

Recent improvements in modelling energy consumption of electric arc furnaces

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ABSTRACT

A formula for calculating the electrical energy demand of arc furnaces had previously been developed by statistical analysis of average values from more than 50 furnaces. Specific consumption of total and some individual (DRI, HBI and hot metal) ferrous materials, slag formers, burner gas, lance and post-combustion oxygen, as well as tapping temperature and tap-to-tap time were taken into account.

Within a current project, data from more than 5000 heats were acquired at 5 furnaces of different mechanical and electrical design, together with monthly averages for one of them over nearly 3 years. The application of the formula to this largely extended data base gave reason to adapt the factors of several influencing variables. The accuracy of the formula was further improved by including shredded scrap and furnace energy losses if measured.

Typical values for the standard deviation of the calculation error are 25 kWh/t for single heats and less than 10 kWh/t for monthly averages. The modification of the formula had no great influence on its error for earlier investigated furnaces. With the presented formula, effects of variation in the respected process conditions can be eliminated for evaluating electrical energy consumption of different furnace types or operating practices.

KEYWORDS : electric arc furnace, electrical energy consumption, statistical model

INTRODUCTION

At the 4th EEC in Madrid 1992, the author presented a formula for calculating the specific electrical energy demand of arc furnaces [1]. This formula had been derived by statistical analysis of average values from several AC single shell furnaces for scrap melting without preheating. By evaluating other AC furnaces, in 1997 the formula had been extended to post-combustion [2]. For the latest IISI Study on EAF Technology [3, 4], DRI, HBI and hot metal as alternative ferrous materials were included in the formula to investigate average values from AC and DC furnaces, as reported at the preceding EEC in Düsseldorf.

Within a current ECSC project, data from more than 5000 individual heats were acquired at 5 furnaces, as well as monthly average values for one of them over nearly 3 years [5]. These furnaces are of different electrical as well as mechanical design: AC and DC single shell, DC twin shell, DC single shaft, AC double shaft. At four of these furnaces, energy losses were determined from measured values of wall, roof and exhaust duct cooling, together with the heat content of the exhaust gas behind its cooling.

The application of the energy demand formula to this largely extended data base gave reason to adapt the factors of several influencing variables to fit the individual heats better. The accuracy of the modified formula was further improved by including the energy losses if measured and the charged weight of shredded scrap.

ORIGINAL ENERGY DEMAND FORMULA

The first version of the electrical energy demand formula took into account only specific consumption of ferrous materials, slag formers, burner gas and lance oxygen, as well as the tapping temperature and the tap-to-tap time, divided in power-on and power-off time, see **Table 1**. Calculated versus actual electrical energy consumption is plotted in **Fig. 1** for 13 furnaces investigated in 1992.

Table 1: Original formula for electrical energy demand of arc furnaces

$\frac{W_R}{\text{kWh/t}} = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 80 \cdot \frac{G_{DRI} + G_{HBI}}{G_A} - 300 \cdot \frac{G_{HM}}{G_A} + 1600 \cdot \frac{G_Z}{G_A}$ $+ 0.7 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.85 \cdot \frac{t_S + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} - 15 \cdot \text{CON}$			
G_A	furnace tap weight	t_S	power-on time
G_E	weight of all ferrous materials	t_N	power-off time
G_{DRI}	weight of DRI [3]	M_G	specific burner gas
G_{HBI}	weight of HBI [3]	M_L	specific lance oxygen
G_{HM}	weight of hot metal [3]	M_N	specific post-combustion oxygen [2]
G_Z	weight of slag formers	CON	+1 for continuous operation -1 for discontinuous operation [3]
T_A	tapping temperature		

Comparison of the energy consumption for 7 other furnaces included in Fig. 1, which were operated without and with post-combustion, allowed to extend the formula for additional oxygen input for post-combustion within the furnace shell [2].

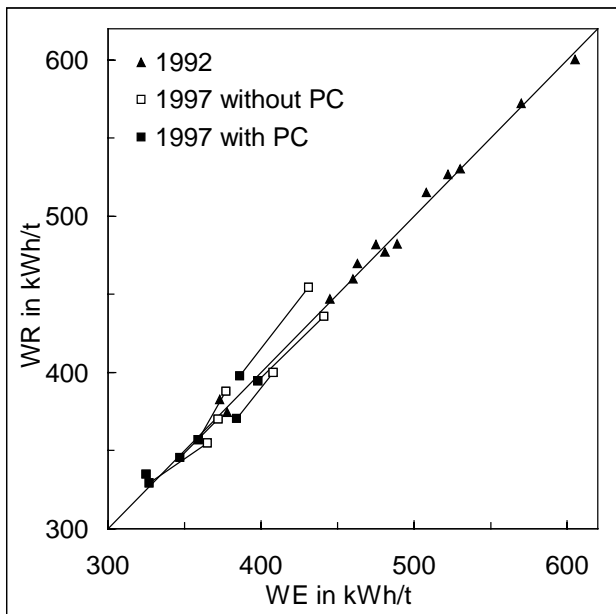


Fig. 1: Calculated versus actual electrical energy for furnaces investigated in 1992 [1] and in 1997 [2]

