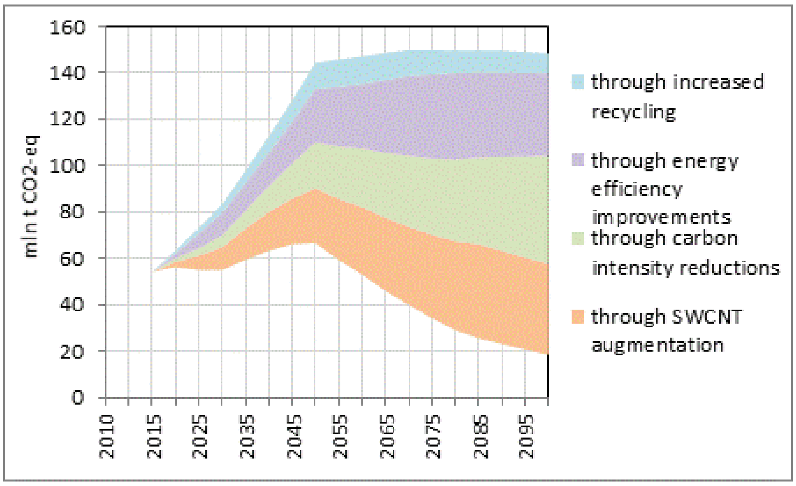
Figure 8.6 Specific Embodied GHG Emissions from Copper Production



Source: CENEF-XXI

In the baseline scenario, the embodied GHG emissions from copper production increase and will reach 150 Mt CO_2eq by mid-century and then stabilise at this level (Fig. 8.7). An increase in the use of secondary copper will help reduce emissions by 9–12 Mt per year in 2050–2100. Due to energy efficiency improvement, GHG emissions are reduced by 23 Mt CO_2eq in 2050, and by 36 Mt CO_2eq in 2100. The contribution of fuel replacement and increased share of low-carbon energy sources is equal to 20 Mt CO_2eq in 2050 and 47 Mt CO_2eq in 2100. All these factors can significantly slow down the growth of emissions and even decrease it after 2050 (Fig. 8.7). However, the emission level stays above the level of 2015. A further significant reduction is possible by greater decarbonisation of the electric power industry, including widespread application of the carbon capture and storage technology.

Figure 8.7 GHG Emissions from Copper Production Dynamics



Source: CENEF-XXI

Adding SWCNT to copper in the proportion 0.1% per unit mass increases the ultimate tensile strength by 100%, i.e. halves the need for copper (see Chapter 7). The rate of this reduction depends on the strategy for increasing the use of SWCNT for that purpose. Assuming that in 2020 one thousand tonne of SWCNT will be used for these purposes and the usage will increase by 2 kt every 5 years, not only will this additional measure stop the growth of emissions but it will also reduce it almost to zero by the year 2100 (Fig. 8.7). ***The contribution of the SWCNT augmentation factor is 29 Mt of CO_2eq in 2050 and 45 Mt CO_2eq in 2100, i.e., it is as important as reduction in energy consumption and carbon intensity.***

13 kt of SWCNT are required in 2050 and 33 kt in 2100, and a total of 7.4 Mt during the period of 2015–2100 in order to reduce emissions by 20% in 2050 and by 30% in 2100 due to this factor alone, and by 54% in 2050 and 87% in 2100 in combination with other factors.

8.3 Construction Materials

8.3.1 Concrete and Cement

The amount embodied GHG emissions from cement production in 2014 are estimated to be 3.1 bt of CO_2eq. This accounts for 6% of total anthropogenic greenhouse gas emissions, 7.6% GHG emission (not including the emissions from AFOLU) and 10% of industrial greenhouse emissions from fuel combustion and the industry (see Chapter 4). Using the specific GHG emission index provided by IPCC (2014), i.e., 0.77 t CO_2eq per 1 t of cement, the GHG emission amount in 2014 can be calculated as 3.2 bt CO_2eq. The specific emission index (IPCC, 2014) includes emissions from fuel combustion in clinker production (0.21 t CO_2eq per 1 t of cement), emissions from calcination during clinker burning (0.51 t CO_2eq per 1 t of cement) and indirect emissions from the processes of electricity generation for cement production (0.05 t CO_2eq per 1 t of cement). As a result, we have a slightly higher value than the volume of the embodied emissions according to the database of the University of Bath, i.e., 0.74 t CO_2eq per 1 t of cement (University of Bath, 2011). The latter is strongly dependent on the amount of other additives (blast furnace slag, ash, etc.) in cement. The specific embodied emission index for concrete is 0.112 t CO_2eq per 1 t.

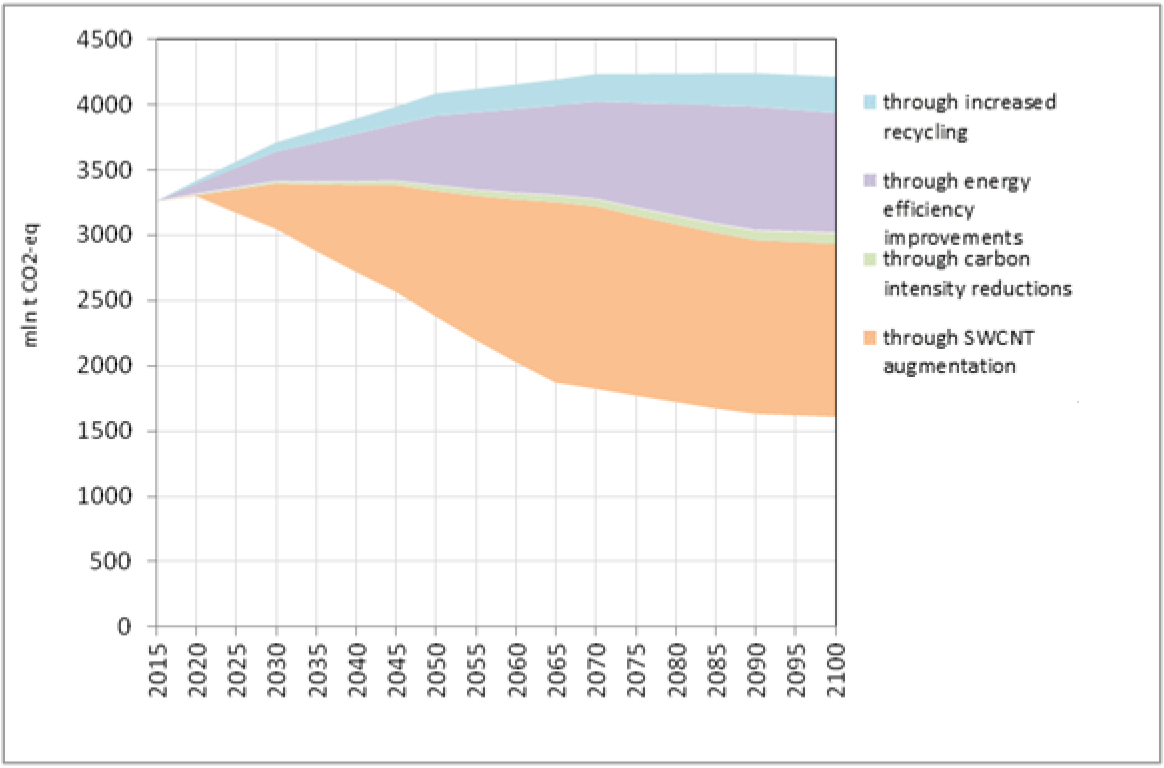
The main ways to reduce GHG emissions from cement and concrete production are as follows:

- **Reduction of material intensity**—a more efficient use of cement by increasing its strength properties. IPCC (2014), Muller and Harnish (2008) and van Oss and Padovani (2002) show that the use of high-strength concrete helps to reduce the demand for cement by 40–50%;
- **Increasing the use of cement additives.** Currently, according to IEA (2012), the average share of additives is 20%. It can be increased to 28–34% by 2050 (IEA, 2012 and 2015) and to 34–40% by 2100. As the energy consumption of additives production (blast furnace slag, ashes, etc.) is lower than that of clinker production or almost zero (if industrial waste is used for this purpose, the energy is used only for transporting the additives), increased use of additives helps to reduce specific energy consumption per tonne of cement;
- **Improving the energy efficiency of clinker production** by switching from the wet production technology to the dry technology and improving the latter, including through heat recovery and reduction of the burning temperature. The theoretical minimum of energy consumption for cement production is 1.6–1.85 GJ/t of clinker (IPCC, 2014). The current global average is 4.4 GJ/t of clinker, and the BAT parameters are 2.7 GJ/t of clinker. Thus, it is possible to reduce the specific consumption by bringing the global average to the BAT parameters while reducing of the BAT parameters themselves;
- **Reduction of carbon intensity of the fuel and electrical power** by increasing the use of renewable biomass and reducing the carbon intensity of the electrical power used. According to the IEA estimates (2012), the share of biomass in 2050 is expected to grow from 4% in the IEA baseline scenario to 28% in the scenarios with an active emission control policy;
- **development of carbon capture and storage technology.** These technologies are at the initial stage of development. Therefore, their parameters are still not clear. According to the IEA estimates (2012), the solution to the issue of reducing GHG emissions at the expense of

great efforts to capture and store carbon in the cement manufacturing sector may cost $400–450 billion of additional capital expenditures.

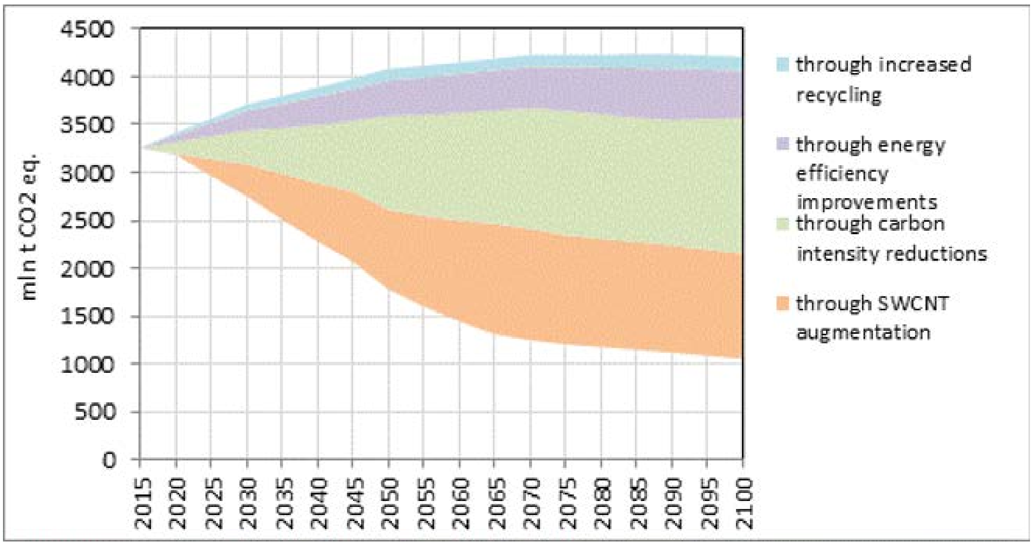
In the baseline scenario, the embodied GHG emissions from cement and concrete production increase in proportion to the production volumes as described in Chapter 6, and will reach its peak of 4.3 bt CO_2eq in 2070, and then almost stabilise at this level (Fig. 8.8). The IEA baseline projection (2012) provides only direct emission volumes, which increase to 3 bt CO_2eq by 2050. It already adopts some of the measures to improve energy efficiency and change the fuel balance of the cement industry. In the projection made by Muller and Harnish (2008), the direct and indirect emissions, at a constant energy and carbon intensity, will increase to 5.7 bt CO_2eq in 2050.

Figure 8.8 GHG Emissions from Cement Production Dynamics



Source: CENEF-XXI

Figure 8.9 GHG Emissions from Cement Production Dynamics (Significans Carbon Intensity Reduction due to CCS Technologies Penetration) in 2015-2100

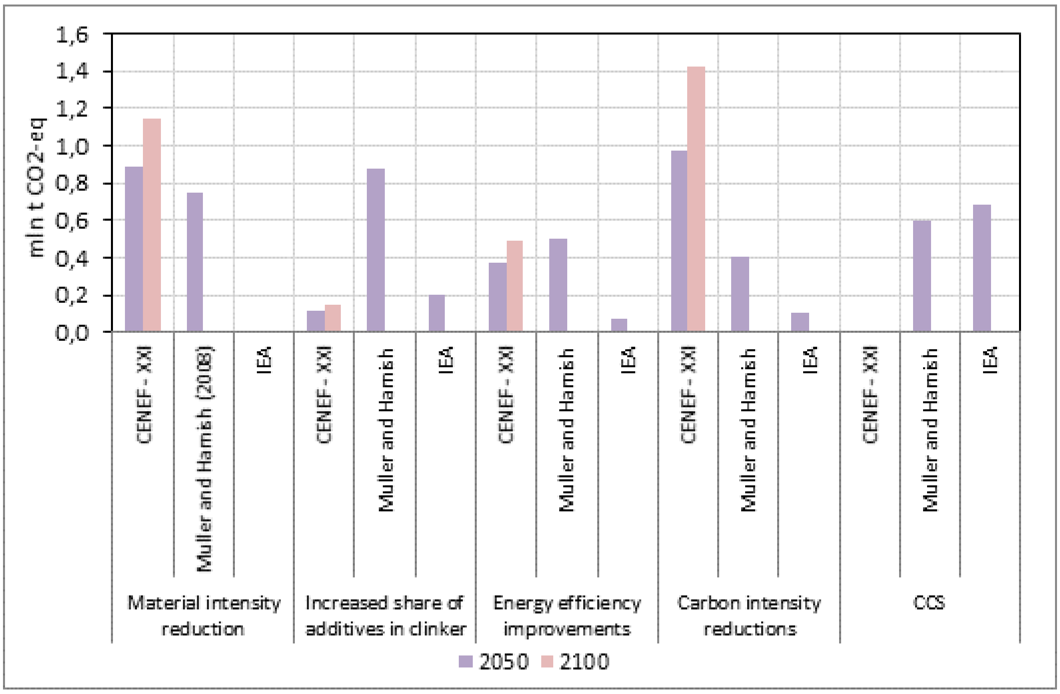


Source: CENEF-XXI

As shown in Chapter 7, adding 0.001% of SWCNT can increase compressive strength of concrete by 70%, which should result in reducing the concrete consumption by 1.7 times per unit of useful function. The SWCNT utilisation increases to 1 t in 2020 and then to 22 t every 5 years (to the point of full saturation), and reaches 133 t in 2050 and 202 t in 2100. In total, for the period of 2015–2100, 80 kt SWCNT are to be used. ***More efficient use of cement through increasing its strength properties by adding SWCNT helps to reduce the emissions by 891 Mt CO_2eq in 2050 and by 1,143 Mt CO_2eq in 2100.***

If we use the IEA estimates for the carbon intensity reduction due to wide use of the carbon capture and storage technology, the opportunity to reduce GHG emissions from cement production are further increased (Fig. 8.9). IEA (2012) estimates the possibility of reducing GHG emissions from cement production by taking the above-mentioned measures, including carbon capture and storage, within the range of 0.8 to 1 bt CO_2eq by 2050. ***The potential for reducing emissions by augmenting concrete with SWCNT is comparable to the potential reduction by increasing energy efficiency and by using the carbon capture and storage technology till 2050 and exceeds the potential for reduction by increasing the energy efficiency after 2050 (Fig. 8.9 and 8.10).*** Using this measure with other measures can solve the problem of reducing emissions by 57% in 2050 and by 75% in 2100. Without this measure, the reduction will only be 33% in 2050 and 48% in 2100.

Figure 8.10 Comparison of GHG Emissions from Cement Production Reduction



CENEF-XXI estimation includes CCS technologies into carbon intensity reduction

Sources: CENEF-XXI; IEA (2012); Muller and Harnish (2008).

If we assume that adding 0.001% reduces the need for concrete by 70%, there is an absolute limit (saturation) of the augmentation effect, which is equal to the basic consumption of concrete reduced by 1.7 times provided that all the concrete is produced according the new technology. Reduction potential by augmenting concrete with SWCNT reaches 27% of the baseline level. If there were no progress in improving energy efficiency and switching to low-carbon energy sources and in carbon capture and storage, the emission reductions would be 40%, which is very much in line with the estimates of the effect of improving cement efficiency by increasing its strength properties provided by IPCC (2014), Muller and Harnish (2008) and Van Oss and Padovani (2002).

The realization of the potential for GHG emissions reduction in the cement and construction industries by augmenting concrete with SWCNT will require us to formulate and solve the problem of reducing GHG emissions through the use of high-strength concrete as an important element of the business model of the development of these sectors of the economy; introduction of regulatory restrictions on the use of low-strength concrete; changes in the standards for cement and concrete; changes in building norms and regulations; inclusion of specific parameters of the integral (embodied) emissions as an important criterion for facilities construction; introduction of restrictions on GHG emissions per 1 m^2 of the constructed area of buildings (similar to vehicle emission standards); introduction of a carbon tax or a price for carbon in the emissions trading schemes; training professionals able to integrate innovation in the cement industry and construction into the daily practice of these industries (Muller and Harnish, 2008).

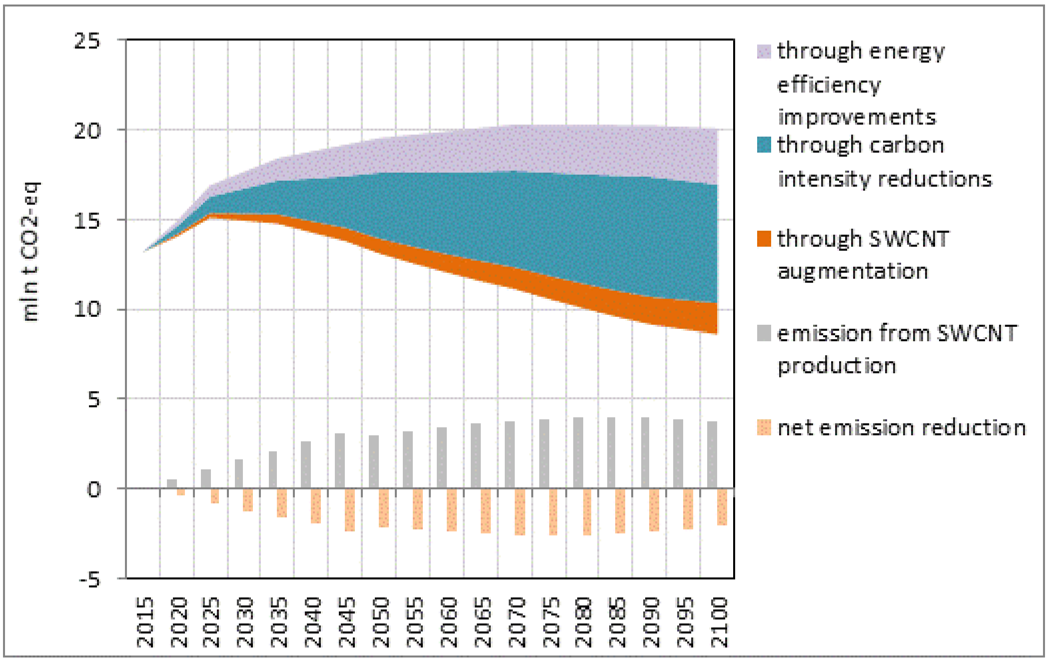
8.3.2 Brick

Embodied GHG emissions from brick manufacturing in 2014 were estimated at 13 Mt CO_2eq. The main ways to reduce GHG emissions from brick manufacturing are as follows: reduction of material intensity by increasing the strength and other characteristics by SWCNT augmenting; improvements in energy efficiency; reduction of the carbon intensity of the energy resources consumed, including development of the carbon capture and storage technology.

