Reprinted from

BEYOND THE ENERGY CRISIS
OPPORTUNITY AND CHALLENGE

Edited by
R. A. FAZZOLARE and C. B. SMITH

PERGAMON PRESS OXFORD and NEW YORK 1981

ENERGY ANALYSIS IN SCRAP - BASED MINI-MILLS. AN EVALUATION OF DIFFERENT METHODS OF ELECTRIC ARC FURNACE OPERATION

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ABSTRACT

This paper deals with an analysis of direct and indirect energy inputs in the electric arc furnace steelmaking process. The model which has been developed provides a coherent frame of reference for comparing various technological options. The following significant cases have been analyzed utilizing operational data from industrial plants:

(i) conventionally operated electric furnaces;
(ii) electric furnaces in which oxy-fuel burners are used as an auxiliary heat source during the melting-down phase;
(iii) electric arc furnaces in which scrap is continuously charged and smelted after having been pre-heated in a separate furnace (the BBC-Brusa process).

On the basis of our analysis, we proposed a multiple criteria evaluation of the energy impact of various methods of electric furnace operation.

KEYWORDS

Industrial energy conservation; electric arc furnace steelmaking; process energy analysis; total energy requirement; electricity substitution; electrical load leveling; evaluation of technology options; multiple criteria preference space.

INTRODUCTION

In 1979, Italy used 8,700 GWh of electric energy in the production of crude steel in electric furnaces. This figure represents 44.7 per cent of the electrical energy used in the iron and steel industry (19,395 GWh), which in turn represents 20.2 per cent of the electrical energy consumption in all industrial sectors (96,125 GWh) and 12.1 per cent of the total consumption of electrical energy (160,012 GWh).

The production structure of the Italian iron and steel industry is actually quite unique in comparison to other industrialized countries, and is characterized by the widespread development of so-called "mini-mills" where steel is produced from scrap iron in electric furnaces. As a matter of fact, in 1979, out of a total of 24.25 million tons of steel, 12.9 million tons (53.3 per cent) were produced by electric furnaces, and 10.2 million tons (42.0 per cent) were produced in basic oxygen furnaces (the BOF process) through refining of the pig iron produced in blast furnaces (the remaining 4.7 per cent was steel produced in open-hearth furnaces by the Martin-Siemens process).

In comparison, the production figures for 1979 for electric steel in other industrialized countries were the following : 34.2 per cent in Great Britain, 24.6 per cent in the U.S.A., 23.6 per cent in Japan, 15.3 per cent in France and 14.0 per cent in Germany (F.R.).

METHODOLOGY

In this study we will preliminarily examine an energy analysis model which applies engineering process analysis techniques.[1] This model should provide a coherent frame of reference for evaluating energy conservation measures and deciding upon various alternatives.

It should be stated that this study will only analyze energy consumption as measured in physical units, and that only economic analysis techniques would permit us to fully evaluate other production factors such as raw materials, work and capital.

Our engineering process analysis should provide us with useful information on total energy requirements for the production of a given quantity of electric steel in different plants. In general, the total energy requirement is the sum of all the energy inputs directly and indirectly needed in the production of one ton of steel (i.e., all energy needed in the general production system, and not just in the steel plant itself). We must therefore consider not only the final stage of the process (in our case, the steel plant), but also the preceding stages, in order to identify the energy needed for the production of material, energy, and equipment utilized in the steel plant. The "backtracking" process to be followed is represented in Fig. 1, where we have arbitrarily defined four levels of regression in establishing the boundaries of the system (Long, 1978).

We decided not to consider energy inputs beyond the second level of regression. We will separately show the results obtained from an analysis considering only the first level, or the first and second levels together.

Figure 2 shows the scheme that we have followed in our analysis and all the inputs that we have attempted to quantify. It should be noted that we did not consider energy requirements for transport, since they are quite difficult to evaluate and are not fundamental to a comparison of various technological alternatives in already existing plants. Furthermore, we did not consider specific preliminary treatments of scrap, such as shredding, cryogenic shredding, scrap pressing, etc.