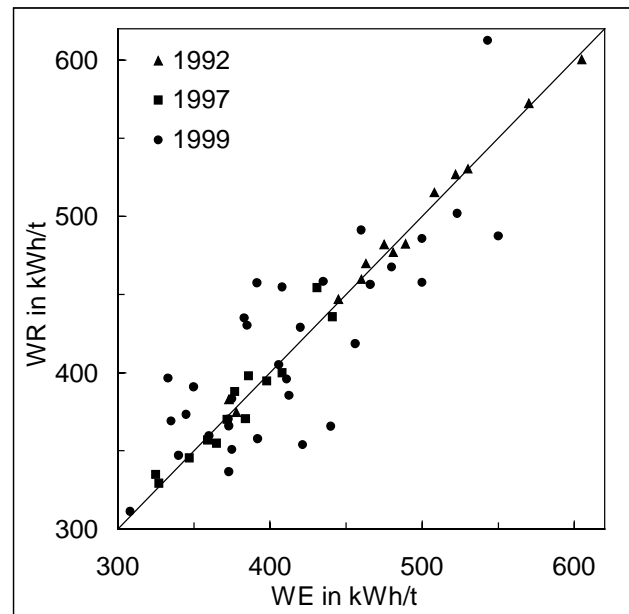


Fig. 2: Calculated versus actual electrical energy including furnaces from the IISI Study in 1999 [3, 4]

Fig. 2 additionally presents 34 furnaces from the IISI Study. To evaluate these furnaces, the formula was extended to higher energy demand for DRI or HBI and to lower energy demand for hot metal [3, 4]. Pig iron is not included in the formula, as the reduction in electrical energy consumption due to its use results from the increased oxygen input which is taken into account separately. It was also regarded if a furnace was operated continuously or not, e. g. because of frequent interrupts with respect to energy tariffs.

For the furnaces investigated in 1999, the scatter of the calculation error $dWR = WR - WE$ is much larger than from the previous investigations. Some high positive errors were explained by energy saving from scrap preheating in baskets or furnace shafts, as this is not regarded by the formula. Some great negative errors were explained by reduced efficiency of more than $\approx 35 \text{ m}^3/\text{t}$ oxygen input, or by low efficient scrap preheating with burners in the non-melting vessel of twin shell furnaces. No advantage in energy consumption could be seen for DC furnaces, as often had been claimed. This agrees with earlier results from Bowman who compared energy consumption of AC and DC furnaces and found that the same formula can be used for both furnace types [6].

APPLICATION OF THE ORIGINAL FORMULA TO SINGLE HEATS

The formula in Table 1 had been developed by statistical analysis of average values from more than 50 furnaces. For evaluating single heat values from an individual furnace, the formula had to be checked critically. **Table 2** gives some data of the furnaces investigated in a current project and the numbers of heats evaluated for each furnace [5]. All relevant operating values per heat were measured. Energy losses from vessel cooling and with gas exhaustion were measured at furnace C for all heats, and during some data acquisition periods also at furnaces A, B and D. In addition to single heat values, monthly averages of operating values were evaluated for furnace A over a period of nearly 3 years.

Table 2: Investigated furnaces and numbers of evaluated heats

EAF	design		MVA	t	remarks	heats
A	single shell	AC	70	80	up to 35% shredder	644
B	single shell	DC	140	155		1185
C	twin shell	DC	140	150		1200
D	single shaft	DC	110	160	up to 30% hot metal	1288
E	double shaft	AC	105	110		1136

In **Fig. 3** the electrical energy demand WR, calculated with the original formula, is plotted versus the actual consumption WE for 227 heats from furnace B as an example. The three lines in this plot, crossing each other at the mean values, need to be explained. The line "Reg WR(WE)" with the lowest slope results from the regression for WR versus WE. The inverse regression gives the line "Reg WE(WR)" with the highest slope. The slope of the medium line "mean Reg" is the square root of the slopes from both others. As stronger WR and WE are correlated, described by the square R^2 of their correlation coefficient, as more equal the three lines become.

