Towards sustainability in ferroalloy production

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Synopsis

Ferroalloy production is an energy-intensive industrial sector with significant CO_2 emissions. In this paper the current situation in ferroalloy processes is discussed from the standpoint of global environmental issues, trends and development. Progress and data of ferroalloys production are frequently compared with the steel industry, which is a closely related sector and the main user of ferroalloys. Emission factors of processes and electricity production are examined as well as possibilities and future scenarios of how to diminish CO_2 emissions. As a part of this study a questionnaire was submitted to experts in the field of ferroalloys worldwide to survey opinions on the ferroalloy industry today and in the near future (2020). Eighteen questions concerning raw materials, energy, environmental aspects, by-products and economic aspects were responded to by seventeen experts, the answers were analysed and conclusions were drawn.

Keywords
Ferroalloys, energy, CO_2 emissions, electricity, sustainability, questionnaire.

Introduction

Production is sustainable if it meets the present needs without compromising the ability of future generations to meet their own needs. The sustainability of a process can be evaluated by using environmental, economic and social indicators. In public debate, environmental issues and CO_2 emissions have been the central focus. This paper also discusses energy consumption and saving, carbon dioxide emissions and the possibilities of decreasing them in ferroalloy production. The related industrial branch, the steel industry as the major customer and user of ferroalloys, is often seen as a benchmark for progress.

Ferroalloys are defined as iron-bearing alloys with a high proportion of one or more other elements—manganese, chromium, silicon, molybdenum, nickel, etc. They are used as alloying additions in steel to improve the properties, especially tensile strength, toughness, wear, and corrosion resistance. Their production is thus firmly related to steel production. The approximate ratio of annual production of ferroalloys versus steel is roughly 2.5:100, which means an 'average alloying degree' of 2%. In practice the distribution is not regular but the vast majority of steels utilize only around 1–2% of these alloys. There are also groups of high alloyed steels, stainless steels being the most important group containing 10 to 30% or more alloying elements. In making steels with high Cr, Ni, Mo, recycled material makes a remarkable fraction of the alloyed material balance.

The world steel production had an unforeseen rapid growth from the end of 1990s until the recent recession. The world production grew from 800 million ton (Mt) to 1 350 Mt in 2007 (Figure 1)[1]. It is, however, noteworthy that most of this tremendous growth was due to the erection of numerous new steel plants in China, whereas the growth was rather calm in other countries. China's steel production was about 500 Mt in 2007. The future scenarios are more conservative but due to presumable recovery in BRIC countries (Brazil, Russia, India and China) and inevitable progress in many developing countries enormous investments are required in infrastructure, housing, transportation etc. This must mean that steel consumption per capita will drastically grow in those countries, which leads to a clear and continuously growing demand for steel during the next decades[2].

Ferroalloy production, firmly connected to the progress in the steel industry also experienced a corresponding production growth from about 18 million tons in the

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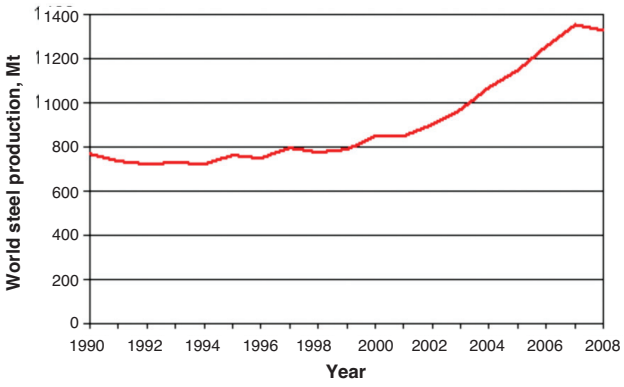

Figure 1—World crude steel production from 1990 to 2008 (million tons)[1]

1990s to 34 Mt in 2007 (Figure 2)[3]. As an example, FeCr production is presented separately showing growth from 3–5 Mt to over 8 Mt in 2007.

Energy consumption and CO_2 emissions from production

General

According to an IEA report the global energy use was 12 000 million tonnes of oil equivalent (Mtoe) in 2007[4]. On the other hand, the global CO_2 emissions were reported as 29 Gt in 2007, which is in good agreement with the energy figure when taking into account the distribution of different energy forms[4]. The industrial activities were responsible for 4.8 Gt CO_2 of which iron and steel production emitted 1.47 Gt CO_2[4]. That is approximately 5% of total world CO_2 emissions. This figure concerns, however, only the primary energy use (coke, coal, gas, oil) but not indirect emissions due to e.g. electricity production. If they are taken into account, higher figures are obtained for the iron and steel industry, i.e. 6–7% of the total CO_2 emissions[5].

