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Thermal Efficiency of Steel Melting

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Abstract.

This paper presents the results of energy consumption measurements at steel foundries using induction and/or electric arc furnace melting. Statistical methods, infrared thermography, and numerical investigations were used for analysis of heat losses. The influence of different melting practices on energy losses was examined. Industrial experiments in isothermal holding of liquid steel in induction furnaces under different power inputs were used for evaluation of the real values of heat losses by radiation from liquid steel and conductivity through lining. Average values and statistical distributions of energy consumptions for melting steel are presented in this article.

Introduction

The higher temperatures required for the melting of steel results in significantly higher energy losses in comparison with melting other industrial cast alloys. For example, the rate of heat loss from the surface of liquid steel in a furnace or ladle is 10-15 times greater than a similar sized molten aluminum surface. Therefore, the energy costs associated with heat losses during melting are significantly higher for steel foundries than foundries melting other cast alloys. Today's steel foundries use both induction furnaces (IF) and electric arc furnaces (EAF) for melting steel. Within the steel foundry industry there is great variety in furnace capacity, power supply, age of equipment, rate of production, melting schedule, and operating practice, all of which have major influences on energy consumption. The purpose of this paper is to provide benchmark information on the energy consumption for steel melting in the steel foundry industry based on the type of charge materials, melting technologies, furnace type, and operating practices. This study is one of the first tasks in the "Energy Efficiency in Melting" research project started in 2004 at UMR funded by the US Department of Energy (through ATI) and member steel foundries of the Steel Founders of America. This paper summarizes measurements of energy consumption collected during trials at seven of these member companies.

Methodology

Experimental measurements, statistical data, heat transfer calculations, and numerical simulations were used to evaluate the energy consumption and heat losses during steel melting in seven different steel foundries utilizing both induction and electric arc melting. In this paper, the seven foundries are designated Foundry A through Foundry G for reasons of confidentiality.

Experimental measurements in steel foundries. A team from UMR visited each foundry and observed the melting of several heats. During the visit, three to five special trial heats were melted in which detailed energy data was generated and collected including:

- Power setting and power on times
- Electrical consumption
- Weights and compositions of all charge materials
- Weights of liquid metal and amount cast into product and pigged
- Oxygen and natural gas consumption
- Frequent temperature measurements using immersion thermocouples and high temperature infrared camera (Snap Spot by Infrared Solutions).

Statistical data. In addition to the detailed data collected during the melting trials, information was collected from 20 to 100 additional heats at each foundry using heat reports, casting reports, etc. to provide sufficient data on each foundry for statistical analysis of the melting time, energy consumption, charge materials, and steel chemistry.

Energy/Heat balance. One important part of this study was an evaluation of the total energy use during the melting operation in each foundry. To evaluate the total energy consumption, an energy balance during melting was required which included determining the typical energy losses to refractories, water cooling, electrical systems, and radiation. Two specific experiments were:

- "Power-off" experiments both free of slag and under slag allowing evaluation of total and radiation heat losses.
- Isothermal holding experiments which provided data on the minimum amount of electrical energy required to compensate for electrical and heat losses.

Two IF foundries were equipped with thermometers and flow meters for each of the cooling water lines. This allowed for measurements of the conduction heat losses through the refractory as well as the electrically generated heat (Joule) losses when combining the water flow and temperature measurements with the normal, power-off, and isothermal holding experiments. These experiments provided validation for the thermal modeling required to estimate the losses at facilities that did not have the ability to measure the temperature or flow-rates of cooling water. In these cases, only cumulative and operational electrical energy efficiency were measured and calculated. Thermal efficiency of chemical energy during oxygen blowing was evaluated in one foundry in which the EAF was equipped with an oxygen flow meter by measuring the temperature changes and chemistry of the melt before and after oxygen blow. The EAFs using oxy-fuel burners did not have flow meters on the oxygen or natural gas. In this case, consumption was estimated based on design and use of the burners.

Induction Furnace (IF) Melting

Four steel foundries with different capacity IFs are included in this study. All furnaces had medium frequency power supplies and were lined with alumina based (alumina spinel) refractory. Heats were batch melted and often utilized a liquid heel resulting from excess steel being returned from the previous heat instead of pigging. Foundries A, B, and F typically melt 8 to 12 hours per day with the furnaces setting idle (and cold) during the off-shifts. Foundry G melts by induction furnace occasionally and on those days typically melts only one heat per day in a furnace. The variety in melting schedules resulted in wide differences in the percentage of heats melted in furnaces with hot linings (ranged from 0% to greater than 80%). Table 1 compares the furnace capacity and transformers at each of the plants.

Table 1. Induction furnace capacity and transformer characteristics

Foundry	Capacity, lb	Power supply, KW	Frequency, Hz
A	2500	500	700
B	9500	4500	500
F	900 1800	250 500	800 900
G	2000	450	900

The following summarizes some of the findings and discusses energy issues at each of the induction furnace melting facilities.

Foundry A. Figure 1 is the time-operational plot of low carbon steel production in a 2500 lb capacity IF. In this case, the furnace was hot and utilized 200 lbs of liquid metal returned from the previous heat. The lower half of this figure reflects the sequence of charging, alloying, deslagging and tapping. Energy usage and temperature of the melt are plotted in the upper half of this figure. The energy used for heating and melting of the charge materials was projected based on the weight of charge material, the theoretical energy requirements for heating and melting, and the liquid temperatures after complete melting. The calculated energy losses (gray areas in upper plot) are the difference between the total electrical energy supplied to the furnace and the useful electrical energy (theoretical energy requirements to heat and melt the solid charge and superheat the liquid). The heat can be divided into four main periods (divided by dotted lines in the figure), each of which has dramatically different energy efficiency. The highest operational efficiency occurred during the first period when the scrap was heated to the melting temperature, melted, and then superheated. During this period, electrical efficiency was nearly 80%. However, during the second period, the energy efficiency dropped to nearly zero because only sufficient electrical energy was supplied to hold the liquid metal at temperature (overcome heat losses) while taking chemical samples, waiting for chemical analysis and making alloy additions. Heat losses were minimized from the top of the furnace by maintaining a coagulant cover on the liquid melt during hold times.

During the third period, the slag coagulant was removed and a higher tap setting used to heat the steel to the tap temperature, resulting in an electrical efficiency of 30-40%. Figure 2 compares the energy efficiency during each of the four periods for heats utilizing a hot heel practice (Figure 2a) and the energy efficiency for melting in cold furnaces (Figure 2b). This figure illustrates the increased energy required to soak an initially cold induction furnace and the resulting increase in tap time to provide the necessary energy.

A modified Sankey diagram (Figure 3) illustrates the energy flows for the overall energy balance. Input energy consisted of the sensible heat in the liquid heel and 500 KWH per ton of electricity, of which only 67.6% was required to melt and superheat the steel to the tap temperature. The main heat loss was to the cooling water for the coil. The energy transferred from the melt by heat conduction through the lining and Joule heat losses were calculated from the experiments in which the water temperature changes were measured with and without power. In this case, the sum of radiation losses and heat of lining accumulation, calculated as the imbalance between output and input, was not significant. Figure 4 is the modified Sankey diagram for melting in the cold induction furnace. Significantly greater energy is required to soak the lining and the longer time in the furnace resulted in greater radiation losses from the surface resulting in much higher energy consumption (666 KWH/ton versus 500 KWH/ton) and longer heat time (207 minutes versus 120 minutes). Table 2 summarizes the data for this plant.

Table 2 Influence of melting practice on energy consumption (Foundry A)

Heat	Melt, lb	Heat time, min	KWH/ton
Cold start	2450	200	666
Hot start	2450	120	500

Foundry B. This plant simultaneously melts in two 9500 lb capacity induction furnaces with only one 4500 KW power supply unit. As melting progresses, power is switched between furnaces based on the melting practice so that utilization of the transformer is nearly 100%. This facility also had an automatic charging system making it easy to keep the furnace full at all times during the melt down. Typically, each of the furnaces is at different stages, one furnace is melting scrap with the power on while the second furnace is taking chemistry samples, waiting on chemical analysis and getting alloys ready once the chemical analysis has been received. Once alloys are added to the second furnace, the power is switched to that furnace to raise the temperature for tap. During tapping and preparing of the furnace, the power is switched back to the melting furnace. Figure 5 is a time-operational graph for one of the furnaces and reflects the extended idle time for the furnace due to the single power supply. During the delays, coagulant was added to the surface and a refractory lid covered the melt to reduce the heat losses. Although this minimizes the heat losses through the top surface of the steel, it does not reduce the heat losses through the side walls resulting in a drop of temperature during the idle time. This is indicated in Table 3 as a negative energy efficiency value because heat losses exceeded the heat input. During the initial melting stage, a high tap setting (>950 KW/ton) is used resulting in fast melting (35-40 min) and a fairly short heat time (95-100 min) even though both furnaces are operated with a single power supply and must share total power-on time. This plant utilized a number of technologies that helped decrease the total energy consumption including high density charges, maintaining furnace at full capacity (9500–9800 lb.), continuous charging during melting using a scrap conveyor, hot lining practice, and a furnace lid using a low heat conductivity ceramic.