In the baseline scenario (with no changes in the level of carbon intensity), the embodied GHG emissions from brick manufacturing increase to 20 Mt CO_2eq by the end of the reporting period. Due to enhanced energy efficiency (furnace electrification and other furnace improvement technologies), GHG emissions are reduced by 2 Mt CO_2eq in 2050, and by 3 Mt CO_2eq in 2100; due to fuel replacement and increase in the share of low-carbon electric power, the emissions are reduced by 4 Mt CO_2eq in 2050 and by 7 Mt CO_2eq in 2100. Due to all these factors, the increase in GHG emissions can be stopped (Figure 8.11). These results are consistent with the similar results obtained for Europe in terms of GHG emissions reduction due to the introduction of low-carbon technologies.[71]

Adding SWCNT to bricks in the proportion 0.05% per unit mass increases the ultimate tensile strength by 30% (see Chapter 7 for details). For given augmentation conditions (using 1 kt SWCNT in 2020 and increasing the volume by 1 kt every 5 years), the volume of GHG emission reduction in relative terms is quite significant, but the absolute value is limited. Due to the moderate effect of the reduction of material intensity, it is less important than the reduction in carbon intensity and energy consumption. Due to augmentation of bricks with SWCNT the GHG emissions decreases by 0.8 bt CO_2eq in 2050 and by 1.7 bt CO_2eq in 2100.

Figure 8.11 GHG Emissions from Brick Production Dynamics



Source: CENEF-XXI.

[71] http://www.klimaat.be/2050/files/9813/8323/7398/3_Industry_-_Ceramic.pdf

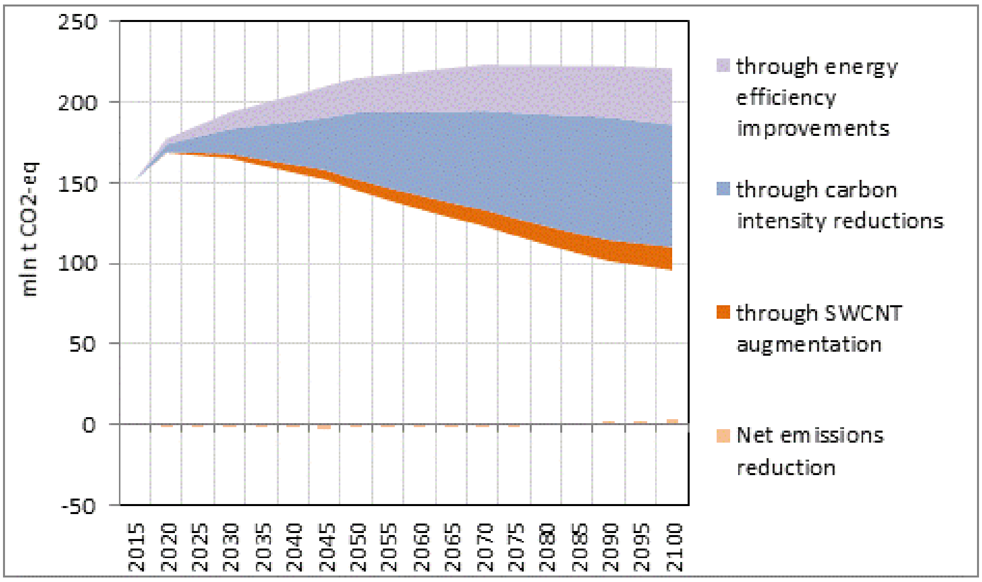
The embodied emissions from the production of the required amount of SWCNT outweigh the potential emission reduction due to the use of modified bricks, and the net amount of emissions is negative (Fig. 8.11)**.** It could be positive only if the embodied emissions from SWCNT production were not so high or if lower amounts of additives were required to improve the strength for given embodied emissions from brick manufacturing.

8.3.3 Ceramics

Embodied GHG emissions from ceramics manufacturing in 2014 were estimated at 152 Mt CO_2eq. The main areas considered for the reduction of GHG emissions from ceramics manufacturing are as follows: reduction of material intensity by increasing the strength and other characteristics using SWCNT augmentation; enhanced energy efficiency of production; reduction of carbon intensity of the fuel and energy resources consumed, including the development of carbon capture and storage technology (Fig. 8.12).

In the baseline scenario, the embodied GHG emissions from ceramics manufacture increase to 221–223 Mt CO_2eq by the end of the reporting period. Enhanced energy efficiency reduces GHG emissions by 21 Mt CO_2eq in 2050 and by 35 Mt CO_2eq in 2100 due to the introduction of electrification of furnaces and other furnace improvement technologies. Due to fuel replacement and the increase in the use of low-carbon electric energy, the emissions are reduced by 42 Mt CO_2eq in 2050 and by 76 Mt CO_2eq in 2100.

Figure 8.12 GHG Emissions from Ceramics Production Dynamics



Source: CENEF-XXI.

Adding SWCNT to ceramics in the proportion 0.05% per unit mass increases the tensile strength by 30%. If we use 1 kt in 2020 for this purpose and then add 3 kt every 5 years, we will use 19 kt SWCNT in 2050 and up to 49 kt in 2100. This makes it possible to achieve the net emission reduction, only if the embodied energy consumption in SWCNT production decreases faster than the embodied energy consumption of ceramics manufacture. Since in the first half of the century, before 2075, the relation is reverse, there will be no net emission reduction. It reaches 3.5 Mt CO_2eq in 2100. In total, the net savings from using SWCNT for ceramics augmentation is insignificant. However, unlike the benefit for brick manufacture, it may still be positive, because the specific embodied GHG emissions from ceramics manufacture is almost 3 times higher than that for brick manufacture.

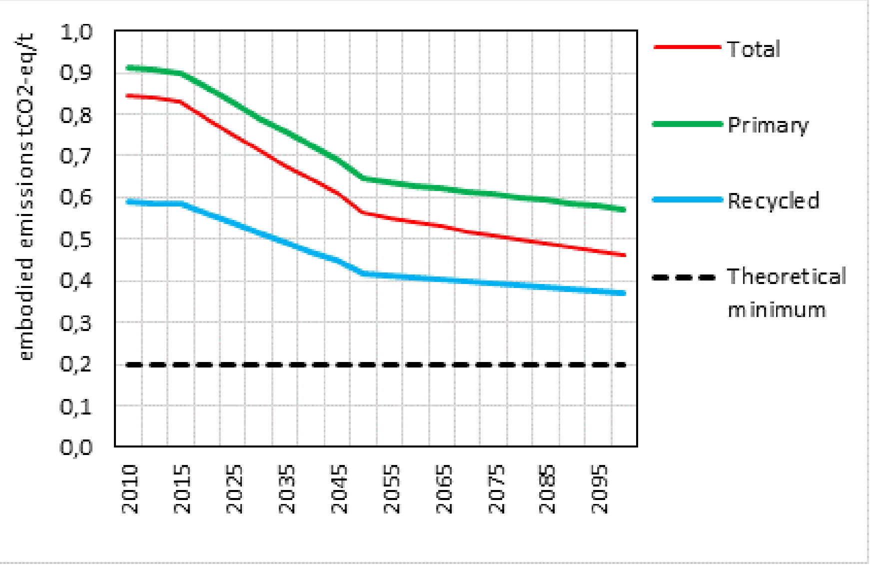
8.3.4 Structural Glass

The embodied GHG emissions from glass production were about 50 Mt CO_2eq in 2014. This is less than 0.1% of total anthropogenic greenhouse gas emissions and accounts for 0.5% of industrial anthropogenic GHG emissions. The specific embodied emission from glass production is estimated at 0.9 t CO_2eq per 1 t of primary glass and 0.6 t CO_2eq per t of secondary glass (University of Bath, 2011).

The use of secondary glass is an important factor in the manufacture of flat glass. Currently, the proportion of secondary glass in the production of flat glass is about 15–25%.[72] As glass is 100% recyclable and can be recycled an infinite number of times with no loss in purity, secondary glass is an important resource, and increase in its use in the manufacture of glass is a significant factor for reducing the carbon intensity of the glass industry.

In the structure of the embodied GHG emissions from a tonne of flat glass,[73] fuel burning has the largest share (42%), production of raw materials for glass has the second largest share (25%), another 17% are indirect emissions from the use of electric energy and emissions from carbonate decomposition. About 0.2 t CO_2 are emitted by carbonate raw materials needed to produce one tonne of flat glass. This value is used as the theoretical minimum. Dynamics of the embodied energy consumption reduction per tonne of glass is estimated based on the estimates for energy consumption reduction for production under the assumption that the relative costs of production will be gradually approaching the theoretical minimum (the value of the theoretical minimum for flat glass production according to GTI[74]) till the end of the century (Fig. 8.13).

Figure 8.13 Embodied Unit Emissions from Production and Consumption of Glass



Sources: University of Bath, 2011, NSG Group, CENEF-XXI

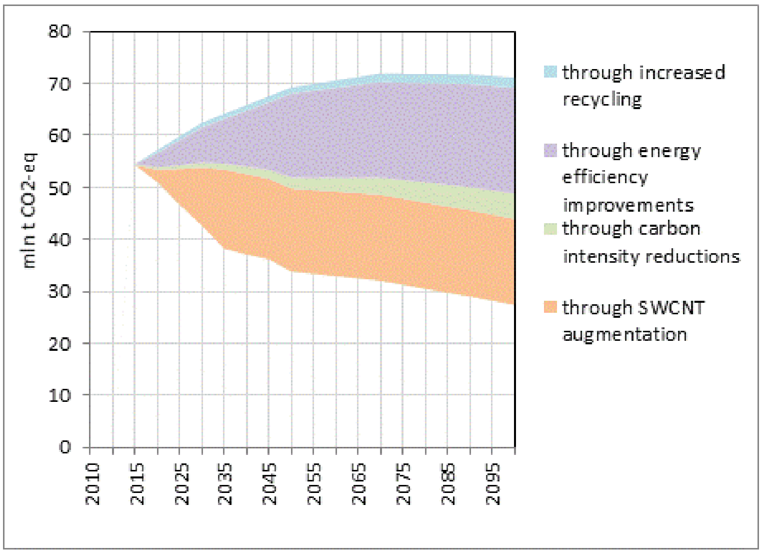
In the baseline scenario, the embodied GHG emissions from glass production increase in proportion to the volumes of production, as described in Chapter 6, and reach 70 Mt CO_2eq in the middle of the century and then stabilise at this level (Fig. 8.14). A growing use of secondary glass reduces emissions by 1–2 Mt per year in 2100–18. Enhanced energy efficiency reduces GHG emissions by 18 Mt CO_2eq per year in 2050 and by 20 Mt CO_2eq per year in 2100. The

[72] https://www.pilkington.com/north-america/usa/english/building+products/sustainability/sustainability+faqs.htm#faq1, https://www.pilkington.com/resources/pfgi2010.pdf
[73] http://www.nsg.com/en/sustainability/glassandclimatechange/embodiedc02infloatglass
[74] http://www.gmic.org/Industrial%20Glass%20Bandwidth%20Analysis.pdf

contribution of fuel replacement and the increase in the share of low-carbon electric energy is 2 Mt CO_2eq in 2050 and 5 Mt CO_2eq in 2100.

Adding SWCNT to glass in the proportion 0.014% of SWCNT per unit mass increases its ultimate tensile strength by 50%, and reduces the need for glass by 1.5 times (Chapter 7). Thus, if the entire volume of the flat glass produced is augmented, the demand for it can be reduced by 1.5 times by 2100. The rate of this reduction depends on the possible increase in the use of SWCNT for that purpose. Assuming that in 2020 one thousand tonne of SWCNT will be used for these purposes and the usage will increase by 2 kt every 5 years, this additional measure will significantly reduce GHG emissions (Fig. 8.14). The contribution of this factor is 18–19 bt CO_2eq in 2050–2100, and the net emissions reduction is 16–17 bt CO_2 in 2050–2100. For this purpose, 7 kt are required in 2050 and 8 kt in 2100, and a total of 7.4 Mt of SWCNT are required during 2015–2100.

Figure 8.14 GHG Emissions from Flat Glass Production Dynamics



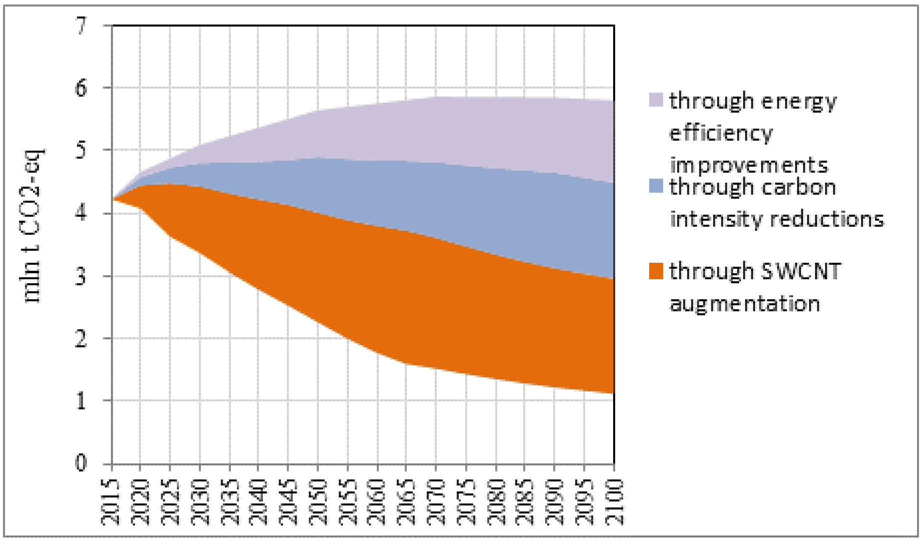
Source: CENEF-XXI.

8.3.5 Insulation materials

The embodied GHG emissions from **mineral wool** production in 2014 were estimated at 4.2 Mt CO_2eq. In the baseline scenario, they increase to 6 Mt CO_2eq by 2100. Improving the energy efficiency reduces GHG emissions by 0.9 Mt CO_2eq in 2050 and by 1.5 Mt CO_2eq in 2100. Replacing the fuel and increasing the share of low-carbon electric energy reduces emissions by 1 Mt CO_2eq in 2050 and by 1.8 MT CO_2eq in 2100 (Fig. 8.15).

The expected annual production of mineral wool in 2015 is 3.3 Mt. Adding SWCNT to the mineral wool in the proportion 0.1% per unit mass increases the ultimate tensile strength by 100% (see Chapter 7 for details). Thus, to augment the entire volume of current production of mineral wool, only 3.3 kt SWCNT are needed. The assessment of the contribution of SWCNT in the emission reduction is based on the assumption that, in 2020, 300 t of SWCNT will be used and the volume of usage will increase by 200 t every 5 years. When combined with other measures, it will reduce GHG emissions to 1.7–2 Mt CO_2eq in 2050–2100. The net emission reduction in 2050–2100 is 1–1.3 Mt CO_2eq.

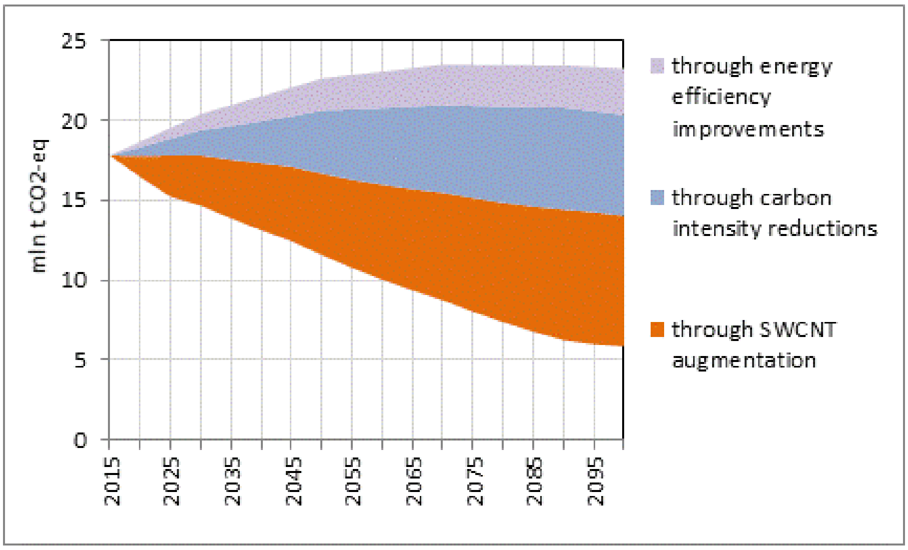
Figure 8.15 GHG Emissions from Mineral Wool Production Dynamics



Source: CENEF-XXI.

The embodied GHG emissions from fibreglass wool production in 2014 were estimated at 18 Mt CO_2eq. In the baseline scenario, the embodied GHG emissions from fibreglass wool production increase to 23 Mt CO_2eq by the end of the reporting period (Fig. 8.16).

Figure 8.16 GHG Emissions from Fibreglass Wool Production Dynamics



Source: CENEF-XXI.