The aim in modelling WE by WR for an individual furnace is to achieve a strong correlation between both and to get their mean regression line in parallel to the unity line. This is not the case in Fig. 3 with the original formula, but the variation in WR is higher than in WE. The situation is very similar for single heat values from the other investigated furnaces.

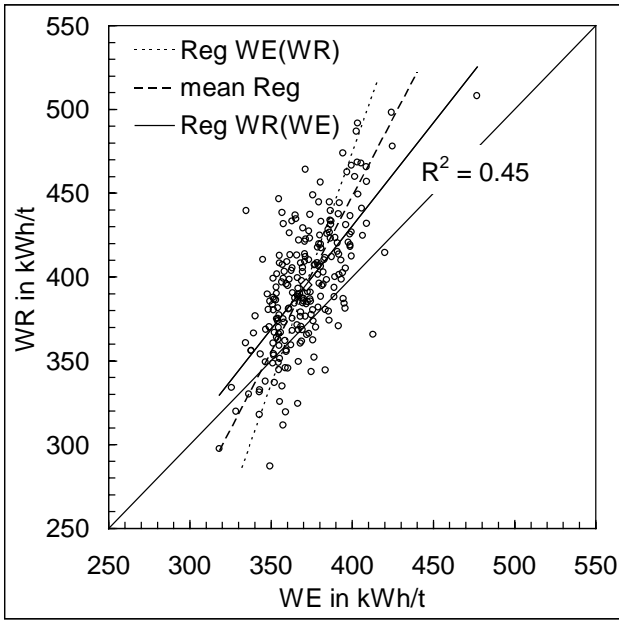


Fig. 3: Calculated versus actual electrical energy (227 heats from furnace B)

A detailed analysis of the calculation error $dWR = WR - WE$ revealed that it is strongly correlated with the specific ferrous material consumption $gE = GE/GA$ for all the sets of single heat values, but not for the average values from earlier investigations. For the heats from Fig. 3 this is shown in **Fig. 4**.

The regression coefficient of 0.56 kWh/kg is more than half as high as the corresponding factor of 900 kWh/t or 0.9 kWh/kg in the formula. This could mean that this factor is too high, so that with increasing ferrous material the calculated electrical energy demand grows stronger than the real consumption. But the correlation observed for the calculation error could also be introduced by other effects and required further investigations.

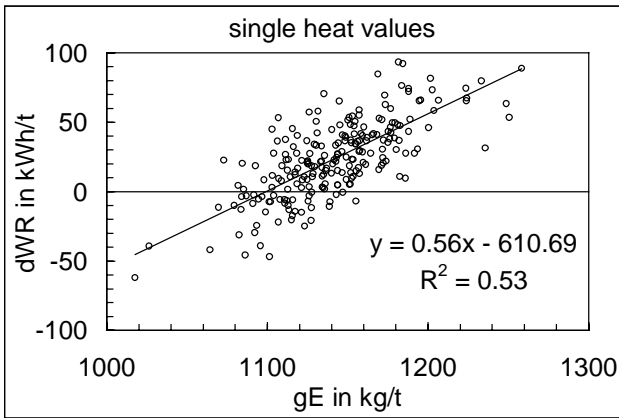


Fig. 4: Calculation error versus total ferrous material for single heats

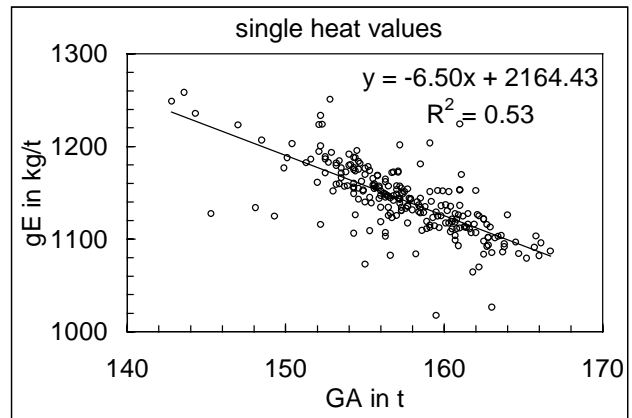


Fig. 5: Total ferrous material versus tap weight for single heats

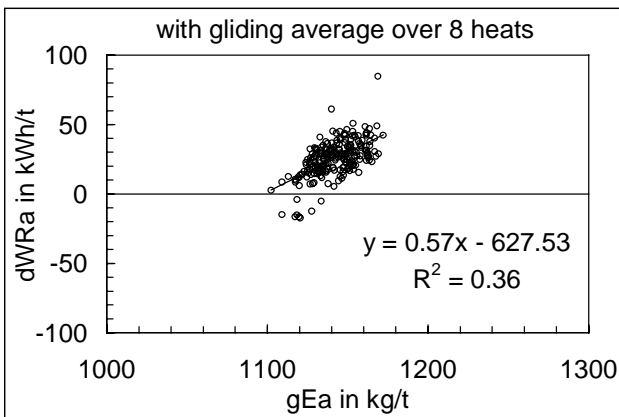


Fig. 6: Calculation error versus total ferrous material with average over 8 heats