HYPOTHESES, GUIDELINES, AND PARAMETERS UTILIZED IN THIS STUDY

1. In the quantification of direct energy inputs, i.e., fuels, electrical energy, exothermic reactions, we followed various guidelines according to the energy source used. Thus, for fossil fuels (primary energy

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[1] A more detailed description of the energy analysis model and of its practical application to electric steel plants is given in a previous paper (Borroni and others, 1981).

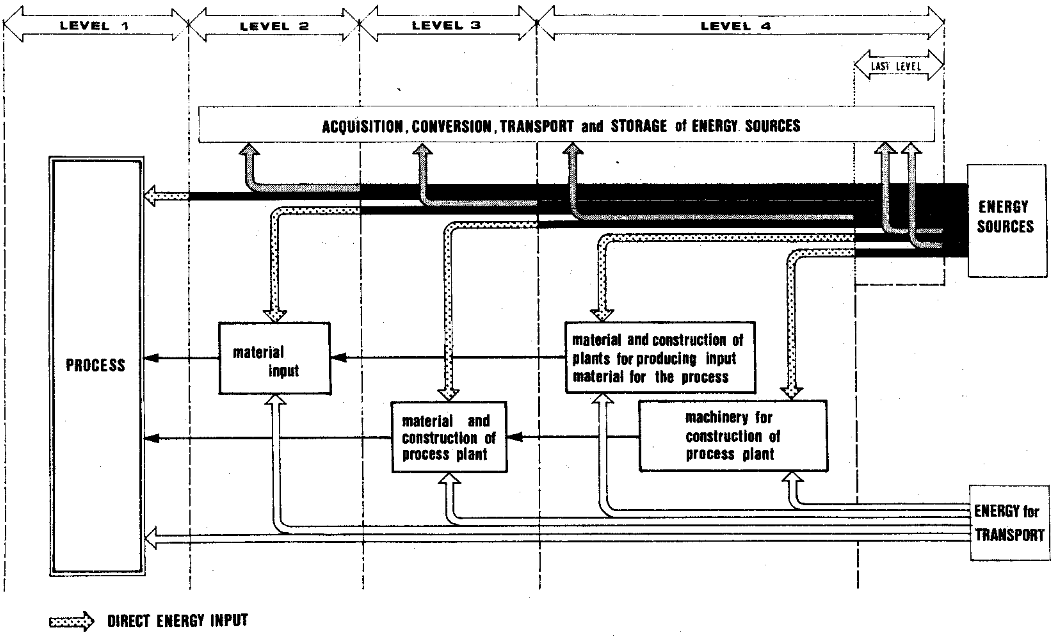

Fig. 1. Energy analysis scheme for a general process: specification of different inputs and definition of possible system boundaries.