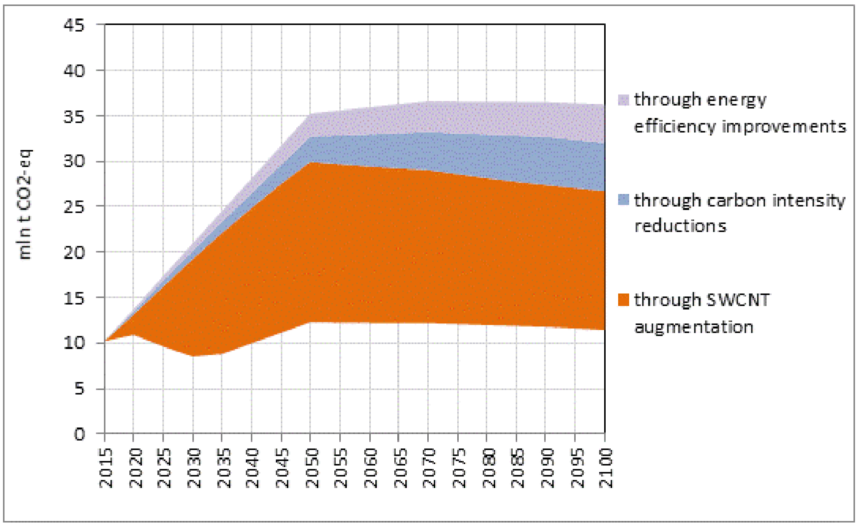
Due to energy efficiency improvement, GHG emissions are reduced by 2 Mt CO_2eq in 2050 and by 2.9 Mt CO_2eq in 2100. Switching to low-carbon energy sources reduces emissions by 4 Mt CO_2eq in 2050 and by 6.3 MT CO_2eq in 2100 (Fig. 8.16). ***Adding SWCNT to fibreglass wool in the proportion 0.1% per unit mass increases*** the ultimate tensile strength by 100% (see Chapter 7 for details). Under given conditions (using 1 kt SWCNT in 2020 and increasing the volume by 0.5 kt every 5 years), this ***will reduce the volume of GHG emissions by 5 Mt CO_2eq in 2050 and by 8 Mt CO_2eq in 2100***. The net emission reduction will be 3 Mt CO_2eq in 2050 and by 6 Mt CO_2eq in 2100.

8.3.6 Construction composites

The embodied GHG emissions from **glass-reinforced plastics** production in 2014 were estimated at 10 Mt CO_2eq. In the baseline scenario, they increase to 36 Mt CO_2eq by 2100. Improving the energy efficiency reduces GHG emissions by 3 Mt CO_2eq in 2050 and by 4.2 Mt

CO_2eq in 2100. Switching to low-carbon types of energy reduces emissions by 4 Mt CO_2eq in 2050 and by 5.3 Mt CO_2eq in 2100 (Fig. 8.17).

Figure 8.17 GHG Emissions from Fiberglass Plastics Production Dynamics



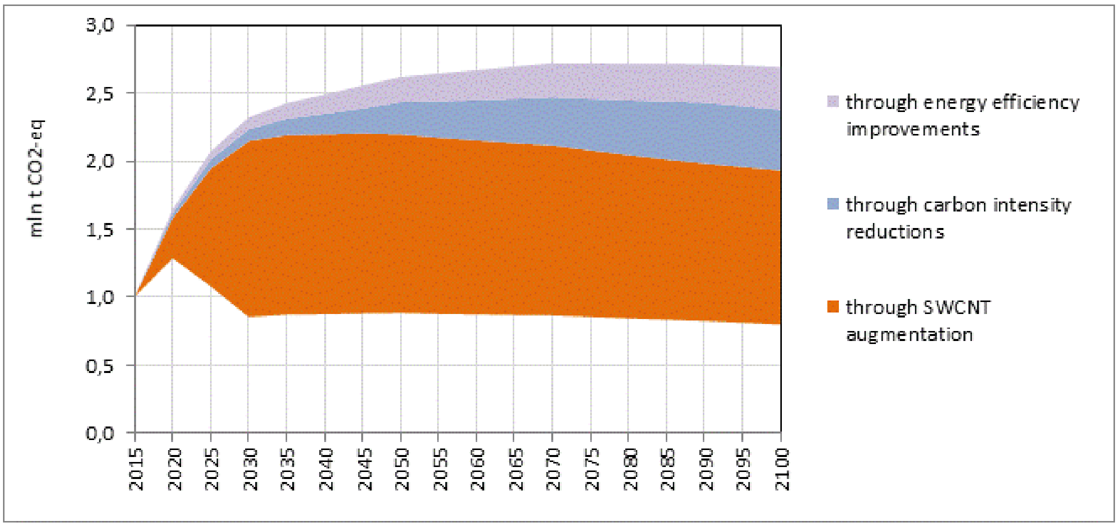
Source: CENEF-XXI.

Adding SWCNT to glass-reinforced plastics in the proportion 0.05% per unit mass increases the ultimate tensile strength by 150%. Under given conditions (using 0.5 kt SWCNT in 2020 and increasing the volume by no more than 1 kt every 5 years), this will reduce the volume of GHG emissions by 15–17 Mt CO_2eq in 2050-2100. The net emission reduction will be 15 Mt CO_2eq in 2050 and by 14 Mt CO_2eq in 2100.

The embodied GHG emissions from **carbon plastics** production in 2014 were estimated at 1 Mt CO_2eq. In the baseline scenario, the embodied GHG emissions from carbon plastics production increase to 2.7 Mt CO_2eq by 2100 (Fig. 8.18). Due to energy efficiency improvement, GHG emissions can be reduced by 0.2 Mt CO_2eq in 2050 and by 0.3 Mt CO_2eq in 2100. Switching to low-carbon fuel can reduce emissions by 0.2 Mt CO_2eq in 2050 and by 0.4 Mt CO_2eq in 2100.

Adding SWCNT to carbon plastics in the proportion 0.05% per unit mass increases the ultimate tensile strength by 150%. Under given conditions (using 0.02 kt SWCNT in 2020 and increasing the volume by 0.01 kt every 5 years), this will ***reduce the volume of GHG emissions by 1.1–1.3 Mt CO_2eq in 2050–2100.***

Figure 8.18 GHG emissions from Carbon Plastics Production Dynamics



Source: CENEF-XXI.

8.4 Chemicals and Petrochemicals

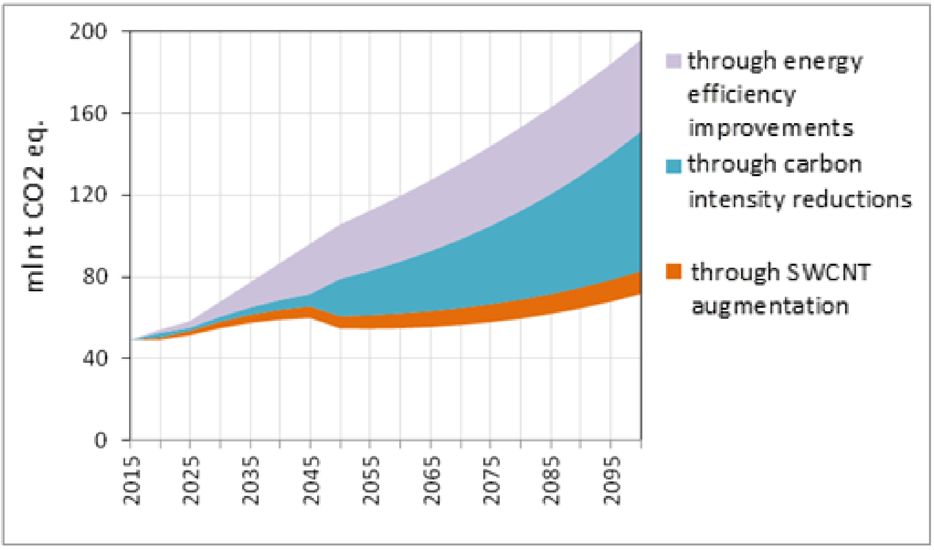
8.4.1 Synthetic Rubber

Embodied GHG emissions in the manufacture of synthetic rubber in 2014 are estimated to be 47.6 Mt CO_2eq, which is less than 0.1% of the total anthropogenic emissions and less than 0.5% of the anthropogenic emissions in the industrial sector.

In the baseline scenario, the embodied GHG emissions from synthetic rubber production increase to 196 Mt CO_2eq by 2100. Improving the energy efficiency reduces GHG emissions by 22 Mt CO_2eq in 2050 and by 34 Mt CO_2eq in 2100. Reducing the carbon intensity of energy reduces emissions by 12 Mt CO_2eq in 2050 and by 35 Mt CO_2eq in 2100 (Fig. 8.19).

Adding SWCNT to synthetic rubber in the proportion 0.5% per unit mass increases the ultimate tensile strength by 200%, and, therefore, reduces the need for the material by 3 times (see Chapter 7 for details). Under given conditions (using 1 kt SWCNT in 2020 and increasing the volume by 7 kt every 5 years), this ***will reduce the volume of GHG emissions by 6 Mt CO_2eq in 2050 and by 11 Mt CO_2eq in 2100***. The net emission reduction will be 3 Mt CO_2eq in 2050 and 7 Mt CO_2eq 2100.

Figure 8.19 GHG Emissions from Synthetic Rubber Production Dynamics



Source: CENEF-XXI.

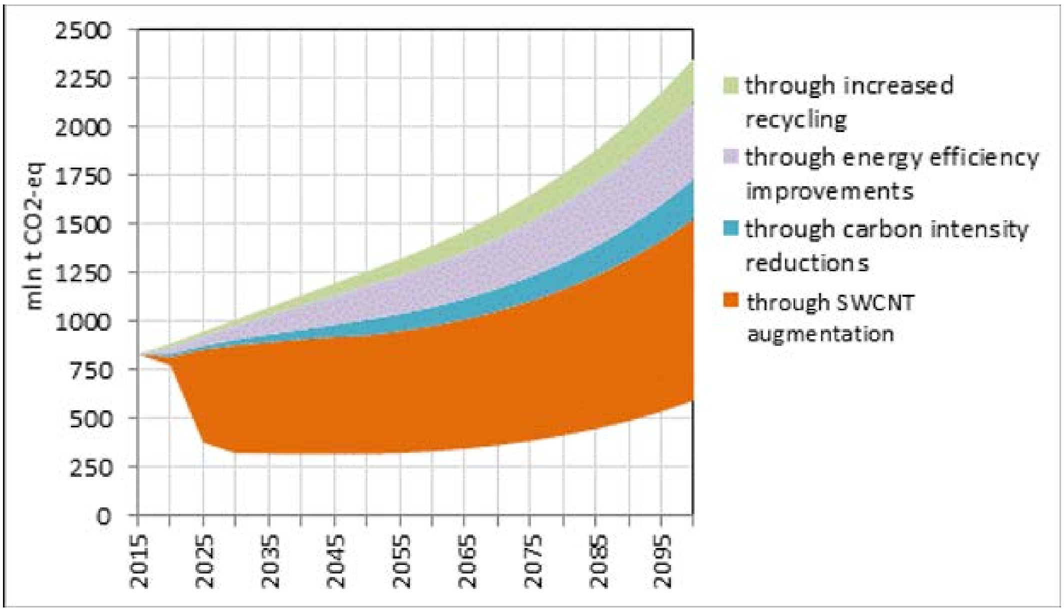
8.4.2 Plastics

The total volume of **thermoplasts** in 2014 was estimated at 269 Mt, or 88.5% of the total plastics production. The embodied GHG emissions from the manufacture of thermoplasts in 2014 are estimated to be 842 Mt CO_2eq, which is about 1.6% of the total anthropogenic emissions and 8% of the anthropogenic emissions in the industrial sector. In the baseline scenario, the embodied GHG emissions from thermoplasts production increase to 1,257 Mt CO_2eq by 2050 and to 2,351 Mt CO_2eq by 2100.

It should be noted that increasing the proportion of recycling of plastics as a way to reduce GHG emissions is only appropriate in relation to thermoplasts that can be used as secondary raw materials (some of them are often burned after utilisation). There are certain problems in their use for this purpose that do not give any reason for the assumption of reaching a large share of recycling by the end of the period under review. Firstly, plastics cannot be mixed. Secondly, secondary mechanical processing[75] of plastics deteriorates their properties because of the presence of various impurities and additives (for example, to change the colour and properties) and fillers (such as chalk for stiffening). Thirdly, plastics can be used for other purposes (for example, as fuel for energy generation). To increase the proportion of plastics processing, it is necessary to organise an effective separate collection of waste and enhance sorting. By increasing the proportion of recycling, the GHG emissions from thermoplasts production are reduced by 94 Mt CO_2eq in 2050 and by 223 Mt CO_2eq in 2100 (Fig. 8.20).

Improving the energy efficiency reduces GHG emissions by 197 Mt CO_2eq in 2050 and by 397 Mt CO_2eq in 2100. Increasing the share of low-carbon fuels and electric energy reduces emissions by 90 Mt CO_2eq in 2050 and by 204 Mt CO_2eq in 2100.

Figure 8.20 GHG Emissions from Thermoplasts Production Dynamics



Source: CENEF-XXI.

Adding SWCNT to thermoplasts in the proportion 0.01% per unit mass increases the ultimate tensile strength by 150% and, therefore, reduces the need for the material by 2.5 times (see Chapter 7 for details). Under given conditions (using 1 kt SWCNT in 2020 and increasing the volume by 2 kt every 5 years), this ***will reduce the volume of GHG emissions by 610 Mt CO_2eq in 2050 and by 933 Mt CO_2eq in 2100***. Production of single-wall nanotubes will increase the GHG emissions by 7 Mt CO_2eq in 2050-2100. Therefore, the net emission reduction will be 603 Mt CO_2eq in 2050 and 926 Mt CO_2eq in 2100. To achieve this, 13 kt SWCNT is required in 2050 and 33 kt in 2100.

2.1. Wood Products (Wood Panels)

The embodied GHG emissions from the manufacture of the four kinds of wood panels (plywood, wood chipboards, wood boards and MDF) in 2014 are estimated to be 224.4 Mt CO_2eq, which is less than 0.5% of the total anthropogenic emissions and accounts for 2.5% of the anthropogenic emissions in the industrial sector. ***Wood panel augmentation with SWCNT is inappropriate at the current level of technology***, since carbon dioxide emissions from the production of single-wall nanotubes exceed the effects of improving the strength characteristics of wood panels (see Chapter 7 for details).

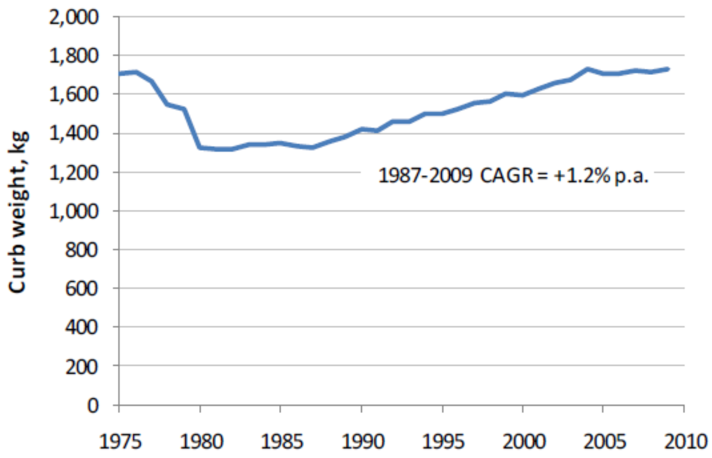
[75] Pyrolysis is an alternative plastics recycling process, which produces raw materials for reproduction as well as for other purposes.

8.5 Reducing GHG Emissions by Reducing the Weight of Cars

8.5.1 Cars

The Ford T (Tin Lizzie) weighed only 850–880 kg. Just before the first oil shock, the average weight of a new American car had doubled and exceeded 1700 kg. Due to sharp rise in price of liquid fuel, by 1980 it dropped to 1,350 kg and stayed at that level till 1986. However, after the drop of liquid fuel prices, it began to increase again by about 1.2% per year, returned to the level of 1975 (1,730 kg) and has stabilised at this level in recent years (Fig. 8.21)[76]. This is partly explained by the increase in the average size of a car, which dropped in the 1975–1980, but then began to grow in 2005–2010 and exceeded the initial level in of 1975.

Figure 8.21 Average New USA Vehicle Curb Weight, 1975-2009



Source: Cheah L.W. 2010. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. MASSACHUSETTS INSTITUTE OF TECHNOLOGY. SEPTEMBER 2010.

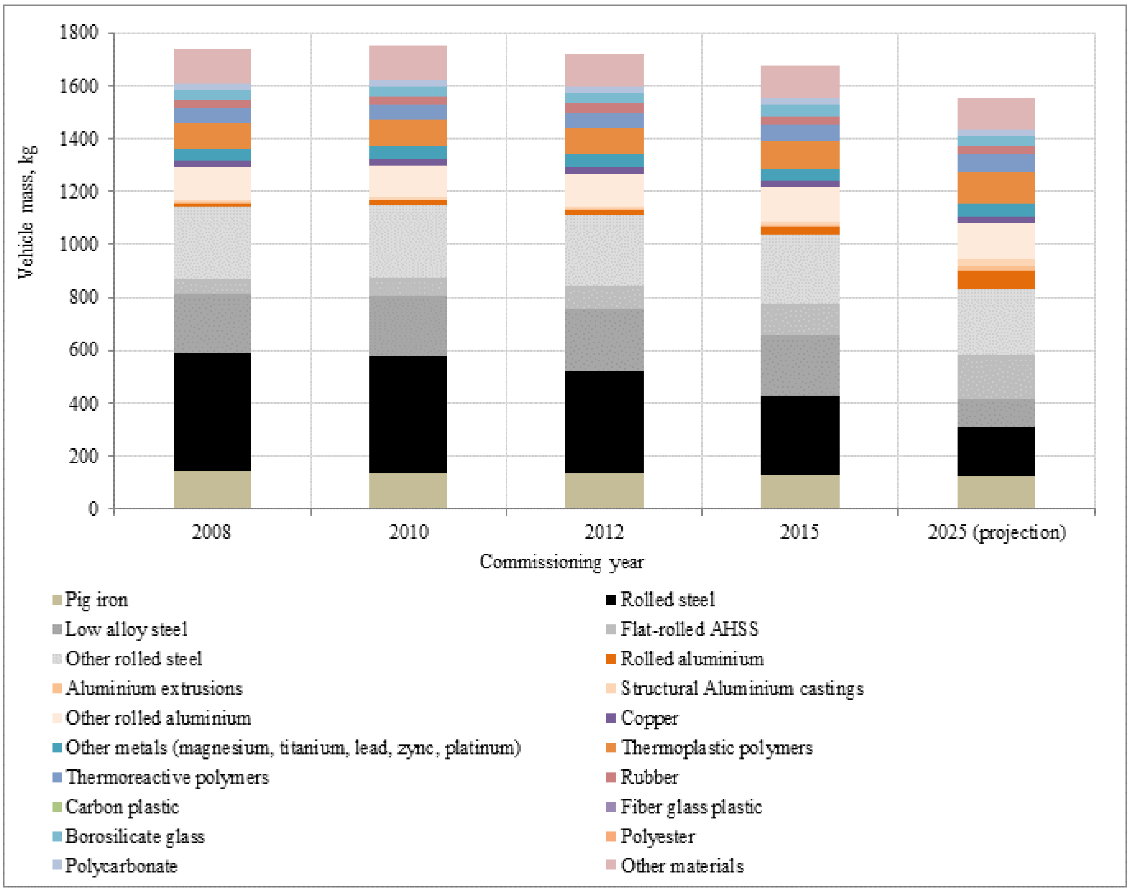
In other countries, the average weight of a car is smaller than that in the USA, but the trends are similar. For example, in the United Kingdom over the past 40 years, the average weight of a car has increased by 35–75% depending on the manufacturer (Allwood et al., 2011). Weight reduction through the use of lighter materials was compensated by an increase in the size of a car (30%) and installation of equipment for additional functionality, including improved comfort (15%), as well as increa Figure 8.22 **Materials used in production of new light-duty vehicles for sale in USA** ed acceleration, ease of steering, safety, etc.