Ferroalloy production

Ferroalloy production is regarded as an energy-intensive industry with high consumption of electricity and coke and minor amount of other fuels and reductants. That means also high CO_2 emissions. What is actually the role of the ferroalloy industry in global emissions? Only a few studies have discussed energy consumption and CO_2 emissions in ferroalloy production. The Intergovernmental Panel on Climate Change Report 2007 (IPCC)[6] has used the data by Sjardin (2003)[7]. In Table I the emission factors were adopted from Sjardin and combined with the production figures of common ferroalloys in 2007[3]. FeCr and FeMn include different grades (high, medium, low carbon) with different emission factors. FeSi also comprises different grades with different Si contents. The value 2.92 is a weighted mean value. Carbon dissolved in ferroalloys was not included as an emission in FeCr production. For comparison, emission factors from another publication are given too[8].

As seen, the total emissions from four main ferroalloys with 27.77 Mt production were about 55 Mt from which an approximate figure of about 70 Mt CO_2 for the total ferroalloy production (34 Mt) can be estimated. That is about 5% of the emissions of the global iron and steelmaking.

Best available technologies

Best available techniques (BAT) were defined by EC Directive 96/61 in Article 2[11] as 'the most effective and advanced stage in the development of activities and their methods of operation which indicates the practicable suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent, and where that is not practicable, generally to reduce the emissions and the impact on the environment as a whole'. This definition implies that BAT covers not only the technology used but also the way in which the installation is operated, to ensure a high level of environmental protection as a whole. BAT takes into account the balance between the costs and environmental benefits.

BAT studies were initiated by the Directive 96/61/EC on integrated pollution prevention and control (IPPC). Concerning the non-ferrous industry including ferroalloys, a comprehensive study was prepared at the turn of the millennium and published in December 2001[9]. A revised version was later prepared and published as a working draft in July 2009, referenced to the codified IPPC Directive 2008/1/EC[10]. The report works are based on information and data from experts groups and are thus considered authentic. As an example, some data of FeCr processes are reviewed here.

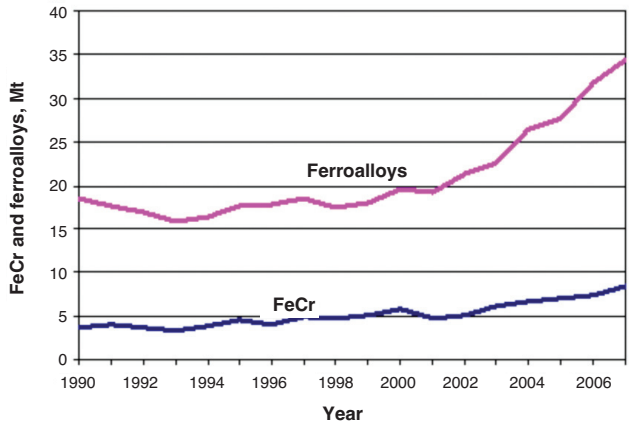

Figure 2—World production of ferroalloys and FeCr from 1990 to 2007 (million tons)[3]

Table I

Emission factors, production and estimated global emissions for common ferroalloys

Ferroalloy	Emission factor t CO_2/t Fe alloy[7,8]	Production (Mt/2007)[3]	Global CO_2 emissions (Mt)
Ferrochromium	1.63/1.6	8.503	13.860
Ferromanganese	1.79/1.3	5.194	9.300
Ferrosilicon	2.92/2.5–4.0	6.760	19.740
Silicomanganese	1.66/1.4	7.310	12.130
Total	Avg. ~ 2	27.770	55.030

Towards sustainability in ferroalloy production

In ferrochromium production the main issue is the submerged arc furnace (SAF). The conventional furnace type is an open furnace in which furnace off-gas is mixed with large amounts of air. A 'closed furnace,' however, is designed to maintain CO-rich off-gas by collecting, cleaning and storing for further utilization. An intermediate type, the 'semi-closed' furnace, is still common for FeSi and special alloy production. The furnace off-gas is therefore possible to recover but is less calorific due to dilution with air. In Table II the two types, open and closed processes are compared for some crucial features. The IPPC Report also represents two other alternative processes, namely the use of pre-reduced pellets in close SAF and DC furnaces without pre-reduction[10]. As the data for these were incomplete, they are not discussed here.