Table 3. Operational energy efficiency melting steel in induction furnace (Foundry B)

	Melting	Heat up	Idle	Total
Time, min	37	5	58	98
Energy efficiency, %	70.5	48	-7.1	63.5

Foundry F. Foundry F was a jobbing foundry and operated two IFs during the trial period of observation. The melting process was interrupted many times while the melt was waiting for molds. Two different time-energy consumption graphs are depictured in Figure 6 for the same IF with similar charges. The heat time for the first heat was 80 minutes, much lower than the second heat which has been included for comparison (120 minutes heat time with several delays waiting for molds). The total energy consumption varied between a low of 590 and a high of 750 KWH/ton.

Foundry G. This foundry melts several heats of steel daily in EAFs and only occasionally melts in one of the IFs. An example energy balance for a heat in this IF is given in Figure 7. The weight of this heat was only 70% of furnace capacity which contributed to less efficient melting. Additional energy was required due to a cold lining at the start of melting and a lack of coagulant cover or lid resulting in higher radiation losses. Therefore, as a result, the total energy consumption was 753 KWH/ton and the energy efficiency was only 47%. In this case, the radiation losses from the open surface were 7% and the sum of the lining accumulation heat requirements and electrical losses were 28%.

EAF

The four foundries participating in this study used EAFs with capacities between 2.5 and 15 tons. Two of the plants used basic refractory linings and two used acid refractory linings. A summary of the EAF equipment is included in Table 4.

Table 4. EAFs included in study

Foundry	#EAF	Typical heat, lb	Transformer, KVA	Lining
C	1	19000	6500	Magnesia
D	1, 2	11000	2500	Silica
E	1	6500	2000	Silica
	2	8500	3300	
	3	9400	2000	
G	2	20000	7500	Magnesia
	4	8500	2600	

Neither of the two EAFs at Foundry D or the #2 EAF at Foundry G had KWH meters. In foundry E, EAF #3 was equipped with PLC controls for the electrical system and EAF #1 and #2 used oxy-fuel burners through the slag door. All of the foundries blew oxygen but only Foundry C had an oxygen flow meter. The energy balances were calculated at Foundries C, E, and EAF #4 at Foundry G by taking into account:

- electrical energy input
- input of chemical energy from the reaction between oxygen and carbon in the melt and from the oxidation of graphite electrodes (Foundry C). For purposes of energy balances, it was assumed that the oxygen combusted with C to form CO and the energy was recovered by the melt. This assumption was confirmed by temperature measurements in two plants. The complete combustion of CO is assumed to be in the off-gas system and not recovered in the EAF.
- output energy for melting steel and slag formation (including $CaCO_3$ decomposition).

Foundry C. Three heats with different melting practices were observed, including the first heat of the day (cold furnace), a heat in a hot furnace with a heel, and a heat in a hot furnace with liquid metal returned from the previous heat (heel). As summarized in Table 5, melting in a hot furnace with a heel reduced the heat time and the KWH/ton. This foundry had energy supply restrictions and demand often interrupted the melting process. This along with other delays resulted in power-on time typically being less than 50% of the heat time. Figure 8 is an example time-operational graph for a heat melted in a hot furnace with a liquid heel. The energy consumption per ton of tapped metal was adjusted considering the sensible heat value of the liquid heel from the previous heat. Foundry EAFs are more efficient in using energy during the melting of the solid charge than when superheating molten steel. This is because there are greater losses from molten steel's surface and through the refractory walls. The total values of the input energy, consisting of electrical and chemical energy and sensible heat (heel) and output energy for melt steel and slag are shown in Figure 9 for different practices.

Table 5. Parameters of melting steel in EAF at Foundry C

Heats	Total weigh, lb	Heel, lb	Heat time, min		Energy consumption, KWH/ton	
			Power	Total	Total	Adjusted
Cold start	20200	0	79	122	525	525
Hot start with heel	22000	7000	46	100	348	510
Hot start with melt back	15700	7000	35	115	295	520

Statistical analysis was used to evaluate the influence of different melting parameters on energy consumption. The average electrical consumption in KWH/ton was significantly higher for heats with cold furnaces versus hot furnaces. However, melting with heel in a hot furnace did not show any statistical improvement in energy consumption (see Figure 10). Although the KWH/ton would appear to decrease in heats using heels, when the energy is adjusted for the liquid heel, the actual KWH/ton used to melt the solid scrap is not significantly different (see top in Figure 10b). On the other hand, Figure 11 shows that there is statistical significance between melting time and charge weight for each of the different melting practices and that although there is no significant energy advantage to using a heel, there is a significant productivity advantage to using a heel versus no heel in a hot furnace. It is also important to note in Figure 11b that electrical (and total) energy consumption decreased with increasing productivity when melting steels in the same furnaces.

Table 6. Statistics of electrical energy consumption KWH/ton for melting steel in EAF at Foundry C

	Average	Melting practice		
		Cold start	Hot start with solid	Hot start with heel
Unadjusted	486	567	510	368
Adjusted with energy of heel	515	567	510	511

Foundry E. One of the furnaces at this plant (#3) was equipped with a PLC system. This technology resulted in better management of the electrical characteristics of the furnace operation and allowed for the collection of precise statistical data. For example, in this furnace, it was found that there was not only a measurable difference in the productivity and energy consumption for the first heat each day in a cold furnace, but the second heat on a lining also showed lower productivity and higher energy consumption than later heats when the lining greater heat saturation (see Figure 12a and 12b). Increasing productivity decreased the average electrical energy consumption for all practices (Figure 13).

Furnaces #1 and #2 have oxy-fuel burners mounted in the door. These are only used during the first 10 minutes of melting and provide chemical energy to assist the arc melting process. This resulted in significantly higher productivity than Furnace #3 (no burner) and lower electrical energy consumption (see Table 7). A typical energy balance based on statistical data from Furnace #2 is illustrated in the modified Sankey diagram in Figure 12c.

Table 7. Statistics of electrical energy consumption KWH/ton for melting steel in EAF at Foundry E

	EAF		
	#1	#2	#3
Melt time, min	54.2	56.2	84
KWH/ton	457	329*	489

* This data was calculated from one week's energy consumption and will be validated in the future.

Foundry G. This foundry typically tapped 1-2 heats per day in each EAF during the period of this study. The energy consumption for 3 observed heats in #4 EAF are given in Table 8. There was no statistical correlation between charge weight, specific energy consumption, and melt time in this foundry (see Figure 14).

Table 8. Parameters of melting steel in EAF at Foundry G

Lining	Charge, lb	Melt time, min	Tap T, F	KWH/ton	Electrical energy efficiency, %			
					Operational			Total (steel+slag)
					Melt	Heat up	Correction	
Cold	9500	165	3146	779	75.8	30	9	54.3
Cold	6600	146	3024	700	72.2	-	-	53.2
Hot	5600	86	3263	643	79.4	32.4	-	67.6

Discussion and summary

The purpose of this article was to analyze the current situation with respect to energy consumption (benchmark) in existing steel foundries. Industrial observations, experiments, measurements, and statistical evaluations showed a wide variability in energy consumption for steel melting.

Induction Furnaces - Figure 15 reflects the spectrum of energy consumption for steel melting in induction furnaces at four foundries. The electrical energy varied from a low of 450 KWH/ton to a high of 800 KWH/ton representing 35% to 235% excess energy from the approximately 345 KWH/ton required to melt room temperature scrap and heat to tap temperature. Table 4 summarizes some of the factors that contribute to the excess electrical energy consumption at the participating foundries.

Table 9. Factors which contribute to excess energy consumption in induction furnace melting

Foundry	Capacity, lb	Time, min			KHW/ton	Factors influencing energy losses
		Melting	Holding	Total		
A	2500	80-90	40-110	120-180	480-650	Cold starts, idling for chemical analysis
B	9500	35-40	40-55	75-95	534	Idling for parallel heat
F	900 1800	70-80 80-90	10-30 10-90	85-120 90-180	580-750 550-750	Cold starts, idling for molds
G	2000	80	20	100	753	Cold start, melt without cover, small charge

There were several factors that helped contribute to decreasing the energy consumption including:

- Melting in furnace with hot lining
- Shorter melting time which was achieved by higher density charges, continuous charging of scrap during melt, and larger power supplies (KW capacity per ton)

- Melting under slag (coagulant) which decreases radiation losses (high temperature liquid metal is not exposed)
- Furnace lids constructed from low thermal conductivity ceramics which decrease heat losses (conduction and radiation).

Electric Arc Furnaces – A comparison of the heat time (Figure 16) and the electrical energy consumption (Figure 17) are included for five of the furnaces participating in this study. Heat time ranged from a low of 40 minutes (Furnaces #1 and #2 at Foundry E) to as high as 240 minutes at Foundry G. The electrical energy consumption ranged from a low of 320 KWH/ton (Furnace #2 at Foundry E) to a high of 780 KWH/ton (Foundry G). The two EAFs with the lowest electrical consumption both employed oxy-fuel burners (additional chemical energy) which significantly decreased the required electrical energy and the heat time. When considering total energy (chemical plus electrical), furnaces utilizing oxy-fuel burners were overall more efficient (79% in Figure 12) than those without oxy-fuel burners (69% in Figure 9b).