As the fuel efficiency only ranks 9th on the consumer list, it has been neglected for a long time. The situation changed with the introduction of maximum permissible emissions per unit mileage, which in Europe equal 130 g CO_2/km in 2015 and 95 g CO_2/km in 2020. It is only in recent years that the weight of cars began to decline (Fig. 8.22) due to the increase in the proportion of lightweight materials.

There are three main strategies of car weight reduction: the use of lightweight materials, modification of the design and reduction in size. The use of some materials considerably reduces car weight: high strength steel, aluminium, magnesium and polymer composites (Bandivadekar et al., 2008). In 2025, the average car weight is expected to be reduced to 195 kg or by 11% (Fig. 8.22). However, there are other possibilities for weight reduction.

[76] According to other sources, the average weight of a new car in the United States was equal to 1,880 kg (Bandivadekar et al., 2008) or 1,524 kg (American metal market, 2003). At the same time, according to the latter, the average weight of a car was equal to 1,663 kg in 1977 and 1,442 kg in 1987, i.e., the dynamics was similar to that shown in Fig. 7.

Figure 8.22 Materials Used in Production of New Light-Duty Vehicles for sale in USA



Source: Reisman L. Car Wars: Aluminum v. Steel, Episode Two. https://agmetalminer.com/2011/05/06/car-wars-aluminum-v-steel-episode-two/; https://agmetalminer.com/2011/09/19/aluminum-cars-all-time-high-alcoa-novelis-taking-the-bank-part-one/

For the modern models, including car body elements, aluminium and plastics are used more frequently. Car body elements such as the front and rear bumpers are made of plastic in most modern cars. Plastic front wings are not only used on low-cost cars, but also on rather expensive models such as the Volkswagen Touareg. Aluminium is widely used in car production as replacement for heavy metals. In 1977, it accounted for only 2.6% of the weight of a car[77] (American metal market, 2003), but during the recent years, the proportion of aluminium was 8–12%, and this figure may reach 16–17% by 2025.[78] Honda is the leader in respect to this value. The proportion of aluminium in Honda car parts is 10.7%. In the US market, General Motors is the leader in the use of aluminium for car manufacture. The weight of aluminium parts in GM cars is about 167 kg. The body of the 2015 Ford F-150 pickup is completely made of aluminium. Its elements are mounted on a steel frame. Extensive use of aluminium in this model reduced the vehicle's weight by 300 kg[79].

It should be noted that ***lightweight materials, such as aluminium, are used not only in car body parts, but have also found an extensive use in the production of elements of the power unit, in particular, the transmission.*** Some power unit elements can be made of other lightweight materials. In car racing, transmissions with carbon fibre housings are already widely used, and racing technologies always come to ordinary cars. Lotus Engineering has been developing an urban car, in the parts of which magnesium will be actively used. Its share will amount to 16% of

[77] In 1977, the share of ferrous metals was 74% (American metal market, 2003).
[78] https://agmetalminer.com/2011/09/19/aluminum-cars-all-time-high-alcoa-novelis-taking-the-bank-part-one/.
[79] http://www.ford.com/trucks/f150/.

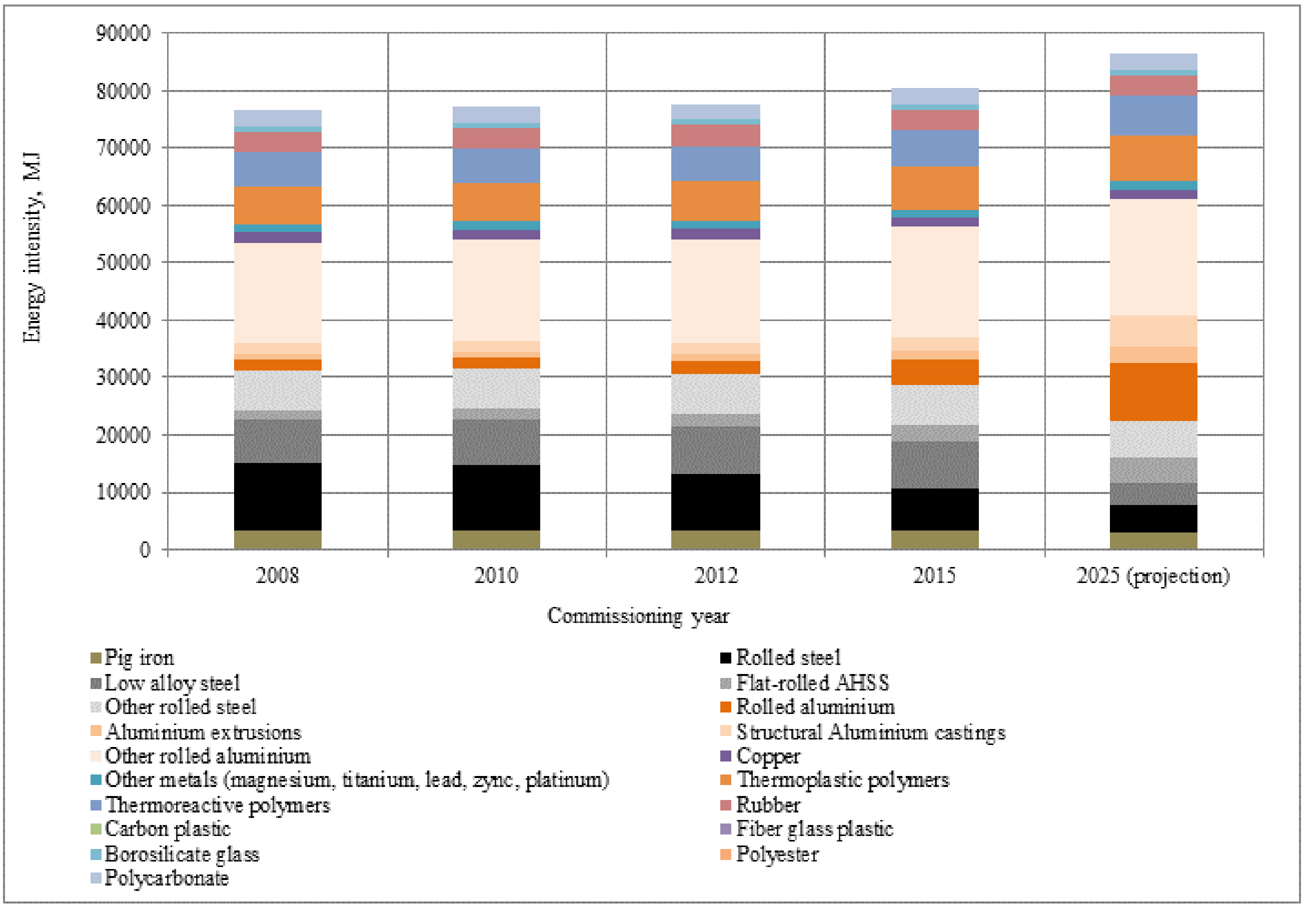
all the materials used for the construction of the car. The weight of the model that should be brought into production in 2020 will be 38% lower due to the use of lightweight materials, 453 kg.

Lotus's research (2010) shows that the reduction of car weight by 38% (without transmission) can be achieved by 2020 without any substantial additional costs. Frangi (2001) showed that the weight of a car body can be reduced from 350 kg (steel body) to 205 kg (aluminium body) and even to 162 kg (carbon fibre body). The secondary weight reduction can be achieved by reducing the weight of the subsystems. Furthermore, it is possible to reduce car's weight through revision or reconfiguration of the vehicle and minimise the outer dimensions, while maintaining the same internal space. Bandivadekar et al. (2008) estimate the ***possibility of weight reduction by 20–35% by 2035 with aggressive replacement of materials*** at a cost of weight reduction in all the three approaches ranging from $2 to $3.5 per kilogram of the reduced weight.

The price for weight reduction also includes an increased energy consumption (Fig. 8.23) and carbon intensity (Fig. 8.24) of car production. The increase in energy consumption is 52 MJ per 1 kg of weight reduction, and the increase in carbon intensity is 2.66 kg CO2. ***However, the reduction in car weight results in the reduction of fuel consumption during their operation*** (Fig. 8.25a) and the reduction of emissions that directly depend on the level of fuel consumption (Fig. 8.25b). There are different estimates of this effect (Fig. 8.25c–8.25f).

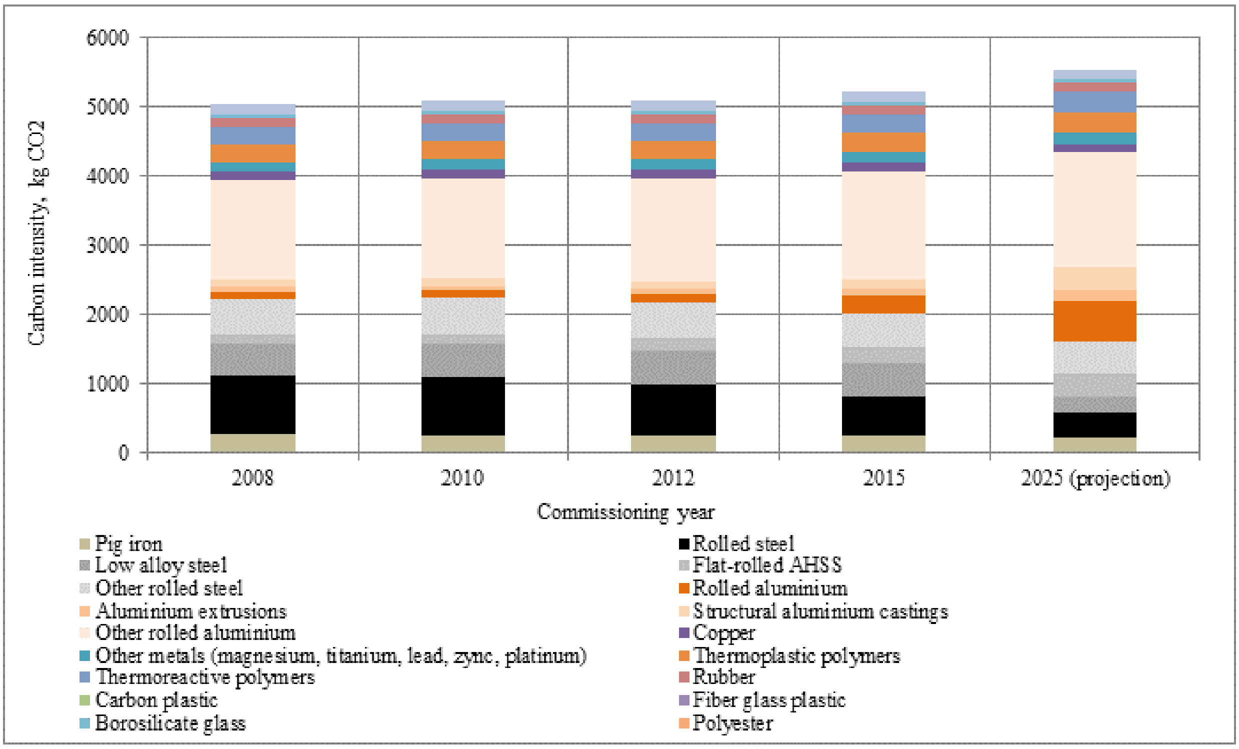
Ashby (2009) presents a table which shows that for petrol cars this effect is 2.1 $MJ/km*10^{-3}$. This is equivalent to 0.0064 l/100 km/kg. This result is close to the results obtained for the USA, i.e. 0.0053–0.007 l/100 km/kg. However, a comparison of the models with more similar characteristics leads to a decrease in this coefficient to 0.0036–0.0037 l/100 km/kg. The estimates made by CENEf-XXI on a limited number of models of different weight provide a coefficient of 0.003 l/100 km/kg. Finally, modelling of the impact of weight reduction on the fuel efficiency has a better result: 0.004–0.005 l/100 km/kg and 0.4–0.5 l/100 km/100 kg, which is higher than the value given by Allwood (2011), 0.13 l/100 km/100 kg.

Figure 8.23 Energy Intensity (Using Embodied Energy) of Production of New Light-Duty Vehicles for Sale in USA



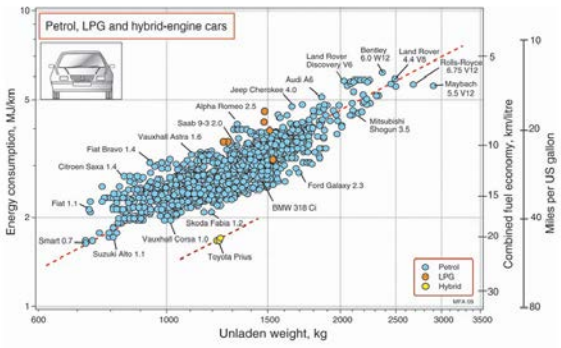
Source CENEF-XXI based on fig. 8.22.

Figure 8.24 Carbon Intensity (Using Embodied Energy) of Production of New Light-Duty Vehicles for Sale in USA

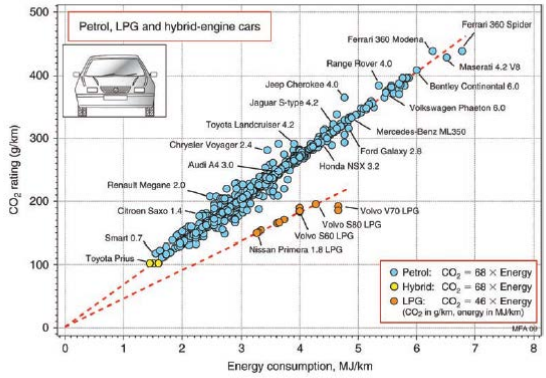


Source CENEF-XXI based on fig. 8.22.

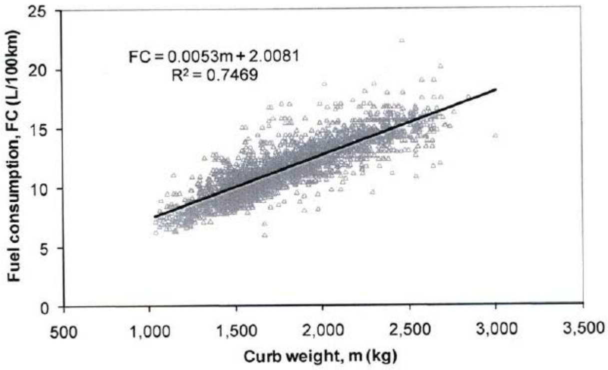
Figure 8.25 Specific Fuel Consumption to Curb Weight Ratio



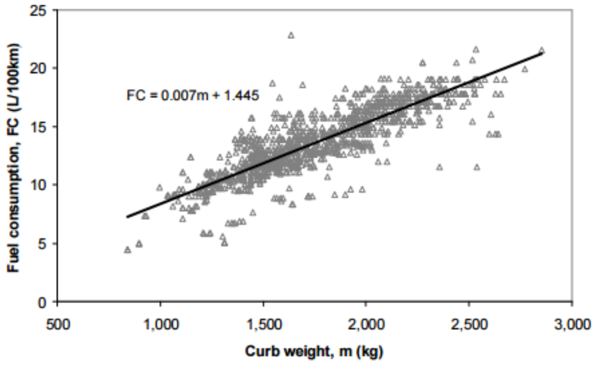
a



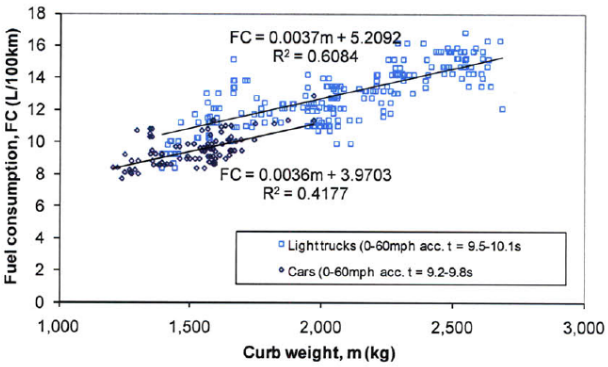
b



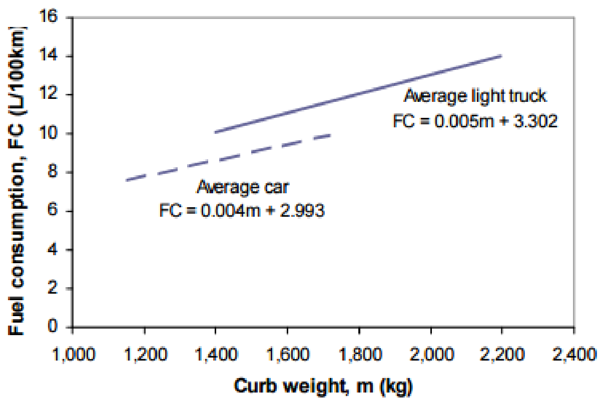
c



d



e

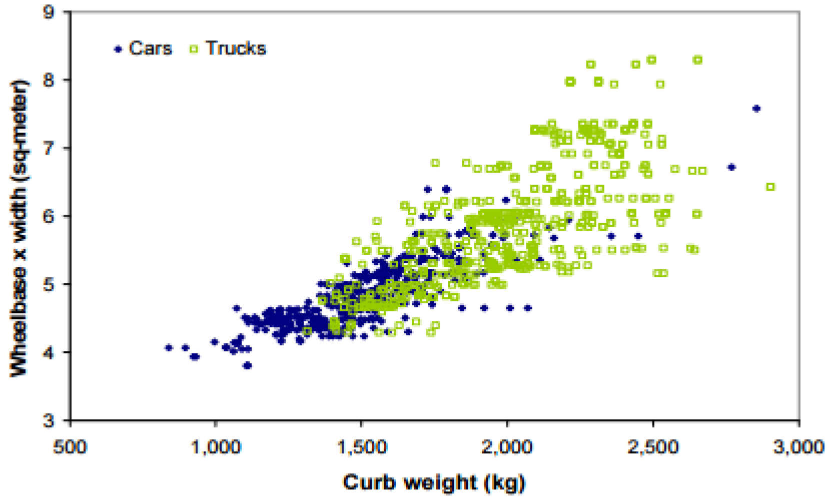


f

Note: a—energy consumption of petrol, LPG and hybrid engine cars (Ashby, 2009); b—CO 2 emission of petrol, LPG and hybrid engine cars (Ashby, 2009); c—curb weight and fuel consumption of USA MY2006-2008 vehicle (Cheah, 2010); d—Curb weight and fuel consumption of USA model year 2005 vehicles (Bandivadekar et al. (2008); e—Curb weight and fuel consumption of select MY2006-2008 USA gasoline cars and pickups (Cheah, 2010); f—Simulation results: curb weight-fuel consumption relationship for today's vehicles (Bandivadekar et al., 2008).