The report also gives emission data for air and water. Of these only the CO_2 emissions are referred to here. For HC FeCr in a closed SAF, the CO_2 emissions were reported in the range of 1200–2000 kg/t FeCr including total emissions from pre-treatment, smelting and post-furnace processes. The external use of CO gas was considered to reduce local emissions from the FeCr plant.

In order to summarize the most effective and advanced technologies for the ferroalloy production line, the following items are appropriate[9,10]:

- Concentrate sintering by utilizing CO gas from the smelting furnace
- Preheating charge material for the smelting furnace by utilizing CO gas
- Pre-reduction might be a potential sub-process for certain ferroalloys in the future
- Smelting in closed electric arc furnaces with efficient off-gas recovery, filtering and energy utilization in-plant as fuel, and in neighbouring plants for energy production
- Semi-closed furnace (FeSi) if energy can be recovered from CO gas
- Efficient gas cleaning for dust, heavy metals and toxic emissions
- Closed water system with removal of particulates and harmful components
- Recycling, reuse and utilization of solid wastes such as slags as by-products.

Possibilities of decreasing CO_2 generation

Steel industry's commitment toward 2030

The World Steel Association has published seven commitments to reduce steel-related greenhouse gas emissions[2]. These statements could apply to the ferroalloy industry:

- Expanding best available technologies in ferroalloys industry to improve energy efficiency and to decrease CO_2 emissions. This is an economical way which also really decreases CO_2.
- Undertaking research and development for new technologies to radically reduce the specific CO_2 emissions for each ton of ferroalloy produced. Some aspects are discussed later.
- Improving recovery and winning of alloy metals by improved recycling systems, by improved melting technologies, and in-plant recycling. Could the use of secondary raw materials be intensified and increased in ferroalloy production?
- Maximizing the value of by-products, e.g. slags, dust, etc. from ferroalloy production.
- The principle of facilitating the use of the new generation steels to improve the energy efficiency of steel-using products could be adapted to the ferroalloy industry by maximizing the value of ferroalloys for steelmaking via 'tailored' products/alloys. The merit of an increased lifetime of a steel product with less CO_2 emissions per annum could be 'integrated' upstream to ferroalloy production as well.
- Adopting common and verified reporting procedures for CO_2 emissions (e.g. applying IPPC Directive 2008/1/EC).

Table II

Consumption of raw materials and energy when producing HC ferrochromium[10]

Raw material	Open SAF*	Closed SAF**
Chromite kg/t	2400–3000	2300–2400
Reducing agent kg/t	550–700	500–550
Fluxes kg/t	100–400	200–300
Electrodes kg/t	8–25	7–10
Remelts	0–300	-
Electricity kWh/t	3800–4500	3100–3500
Calculated potential energy by using coke kWh/t	4235–5390	3850–4235
Total energy input kWh/t	8035–9890	6950–7735

*Data for open SAF with lumpy and fine ore without agglomeration and preheating

**Data for closed SAF using preheated pellets. For the coke /electricity conversion a value 7.7 kWh/ kg coke was used

➤ Adopting a global sector-specific approach for the ferroalloy industry in the post-Kyoto period.

Possibilities of decreasing CO_2 emissions from Ferroalloy production

In current ferroalloy production, the main role of carbon (coke) is as a reducing agent. Hydrogen (or natural gas) which is used for direct reduction of iron ore to metallic iron is not strong enough to reduce e.g. chromium, silicon or manganese from their oxides. Although carbon is necessary, its need should be minimized and efficiency maximized. A key point in submerged arc furnaces is a perfect recovery of furnace gas and its reasonable usage for maximum value. For FeCr, FeMn and SiMn closed furnaces are nowadays most common. In these processes the coke carbon is almost quantitatively converted to CO gas (except for the carbon dissolved in the ferroalloy). In an example case of an FeCr process, the gas contains 75–90% CO, 2–15% H_2, 2–10% CO_2 and 2–7% N_2[11]. The gas has a high calorific value of 10.1–11.5 MJ/Nm^3 and a specific energy content of 7200–8280 MJ/t FeCr (2.0–2.3 MWh/t FeCr). If the CO gas is treated as a credit, the CO_2 emissions from the core process of FeCr smelting can be quite small, only about 600 kg/ t FeCr[11]. This is much lower than the emission factor value of 1.6 given in Table I for FeCr. A reason for the different values comes from the definition of system boundaries which is discussed further later in this paper.