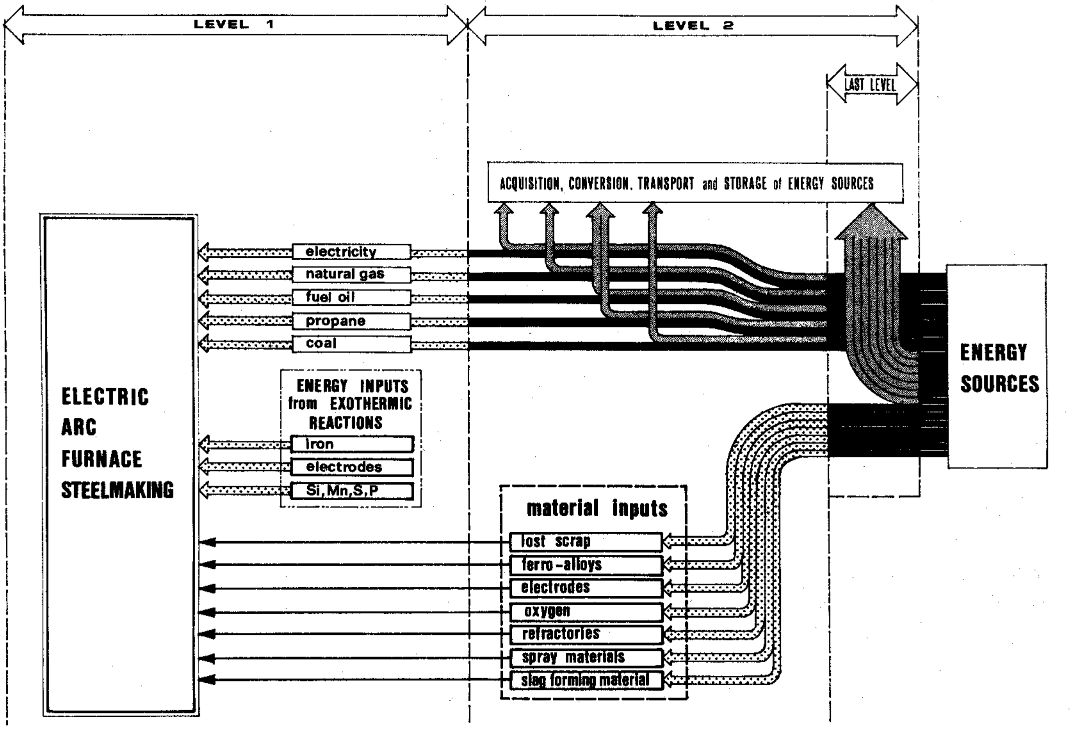

Fig. 2. Energy analysis scheme applied to electric steel plants: definition of system boundaries at levels 1 and 2 and specification of direct and indirect energy inputs.

sources) the quantity consumed was converted into energy units, using the net heat values.[2] Electrical energy input was converted in MJ according to the ratio of 3.6 MJ/kWh. Finally, for exothermic reactions occurring in the arc furnace process, we applied the value of ΔH^{0} at 1,600° C to the quantity of substance reacted upon.[3]

2. To quantify the indirect energy inputs related to the supply of direct energy inputs, we evaluated all of the losses occurring in each step of the conversion process from the primary energy sources. In the case of inputs utilized as electrical energy, it was necessary to distinguish the amount deriving from hydroelectric power plants and that from thermoelectric plants. This is the only correct method for evaluating all of the energy requirements needed in the conversion from the primary energy sources, respectively dam water and fossil fuels.[4]

3. To quantify the indirect energy inputs related to the consumption of materials, we considered the direct and indirect energy inputs in their production processes.[5] Furthermore, we considered only the energy required for the production of the amount of material used. Special attention must be paid to the energy input related to scrap. In this case, the consumption is only the quantity lost in the process. In other words, we considered only the energy embodied in the amount of scrap needed to cover the metallic losses and the steel plant recycling.

ENERGY ANALYSIS OF THE OPERATIONAL DATA OF VARIOUS STEEL PLANTS

Three significant varieties of the electric arc furnace steelmaking process were chosen for this energy analysis :

(i) conventionally operated electric furnaces (plant A);
(ii) electric furnaces in which oxy-fuel burners are used as an auxiliary heat source during the melting-down phase (plants B and C);[6]
(iii) electric arc furnaces in which scrap is continuously charged and smelted after having been pre-heated in a separate furnace (the BBC-Brusa process, plant D)(Brusa, 1977).

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[2] Fuel oil 41.06 MJ/kg, natural gas 34.57 MJ/Nm^3, propane 91.13 MJ/Nm^3, coal (recarburizers) 30.17 MJ/kg.

[3] The main oxidation reactions considered are the following: $Fe \rightarrow FeO$ (corresponding to the metallic losses in the furnaces), $Si \rightarrow SiO_2$ and $Mn \rightarrow MnO$ (from silicon and manganese charged with ferro-alloys). For the electrode combustion reaction, the energy input was taken to be equal to the coal heat value.

[4] For the Italian electricity generation system (27.74 per cent of electricity supplied by hydroelectric power plants and 72.26 per cent by thermoelectric plants), a conversion coefficient between electric energy units and primary energy units of 9.22 MJ/kWh was obtained.