In further calculations, we used the value of 0.4 l/100 km/100 kg, or 0.429 kgoe/100 km/100 kg. This is equivalent to a decrease in specific fuel consumption by 8.4% with a reduction of the curb weight of a car (a medium car with a weight of 1,360 kg) by 10%. With regard to this characteristic, the literature review given by Cheah (2010) shows that the specific consumption decreases by 2.6–6.8% for a small car and 1.9–8.2% for a medium car. According to other estimates, a 10% car weight reduction decreases the fuel consumption level in the range of 7%[80] to 9.3%.[81] Therefore, the obtained estimate can be considered reliable. According to Fig. 8.26, it corresponds to the reduction of GHG emissions by 8.4%, or 1.287 kg CO_2/100 km/100 kg. Similar characteristics were obtained for trucks (Helms and Lambrecht, 2004; IEA, 2009).

Figure 8.26 Size (Footprint) vs. Weight of USA Vehicles Offered in Model Year 2005



Source: Bandivadekar et al., 2008

An aggregate global model for motor transport, which includes car and truck blocks, was built to assess the possible emission reduction resulted from the further reduction in the weight of cars. It describes the dynamics of the average car weight, the car fleet turnover, the average mileage, the total and specific fuel consumption, as well as the specific and total GHG emissions. The model parameters were calibrated according to the GEA forecast data (2012). The main assumptions are also made according to the GEA forecast. They were supplemented with the assumptions about the car weight reduction. The impact of the reduction on the specific fuel consumption and the specific emissions is evaluated based on the above derived dependencies at 100 km/100 kg. This model does not include buses or two- and three-wheeled motor vehicles.

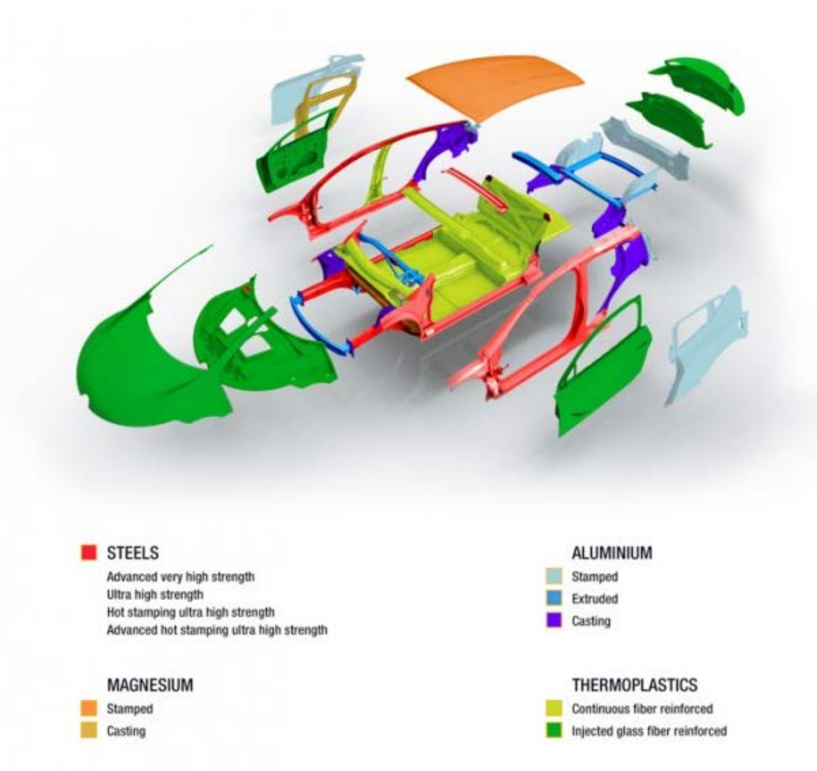
The potential for the car weight reduction is quite significant. Fig. 8.26 shows that at the same area under the wheels of a car its weight varies greatly. Furthermore, there is a two-fold difference in the weight at a similar area. Apparently, the average car weight may be reduced in a “natural way” (i.e. without the augmentation of the materials with SWCNT) by about 20% by 2050 and by 40% by 2100, that is it will return to the original weight of the Ford T in the beginning of the century in Europe, while it will still exceed it in the US.

It is assumed (see Fig. 8.22) that the share of ferrous metals will decline from the current 66% to 54% in 2025 and then to 45% in 2050 and 30% in 2100. This means that the proportion of aluminium, plastics, and composite materials will grow accordingly. If the specific demand for the materials will fall by half through their augmentation with SWCNT in a proportion of 0.1%, the weight reduction of a car can be significantly accelerated as compared to the baseline scenario. ***It is assumed that*** due to this ***the average weight of a car can reach 600 kg in 2100. As a result, the car weight is reduced by an average of 400 kg.*** The concept car Renault EOLAB weighs 400 kg[82] less than the current version of the Renault Clio IV with an average

[80] Data of the USA Department of Energy http://www.ctemag.com/aa_pages/2011/110903-MakingAutoParts.html.
[81] Calculation based on the data provided by Ashby (2009).
[82] http://blog.caranddriver.com/french-hypermiling-ultralight-renault-eolab-pegged-at-235-mpg-2014-paris-auto-show/.

weight of 1,000 kg[83]. Ford has developed a concept car based on the model Ford Fusion (in Russia and Europe, this model is called Mondeo) using lightweight materials, thus reducing the weight of the car by 363 kg[84]. A car weight reduction of about 400 kg was achieved by increasing the share of aluminium, magnesium, and thermoplasts, in both the car body (Fig. 8.27) and the elements of the hybrid power unit (engine, hybrid, transmission) and suspension as well as everywhere else where it was possible.

Figure 8.27 Lightweight Materials used in Renault EOLAB Concept-Car Production



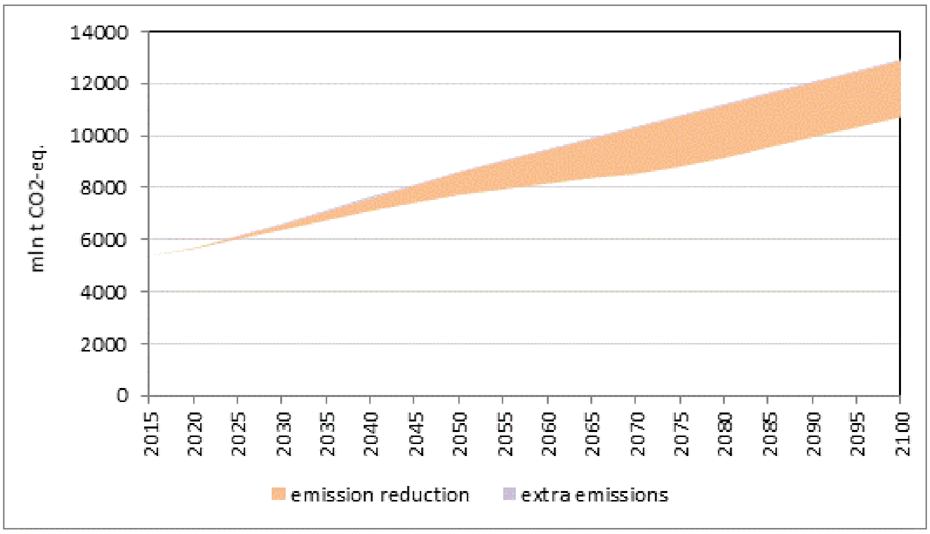
Source: http://www.clioiv.com/downloads/tech.pdf.

Adding SWCNT leads to some increase in carbon intensity per weight unit of an augmented basic material but reduces carbon intensity per unit service (function) of the material and, moreover, decreases the specific fuel consumption and GHG emissions. ***According to the GEA forecast (2012), the GHG emissions from motor transport increase in the baseline scenario (the emissions are estimated based on the fuel consumption data) from the current 5.4 bt CO_2 to 8.6 bt CO_2 in 2050 and to 12.9 bt CO_2 in 2100*** (Fig. 8.28). IPCC provides similar assessments: In the scenarios with a GHG concentration of more than 660 ppm, the emissions increase by 1.5–2 times in 2010–2100 (Sims et al, 2014).

The production of SWCNT that are used for the augmentation of the basic materials employed in cars requires an increase in emissions of 76 Mt CO_2 in 2050 and 183 Mt CO_2 in 2100. However, ***the reduction in the weight of cars and trucks can produce the effect of fuel economy and a consequent reduction in GHG emissions by 0.94 bt CO_2 in 2050 and 2.4 bt CO_2 in 2100.*** Thus, the net effect of the car weight reduction is equal to 0.86 bt CO_2 in 2050 and 2.2 bt CO_2 in 2100.

[83] http://www.clioiv.com/downloads/tech.pdf.
[84] http://autoweek.com/article/car-news/ford-builds-800-pounds-lighter-fusion

Figure 8.28 GHG Emissions Reduction through Extra Vehicle Mass Reduction after SWCNT Augmentation of Basic Materials

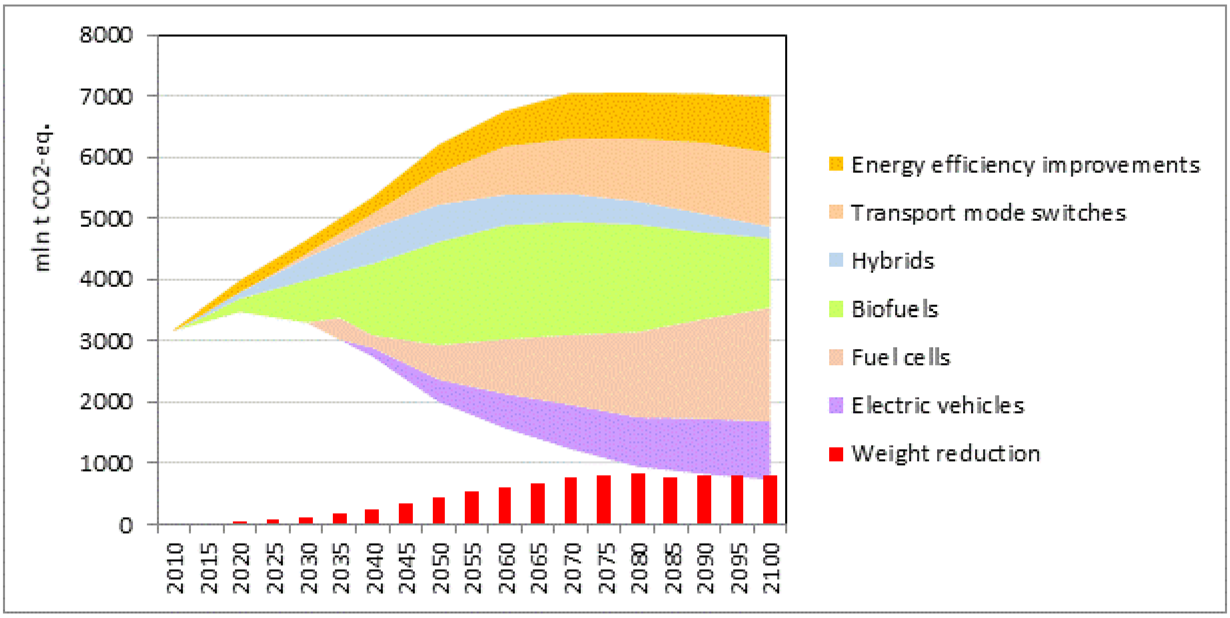


Source: CENEF-XXI and GEA (2012).

The evaluation of the relative importance of the measures to force the reduction of the average car weight through the additional weight reduction by augmenting the materials with SWCNT was estimated in the light of the assessments of the effect of various measures on the possible reduction in GHG emissions from cars (well-to-wheel) worldwide in the GEA-Mix scenario (Fig. 8.29).

For passenger cars, the effect is equal to 0.66 bt CO_2 in 2050 and 0.8 bt CO_2 in 2100, which exceeds the potential effects of switching to hybrid cars and electric cars and increasing the fuel efficiency and is only slightly lower than the effect of switching to biofuels and changing the mode of transport.

Figure 8.29 Contributions by Various Measures to Possible Reduction of Well-to-Wheel GHG Emissions from Light-Duty Vehicles



Source: CENEF-XXI and GEA (2012).

In other GEA scenarios (GEA-supply and GEA-efficiency), the share of individual technologies varies, but, this fact apart, two main conclusions remain valid:

- ✓ *a further reduction in the car weight by SWCNT augmentation of materials* is a GHG emissions reduction factor for the motor transport of the same order as the increase in the fuel efficiency of cars due to other technical solutions, switching to hybrid cars, electric cars, and fuel cell cars, increasing the share of biofuels, or replacing car trips with trips using other modes of transport; and
- ✓ unlike a number of these competing technical solutions, the GHG emissions reduction by *further reducing the car weight through the SWCNT augmentation of materials* does not require the infrastructure replacement and change in the behaviour of drivers.

The estimates of the integrated models analysed by IPCC (Sims, 2014) also show that a significant emissions reduction requires a significant change in the fuel balance of motor transport and an almost two-fold increase in its fuel efficiency, which is much facilitated by a further car weight reduction by the SWCNT augmentation of materials.

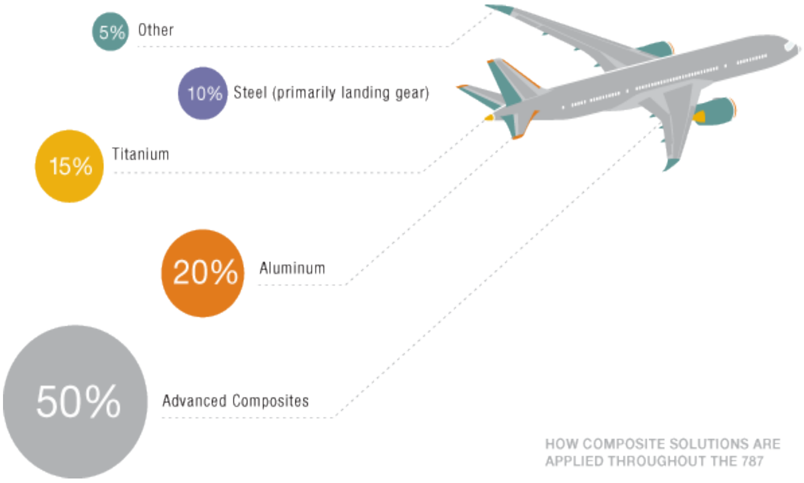
To assess the scale of such an effect, it is shown for passenger cars in the light of the effects of other measures to reduce emissions (Fig. 8.29).

8.5.2 Aircraft

Historically, the fuel efficiency of an aircraft was not considered of much importance. Speed and comfort have been the main criteria. A typical modern air liner fuel consumption per passenger-kilometre is at the level of the piston air liners of the mid-50s.

The aircraft weight reduction is the key factor in the reduction in the specific fuel consumption. In the latest models of aircraft, such as Airbus A380, Airbus A350 XWB, Boeing 787, and Bombardier C series, advanced composite materials and aluminium-lithium alloys are already widely used, which reduces the specific fuel consumption as compared to the conventionally built aircraft with an extensive use of aluminium alloys (Fig. 8.30).

Figure 8.30 Materials used for Boeing 787 Construction



Source: http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html

The use of lightweight materials can significantly reduce the weight of an aircraft and thus the fuel consumption. The composite materials based on Carbon Fibre Reinforced Plastic (CFRP) account for 50% of the Boeing 787 Dreamliner[85] weight, 53% of the Airbus A350 XWB[86] weight, and 46% of the Bombardier C series weight.[87] The composite materials were actively used already in the model Boeing 777. The carbon-plastic tail of the model 777 weighed

[85] Transport 2009.
[86] ICAO. 2013. ICAO Environmental report 2013. Aviation and climate change. http://cfapp.icao.int/Environmental-Report-2013/#101/z.
[87] https://ru.wikipedia.org/wiki/Bombardier_CSeries.

25% less than the aluminium tail of the model 767[88]. The weight of the Boeing 787 Dreamliner is 20% less than the weight of the similar models in which aluminium was used.

The use of lightweight materials reduced the weight by 20%, which provided one third of the 20% fuel economy achieved for this model. Thus, a 20% weight reduction provided a 6.7% fuel economy. Earlier, it was expected that a full transition from aluminium to carbon plastics would lead to a 10% weight reduction for medium-haul and 15% for long-haul aircraft[89], but the example of the Boeing 787 Dreamliner has provided an even greater effect than expected.

In the Airbus A380, composite materials are used for a significant portion of the airframe structure and account for about 25% of the total weight, while in the Bombardier C series they account for 20% (composite materials are in the centre and the rear sections of the centre body, the tail cone, and the wings). A further reduction in the aircraft weight can be achieved by using Fibre metal laminate. In the design of the Airbus 380, 3% of this material is used. This material is stronger and can reduce the weight of an aircraft by another 20%. As is the case with cars, fuel efficiency is not only due to improved body parts but also due to lighter materials used in the production of engines. For aircraft that can cover 15,000 km (such as the Airbus A340), a 10% engine weight reduction provided a 1% fuel economy.