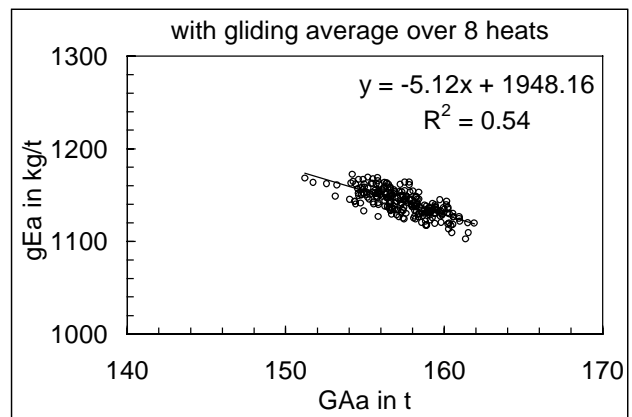


Fig. 7: Total ferrous material versus tap weight with average over 8 heats

As shown in **Fig. 5**, ferrous material consumption is strongly correlated with the tap weight; also this is very similar for all single heat data sets. This correlation could be caused by variation in the weight of the hot heel remaining in the furnace after tapping. Such variation would falsify the tap weight which became different from the real weight of steel produced by the individual heat. This tap weight error would be transferred to errors in all specific consumption values, so that between the electrical energy consumption and all other consumption items artificial correlation would be introduced in addition to real dependencies.

A solution for this problem was found by averaging the single heat data. Gliding averages over 8 heats were built for all input variables of the formula, and electrical energy demand was calculated from the resulting average values. The electrical energy consumption and the tap weight were averaged in the same way. With averages over 8 consecutive heats, the influence of hot heel weight variation should be reduced remarkably. But the plots with averaged values in **Fig. 6** and **Fig. 7** show the same relations as the plots with the original single heat values, only the scatter is reduced by averaging. Thus it is concluded that the possible variation in the hot heel weight has no remarkable impact on observed relations between the energy calculation error and total ferrous material consumption. Its factor in the original energy demand formula was too high and had to be reduced.

MODIFICATION OF THE ENERGY DEMAND FORMULA

Because of inter-correlation between total ferrous material consumption and other input variables of the energy demand formula, several of its factors had to be adapted. The aim was to get a good correspondence between calculated demand and real consumption of electrical energy for the earlier as well as for the presently investigated furnaces. For the single heat values of each of these furnaces this means to achieve a strong correlation between WR and WE and to get their mean regression line in parallel to the unity line, as explained above in the description to Fig. 3. The mean value of the calculation error for the single heat values of an individual furnace is not relevant under this aspect, as an error may be caused by specific furnace design or operating practices. The modified formula is given in **Table 3** as the result from an iterative optimisation procedure.

Table 3: Modified formula for electrical energy demand of arc furnaces

$\frac{W_R}{\text{kWh/t}} = 375 + 400 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 80 \cdot \frac{G_{DRI}/\text{HBI}}{G_A} - 50 \cdot \frac{G_{Shr}}{G_A} - 350 \cdot \frac{G_{HM}}{G_A} + 1000 \cdot \frac{G_Z}{G_A}$ $+ 0.3 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 1 \cdot \frac{t_S + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} + NV \cdot \frac{W_V - W_{Vm}}{\text{kWh/t}}$			
G_A	furnace tap weight	t_S	power-on time
G_E	weight of all ferrous materials	t_N	power-off time
G_{DRI}	weight of DRI	M_G	specific burner gas
G_{HBI}	weight of HBI	M_L	specific lance oxygen
G_{Shr}	weight of shredder	M_N	specific post-combustion oxygen
G_{HM}	weight of hot metal	W_V	energy losses (if measured)
G_Z	weight of slag formers	W_{Vm}	mean value of W_V
T_A	tapping temperature	NV	furnace specific factor (0.2 ... 0.4)

Comparison with Table 1 shows how the formula has been modified:

- for total ferrous material the factor was decreased from 900 to 400 kWh/t,
- for energy reduction by hot metal the factor was raised from 300 to 350 kWh/t,
- for slag formers the factor was decreased from 1600 to 1000 kWh/t,
- for tapping temperature the factor was decreased from 0.7 to 0.3 kWh/t/K,
- for power-on and power-off time the factor was increased from 0.85 to 1 kWh/t/min,
- the term for continuous / discontinuous operation was eliminated,
- the constant term had to be raised from 300 to 375 kWh/t.