[5] The direct energy inputs for production of material inputs were taken as follows : electrodes 34.7 MJ/kg, ferro-manganese (75 per cent Mn) 7.2 MJ/kg, ferro-silicon (75 per cent Si) 34.9 MJ/kg, ferro-silicon-manganese (20 per cent Si, 70 per cent Mn) 14.6 MJ/kg, oxygen 6.5 MJ/Nm^3, lime 4.9 MJ/kg, furnace and ladle lining 9.9 MJ/kg, cement and spray material 4.1 MJ/kg, tundish panels 5.2 MJ/kg, scrap 3.2 MJ/kg.

[6] Case (ii) represents two plants using burners fed by fuel oil (B) and natural gas (C) respectively.

Case (ii) was chosen in order to evaluate the suitability of integrating electric energy with other sources in already existing plants. Case (iii) was chosen because it represents a new plant in which an energy conscious design substitutes a larger amount of electric energy, carrying on the pre-heating phase and the smelting phase in separate furnaces.[7]

Table 1 shows the main features of steel plants A, B, C and D. It should be noted that all four plants represent comparable alternatives from an energetic point of view, despite their differences in scale, operation and design. In fact, not only the raw material used (100 per cent scrap iron) and the steel produced (carbon steel for bars, rods, beams, etc.) are practically identical in the different cases, but also the electric furnaces are characterized by significant technological parameters (i.e. specific electric power and productivity) which rank all of them among the HP furnaces.[8]

Table 2 shows the relative figures for energy and material consumptions in producing one ton of billet, as ascertained from the four plants of our study. For plants A, B and C, the data presented here refer to a normal production period of one year (1979); for plant D (which applies the BBC-Brusa process), we refer to a start-up period (in 1979) of two months.

Table 3 shows the results of the energy analysis in terms of energy requirements per ton of billet at levels 1 and 2.

ENERGETICS MULTIPLE CRITERIA FOR IDENTIFYING PREFERRED ALTERNATIVES

Now that we have presented the results obtained from an energy analysis of the four plants, we shall deal with two probleems, i.e., (i) how to evaluate different solutions regarding technology and plant design, and (ii) how to choose a preferred alternative.

With an energy outlook limited only to considering the final stage of the process (in our case, the steel plant), a decision maker would be led to establish a scale based on the amounts of direct energy inputs (level 1). In this case, the scale would be B, C, A, D, as can be seen in Table 3. However, the following observations should be made :

1. the direct energy input required by the "least efficient" plant (D) is 44.5 per cent higher than that of the "most efficient" plant (B): plant B would seem to be by far the best;
2. the direct energy inputs required by plants A and C are practically identical (plant A requires 0.16 per cent more energy than plant C): therefore, the choice between one or the other would be indifferent.

On the other hand, if we continue to maintain an outlook limited exclusively to energy, but take into consideration indirect energy inputs too (as would be the case, for example, for a decision maker who has the responsibility of administering the energy use on a larger scale, i.e. regional, national, etc.), the following order of preference would be established: B, D, C, A. However, it should be pointed out

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[7] Since this case represents great differences in design and construction of process plant, it would be more appropriate to extend our energy analysis to level 3 of Fig.1, to include the direct energy inputs for material and construction of equipment. Nevertheless, by limiting the energy analysis to only the first two levels, the conclusions resulting from our study are not substantially altered.

[8] Generally speaking, the following distinction is made between HP and UHP arc furances:

– HP(High Power) furnaces: specific electrical power 0.25 ÷ 0.35 MVA/t, productivity 15 ÷ 20 t/h (increasing to a maximum of almost 30 t/h when using auxiliary burners);

–UHP (Ultra High Power) furnaces: specific electrical power 0.45 ÷ 0.55 MVA/t, productivity : approximately 40 t/h (increasing to more than 50 t/h when using auxiliary burners).