In general, accurate energy data was difficult to obtain because most foundries do not have complete instrumentation or measuring devices to monitor energy consumption. For example, several foundries do not have functional KWH meters to monitor electrical consumption. Only one furnace had an oxygen flowmeter. Therefore, the quantity of oxygen used in this study was based on the carbon consumption during the oxygen blow and a back calculation of the necessary oxygen required to form carbon monoxide. Theoretically, each 0.1%C in the melt when oxidized by oxygen stoichiometrically (with no excess oxygen) will increase the temperature of the steel by 20^{o}F if CO is formed or 72^{o}F if CO_2 is formed. In several melting trials during this study, the temperature was measured to increase by 20-25^{o}F per 0.1% C confirming the formation of CO stoichiometrically with oxygen and also indicating that very little effective post combustion of CO is occurring in foundry furnaces. Accurate oxygen data would provide a more precise evaluation of oxygen usage.

Some of the important factors that impact energy consumption and energy cost of melting in current foundries are:

- Melting in cold furnaces increase the energy required by as much as 30-50% which indicates that some foundries may want to consider creative scheduling (fewer melting days per week, fewer furnaces, etc.) to maximize the number of heats each day in a single furnace.
- Productivity delays result in higher energy losses through conduction to the refractory and from liquid surface radiation (EAFs have a large surface to volume ratio)
- Better instrumentation (electrical regulation, PLC, computer controls, etc.) help monitor and reduce total energy consumption
- Oxy-fuel burners are one of the most effective methods of reducing electrical consumption and increasing productivity. Although chemical energy increases, the cost of energy for chemical is typically much lower than electrical and the advantages to higher productivity reduce energy losses because of the faster heat time.
- Ladle practice can significantly reduce energy consumption because heat losses to insufficiently preheated ladles increase the energy required in the furnace prior to tap.

- Scheduling is important - plants that are driven by productivity (tap as many heats as possible every shift) are far more energy efficient than plants that are limited in productivity by the schedule (limited number of heats per shift).

There are many opportunities for energy, productivity, and cost improvements in steel foundry melting operations. The steel mini-mill industry has utilized technologies such as foamy slag, long arc practice, heavy use of chemical energy (oxy-fuel burners, oxygen during melt-down and post-combustion), and real time computer monitoring and controls. Table 10 compares the energy consumption in EAFs from foundries with data collected at several mini-mills in the US.

Table 10: Comparison of energy characteristics (minimum – **average -** maximum) for EAFs in steel foundries and mini-mills.

	Data from 6 Foundry EAFs	Data from 8 mini-mill EAFs
Electrical Energy (KWH/t)	330 – **500** - 780	320 – **377** - 424
Chemical Energy (KWH/t)	30 – **60** – 120	149 – **183** - 244
Total Energy (chem. + elec)	440 – **560** – 820	535 – **560** -603
Average Heat time (minutes)	54 – **90** – 120	40 – **54** - 73
Power-on-time (%)	30 - **60** - 75	76 – **84** - 91

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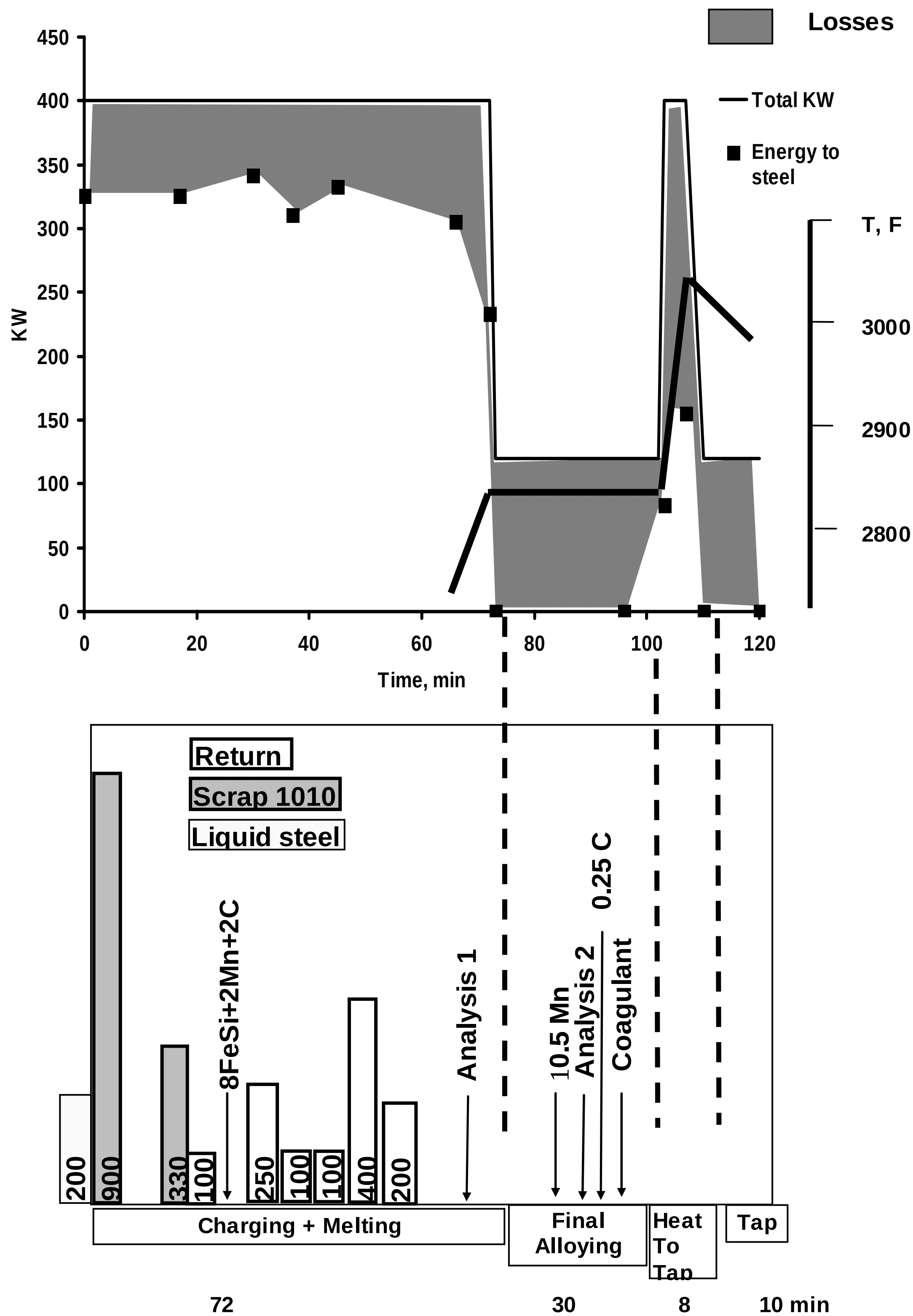
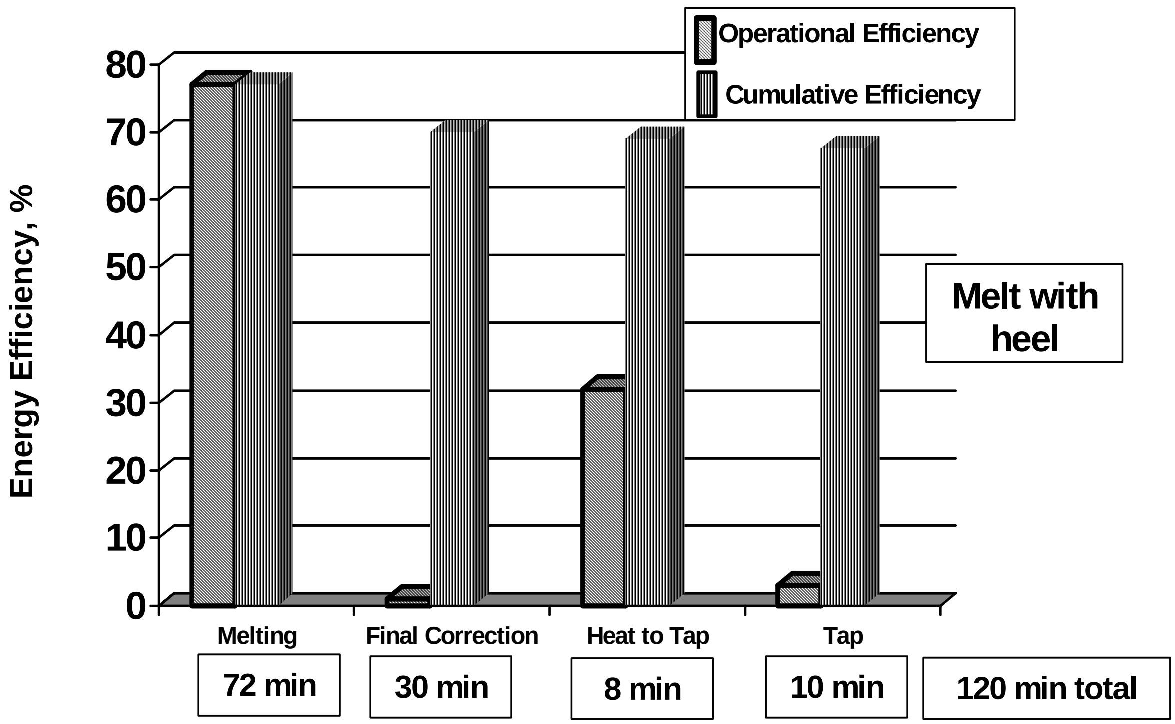
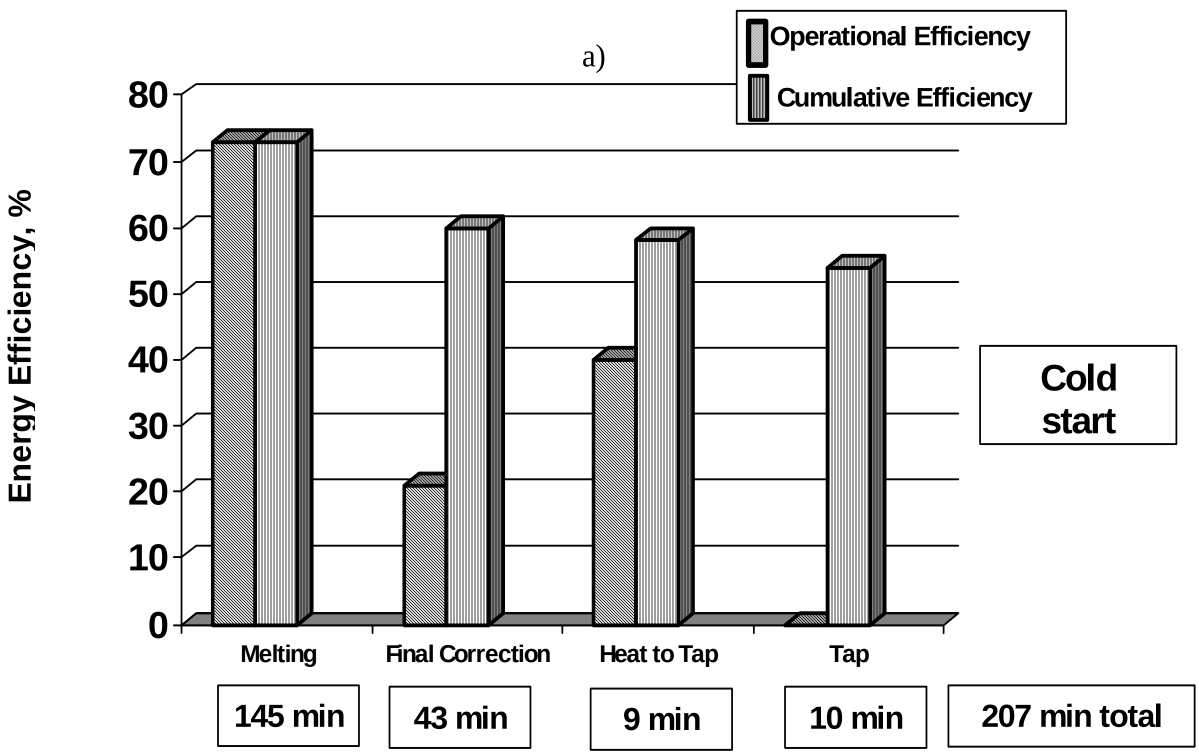