Besides these adaptations, the formula was extended for shredded scrap and for energy losses if measured. The difference between energy losses of an individual heat and their mean value is taken into account with a furnace specific factor NV. No reason was found to change the original factors for burner gas, lance oxygen and post-combustion oxygen.

For the heats in Fig. 3, the electrical energy demand from the modified formula is plotted versus the actual consumption in **Fig. 8**. The correspondence between both is obviously improved. Measured energy losses are taken into account at this furnace with $NV = 0.25$.

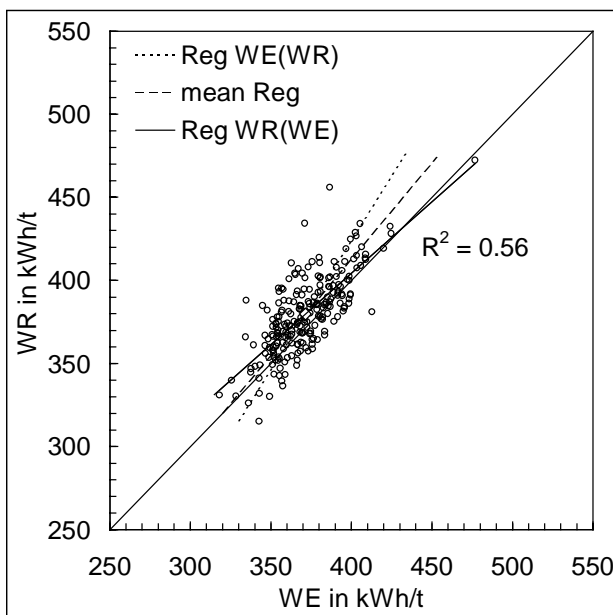


Fig. 8: Heats from Fig. 3 after modification of the energy demand formula

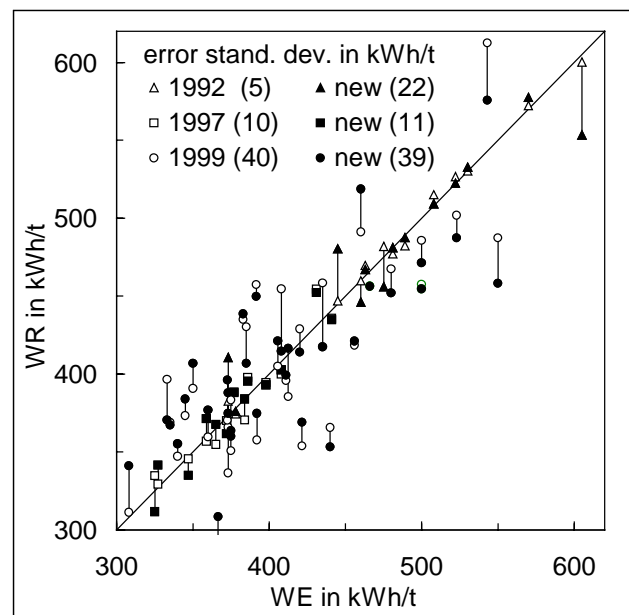


Fig. 9: Earlier investigated furnaces before and after modification of the formula

For the earlier investigated furnaces, electrical energy demand from the original formula (see Fig. 2) and from the modified formula are plotted versus actual consumption in **Fig. 9**. No dramatic differences can be seen. For the first group of these furnaces however, the standard deviation of the calculation error increased from 5 to 22 kWh/t. This result is not surprising, as those furnaces were the basis to develop the original formula, and its factors were perfectly adapted to that data set. The evaluation of average values from both subsequently investigated furnace groups gave no reason to modify the factors; the error standard deviations for these groups remained nearly the same as before.

Inclusion of measured energy losses. The effect of energy losses on the calculated electrical energy demand can best be demonstrated by example of furnace C, at which energy losses were measured for all evaluated heats. Without regarding energy losses, the calculated demand is nearly not correlated with actual consumption of electrical energy for this furnace, see **Fig. 10**. Including measured energy losses (with $NV = 0.4$) improves

the situation remarkably as shown in **Fig. 11**. For the other furnaces, correlation between WR and WE without regarding energy losses is stronger than for furnace C, so that the improvement by including the energy losses is not so impressive for them as shown here.