An important aspect is also the recovery of the alloy metal into a ferroalloy. There are still possibilities to improve yield, e.g. for Cr in FeCr typical yield is 90–95% and for Mn in FeMn production from under 80% to over 90%, depending on the slag practice and recycling[10,12]. The yield of alloy metals in smelting processes depends highly on slag chemistry, basicity being a central factor influencing distribution of certain metal between the slag and the formed liquid ferroalloy[13]. Also, physical properties such as viscosity are important because a significant part of yield losses exist as metal particulates dispersed in the slag. There is still much potential for metallurgists to improve bothe these aspects.

Importance of system boundaries

As seen in the previous section and discussed in literature[14,15] the energy consumption and CO_2 figures of a certain process can greatly depend on how the boundaries of the system were defined. Tanaka[14] has shown how the energy consumption per ton of crude steel can range from 16 to 21 GJ depending on the boundaries set for the system. 'Measures of energy efficiency performance' (MEEP) can be estimated by physical-thermodynamic indicators, economic-thermodynamic indicators, or pure economic indicators. Of these the first one, 'thermal efficiency', is the traditional 'engineering' concept energy output/energy input or 'energy consumption intensity' (unit or specific energy consumption), for instance energy consumption per 1 ton product. That makes comparison between different plants possible providing that the boundary definition is similar. Applied to the ferroalloy industry, the smallest unit might be the smelting furnace, e.g. comparison of open, semi-closed and closed furnaces. However, this turns out to be quite difficult as, for instance, the input raw materials are very different with different 'energy histories' too. The valuation of gases can also be problematic. A better way is to define the system consisting of the whole ferroalloy plant from raw materials to liquid ferroalloy (pretreatments, sintering, preheating, smelting, gas cleaning and recovery). A manifest problem is the furnace off-gas (e.g. in the FeCr process). It seems accepted that the fraction of CO-gas (which is not used inside the FeCr plant) can be valued as credit when used externally for electricity production, heating, etc. In large integrated plants including FeCr and stainless steel production in the same site, the CO-gas can be stored and effectively utilized for preheating materials, reactors, ladles, etc. and then finally converted to CO_2[11]. If the energy efficiency is then evaluated for the whole integrates site, the CO gas has its value as an energy rich and economic fuel.

Further, the energy of CO-gas or other less intensive energy forms (steam, hot water, waste heat) can be utilized inside the plant or for the neighbouring community. In the latter case, they bring credit to the plant.

One almost neglected energy source concerning the ferroalloy industry are the latent heats of liquid ferroalloy and slag from the smelting furnaces. As far as is known, the only plants utilizing the latent heat of liquid FeCr as direct liquid charging in stainless steelmaking are Outokumpu Tornio Stainless in the integrated FeCr-stainless steel plant in Finland and Columbus Stainless in Middelburg, South Africa which gets liquid FeCr from neighbouring Samancor Middelburg Ferrochrome. Besides for the enthalpy of liquid metal liquid slag also has remarkable heat content which is, evidently not utilized in any systematic way. Outokumpu Tornio Works utilizes the heat content of slag to decompose cyanides in gas washing water in slag granulation[16]. Otherwise, there seems to be no information on the utilization of the latent heats of furnace products of other ferroalloys.

Toward sustainability

General

The influence of anthropogenic emissions on climate change is generally admitted. Growth of emissions increases CO_2 (in general GHG) content in the atmosphere, which then causes global warming. Since the UN Framework Convention on Climate Change was adopted in 1992 in Rio de Janeiro, the imminent danger was universally recognized and corrective and limiting actions were started. Recently, the United Nations Climate Change Conference was held in Copenhagen in December 2009 (COP15). It was loaded with ambitious targets but, with 193 parties, the meeting had problems coming to a unanimous agreement[17]. Due to the diversity of parties (as to their population, industrialisation, development level, economy, natural resources, cultural aspects etc.) it is understandable that most of decisions were indicative only of next endeavours. As far as unambiguous and therefore important 'techno-political clauses' went, it was underlined that 'climate change is one of the greatest challenges of our time'. Further, it was 'agreed that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius'. This target had been earlier defined to be consistent with the objective of

limiting the long-term concentration of greenhouse gases in the atmosphere on the level equivalent to 450 ppm CO_2 (450 Scenario)[4]. This is a really challenging target, which means holistic changes from high-carbon energy forms and technologies to low-carbon ones. It means transformations in production, transportation and in the use of energy, 'a veritable low-carbon revolution to put the world on the 450 ppm trajectory'.