Figure 1. Time-operational graph of melting steel in hot induction furnace with 200 lb heel (Foundry A)



a)



b)

Figure 2. Influence of melting practice in induction furnaces on operational and cumulative energy efficiency (Foundry A)

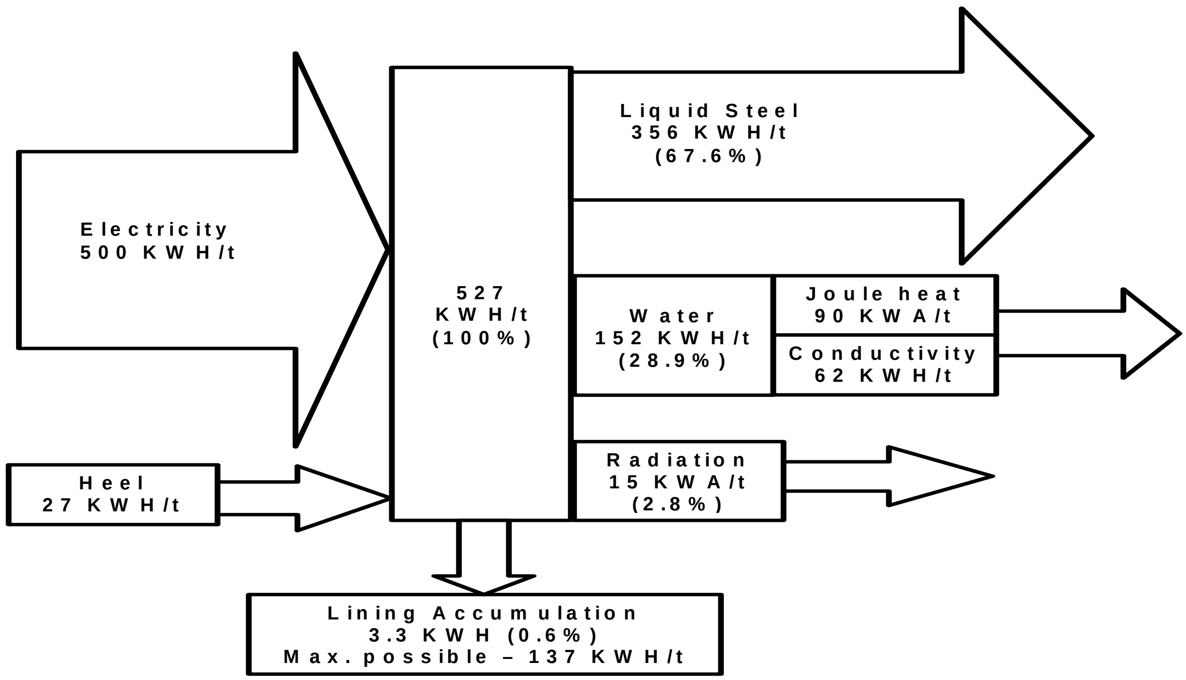


Figure 3. Modified Sankey-diagram (energy flow) of heat in hot induction furnace with heel (Foundry A)

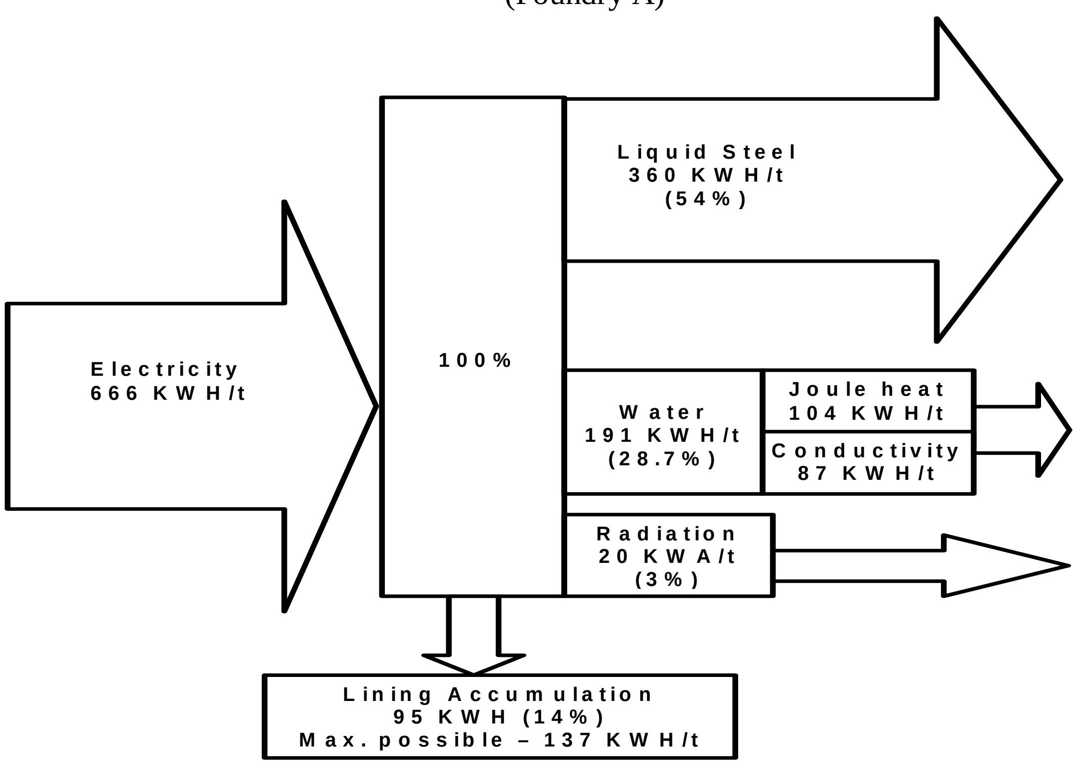


Figure 4. Modified Sankey-diagram (energy flow) of heat in cold induction furnace (Foundry A)