TABLE 1 Description of the Analyzed Steel Plants

Description	HP furnace	HP furnace with oxy-fuel auxiliary burners		HP furnace with scrap pre-heating furnace (BBC-Brusa process)
		Fuel oil	Natural gas	
	(A)	(B)	(C)	(D)
Pre-heating furnace				
Features	-	-	-	See footnote*
Burners number and power (MW)	-	-	-	20 x 2
Fuel	-	-	-	Natural gas
Pre-heating temperature (°C)	-	-	-	1,200
Productivity (t/h)	-	-	-	80
Electric arc furnace				
Features	See footnote **			See footnote***
Number and capacity (t)	2 x 50	3 x 33	1 x 50	2 x 100
Rated electric power (MVA)****	15	12	15	30
Specific electric power (MVA/t)	0.30	0.36	0.30	0.30
Auxiliary burners number and power(MW)	-	2 x 2	2 x 2	-
Working time of auxiliary burners (min)	-	30 ÷ 45	45 ÷ 60	-
Tapping temperature (°C)	1,665	1,665	1,665	1,715
Tap-to-tap time (h and min)	3 : 10	2 : 20	3 : 10	3 : 30
Productivity (t/h)	15.8	14.2	15.8	27.4
Productivity (all furnaces) (t/h)	31.6	42.6	15.8	54.8
Continuous casting				
Machines and lines number	2 x 3	2 x 3	1 x 4	2 x 3
Semis (square billets) size (mm)	115	115	90 ÷ 130	160
Products	Round bar for reinforcing concrete	Round bar for reinforcing concrete, wire rod	Round bar for reinforcing concrete	L and U iron, HE and IPE beams

* Movable hearth furnace; continuous operation; heat recovery from exhaust gases with combustion air pre-heating.

** Conventional type furnace; suction of exhaust gases through a fourth hole in the roof; no heat recovery.

***Furnace rotating on its own vertical axis, with a fixed roof; continuous charging of the pre-heated scrap and suction of exhaust gases both of which occur through a fourth hole in the roof; heat recovery with pre-heating of the combustion air fed to the scrap pre-heating furnace.

****Allowed overload for rated power : 20 per cent.

that :

1. the energy input required by the "least efficient" plant (A, in this new order) is only 7.2 per cent greater than that of the "most efficient" plant (B): the very slight difference in their energy requirements indicates that an advantage regarding direct inputs is, to a certain degree, cancelled out by the disadvantages stemming from the indirect inputs;
2. plant D, which was at a great disadvantage at the first level, has now an energy input only 3.5 per cent greater than that of plant B;
3. viewing the situation from this wider energy outlook, plant A and C no longer appear equal (the

energy required by A is 1.6 per cent greater than that for plant C).

In the present production situation, especially in Italy, the total energy requirement in and of itself does not seem to offer a sufficient energy criterion for evaluating technological solutions. Rather, in the decision-making process regarding energy, in addition to the total requirement, one must also take into consideration that fraction of energy provided as electricity. In fact, the concept of replaceable electrical usage is often found in literature: by this some authors mean that since electricity is a particularly valuable energy form, it should not be utilized for furnishing heat, particularly at low temperatures.

TABLE 2 Consumptions per Ton of Billet

Consumptions	HP furnace	HP furnace with oxy-fuel auxiliary burners		HP furnace with scrap pre-heating furnace(BBC-Brusa process)
		Fuel oil	Natural gas	
	(A)	(B)	(C)	(D)
Electricity (kWh)	682	575	637	530
Electricity for electric furnaces (kWh)	627	528	587	450*
Electricity for accessories (kWh)	55	47	50	80
Fuels				
Fuel oil (kg)	0.1	3.4	-	-
Natural gas (Nm^3)	-	-	6.6	44.8
Propane (kg)	0.2	0.2	-	-
Recarburizers (coal) (kg)	1.1	0.7	0.4	5**
Electrodes (kg)	6.5	4.6	5.3	5.5
Ferro-alloys				
Fe-Mn 75 per cent (kg)	12	14	12	-
Fe-Si 75 per cent (kg)	6	7	6	3
Fe-Si 20 per cent - Mn 70 per cent (kg)	-	-	-	12
Oxygen (Nm^3)	0.5	11.5	10	6**
Slag forming material				
Lime (kg)	35	40	37.5	20
Limestone (kg)	8	3	5.5	40
Fluospar (kg)	2.5	2.5	2.5	-
Refractories				
Furnace lining	8	10	10	12***
Dolomite	13	15	15	3.8
Spray material	2.5	2.5	2.5	-
Cement and others	4.5	4.5	4.5	4
Ladle lining	6	7	6	4.5
Tundish panels	4	4	3	2.4
Lost scrap **** (kg)	116	116	116	63
Scrap ***** /billet ratio	1,163/1,000	1,163/1,000	1,163/1,000	1,111/1,000

* It should be noted that this figure includes a portion of about 35 kWh/t due to the over-heating between 1,665 and 1,715 °C (see Table 1).