Energy consumption and electricity generation

The world energy consumption is strongly based on fossil non-renewable sources, representing totally over 80% of all energy used in 2004[18] (oil 38%, coal 26%, gas 23%, total fossil 86%, hydro and nuclear both 6%). Thus decarbonization of energy seems to play a central role in reducing emissions. Oil has a decisive role, e.g. in transportation and heating. Oil has been considered as non-renewable, depleting resource, which has been forecast to end in few decades. The major position of 'liquid fuels' has been predicted, however, to remain the same also in the near future, partly due to more efficient oil recovery technologies which increase production of conventional resources, and partly due to emerging unconventional oil resources (oil sands, extra heavy oil) and, finally, due to the drastic growth of 'new non-petroleum' liquids, such as biofuels, coal-to-liquids and gas-to-liquids[19]. Easy to transport and user-friendliness are the central reasons why liquid fuels are foreseen to succeed.

Also the use of coal has been predicted to grow strongly towards 2030 in North America and Asia, whereas in Europe it is assumed to decrease[19]. The reasons for this progress are both resources and energy-political. When one uses coal and liquid fuels, discussed above, CO_2 emissions will increase. As a solution, carbon dioxide capture and storage or sequestration (CCS) are proposed. That has been planned for electricity production in coal power stations where it has been already tested on a minor scale since 2008 but is still rather far from final industrial usage[20]. CCS for an end-user like the steel industry is possible as well and has been studied e.g. in the European ULCOS project[21]. Ferroalloy producers are relatively small direct emitters of CO_2 anyway, thus the CCS application is not very realistic.

The share of natural gas is about 20% and will remain about the same until 2030. There are huge unconventional resources whose exploitation is difficult. Anyway, it is believed that natural gas will increase and its share will grow slightly covering over 20% of primary energy[19]. Exploitation of unconventional gas (coal bed and shale reservoirs) will increase, especially in North America. Even an oversupply of gas is possible. Today a big user of gas in the metallurgical industry is direct reduction of iron ore to metallic iron in solid state via shaft furnace and fluidized bed processes. Further potential users are evident. In ferroalloy production natural gas can be used for preheating, pre-reduction and different heating purposes, thus decreasing coke and electricity consumption. It is notable that CO_2 emissions from natural gas are much lower than from coal or coke. In terms of emissions per energy unit, the values for coke and natural gas are 108 and 56 kg CO_2/GJ, respectively[22].

Although coke is the main direct CO_2 source in the ferroalloy industry, electricity takes the major part of energy consumption (over 3 000 kWh/ t FeCr). Therefore it is essential to reveal the origin of electricity and its indirect emissions, depending on the type of the power station. Such a comparison is shown below in Table III. The global average of electricity production was estimated as 504 kg CO_2 /MWh assuming a conversion ratio 1 MWh = 9.8 GJ[22].

Direct emissions mean emissions from combustion and indirect emissions from materials production (mostly steels and other metals), transportation and life-cycle emissions. Carbon capture and sequestration could cut in-site emissions into the atmosphere by 90%, but taking into account the lower conversion rate due to extra energy for capture and storage and indirect effects, the real reduction of emissions could be remarkably lower[24].