According to the ICAO forecast (2013), a further aircraft weight reduction can result in the reduction of the specific fuel consumption by 10–20% by 2020 and by 15–25% by 2030.[90] In addition, it is possible to reduce the fuel consumption by improving the thermodynamic efficiency of power units; improving aerodynamics, and other measures. ICAO has set a target to increase the fuel efficiency by 2% per year and stabilise CO_2 emissions at the level of 2020. This will require considerable resources and investments to reduce emissions in the aviation industry. Therefore, aircraft weight reduction by the SWCNT augmentation of materials can be considered as an important way to solve this ambitious task.

To assess the possible effect of the SWCNT use, an aggregate global aviation model was built, the parameters of which are primarily configured based on the data provided by ICAO (2013), GEA (2012), as well as the data from selected publications.

The aircraft fleet for 2013 according to the ICAO (2013) was 27,810, of which 3,008 are cargo and mail planes. In addition, the business aviation fleet (small planes) is 17,786 more planes, but they account for only 2% of fuel consumption in aviation. 1,500–1,700 passenger and cargo aircraft and about 1,000 small business aircraft are produced annually. The total weight of aircraft built annually does not exceed 100 kt. Aircraft vary greatly in the number of seats and cargo capacity. Based on the ICAO data (2013) on the distribution of aircraft according to the number of seats, the average weight of an aircraft has been estimated (52 t). It will gradually increase (to 88 t by 2100) due to an increase in the proportion of the planes with a seating capacity of more than 400 in the aircraft fleet.

The entire transport operation of aircraft (passenger and cargo) is converted by ICAO into the tariff t-km. ***The amount of such work according to the “most likely” ICAO forecast (excluding the business aviation) will grow from the paid 974 btkm in 2015 to 2,832 btkm in 2040, and 4,062 btkm in 2050. The “most likely” ICAO forecast until 2050 was taken for a baseline scenario in this work. Its extrapolation provides an estimate of 9,990 btkm in 2100.***

ICAO considers three scenarios for reducing the specific fuel consumption: the *low aircraft technology* (specific fuel consumption reduction by 0.57% per year in 2015–2050), the *moderate aircraft technology* (specific fuel consumption reduction by 0.96% per year in 2015–2050) and the *advanced aircraft technology* (specific fuel consumption reduction by 1.16% per year in

[88] http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html.
[89] IEA. 2009. Transport.
[90] ICAO. 2013. ICAO Environmental report 2013. Aviation and climate change. http://cfapp.icao.int/Environmental-Report-2013/#101/z

2015–2050). The average fuel consumption was adjusted for these improvement parameters. The *advanced aircraft technology* scenario is not specified for the elements of technological improvements and does not reach the target parameter of the fuel efficiency increase by 2% per year.

The ICAO report also provides the scenarios for the fuel efficiency improvement depending on the environmental targets and the price of liquid fuel: the “continuation” scenario is the extrapolation of the current trends; the “increased pressure” scenario is the use of additional innovations in the aircraft design which reduce fuel consumption, and the “even more increased pressure” scenario is the use of radical innovations (doing things differently), including changes in the aircraft configuration. These three scenarios are different in the effect of the aircraft weight reduction on the increase in fuel efficiency. The “increased pressure” scenario provides an additional effect of the aircraft weight reduction of 5% fuel economy. The “even more increased pressure” scenario can increase this effect by further 5% and make it reach 25% by 2030. It seems that these scenarios match the parameters of the three scenarios mentioned above.

If according to the ICAO assessments the specific fuel consumption can be reduced by 25% by 2030 due to innovations, it means that the aircraft weight reduction should not be less than that value. If the SWCNT augmentation of materials reduces the part weight by half, the maximum aircraft weight reduction can reach 50%. That is the condition used in the model. The calculation result is largely dependent on the validity of this condition.

The model assumes that the augmentation of the materials of which the aircraft is made in a proportion of 0.1% of its weight will reduce the demand for materials by 2 times. The utilisation capacity of ferrous metals is taken into account (15% on average in 2015). The conditions are accepted that the proportion of materials with the SWCNT additives is increased by 1% per year, and thus the average weight of an aircraft can be reduced by 13% by 2030, 30% by 2050, and 50% by 2100. Since the weight of all the aircraft built will not exceed 800 kt by 2100 if conventional materials are used (less than 9,000 thousand aircraft with an average weight of 88 t), the demand for SWCNT will not exceed 0.8 kt by 2100.

The dependence of the fuel consumption reduction on the aircraft weight reduction is determined based on Helms and Lambrecht data (2004): for the aircraft of the A319–A321 or the Boeing 737 class, it is considered to be 12–13 t of fuel per year per 100 kg of weight reduction for relatively short flights (short-haul) and for long flights (long-haul and medium-haul) of the aircraft of the A330 and the Boeing 747 class, it is 17–21 t of fuel per year per 100 kg of weight reduction. In the model calculations, an estimate of 13 t of fuel per year per 100 kg of weight reduction was used. After correction of this estimate for an average aircraft weight, which is substantially lower than the A319-321 or the Boeing 737 weight, an estimate of 4.9 t of fuel per year per 100 kg of the average aircraft weight reduction was obtained. Then, with a weight reduction of 22% by 2040, the fuel economy will be 6.7%. This is exactly the same proportion as for the Boeing with its 20% weight reduction (see above). Thus, this result based on two independent evaluations can be considered reliable. ***The reduction of the aircraft weight by 50% by 2100 will reduce the average fuel consumption by 20%.***

The number of passenger and cargo aircraft is growing at a rate approximately equal to the rate of the GDP growth, and the number of aircraft per capita is about 5 times greater. The average service life of an aircraft is assumed to be 30 years. By 2050, airlines will have almost 60,000 air liners, and in 2100, 177,000 air liners.

The volume of fuel consumption by global aviation, according to IEA estimates for 2012, is equal to 260 Mtoe. For 2015, it can be estimated as equal to 270 Mtoe. In the absence of progress in reducing the specific consumption for a forecast volume of transport operations, it would be necessary to spend 1,261 Mtoe in 2050 and 3,102 Mtoe in 2100. In the *low aircraft technology* scenario, the fuel consumption increases to 1,031 Mtoe in 2050 and 1,762 Mtoe in

2100. In the *advanced aircraft technology* scenario, the fuel consumption increases to 813 Mtoe in 2050 and 1,062 Mtoe in 2100.

There is no clarity in regard to the possible scale of using alternative fuels in the aviation industry over the long term. Liquid fuel derived from coal or gas, biofuel, and compressed gas are mainly considered as options. There are also more exotic technical solutions. In 2015, the first round-the-world flight was made on a solar cell aircraft (see Insert 8.1).

Insert 8.1. A Solar Cell Aircraft, The Solar Impulse 2

In 2014, as part of the Solar Impulse project, another solar cell aircraft was built, the Solar Impulse 2. It is a Swiss project by A. Borschberg and B. Piccard. This aircraft was planned to be used for a round-the-world flight.

The aircraft is almost entirely built of carbon fibre and weighs only 2,268 kg. The wingspan of the aircraft is 78 m, which exceeds the wingspan of the Boeing 747.

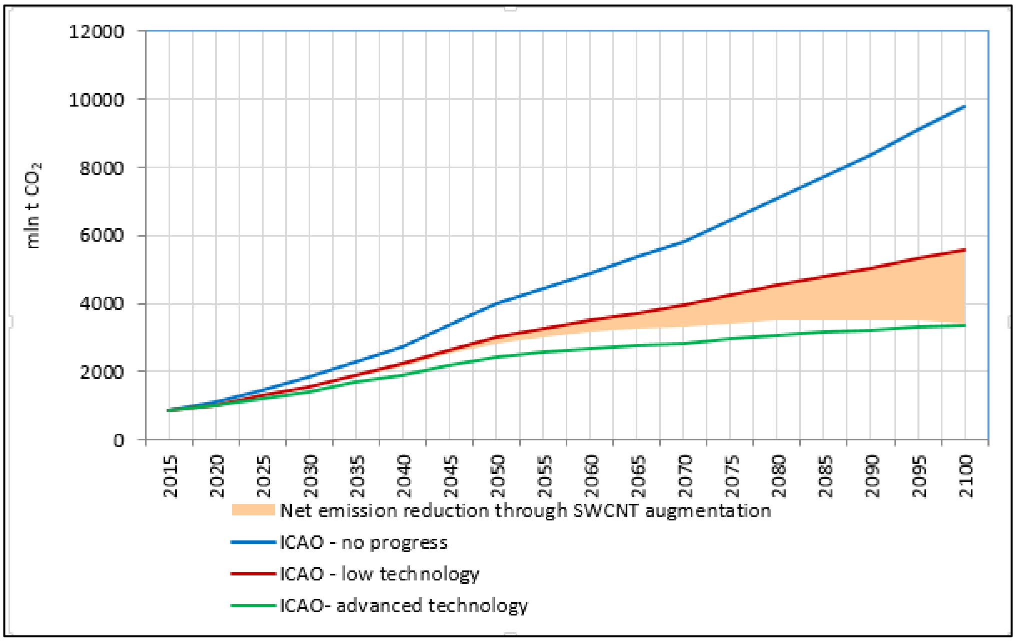
The aircraft flies at an altitude of 8,500 m. It has 17,000 [91]photovoltaic panels installed, the energy is saved into a package of lithium-ion batteries with a capacity of 260 kW/h. The energy is used by four 17.4 hp engines. The aircraft has a small cabin with room for one pilot. In March 2015, A. Borschberg started a round-the-world flight on this aircraft. It started in Abu Dhabi and should have been finished there as well on 15 August 2015. On 3 July 2015, the aircraft has made its longest flight from Japan to Hawaii, during which the solar cells received a thermal damage. The repair will take several months. It is expected that the flight can only be resumed in April 2016.

[91] http://www.wired.com/2015/07/solar-plane-fried-batteries-not-done-yet/.

The use of such alternative technologies and fuels significantly increases the requirements for the aircraft weight reduction. But these are pioneer developments, and their commercial future is not clear. Therefore, the factor of the carbon intensity reduction of the used fuel for aviation was not further discussed. Moreover, since in the ICAO scenarios the aircraft weight reduction is already included in the list of measures to improve fuel efficiency, estimates of the additional energy economy and GHG emissions reduction through weight reduction were not added to the *low aircraft technology* scenario but were compared to the effect of accelerating innovation in the aviation industry in the *advanced aircraft technology* scenario.

In the absence of progress in the specific fuel consumption reduction, GHG emissions from global aviation would increase from 800 Mt CO_2 in 2015 to 3,986 Mt CO_2 in 2050 and to 9,807 Mt CO_2 in 2100 (Fig. 8.31). The implementation of the *low aircraft technology* scenario can slow down their growth to 2,631 Mt CO_2 in 2050 and 5,567 Mt CO_2 in 2100. In the *advanced aircraft technology* scenario, the growth of emissions is at the level of 2,446 Mt CO_2 in 2050 and 3,357 Mt CO_2 in 2100. ***None of these scenarios can achieve the objective of emissions stabilisation after 2020 set by ICAO.***

Figure 8.31 Evaluation of Contribution Made by SWCNT Augmentation of Materials to the Reduction in Global GHG Emissions from Aviation in 2015-2100



Source: CENEF –XXI.

The GHG emissions reduction through aircraft weight reduction by augmentation with SWCNT additives (excluding emissions during their production) is 43 Mt CO_2 in 2035, 174 Mt CO_2 in 2050, and 2,136 Mt CO_2 in 2100 (Fig. 8.31). If this effect is added to the effect of the *low aircraft technology* scenario, the GHG emissions from aviation will achieve their maximum in 2075 and then begin to decline.

Since the annual fuel consumption per weight unit of an aircraft is considerably greater than that of a car (almost by 200 times), the augmentation of the aircraft construction materials with SWCNT additives provides a significantly greater effect than the augmentation of the materials for cars.

For the civil aviation, the following conclusions are true:

- A further reduction of aircraft weight through materials augmentation with SWCNT after 2050 is a factor of reduction of GHG emissions in the air transport of the same order as the increase in fuel efficiency of aircraft due to all other technical solutions combined together.
- The emissions reduction can exceed 174 Mt CO_2 in 2050 and amount to 2,136 Mt CO_2 in 2100.
- Along with other technical innovations, it will stop the growth of emissions from air transport and then reduce them.

Additional effects can also be achieved by changing the composition of the materials used in the business aviation and military aviation. In addition, some emissions reduction can be achieved by reducing the weight of the railway transport (IEA, 2009; Helms and Lambrecht, 2004).

However, ***only cars and aircraft have a potential to reduce GHG emissions by 1,116 Mt CO_2 in 2050 and by 4,500 Mt CO_2 in 2100 by reducing the weight through*** *the SWCNT* ***augmentation of the materials used for their production.***

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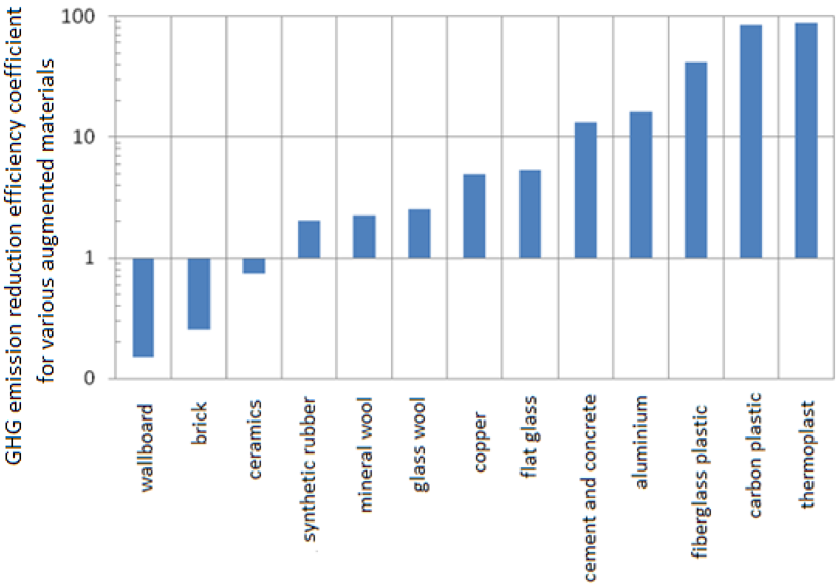
9 Forecast for Global GHG Emissions Reduction through the Use of SWCNT

9.1 General

This chapter summarises (but does not sum) the results of the forecast of a possible contribution of using SWCNT to the reduction of the global anthropogenic GHG emissions, obtained in Chapter 8. In Chapter 8, all the basic materials were considered in isolation. However, on the condition of a gradual increase in SWCNT production and thus a limited possibility of their use for GHG emissions reduction at the early stages, such a use can be optimised. In Chapter 7, it was shown that the modification of basic materials using single-wall carbon nanotubes has an effect if the condition $(k_i-1)/d_i* em_i/em_{swcnt}>1$ is valid, where d_i is the proportion of SWCNT additives during the augmentation of the material i, k_i is the multiplicity of the increase in the consumer properties of the basic material, and em_i and em_{swcnt} are the embodied GHG emissions from the production of the basic material i and SWCNT, respectively. The values of the nondimensional ratio (the coefficient of efficiency of reducing emissions through augmentation) for different materials are shown in Fig. 9.1. The higher is the ratio, the higher is the augmentation effect. With a limited SWCNT production volume, the priorities for their optimum distribution among the basic materials will follow their ranking in the importance of this factor. Since there is a limit for GHG emissions reductions from the production of each basic material i, which is achieved provided that the entire volume of the basic material adjusted to increase its consumer functions is already augmented with SWCNT (it is equal to $em_i*V_{iforecast}*(1-1/k_i)$, where $V_{iforecast}$ is the forecast production volume of the conventional basic material i), after reaching the saturation of the material which has a higher rank, the material of the next rank is actively augmented.

Figure 9.1 GHG Emission Reduction Efficiency Coefficient for Various Augmented Materials



Source: CENEF-XXI.

The processes of augmentation of each material are distributed in time, so the upper limit is defined for the annual increase in the volume of modification of basic materials. As a result, augmentation can take place in parallel for many materials, but according to the logic of the optimisation effect of reducing GHG emissions, with restrictions for both the speed of the increase in the augmentation volume of each of them and the total volume of SWCNT use.

The efficiency coefficient of emissions reduction through augmentation for various materials also shows the multiplicity of possible changes of the ratios $(k_i\text{-}1)/d_i$, which are described in Chapter 7 and which help us save the effect of GHG emissions reduction.

As the specific emission characteristics, the embodied emissions characteristics were used, so the estimates given below include the effects for all GHG, not only for the direct reduction of emissions at the basic materials production stage but for the entire process chain, including all related and multiplier effects up to the transportation of materials.

It should be noted that the imputed energy intensity and the imputed carbon intensity include components such as energy production and transport, therefore, the effects partly take place as GHG emissions reduction, not only in the industry but also in the energy and transport sectors.

For cars and aircraft, the reduction of GHG emissions during their operation by reducing the average weight is reflected. In respect of buildings, the perspective of creating new construction and engineering opportunities, for example, improved floor structures and the reduction of the number of necessary supports, is already reflected in the reduction of emissions from the production of basic materials of which they are built.

The effect of a possible contribution of SWCNT to the reduction of global anthropogenic GHG emissions is significant but is not endless. It is exhausted after the entire amount of the basic materials suitable for augmentation is already covered by this technology. For a number of materials, it is limited with feasibility of their augmentation at a predetermined ratio of the "embodied GHG emissions – proportion of additives – improvement of consumer properties of materials." For certain materials, in the case of significant progress in reducing the embodied specific energy consumption or specific carbon intensity, the initially acceptable ratio of "proportion of additives – improvement of consumer properties of materials" may become unacceptable if their specific imputed carbon intensity decreases faster than the imputed carbon intensity of SWCNT production does. The opposite situation is also possible.

The summarised results are compared with other opportunities of reducing anthropogenic GHG emissions in general, for all anthropogenic sources (see Fig. 5.5) and with the base case scenario of the dynamics of CO_2 emissions from fuel combustion and industrial processes until 2100 (see Fig. 5.6) as well as the base case scenarios of the emissions individually in the industry and the transport sector, which are provided in the estimates of IPCC (2014), IEA (2012, 2014, 2015a), GEA (2012), and other sources.

The basic materials reflected in this chapter are directly used for the production of the end-use product and cannot be the raw material for the production of other basic materials. This allows adding the effects without their noticeable overestimation due to double counting. To avoid double counting, it is assumed that when adding the energy consumption and emissions from SWCNT production through basic materials augmentation, a part of them used in the production of cars and aircraft is taken into account. With the addition of the effects, the problem of double counting does not arise, because the effects of reducing the fuel consumption in the production of basic materials (by reducing the demand for them) do not interfere with the effects of reducing the fuel consumption by operating lightweight cars and aircraft, manufactured of these augmented materials.