** The products of this steel plant (see Table 1) require a refining phase in which the steel is first thoroughly decarburized with an high consumption of oxygen, and then recarburized.

*** Pre-heating furnace included.

****Metallic loss in furnaces and steel plant recycling.

*****Charged, including foreign matter.

TABLE 3 Energy Requirements per Ton of Billet at Levels 1 and 2

Energy requirements (MJ)	HP furnace		HP furnace with oxy-fuel auxiliary burners				HP furnace with scrap pre-heating furnace (BBC-Brusa process)	
			Fuel oil		Natural gas			
	(A)		(B)		(C)		(D)	
DIRECT ENERGY INPUTS								
Electricity and fuels		2,501		2,240		2,534		3,608
Electricity	2,453		2,069		2,294		1,908	
Fuel oil	4		140		-		-	
Natural gas	-		-		227		1,549	
Propane	10		10		-		-	
Coal	34		21		13		151	
Exothermic reactions		680		656		642		578
Iron	273		273		273		202	
Electrodes	197		138		159		166	
Others	210		245		210		210	
TOTAL LEVEL 1		3,181		2,896		3,176		4,186
INDIRECT ENERGY INPUTS								
Acquisition, conversion and transport of energy sources used in the final process stage		3,831		3,242		3,585		3,017
Electricity	3,827		3,228		3,579		2,976	
Petroleum distillates	1		12		-		-	
Natural gas	-		-		5		28	
Coal	3		2		1		13	
Direct energy inputs for production of material inputs		1,260		1,366		1,302		1,005
Lost scrap	370		372		370		201	
Electrodes	227		159		183		191	
Ferro-alloys	296		345		296		280	
Oxygen	3		75		65		39	
Slag forming material	172		196		184		102	
Refractories	192		219		204		192	
Acquisition, conversion and transport of energy sources for production of material inputs		1,271		1,398		1,326		1,009
Lost scrap	550		553		550		299	
Electrodes	227		159		183		191	
Ferro-alloys	431		503		431		408	
Oxygen	5		117		101		61	
Slag forming material	19		22		20		11	
Refractories	39		44		41		39	
TOTAL LEVEL 2		6,362		6,006		6,213		5,031
TOTAL 1 + 2		9,543		8,902		9,389		9,217

In electric arc furnace steelmaking process, heat is supplied within a very wide temperature range, between room temperature and temperatures exceeding 1,700 °C: therefore, from a theoretical point of view, it is particularly important that the most suitable combination of primary and secondary energy sources be identified for use in various temperature ranges. On the other hand, due to the restraints on availability, practical considerations have also contributed to the great interest in limiting electrical energy consumption. This is true both for electrical energy consumed (such restraints are presently very tight in Italy, particularly in areas where the great majority of steelworks are located), and for rated electrical power (this last constraint has led to the adoptation of auxiliary burners in the smelting phase as a means of leveling out the electrical load diagram).

Therefore, let us assume that our hypothetical decision maker adheres to multiple energy objectives or applies multiple energy criteria (i.e., total energy requirement plus electricity consumption). Conflict thus arises and a compromise must be made, i.e., a preferred alternative must be chosen. It should be noted that there is no fundamental conflict between these multiple objectives, but rather between them as a whole and the technological, economic, social and other limits that do not allow for their full and simultaneous implementation.

Zeleny's article (1977) has been our primary source with regard to defining the methodology in order to combine multiple criteria.