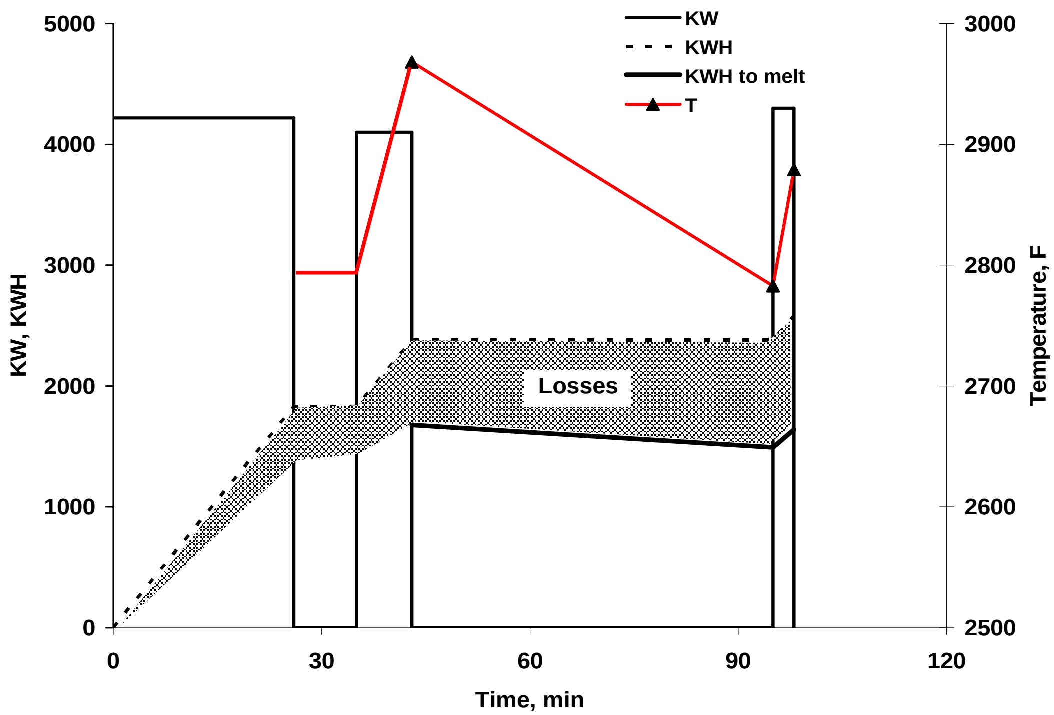


Figure 5. Time-operation graph of melting steel in induction furnaces (Plant B)

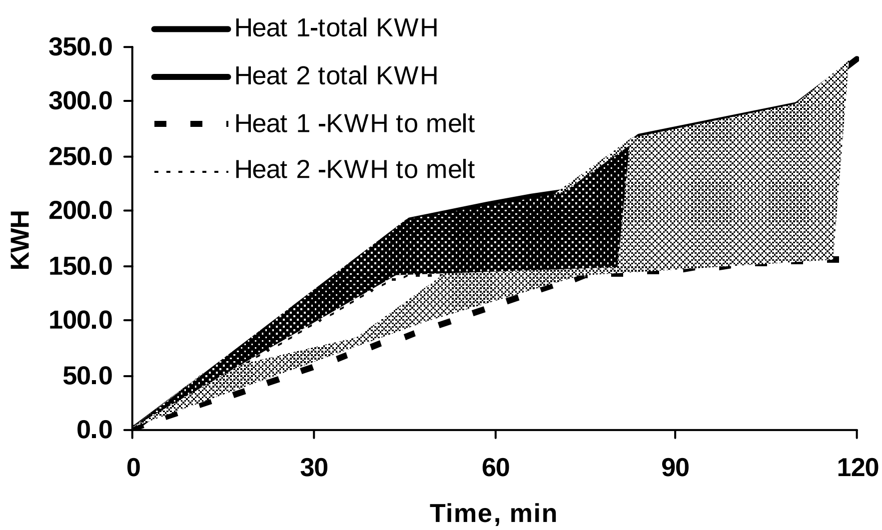


Figure 6. Different time-energy consumption graphs for two heats in induction furnace (Foundry F)

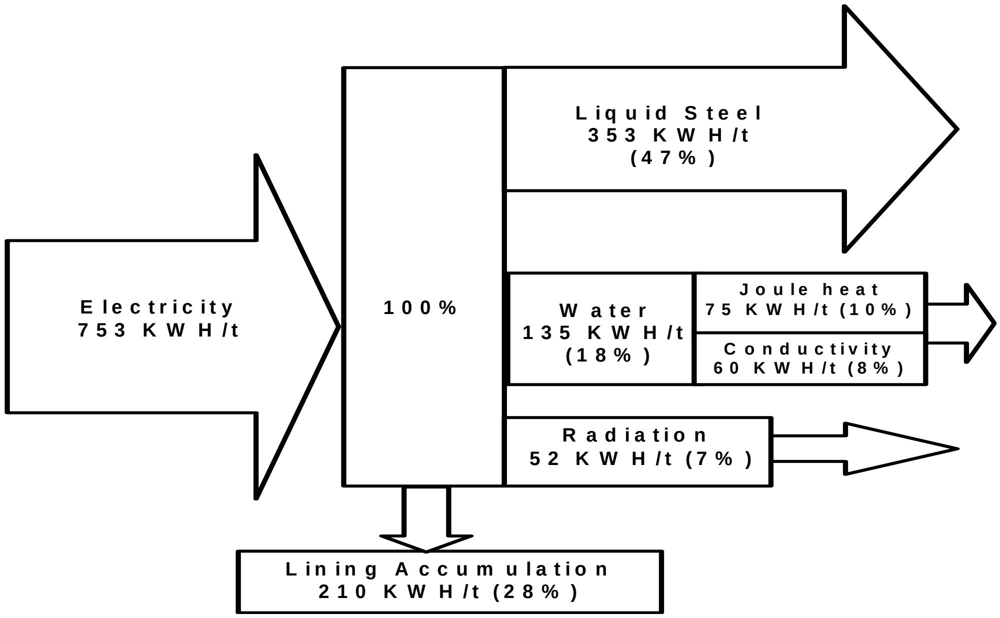


Figure 7. Modified Sankey-diagram (energy flow) of melting steel in cold induction furnace without cover (Foundry G)

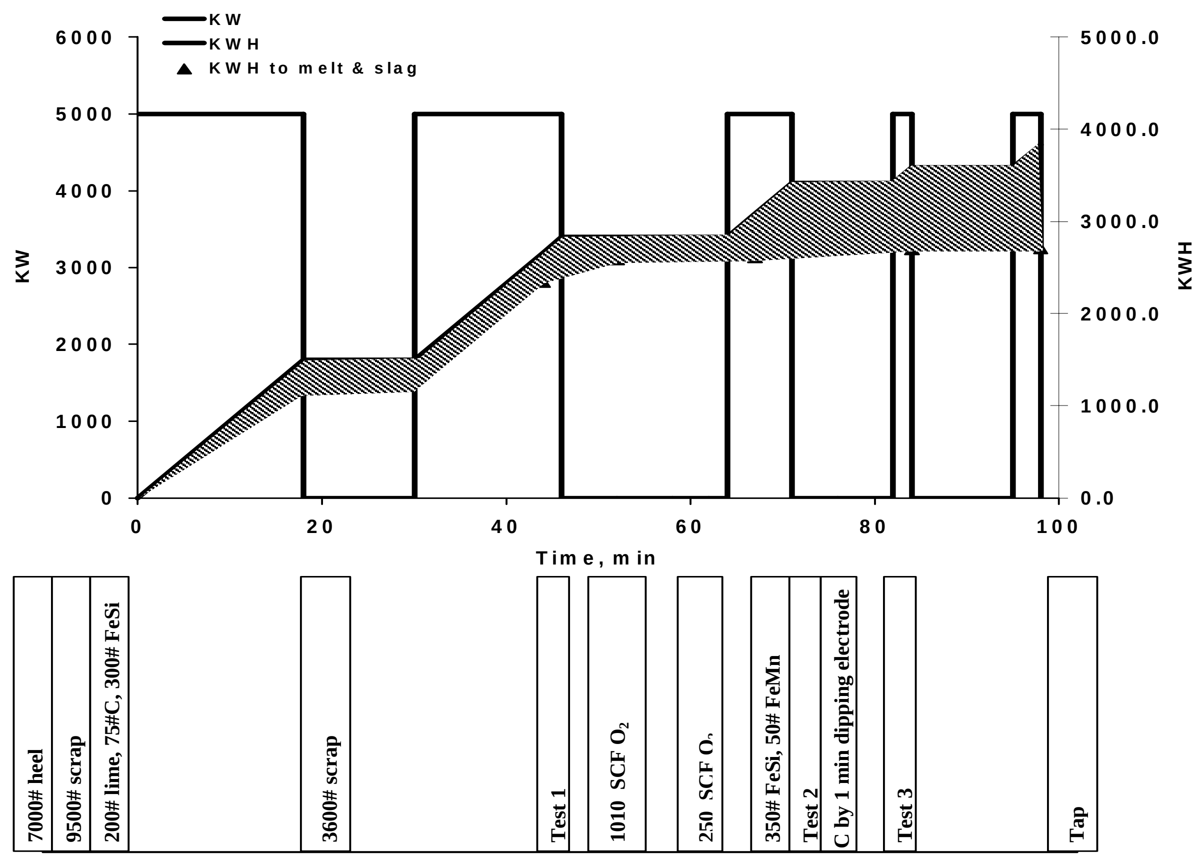
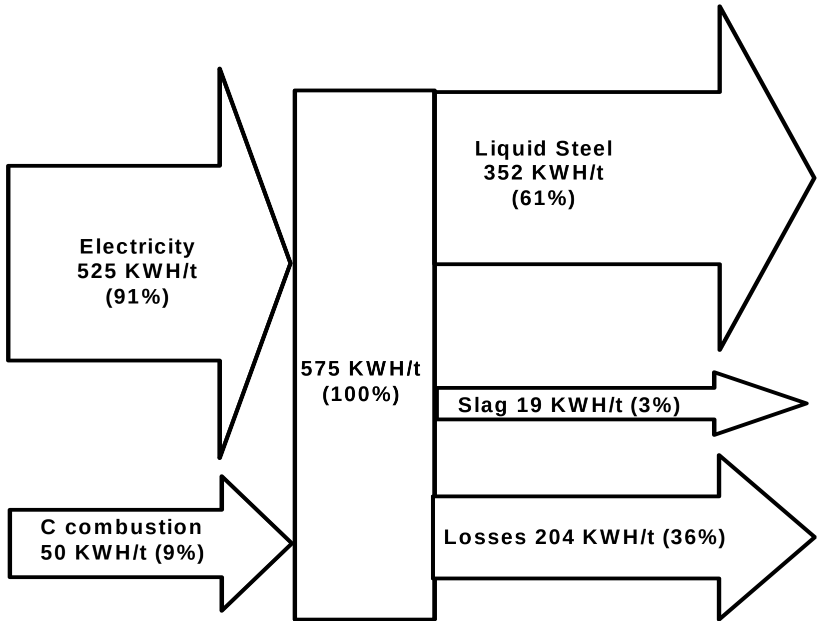
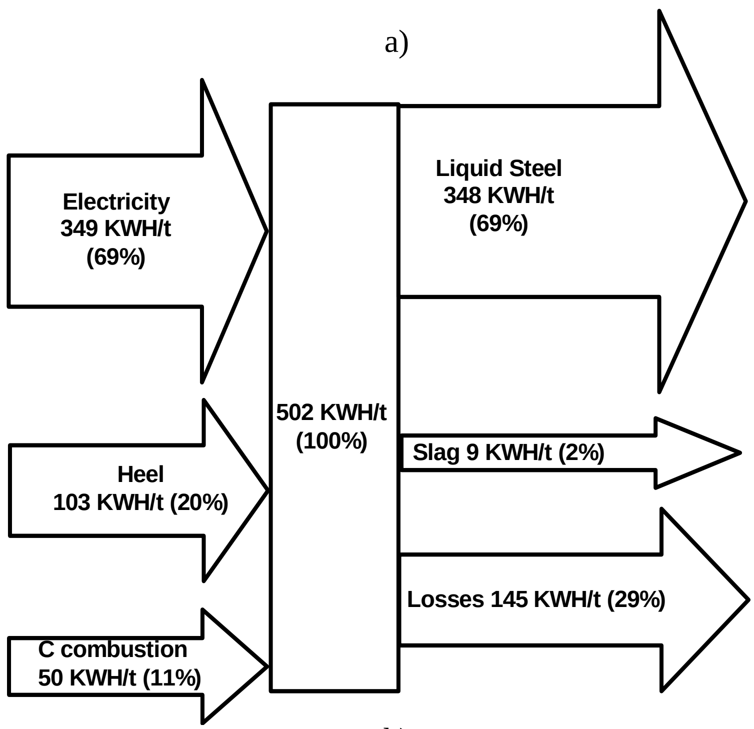