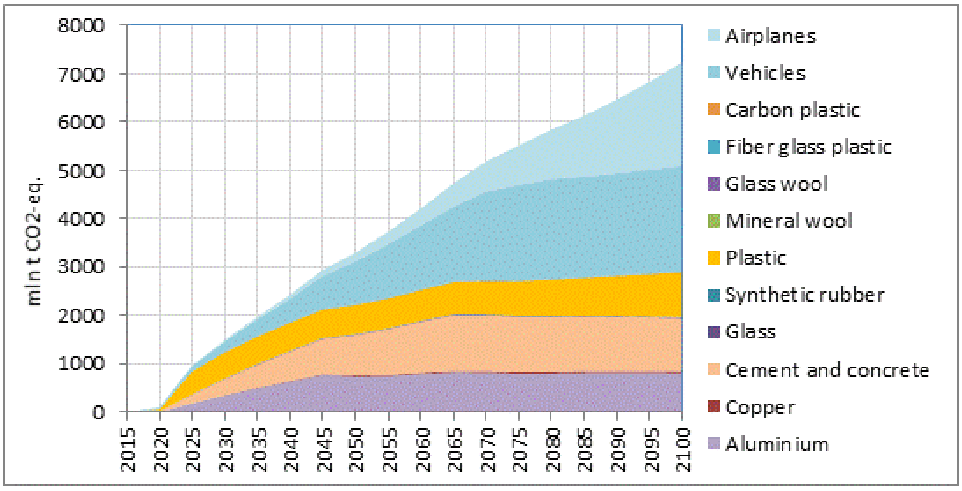
9.2 Summary Forecast of GHG Emissions Reduction through the Modification of Basic Materials with CNT until 2100

In 2014, for the first time in 40 years, there was stabilisation of global GHG emissions (excluding the Agriculture, Forestry and other Land Use sector, AFOLU). This was mainly due to the significant reduction of material intensity of China's GDP, which clearly highlights the importance of the factor of material intensity dynamics as a driver of the global GHG emissions.

An important way of global GDP reduction of material intensity is the reduction of the demand for materials through their augmentation with a unique and universal additive—SWCNT, which has an outstanding strength-to-weight ratio. Its additives can significantly reduce the demand for basic materials per weight unit (light-weighting) and hence the demand for raw materials required for their production, energy at all stages and process stages of their production and the raw materials production, as well as the GHG emissions associated with all the above.

The total net reduction (excluding the GHG emissions from the production of SWCNT) of anthropogenic GHG emissions from the processes of basic materials production by reducing the demand for them during their SWCNT augmentation, as well as by reducing the weight of cars and aircraft, is equal to 1,970 Mt CO_2eq in 2035, 3,300 Mt CO_2eq in 2050, and 7,230 Mt CO_2eq in 2100 (see Fig. 9.2 and Table 9.1). The main share of the effect is generated by only 5 measures: SWCNT augmentation of concrete, plastics, and aluminium as well as weight reduction of aircraft and cars. If during the period before 2035 the main contribution is from the production of basic materials, there is a significant further increase in the effect of weight reduction of cars and aircraft which exceeds more than one fifth of the total effect by 2050 and reaches half of it by 2100. In 2075–2100, the main increase in this effect is due to aircraft weight reduction.

Figure 9.2 Overall GHG Emissions Reduction through SWCNT Augmentation of the Basic Materials



Source: CENEF-XXI.

Cumulative emissions reduction for 2015–2100 is equal to 331 bt CO_2eq, which is a multiple of six volumes of all anthropogenic emissions for 2014 and eight annual GHG emissions from fuel combustion and industrial processes. In other words, the SWCNT augmentation of basic materials is equivalent to a 6-year delay in the global warming.

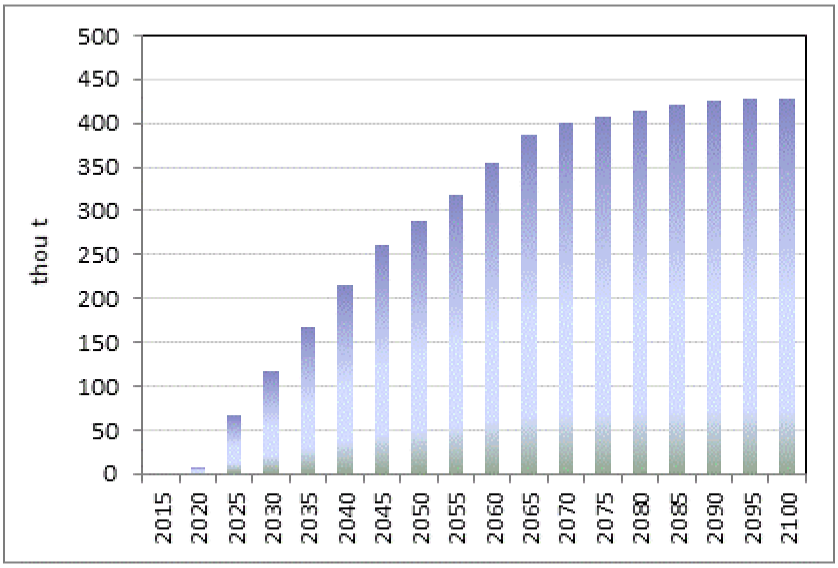
To achieve this, it is necessary to increase production and use SWCNT up to 167 kt in 2035, up to 289 kt in 2050, and up to 429 kt in 2100 (Fig. 9.3). An almost linear growth in the use of SWCNT is replaced by its slowdown in proportion to the saturation of the market of basic materials augmentation due to the slowdown or stabilisation of the production of many basic materials after 2050 (see Chapter 6). Before 2050, the increase in their production takes place gradually because it requires a higher investment and solution of a wide range of technical and regulatory issues and restrictions on the use of lightweight materials.

Table 9.1 GHG Emissions Reduction through the Augmentation of Basic Materials with SWCNT (Mt CO_2eq)

	2020	2035	2050	2075	2100
Aluminium	9	493	738	797	811
Copper	2	13	23	36	39
Concrete and Cement	8	476	834	1143	1098
Glass	3	15	16	17	16
Synthetic rubber	1	2	3	5	7
Plastics	44	564	603	710	926
Mineral wool	0	1	1	0	0
Fibreglass wool	1	2	2	2	3
Glass-reinforced plastics	2	10	12	9	8
Carbon fibre-reinforced plastic	0	1	1	1	1
Total materials	**69**	**1576**	**2,233**	**2,721**	**2,909**
Cars	31	347	891	1,981	2,187
Aircraft	3	43	174	810	2,136
Total transport	**34**	**390**	**1,065**	**2,792**	**4,322**
Total materials plus cars and aircraft	**103**	**1,967**	**3,298**	**5,512**	**7,232**

Source: CENEf-XXI.

Figure 9.3 Overall SWCNT Demand for Augmentation of the Basic Materials

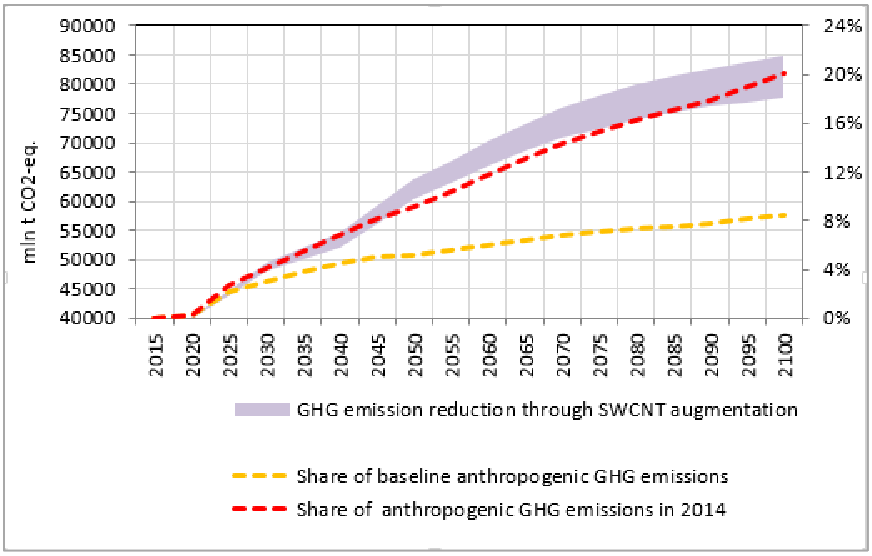


Source: CENEF-XXI.

Using SWCNT reduces anthropogenic GHG emissions from fuel combustion and industrial processes by 3.8% in 2035, almost 5.2% in 2050, and 8.5% in 2100 of the baseline pathway. As compared to the emissions level in 2014, the decrease equals 5% in 2035, 7.9% in 2050, and 16.1% in 2100, respectively (Fig. 9.4).

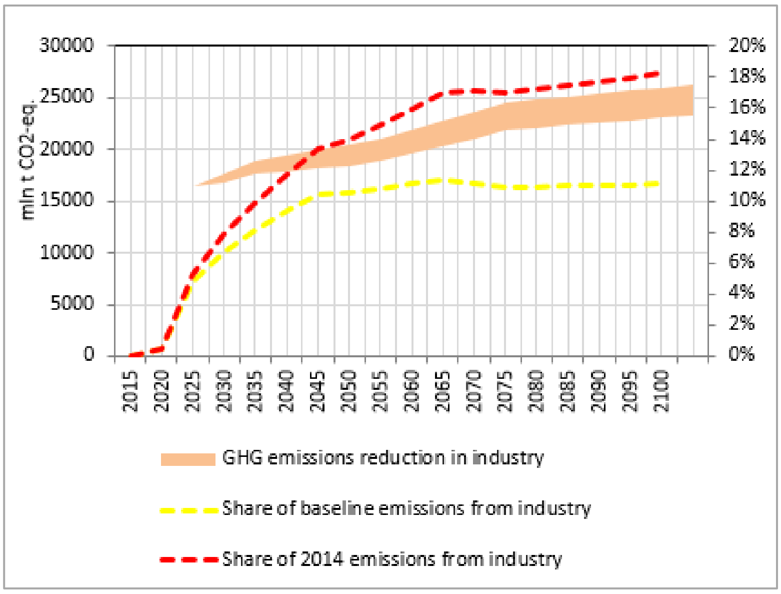
Figure 9.4 Reduction of Global GHG Emission from Fuel Combustion and Industrial Processes (Compared to Baseline) through

SWCNT Augmentation of Basic Materials and Vehicle and Aircraft Mass Reduction



Source: CENEF-XXI.

Figure 9.5 Reduction of Global GHG Emission from Industry (Compared to Baseline) through SWCNT Augmentation of Basic Materials

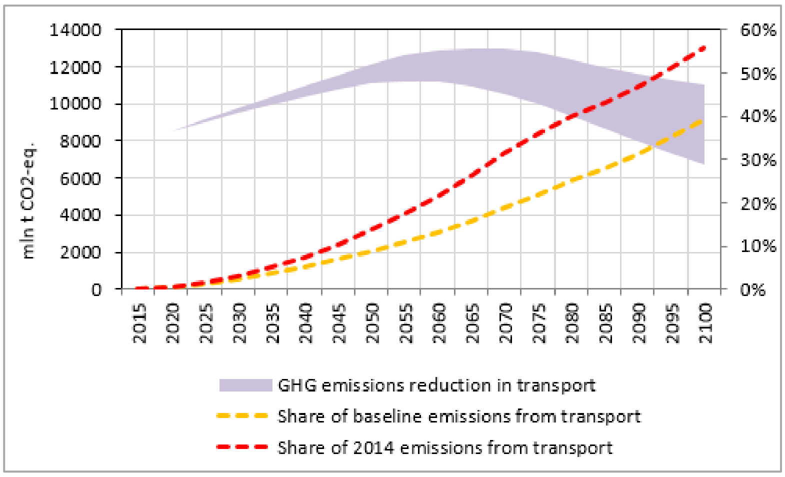


Source: CENEF-XXI.

Using SWCNT reduces GHG emissions in the industry by 2,233 Mt CO_2eq in 2050, 2,909 Mt CO_2eq in 2100, or 10.6% in 2050 and 11.1% in 2100 of the baseline pathway. The reduction of the level of direct and indirect GHG emissions in the industry in 2014 equals 14% in 2050 and 18.2% in 2100, respectively (Fig. 9.5).

Using cars and aircraft that are lightweight due to the use of SWCNT can reduce GHG emissions from transport by 1,065 Mt CO_2eq in 2050 and 4,323 Mt CO_2eq in 2100; or 9% in 2050 and 39% in 2100 of the baseline pathway and 14% and 56% of the emissions level from transport in 2014 (Fig. 9.6).

Figure 9.6 Reduction of Global GHG Emission from Transport (Compared to Baseline) through Vehicle and Aircraft Mass Reduction



Source: CENEF-XXI.

IEA (2015a) considers the scenario of implementing a set of measures to control GHG emissions, allowing to reach 2050 along the pathway corresponding to the restriction of the growth of global average temperature at a level of 2 °C. For that purpose, cumulative emissions in the industry in 2015–2050 are to be reduced by 151 bt CO_2eq and by 138 bt CO_2eq in transport. IEA (2015a) indicates that the importance of the 21st Conference of the Parties (COP21), which is to be held in Paris in December 2015, is not only in the need to achieve the goals that have been set before but also in the formulation of new courses of action. One of these new trends is the use of SWCNT for the augmentation of basic materials and weight reduction of cars and aircraft, which allows to make a significant contribution to the solution of the climate stabilisation problem (Table 9.2).

In the industry, this area is capable of providing the effect of 30% of the potential, already estimated by IEA until 2050 and 6% in the transport sector. This new trend can become an important element of the foundation of the "virtuous circle" and will increase the number of ambitious solutions.

Table 9.2 Cumulative Reduction of the Global GHG Emissions through the Use of SWCNT for the Augmentation of Basic Materials and through Weight Reduction of Cars and Aircraft and its Comparison with the Reduction of Emissions in the IEA Forecast with the Maximum Possible Implementation of Measures for GHG Emissions Control

	Decrease in 2035	Decrease in 2050	Decrease in 2100	Cumulative decrease in 2015–2050	Cumulative decrease in 2015–2100	Emissions level in 2014*	Multiplicity of the cumulative decrease in 2015–2100
	Mt CO_2eq			bt CO_2eq			times (years)
GHG emissions from the production of basic materials	1,576	2,233	2,909	46	180	16	11
GHG Emissions from Transport	390	1,065	4,322	14	151	8	19
Total emissions	1,967	3,298	7,232	59	331	52.6	6
IEA—Industry—2DS				*151*			
IEA—Transport—2DS				*138*			

Source: CENEf-XXI; IEA (2015a).

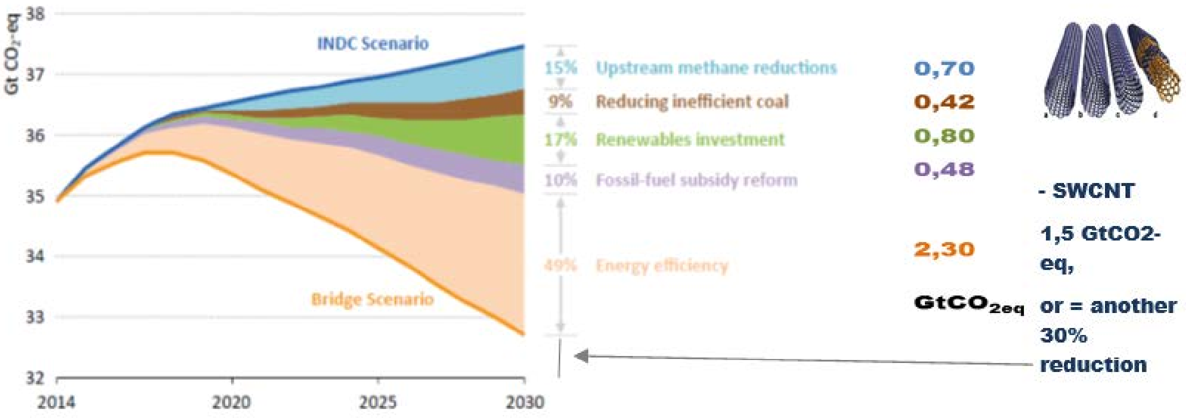
9.3 Contribution of GHG Emissions Reduction through the Modification of Basic Materials with CNT vs. Contribution of Other Technologies

IEA (2015a) considers three scenarios: the Intended Nationally Determined Contributions Scenario (INDCs), the Bridge Scenario; and the 450 Scenario (stabilisation of GHG concentrations in the range of 450 ppm).

The difference in emissions between the first and the second scenarios in 2030 is 3.9 bt CO_2eq. The reduction of emissions in 2030 by using SWCNT equals 1,490 Mt CO_2eq, or 38% of the difference between the INDCs and the Bridge Scenario and 22% of the difference between the Bridge and the 450 Scenario.

The reduction of emissions by modifying the basic materials with CNT is only smaller than the energy efficiency improvement and is greater than the contribution of other main technologies and policies already in 2030 (Fig. 9.7). The effect of using SWCNT is greater than the effect of the reform proposed by IEA for the energy price subsidy system (the effect of less than 0.5 bt in 2030) equals to one third of the effect of carbon capture and storage in 2030, the technology, not yet perfected, but entrusted with overly high expectations in terms of limiting the emissions from the energy sector and the industry. The reduction of emissions from the use of SWCNT in 2050 is equal to 20% of emissions reduction in the industry in the IEA 2DS climate change stabilisation scenarios as compared to the 6DS scenario (IEA, 2015b).

Figure 9.7 Contribution of Selected Measures and Technologies to GHG Emission Reduction in the IEA Bridge Scenario versus the INDC Scenario, and SWCNT Augmentation Effect



Source: CENEF-XXI; IEA (2015a).

If the increase in the use of SWCNT and their effect will be 2 times less than it is, it will still be equal to or greater than the effect of the measures for the reduction of methane emissions, the decommissioning of inefficient coal stations and the elimination of subsidies for energy resources. In other words, the modification of the basic materials with CNT in terms of possible contribution to the reduction of GHG emissions is comparable to other traditionally considered main technologies of emissions reduction even with not the most optimistic assumptions about the increase in their use.