Questionnaire on ferroalloy production

Questionnaire performance

In order to obtain a broader opinion about the importance of different factors concerning the sustainable production of ferroalloys, a questionnaire was prepared and mailed to 25 internationally well-known experts in the field of ferroalloy production. During summer and autumn 2009, a total of 17 responses were received, representing almost same number of enterprises or institutions on six continents and dealing with central ferroalloys (FeCr, FeMn and FeSi). The questionnaire consisted of 18 questions, of which 2

Table III

Comparison of greenhouse gas emissions from electricity production[23]

Primary energy/ production system	Direct emissions g CO_2/kWh	Including indirect emissions g CO_2/kWh
Coal	790–1017	966–1306
Oil	650	~ 800
Natural gas	362–575	440–688
Solar power	-	100–280
Biomass	-	25–93
Wind	-	10–48
Hydropower	-	4–30
Nuclear	-	9–21

concerned raw materials and pretreatment, 4 on energy issues, 5 on environmental issues, 3 on by-products, and 4 on economic aspects. The importance of factors was marked with numbers 1…5 where 1 = not at all important and 5 = very important. Two timescales were asked to assess: 'today' (2009/10) and 'future' (2020). As an extra point, 'other items or opinions' were requested. Several respondents gave useful comments which are taken into account in the following discussion.

Observations on responses

The results are presented in Figure 3 and in Table IV. If one looks at distributions and mean values, the following conclusions can be drawn:

- Almost all the issues were considered important, as indicated by the high average values (3.63/4.67) of all factors shown.
- The importance of most issues is still growing in the future (Δ mean value = +1.04; range +0.29…+1.65).
- Quality of raw materials is a key issue as the known ore reserves will be depleted. The role of pretreatment (pelletizing/sintering) is increasingly important when supply of ore fines increase. Concentrate blending is also relevant.
- Electric energy is already important today and is still rising toward a rating of 5.
- Coke is important as well but other fossil fuels or reductants are less significant (2.29/3.06).
- Biomass today has quite a low status (1.94) but is growing markedly until 2020 (3.36)
- All environmental issues are of great importance and still strongly growing (Δ mean values in the range +1.05…+1.41)
- By-products including CO gas, efficient heat recovery and slag utilization have the greatest potential to be improved in the future (Δ mean value = +1.53…+1.65)
- Economic issues, in general, have very strong weight and in 2020 close to a value of 5. The only deviant is the investment costs/size factor, with a high scatter in answers showing that even rather small units can be economical in favourable conditions.

Other issues seen by the correspondents to be important to focus on were:

- Better yield of alloy metal (Mn, Cr…)
- Low impurity level (S, P…)
- Skills of personnel; education, training
- Social and health issues, development of society (HIV management).

All average values grew from 2009/2010 to 2020 and the differences were marked with + sign. All the score frequencies and distributions can be found in Figure 3. The columns represent the frequency of given marks 1, 2, 3, 4, 5 from left to right in each figure.

Conclusions

Results of the exhaustive survey of endeavours toward sustainability universally, and in the steel and ferroalloy industry, are briefly concluded here.

- It seems indisputable that our planet cannot continue on the route of continuous growth in energy consumption and CO_2 emissions; quite radical actions are needed.
- That means better energy efficiency and saving by regulating and directing consumption by pricing, taxation or other actions.
- Transfer from fossil high-carbon fuels must take place to less-carbon energy sources and to renewable energy forms.
- In the intermediate phase carbon capture and storage is a potential but not a final solution.
- In the steel and ferroalloy industry the challenges, means and actions are parallel.
- Saving energy and materials, and the utmost utilization of energy via integration, are still of first priority
- Transfer from fossil to low-emitting and renewable energy should be followed and promising applications actively adopted by the ferroalloys sector.
- Comprehensive analysis and a radical extension of system boundaries from smelter site to up- and downstream processes, including the evaluation of products and energy production and utilization, will most effectively influence emissions on a global scale.