Figure 8. Time-operation graph of melting steel in 15 ton capacity EAF with 3.5 ton heel (Foundry C)



a)



b)

Figure 9. Sankey-diagrams (energy flows) of melting steel in 15 ton EAF with cold start (a) and with heel (b)

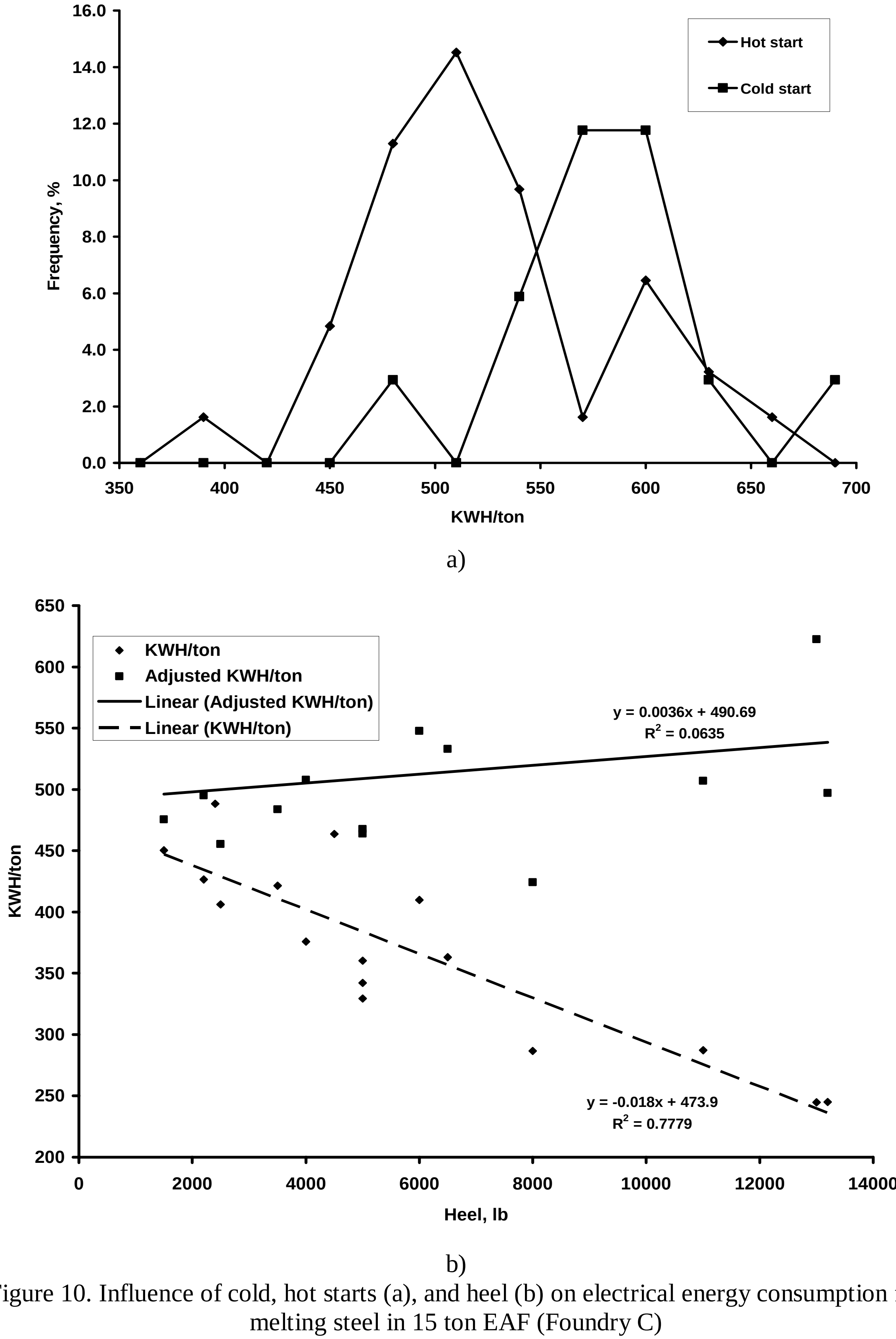
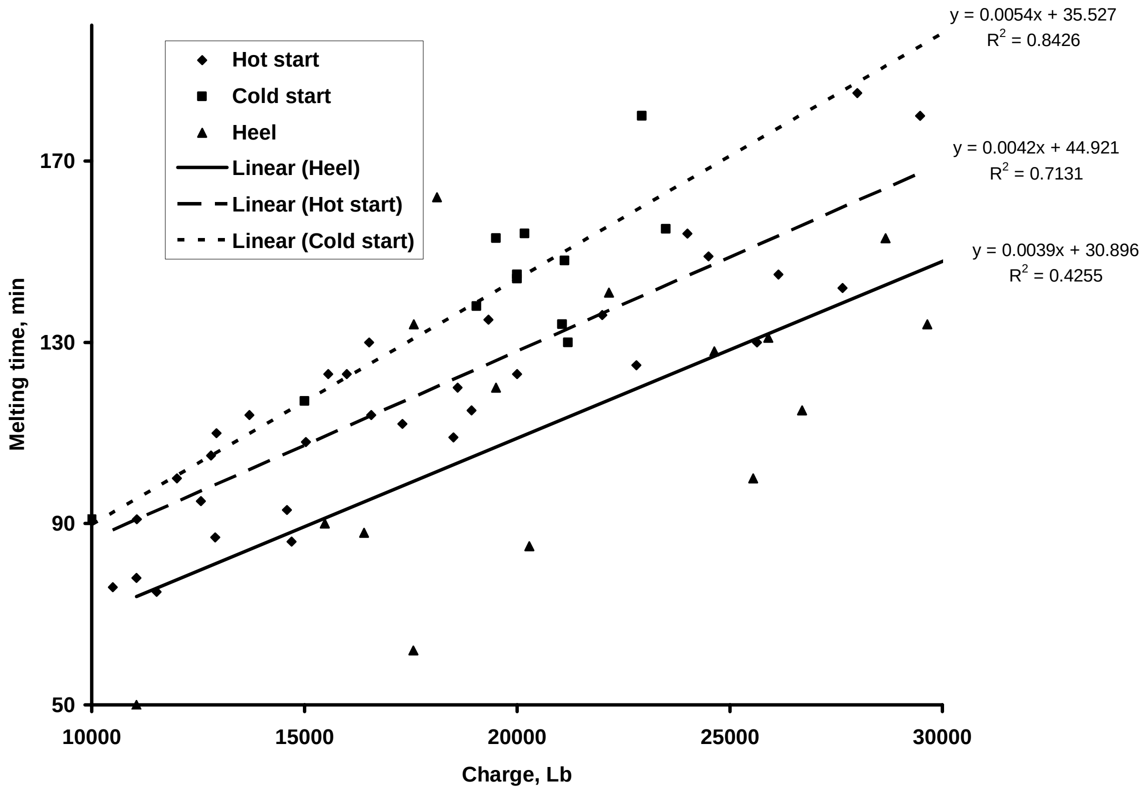
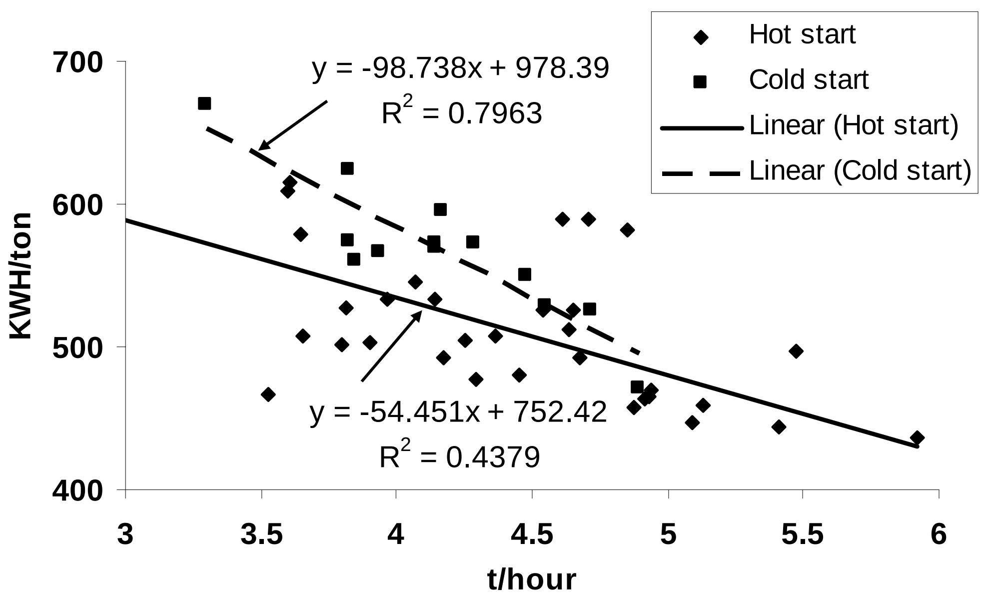