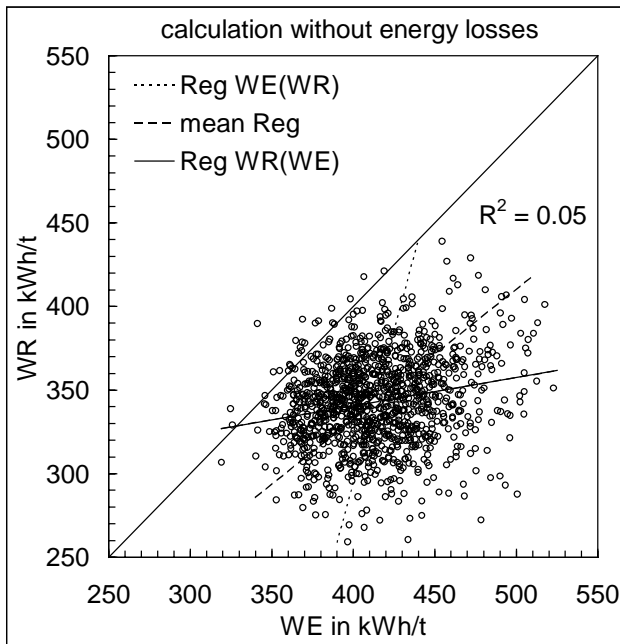


Fig. 10: Calculation of the electrical energy demand without energy losses (1200 heats from furnace C)

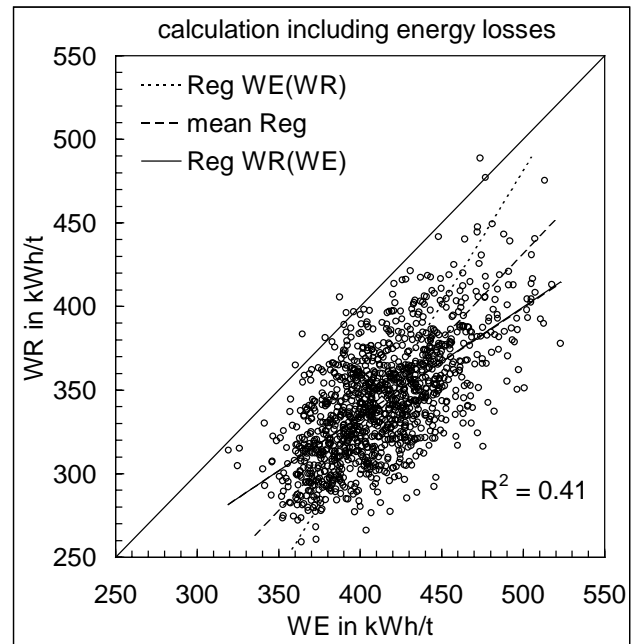


Fig. 11: Heats from Fig. 10 with measured energy losses included in electrical energy demand by $NV = 0.4$

Inclusion of shredded scrap. Monthly average values of the main scrap types consumed at furnace A during the evaluated period are shown in **Fig. 12**. The greatest change can be seen for the shredded scrap weight which was increased up to 35% of the total ferrous material. The lowered electrical energy consumption was not sufficiently modelled by its demand calculated without regarding shredder, but after its inclusion in the formula with an advantage factor of -50 kWh/t the correspondence became excellent, see **Fig. 13**.