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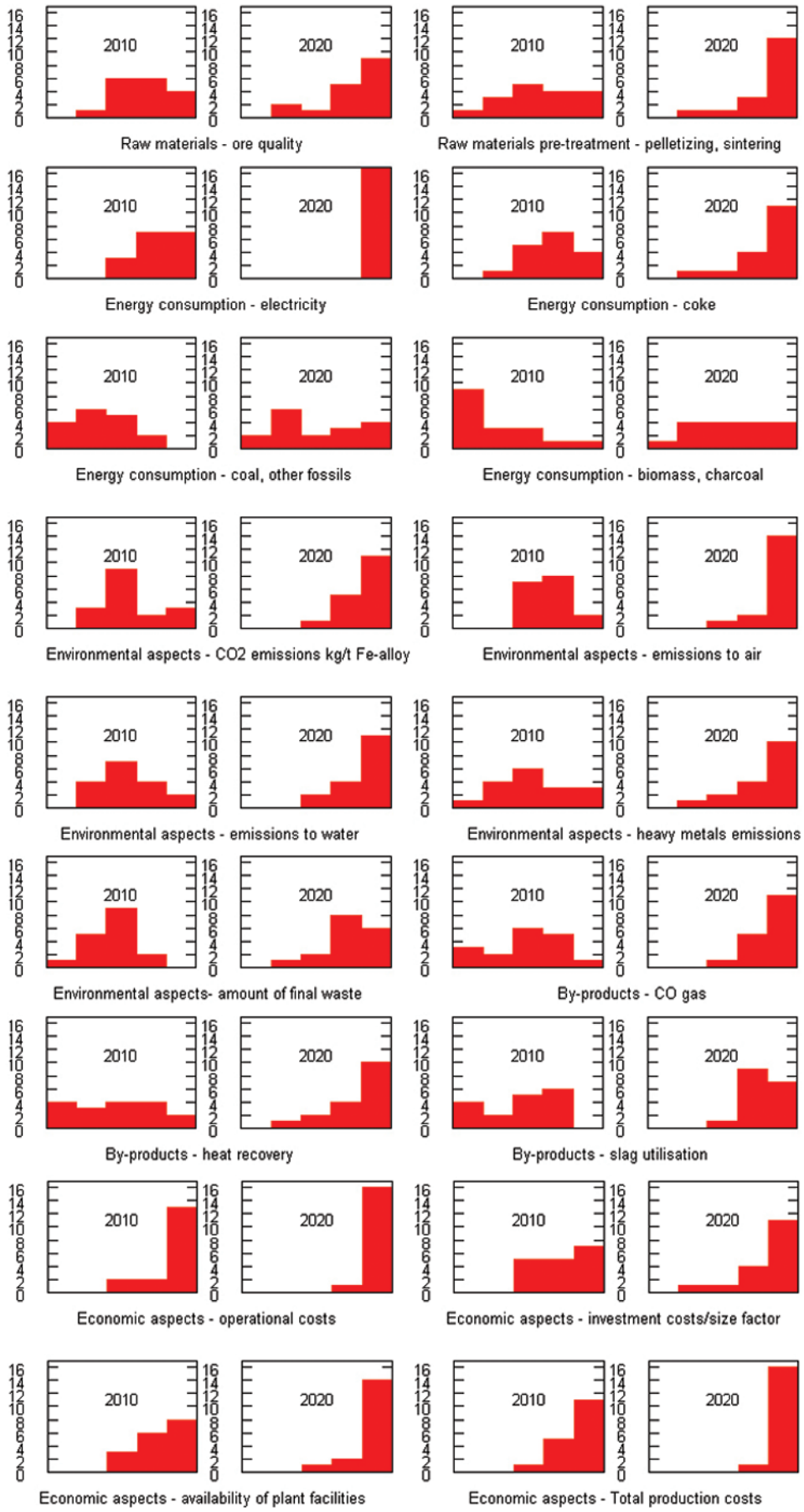

Figure 3—Distribution of scores in the responses of experts concerning the importance of different factors in ferroalloy production today (2010) and in the near future (2020)

Table IV

Summary of questionnaire on ferroalloy production

Factors	Average values		
	2009/2010	2020	Difference
Raw materials—ore quality	3.76	4.24	0.48
Raw materials pretreatment (pellet./sintering)	3.41	4.53	1.12
Energy consumption—electricity	4.24	5	0.76
Energy consumption—coke	3.82	4.47	0.65
Energy consumption—coal, other fossil	2.29	3.06	0.77
Energy consumption—biomass, charcoal	1.94	3.35	1.41
Environmental—CO_2 emissions kg /t Fe-alloy	3.29	4.59	1.3
Environmental—emissions to air	3.71	4.76	1.05
Environmenta—emissions to water	3.24	4.53	1.29
Environmental—heavy metals emissions	3.18	4.35	1.17
Environmental—amount of final waste	2.71	4.12	1.41
By-products—CO-gas	2.94	4.59	1.65
By-products—heat recovery	2.82	4.35	1.53
By-products—slag utilization	2.76	4.35	1.59
Economic aspects—operational costs	4.65	4.94	0.29
Economic aspects—investment costs/size factor	4.12	4.47	0.35
Economic aspects—availability of plant facilities	4.29	4.76	0.47
Economic aspects—total production costs	4.59	4.94	0.35
Total average	3.63	4.67	1.04

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