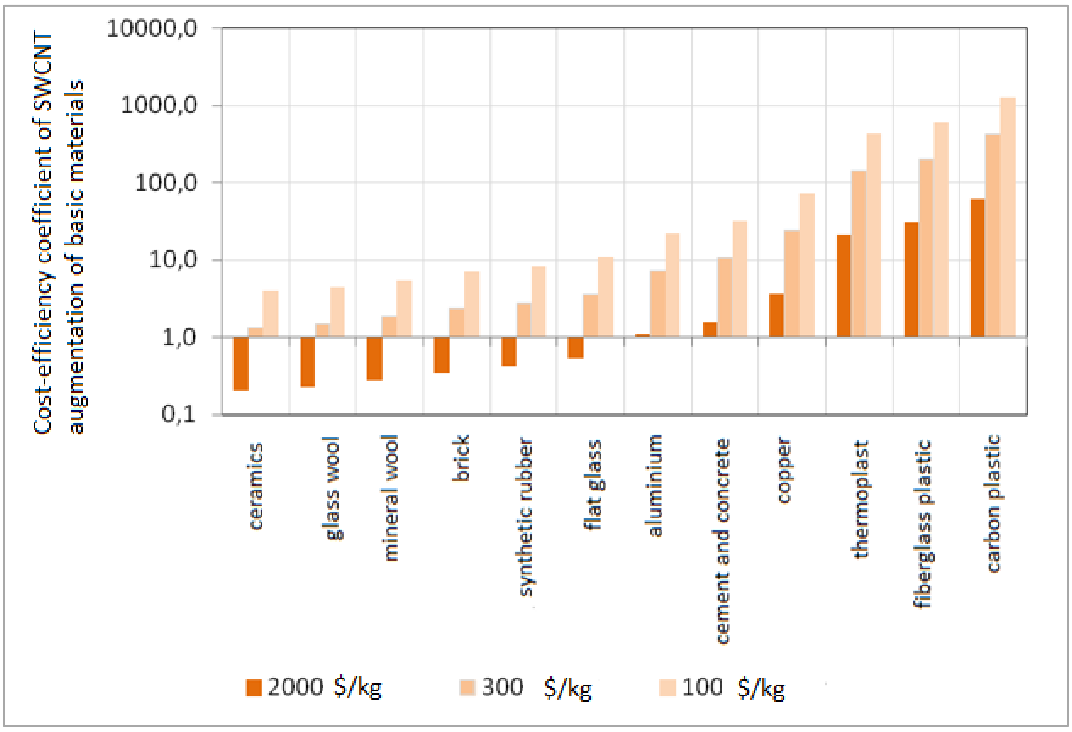
9.4 Economic Feasibility Study

The scheme of the economic feasibility study for modifying the basic materials by their augmentation with SWCNT is similar to the feasibility analysis of their use in order to reduce GHG emissions (see Chapter 7). When adding SWCNT, the volume of augmented material is determined as follows: $V_i = V_{swcnt} / d_i$, where V_{swcnt} is the volume of applied SWCNT, d_i - the share of SWCNT added when augmenting the basic material *i*; V_i is the volume of the doped material *i*. This allows to replace the traditional basic material in the volume of k_i*V_i, where k_i is the ratio of the increase in consumer properties of the basic material. In this case, the reduction in the demand for basic materials will be equal to $V_i*(k_i - 1)$.

The net cost savings (less the cost of SWCNT production) equals $pm_i*V_i*(k_i-1) - V_i*d_i*pm_{swcnt}$, where pm_i and pm_{swcnt} are the price of the basic material *i* and the SWCNT price, respectively. Substitution has an economic effect if the following condition is true: $(k_i-1)/d_i > pm_{swcnt}/pm_i$ or $(k_i-1)/d_i * pm_i/pm_{swcnt} > 1$. The left part of this inequation can be called a cost-effectiveness ratio of basic materials augmentation. The higher it is, the higher the economic effect of augmentation is.

With the development of the SWCNT production technology, the price of SWCNT is expected to change as follows: USD 2,000 per kg in 2015, USD 300 per kg in 2030, USD 100 per kg in 2050 (see the “learning curves” in Fig. 3.6). The prices for basic materials are determined by their state in 2014–2015 from various sources and rated as the world average. The calculation assumes that they will not change. Similar to the efficiency factor of reducing GHG emissions by augmenting various materials shown in Fig. 9.1, the cost-effectiveness ratio for the augmentation of various materials for the three values of the SWCNT price is shown in Fig. 9.8.

Figure 9.8 Cost-Efficiency Coefficient of SWCNT Augmentation of the Basic Materials



Source: CENEF-XXI

At the initial stage, when the price for SWCNT is USD 2,000 per kg, the augmentation is economically inefficient for a wide range of materials: $(k_i-1)/d_i * pm_i/pm_{swcnt}<1$. With the increase of the scale of production and technology development, the SWCNT price drops significantly, and the use of SWCNT becomes cost-effective for all the basic materials shown in Fig. 9.8. For materials that provide the greatest contribution to emissions reduction—plastics, aluminium, and concrete—the augmentation cost-effectiveness factor is greater than 1 even at the SWCNT price of USD 2,000 per kg.

According to the forecast of the IEA (2015), subsidies for fuel and electric energy generated based on this fuel were equal to USD 510 billion in 2014. In addition, the subsidies for energy sector development in the developed countries still account for about USD 90 billion. The total of the subsidies, according to IEA (whose methodology is quite questionable), is equal to USD 600 billion. The subsidies for the development of new renewable energy sources in 2014 amounted to USD 125–130 billion.

The capital investments for the development of new renewable energy sources in the Bridge Scenario should grow from the current USD 270 billion to USD 400 billion or by USD 130 billion. The investment required for the reduction of methane emissions is equal to USD 31 billion. Additional investments in “clean” technologies in the 450 Scenario, as compared to the Intended Nationally Determined Contribution Scenario, are estimated to be USD 807 billion in 2030.

IPCC (2014) estimates the additional annual investments in the scenarios with an active reduction of GHG emissions compared to the base case scenarios in 2010–2030 to be equal to USD 147 billion for low-carbon technologies of electric power generation (new renewable energy sources, carbon capture and storage (CCS), nuclear power plants) and USD 336 billion to improve energy efficiency. For the period 2031–2050, the additional annual capital investments increase up to USD 227 billion for new renewable energy sources, USD 247 billion for CCS, USD 120 billion for nuclear power plants, and USD 680 billion for energy efficiency improvement. The total capital investments in the development of low-carbon technologies of electric power generation (new renewable energy sources, carbon capture and storage, nuclear power plants) for 2015–2029 can be estimated as equal to USD 2,205 billion (147*15 years) and USD 11,880 billion in 2030–2049 (594*20 years).

The construction of facilities for the production of 118 kt of SWCNT per year by 2030 will cost USD 23.6 billion and additional USD 34.2 billion for their increase to 289 kt per year, or a total of USD 57.8 billion. In other words, ***the investments in the SWCNT production technology, which at the level of 2030 has the effect second only to energy efficiency improvement and exceeds the effect of the development of new renewable energy sources, carbon capture and storage, and nuclear power plants taken together in terms of the scale, cost 64 times cheaper (2,205/34.2) and, in 2030–2049, 205 times cheaper (11,880/57.8) than the investments in technology, which are now considered as basic in the struggle to limit GHG emissions and stabilise the Earth's climate.*** The cost of SWCNT sales in the amounts specified in Fig. 9.3 is equal to USD 35.4 billion in 2030 (118 kt).

9.5 Analysis of the Sensitivity of the Results to the Key Assumptions

The estimates of GHG emissions reduction through the SWCNT augmentation of basic materials and weight reduction of cars and aircraft were obtained using a large set of assumptions. The results of many calculations are sensitive to the assumptions, particularly in relation to:

- ✓ volumes of production of the main basic materials (primarily, cement and concrete, plastics and aluminium);
- ✓ opportunities of using SWCNT for the augmentation of the entire volume of the basic materials;
- ✓ rate of expansion of the market niche of basic materials augmentation technologies;
- ✓ pairs of parameters: SWCNT concentrations per weight unit of the basic material and improvement of the strength properties or other consumer properties of basic materials that reduce the demand for them;
- ✓ parameters of car or aircraft weight reduction using SWCNT-augmented basic materials;
- ✓ parameters of specific fuel consumption reduction with car or aircraft weight reduction; and
- ✓ levels of embodied GHG emissions from the production of basic materials, especially in the production of SWCNT.

Below is an analysis of the sensitivity of the results of GHG emissions reduction with some changes in a number of assumptions about the key parameters individually for materials and vehicles.

Volumes of production of the main basic materials Since the main share of the effect during the modification of materials is determined only by cement and concrete, plastics and aluminium, the effect of increasing or decreasing the production of basic materials is only evaluated for them. The spread of the forecast values in the production volumes for cement is from +6% to -20% in 2050 and from +100% to -60% in 2100; for aluminium, from +100% to -60% in 2050 and from +90% to -60% in 2100; for plastics, from +81% to -15% in 2050 and from +158% to -54% in 2100 (see Chapter 6). If the full range of uncertainty is not covered but only its portion where the forecasts are arranged more densely, the sensitivity analysis can be performed on the assumption that the production volume deviates from the baseline by +20% in 2050 and +50% in 2100. By increasing the production of the three basic materials by 20% in 2050, the emissions reduction is improved by 262 Mt CO_2eq (+9%). Increasing their production by 50% by 2100 improves the volume of net reduction of GHG emissions by 1,417 Mt CO_2eq. With a 20% reduction of the production volumes in 2050 lowers the emissions reduction by 268 Mt CO_2eq (+ 9.4%), while with a 50% reduction of the production volumes in 2100 the emissions reduction decreases already by 1,417 t CO_2eq. (32%). Thus, we can conclude that ***the production volume factor begins to play a more important role after 2050***.

The rate of expansion of the market niche of basic materials augmentation technologies. The calculations made an assumption that there are no technical or other limitations on the possibility of using SWCNT for the augmentation of the total volume of basic materials. Therefore, before 2050, the scale of expansion of the technology for SWCNT augmentation of basic materials is an important factor. This process can be suppressed both with a possibility to increase the production of SWCNT and regulatory restrictions on the use of new lightweight materials the removal of which takes time. In the model calculations, a 5-year SWCNT utilisation increase factor for the augmentation of basic materials is specified. Chapter 8 shows that there is a saturation effect when the entire volume of the basic material is subjected to augmentation. After that, an additional use of SWCNT has no effect. In relation to cars and aircraft, an assumption is made that the proportion of materials with SWCNT additives increases by 1% per year (Chapter 8). A sensitivity analysis is conducted on the assumption that the increase or the rate of SWCNT augmentation of basic materials will be 50% lower or 50% higher than the initial one. In the first case, the effect of SWCNT introduction decreases by 726 Mt CO_2eq (-26% of the baseline total emissions reduction) in 2050 and 153 Mt CO_2eq (-3%) in 2100. The relative reduction of sensitivity in 2100 is due to the above-mentioned effect of saturation. In the second case (50% more dynamic use of SWCNT), the effect increases by 415 Mt CO_2eq (15%) in 2050 and only by 7 Mt CO_2eq in 2100 due to the saturation effect. Thus, ***the factor of the rate of expansion of the market niche of the basic materials augmentation technologies significantly affects the results of the evaluation up to its approaching the point of saturation of the market of basic materials augmentation.***

Parameters of SWCNT concentration per weight unit of the basic material and improvement of the strength properties or other consumer properties of basic materials that reduce the demand for them To carry out the sensitivity analysis, it is sufficient to change one of these two parameters. As shown in Chapter 7, the experts do not have a clear opinion on the values of these parameters, and they can affect the result quite significantly. This effect depends on the existence of restrictions for the nanotubes production volumes. With such restrictions, the specified volume of the use of SWCNT can have an effect inversely proportional to the adjusted amount of additives needed to ensure the increase of the consumer properties of materials by a specified value. In the absence of such restrictions, the correction of the proportion of additives results in an increase in the use of SWCNT, and the reduction of GHG emissions decreases only by the amount of emissions embodied in the additional volume of nanotubes. Fig. 9.1 shows the efficiency coefficient of the emissions reduction due to augmentation. For the basic materials, to remove the effect of GHG emissions reduction due to augmentation, the share of additives should increase as follows: by 88 times for plastics, 16 times for aluminium, and 13 times for concrete and cement.

The analysis of sensitivity of the result to this condition was carried out under two conditions: presence or absence of restrictions for the production and the use of nanotubes. In the first case, during the sensitivity analysis, the parameter of SWCNT concentration per weight unit of the basic material was changed in the range from -50% to +100% on the condition that no additional SWCNT volumes can be used. When the required proportion of additives is reduced by 50%, the effect increases by 492 Mt CO_2eq (+17%) in 2050 and then, with saturation of the basic materials with SWCNT, gradually decreases to 57 Mt CO_2eq (+1%) or almost to zero by 2100. With a double increase in the share of the necessary additives, the effect of using SWCNT decreases by 807 Mt CO_2eq (-28%) in 2050 and by 241 Mt CO_2eq (-4%) in 2100. Thus, it can be concluded that ***the accuracy of determining the parameters of SWCNT concentrations per***

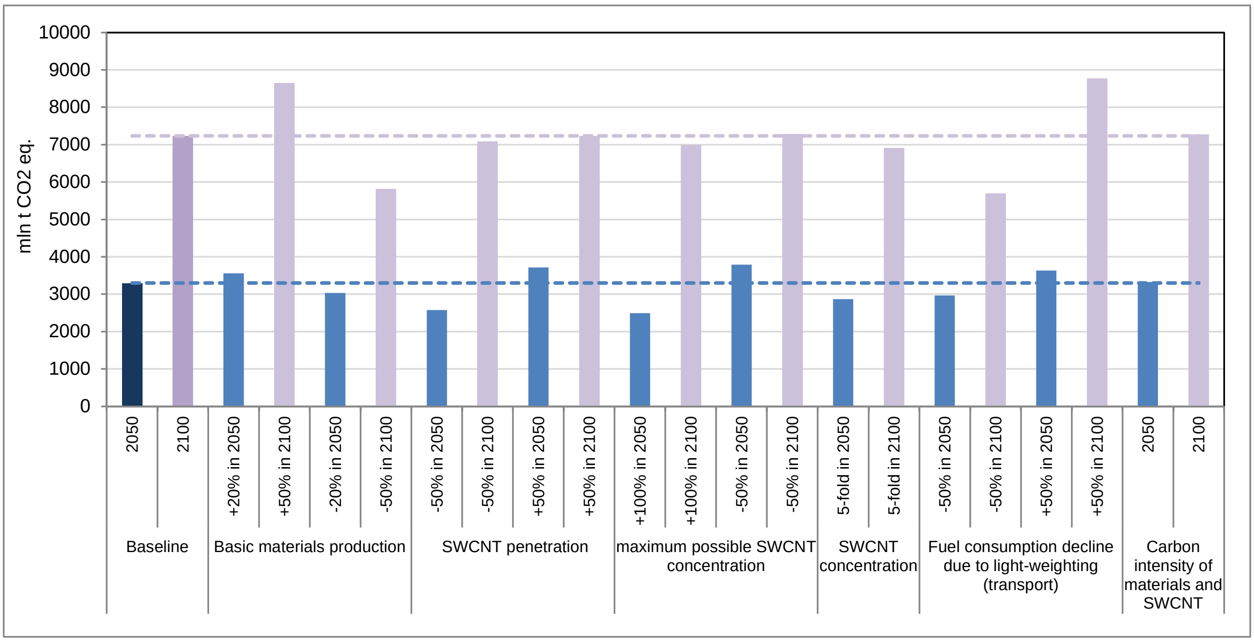
weight unit of the basic material and improving the strength properties or other consumer properties of basic materials that reduce the demand for them, significantly affects the results of the evaluation if there are restrictions for the volumes of the use of SWCNT. In the absence of such restrictions, the effect is limited, even at a 5-fold increase in the proportion of additives. The calculation was performed for aluminium, plastics, and concrete. An assumption is made of a 5-fold increase in the proportion of additives and a proportionate increase in the use of additives for these materials. Then, the effect of the use of SWCNT decreases by 431 Mt CO_2eq (-15%) in 2050 and by 343 Mt CO_2eq (-6%) in 2100.

Parameters of specific fuel consumption reduction with the reduction of the car or aircraft weight are determined based on the analysis of scientific literature. Similar to other parameters, they can be specified with the collection of data on the operation of lightweight cars and aircraft. The sensitivity analysis is conducted with a change in these parameters in the range of ±50%. The effect was completely symmetrical and equal to ±334 Mt CO_2eq (±54% of the effect in transport only) in 2050 and ±1,537 Mt CO_2eq (±53%) in 2100. Therefore, ***the parameters of the reduction of specific fuel consumption with the car and aircraft weight reduction are the main ones for determining the effect of reducing GHG emissions from the use of lightweight cars and aircraft.*** The effect of reducing the weight of vehicles can increase if we include business and military aircraft, buses, three- and two-wheeled vehicles, as well as railway transport in the analysis.

Levels of Embodied GHG Emissions from the Production of Basic Materials, Particularly in the Production of SWCNT. To assess the sensitivity of the calculation, in fact, the ratio of the embodied GHG emissions from the production of basic materials to the level of embodied emissions from the production of SWCNT is important. That is why only the last value was varied. Chapter 7 shows that the direct CO_2 emissions are 426 t CO_2/t of SWCNT and the embodied emissions as estimated by CENEf-XXI are equal to 567 t CO_2eq/t of SWCNT. In the sensitivity analysis, the second value, which was used in the calculations, is replaced by the first one. The effect is observed by the increase in the net effect, during the calculation of which the emissions from the production of SWCNT are subtracted, and in addition, by overcoming the threshold of feasibility of bricks and ceramics. Due to low SWCNT production volumes, the effect was relatively small: 26 Mt CO_2eq in 2050 (1.2%) and 35 Mt CO_2eq in 2100 (0.6%).

The results of the sensitivity analysis are summarised in Fig. 9.8, which shows that even when the basic assumptions for calculations change, the minimum value of GHG emissions reduction through SWCNT augmentation of basic materials and car and aircraft weight reduction does not become lower than 2,044 Mt CO_2eq in 2050 and 4,267 Mt CO_2eq in 2100.

Figure 9.9 Sensitivity Analysis of Global GHG emission reduction through SWCNT augmentation and vehicle and aircraft weight reduction



Source: CENEF-XXI.

Thus, at all reasonable assumptions on the use of SWCNT for the augmentation of basic materials, the effect of GHG emissions reduction by reducing the demand for them and by reducing the weight of cars and aircraft is still significant, and this way of reducing the material intensity of the global GDP and end-use product light-weighting should be considered as a new, ambitious, and potentially highly effective policy direction to limit the global warming at a level of 2 °C.

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