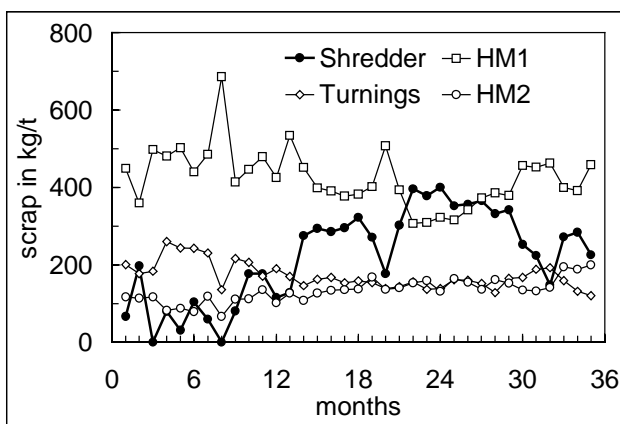


Fig. 12: Trend in main scrap types during 35 months at furnace A

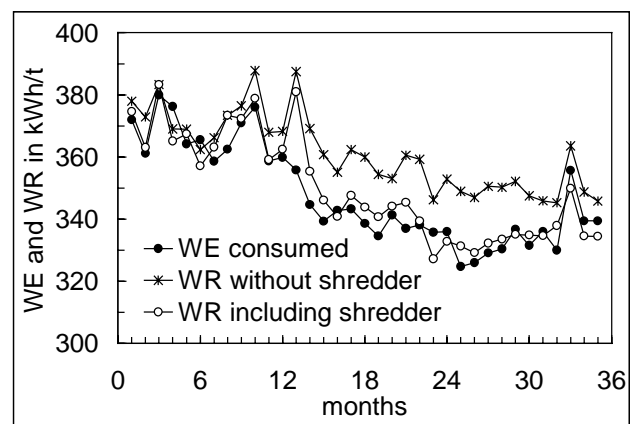


Fig. 13: Calculation of the electrical energy demand without and with shredder

No individual effect on the electrical energy consumption was found for other scrap types, neither at furnace A, nor at the other furnaces. As the shredded scrap weight is lower and more uniform at the others, its inclusion lowers their electrical energy demand by $\approx 5 \text{ kWh/t}$ on average, but has no effect on the modelling accuracy for the other furnaces.

EVALUATION OF ELECTRICAL ENERGY CONSUMPTION

The energy demand formula is based now on average values from about 60 furnaces, on single heat values from about 5500 heats in 5 furnaces and on monthly averages from one of them over nearly 3 years. Thus it is regarded reliable to calculate the electrical energy demand, so that effects of varying process conditions on the electrical energy consumption can be taken into account in evaluating the performance of different furnace types as well as operating practices.

Statistical results with the modified formula are compiled in **Table 4** for the average values of the 3 groups of earlier investigated furnaces, for the monthly averages from furnace A and for the single heat values from all 5 presently investigated furnaces. For the earlier investigated groups, correlation coefficients between calculated demand WR and actual consumption WE of electrical energy are very high, especially for both groups from 1992 and 1997. Correspondingly their standard deviations $\sigma(dWR)$ of the error $dWR = WR - WE$ are lower than for the third group. The error mean values are low for all 3 groups.

Table 4: Results of energy demand calculation for earlier and presently investigated EAF

Investigated furnaces	Evaluated data from	Remarks (WV = energy losses)	\overline{dWR} kWh/t	$\sigma(dWR)$ kWh/t	correlation (WR;WE)
1992	13 EAF		0	22	0.95
1997	7 “		2	11	0.96
1999	34 “		-1	39	0.78
A	35 months	up to 35% shredded scrap	2	7	0.92
A	644 heats	96 heats with WV	-5	15	0.31
B	1185 “	332 heats with WV	1	24	0.54
C	1200 “	with WV, high burner gas	-70	29	0.64
D	88 “	with WV, $\leq 30\%$ hot metal	14	27	0.83
D	1200 “	without hot metal	-21	26	0.61
E	1136 “	preheating in the shaft	48	22	0.60

For the monthly averages of furnace A, the correlation coefficient is also very high, and the error standard deviation is very low, see Fig. 13. For the single heats from this furnace, the correlation coefficient is low because of a low scatter in electrical energy consumption from heat to heat. For the 96 heats with measured energy losses, taken into account with $NV = 0.4$ at this furnace, the correlation coefficient is 0.47 compared to 0.31 for all heats.

The same is observed at furnace B with energy losses measured for 332 heats. For these, with $NV = 0.25$, the correlation coefficient is 0.77 compared to 0.54 for all heats, and their error standard deviation is reduced from 24 to 16 kWh/t. 227 of these heats with measured energy losses were presented in Fig. 8.

For the heats from furnace C, with energy losses measured for all of them, the effect of including these losses with $NV = 0.4$ was demonstrated in Fig. 10 and Fig. 11.

For the 88 heats from furnace D, for which measured energy losses are taken into account with $NV = 0.2$, the high correlation coefficient of 0.83 is caused by a large variation in the electrical energy consumption, as for most of these heats up to 30% of hot metal was charged, so that their energy demand is much lower than for the remaining heats without

hot metal. The correlation coefficient for further 1200 heats of furnace D without hot metal is lower and similar to those for heats from other furnaces.

To discuss the calculation errors for furnaces A - E, mean values of calculated demand and actual consumption of electrical energy are plotted in **Fig. 14** for the monthly averages of furnace A and for the heats of all 5 furnaces. From the 88 heats of furnace D, only those 71 heats with hot metal (HM) were selected. **Fig. 15** presents the calculation error versus burner gas consumption. Whereas the error standard deviations are nearly equal for all the furnaces, except furnace A because of its low scatter in electrical energy consumption mentioned before, their error mean values are very different.