Figure 10. Influence of cold, hot starts (a), and heel (b) on electrical energy consumption for melting steel in 15 ton EAF (Foundry C)



a)



b)

Figure 11. Productivity and energy consumption for melting steel in 15 ton EAF (Foundry C)

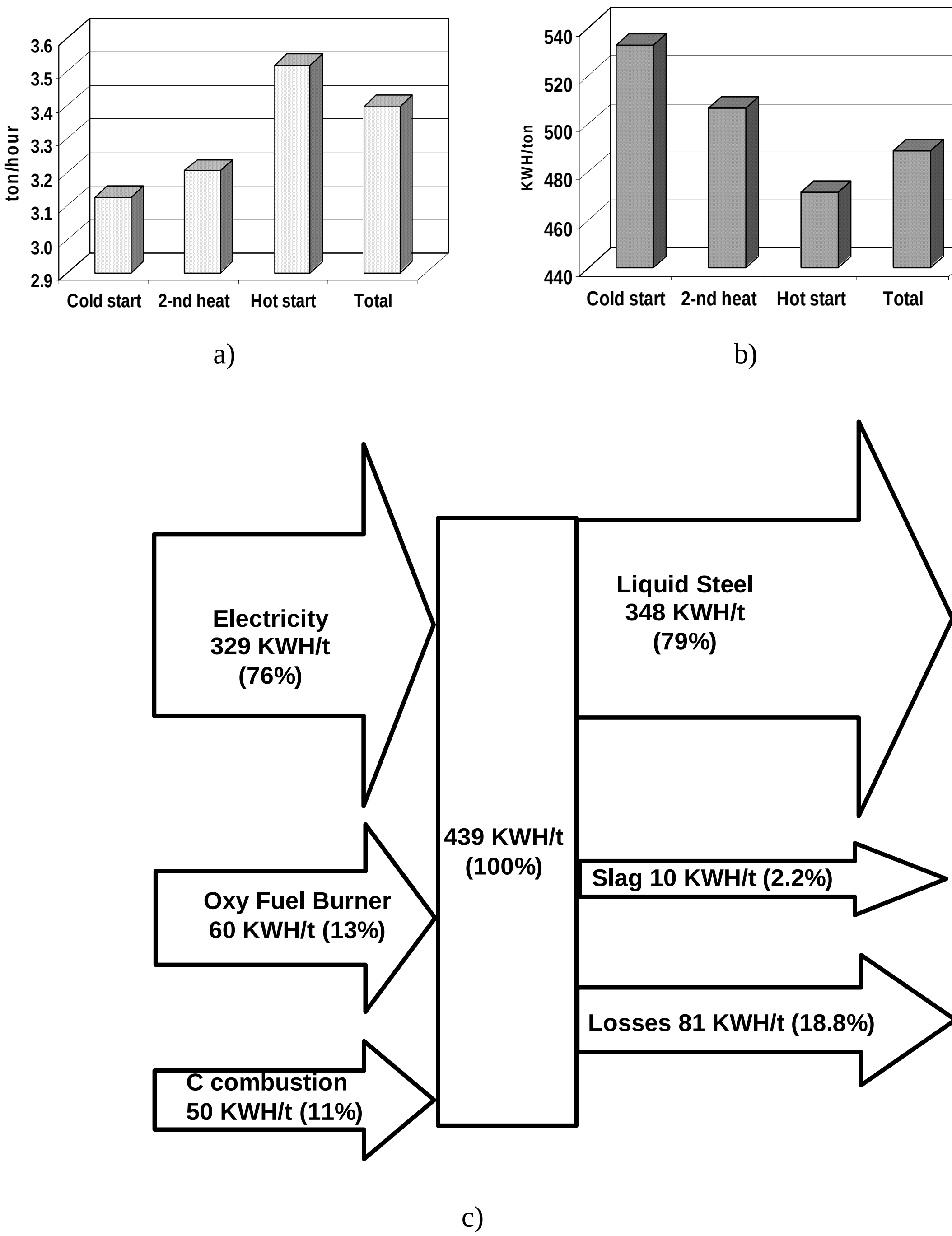


Figure 12. Productivity (a) and average energy consumption (b) for melting steel in EAF 3# with PLC, and Sankey-diagram (energy flow) of melting steel in EAF #2 with oxy fuel burner (Foundry E)

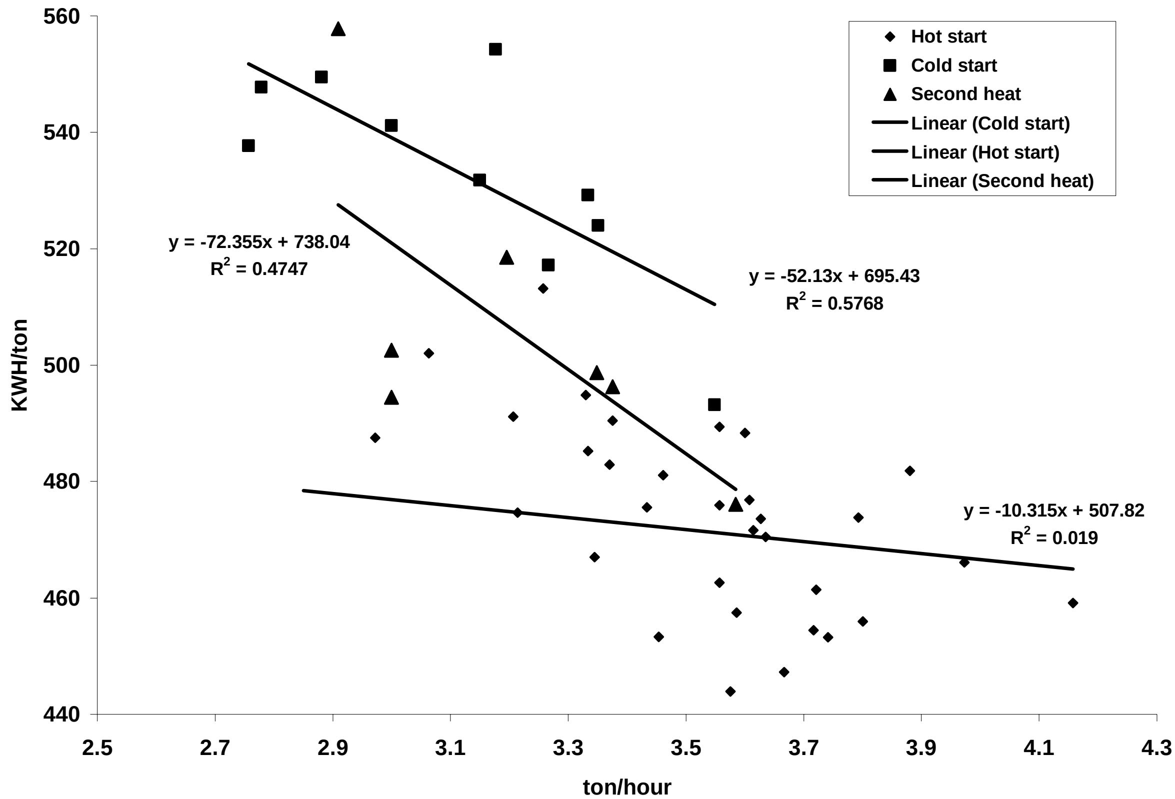


Figure 13. Correlation between productivity and energy consumption in 5.5 ton EAF with PLC (Foundry E)