Let us look at the preference space in Fig. 3. Axis x shows the ratio between the minimum consumption of electrical energy evidenced in the four plants and the consumption of electrical energy in any one of the plants (E.E. min/E.E.). Axis y shows both the ratios between the minimum total energy requirement and the total energy requirement of any one of the plants, calculated by considering separately the first level by itself, and the first level plus the second one [$(\text{T.E. min}/\text{T.E.})_1$ and $(\text{T.E. min}/\text{T.E.})_2$].

In defining the axes, we have explored the limits achieved along each particular attribute of importance in the available set of alternatives. The highest achieved scores with respect to the two attributes assessed in this way form an ideal alternative (I).[9]

On the basis of this definition, the decision maker will consequently prefer an alternative which is as close as possible to the ideal (I). In other words, he will employ the Euclidean measure of distance (i.e., $d = [(x_I - x)^2 + (y_I - y)^2]^{1/2}$) to provide a ranking.

Keeping in mind the criterion of selection used and applying it to the total direct energy inputs, we can see (in Fig. 3) that the order of preference is : B, C, A, D.

The conclusions would be quite different if we considered both the direct and indirect energy inputs. In that case, the plant D would become the preferred one, moving from fourth to first place, while the relative positions of the other three plants would remain substantially the same. This is due to the fact that with steelworks D we have plant design features which aim at substituting electrical energy with other energy. In the other steelworks, however, we are concerned with adjustments in plant installation features which aim at integrating electrical energy with other energy.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to G. Fantinelli and U. Brusa who provided the operational data referring to plants A,B,C and to plant D respectively.

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[9] Note that point I can be displaced depending on changes in the available set of plants. It would therefore become a mobile target.

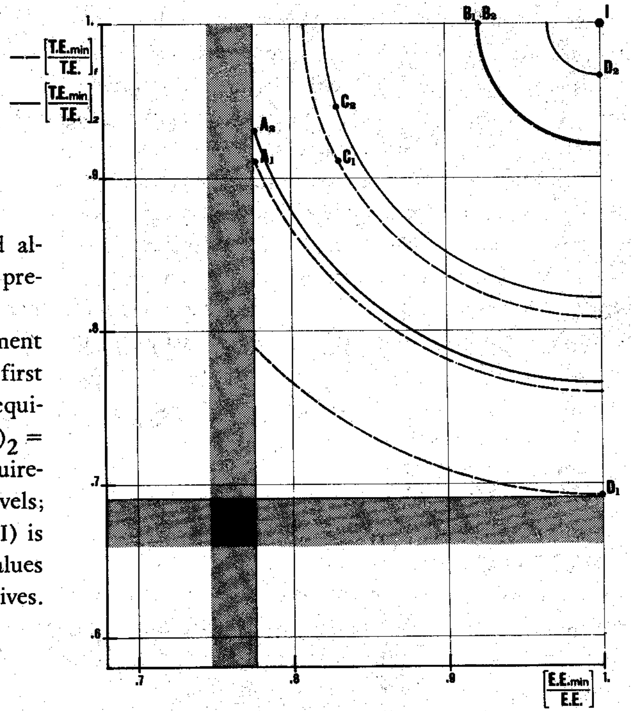

Fig. 3. Identification of the preferred alternative via multiple criteria preference space.
E.E. = electric energy requirement (always considered at the first level); $(T.E.)_1$ = total energy requirement at the first level; $(T.E.)_2$ = = combined total energy requirement for the first + second levels; min = minimum. The ideal (I) is chosen as the best x and y values from the competing alternatives.

Alternatives	Case 1			Case 2		
	Attribute values		Euclidean distance from the ideal	Attribute values		Euclidean distance from the ideal
	$x = \frac{E.E.min}{E.E.}$	$y = \left[\frac{T.E.min}{T.E.}\right]_1$		$x = \frac{E.E.min}{E.E.}$	$y = \left[\frac{T.E.min}{T.E.}\right]_2$	
A	0.778	0.910	0.240	0.778	0.933	0.232
B	0.922	1	0.078	0.922	1	0.078
C	0.832	0.912	0.190	0.832	0.948	0.176
D	1	0.692	0.308	1	0.966	0.034
I	1	1	0	1	1	0

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