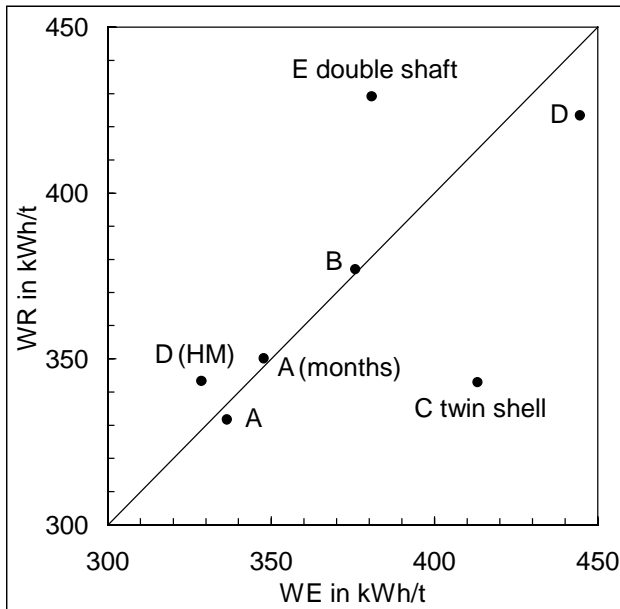


Fig. 14: Calculated versus actual electrical energy for furnaces A - E

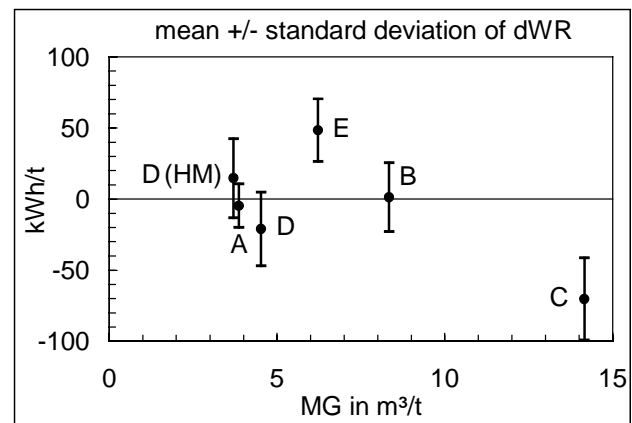


Fig. 15: Calculation error for furnaces A - E versus burner gas consumption

The twin shell furnace C has a high burner gas consumption, mainly to preheat the scrap in the non-melting vessel. This operating practice has a low thermal efficiency and is only justified to increase productivity. The decreasing efficiency of higher burner gas input has been investigated and helps to explain the high error for this furnace [7]. From the total error of -70 kWh/t, decreasing gas efficiency causes ≈ 40 kWh/t. The remaining is related to the long power-off times for each shell. It must be mentioned that for twin shell furnaces the shorter power-off times per heat are regarded for the demand calculation and limited to a minimum of 20 minutes, in order to make them comparable with single shell furnaces.

For the double shaft furnace E, the lower as calculated electrical energy consumption is regarded as advantage from preheating scrap in the shaft by the exhaust gas from the melting vessel. With respect to the power-off time effect discussed before, energy recovery from scrap preheating is even higher than the calculated 48 kWh/t.

The benefit from scrap preheating is low for the heats of furnace D with hot metal from the time when this furnace was operated with shaft fingers. For the later scrap only heats without shaft finger operation, the electrical energy consumption is of course higher than for the hot metal heats, and it is higher than calculated.

The energy calculation errors for the remaining furnaces A and B are very low. Electrical energy for the single heats from furnace A is lower than for the monthly averages, as the single heats are from periods with reduced electrical energy consumption, see Fig. 13.

CONCLUSIONS

With the energy demand formula, effects of variation in any one of the respected process parameters can be eliminated in evaluating the electrical energy consumption of different furnace types or operating practices, as shown for scrap preheating by exhaust gas in shaft furnaces and by burners in the non-melting vessel of a twin shell furnace.

With the modified formula, a typical value for the standard deviation of its calculation error for single heats is 25 kWh/t. Comparing the electrical energy consumption for two sets of e. g. 200 heats each, under statistical aspects their calculation error mean values are thus significantly different from each other if they differ by more than only 5 kWh/t. Different performance of two furnaces or performance deviations at the same furnace under varying process conditions can therefore easily be detected.

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