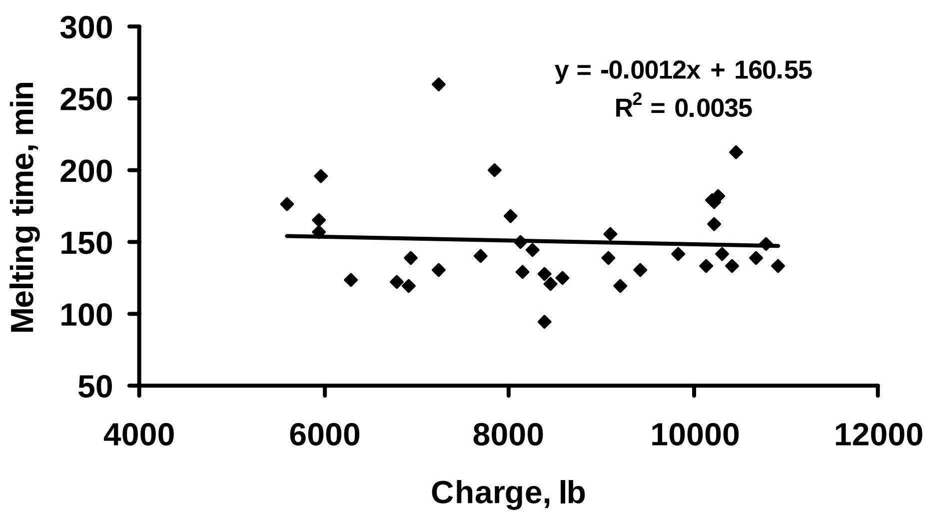


Figure 14. Luck of correlation between melting time and charge weight in 5 ton EAF (Foundry G)

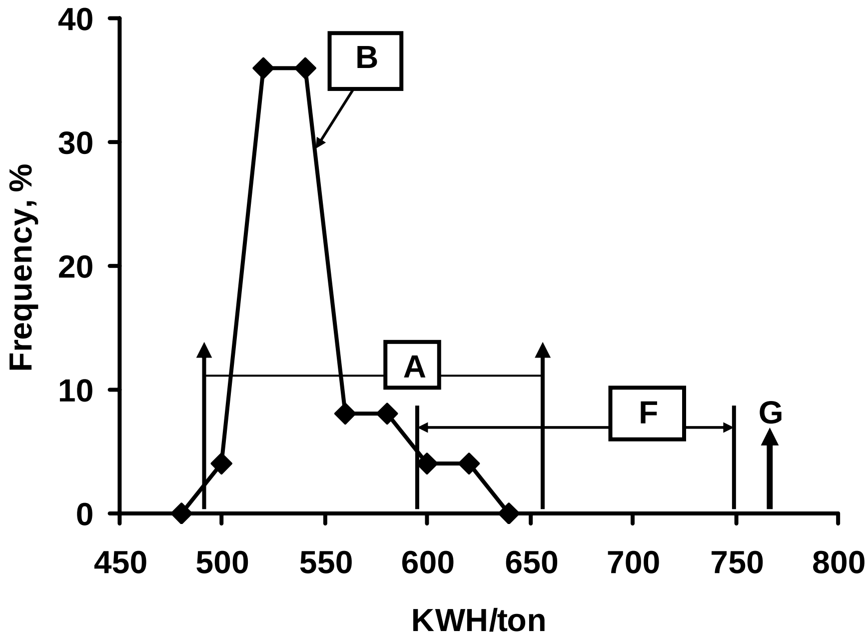


Figure 15. Energy consumption for melting steel in induction furnaces at different foundries

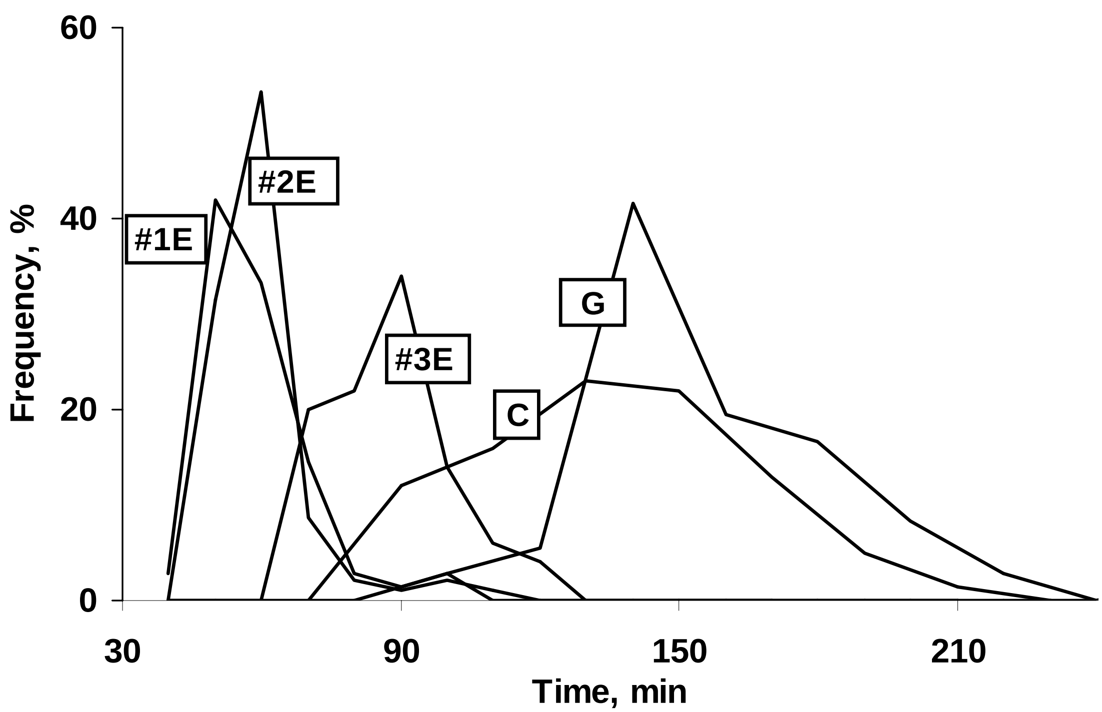


Figure 16. Variation of melting time in EAF at different foundries

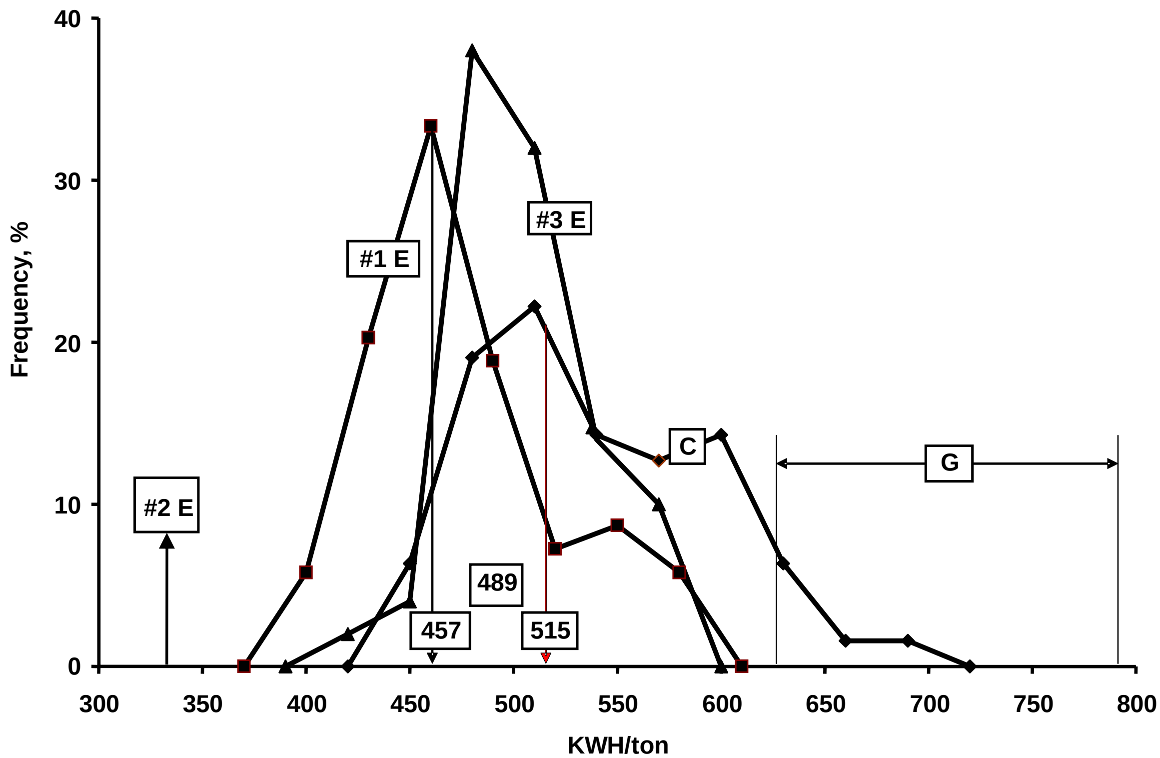


Figure 17. Variation of electrical energy consumption for steel melting in EAF