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ENERGY RECOVERY IN THE NORWEGIAN FERRO ALLOY INDUSTRY[1]

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ABSTRACT

Energy input to ferro alloy furnaces in Norway is roughly divided in two equal parts; chemical energy in the form of carbonaceous reduction materials, and electrical energy. About half of this total energy is preserved in the produced alloy while the rest leaves the process in the form of various heat losses. Total losses are according to this equivalent to the total electrical input to the process, and are accordingly of great interest as a subject for possible recovery.

In this paper the thermodynamic limitations for energy recovery are combined with the characteristic properties of available technologies and with the potential uses for the recovered energy. This is the basis for development of a set of crucial factors that must be considered in order to be successful, economically as well as technologically, in this field. Some examples from energy recovery projects in the industry are given.

The general conclusions are that technologically complicated solutions should be avoided, but on the other hand, a solution that is well integrated with the process as well as with its surroundings is invariably better than solutions undividedly concentrated on the heat losses.

FERRO ALLOY PRODUCTION PROCESSES AND CHARACTERISTICS

The various ferro alloys, including Si-metal, are in Norway produced exclusively in submerged arc furnaces, but there are a few significant differences between the processes and the technology used that play an important role in discussions on energy recovery. It is also important to note that much of the energy that is recovered in this industry is actually initiated by the need to cool the gas before it enters the filters for dust collection.

Open vs. closed furnaces

FeSi and Si-metal are generally produced in furnaces which range from fully open to semi-closed. Complete closing of furnaces have been tried but this type of operation is

[1] This paper is based on several projects supported by The Norwegian Ferroalloy Producers Research Organization (FFF).

presently not used in the FeSi and Si-metal plants in Norway. Completely open furnaces are not in operation in Norway.

A very important factor in this context is that the requirements of the law regarding discharge of solids that were introduced in Norway in the early seventies. This led to the development of silica products[2] and its use especially in concrete and refractories. Presently the capacity in this area is approximately 150000 tons of CSF products per year, representing a value of 300 - 400 mill. NOK. Reclaiming this product from the furnace offgas rule out operations based on fully open or fully closed furnaces. For fully open furnaces this is due to vast volumes of gas and accordingly high filtering costs. Condensation products formed in the upper part of the charge in Si and FeSi production necessitates access to the furnace top for charge manipulation, and in case of wet gas cleaning, also loss of microsilica. The rise in temperature associated with the semiclosed furnaces makes it necessary to cool the gas before filtering and it is this factor that has inspired the development of the flue gas boilers for dusty gas.

Mn containing alloys are on the other hand always produced in completely closed furnaces because this results in smaller gas volumes and also the possibility to utilise the gas as a chemical raw material (synthesis gas). This is done in Porsgrunn where Norsk Hydro use off gas from Elkem's ferromanganese plant (PEA) as a raw material for production of formic acid.

Preheating

The use of thermal energy as such inside the ferro alloy production plants themselves is a topic worth consideration. Generally an obvious possibility would be preheating purposes. Combined with pre reduction this will be of interest in the Mn-processes, but for FeSi and Si-metal preheating is not an option because a cold furnace top is preferable in this case

Some key figures

Typical volumes of gas and temperatures are given in TABLE I.

TABLE I. Typical gas volumes, temperatures and heat losses /1/

TYPE OF FURNACE	AMOUNT OF GAS			TEMPERATURE	SHARE OF LOSS
	[$m^3{}_N$/KWh]	[kg/s][1]	[kg/kWh]	[^{0}C]	[%]
Open	16	200	18	200	65 - 75
Semi Closed	3.5 - 6.5	40 - 80	4 - 7.5	800	
Closed	0.3	4	0.35	300	
All	Cooling water			30 -110	15 - 20
	Radiation				5 - 10

[1] Calculated for a 40 MW furnace

[2] Silica products are made from condensed silica fume (CSF) from silicon- and FeSi-production. Microsilica® is the trade name of CSF products from Elkem.

THERMODYNAMIC CONSIDERATIONS

Energy available for recovery in the ferro alloy industry occurs in the form of *thermal energy* or *chemical energy*, which can be transformed to thermal energy by combustion. Transformation of this energy into useful forms will in most cases proceed in terms of *heat*, which is the transitional form of thermal energy.

First and Second Laws of Thermodynamics and Energy Quality

The First Law of thermodynamics states that energy does not come into being or disappears, it is only transferred from one form to another. The internal energy U of a system will remain constant unless energy transfer in the form of heat q or work w occur across the system borders:

$$\Delta U = q - w \text{ or } q = w \text{ if } \Delta U = 0 \qquad (1)$$

According to (1) it seems possible to transfer heat completely into work in a "heat engine" (e. g. a turbine). This is, however, not the case because of the Second Law of thermodynamics which states that when heat (at a relatively high temperature) is converted to work, heat must also be transferred to a "heat-sink" at low temperature, often the temperature of the surroundings, T_0. So if an amount of heat given by rectangle a in Fig. 1. is converted reversibly, only the part of the total energy that is above T_0 can be converted into work, w_0, while the rest must be transferred as heat to the surroundings. The part of the total heat energy that can be transferred into work (e. g. electrical energy) is often called *exergy*. The rest of the heat energy is the *anergy*, and this part can not be transferred to work but must be transferred to a heat sink in the surroundings of the system.

In a practical energy recovery process, the waste gas is not used directly as the work fluid of a thermodynamic cycle, but rather used to heat a fluid (e. g. water) that serves as working fluid. In this case thermal energy must be transferred, and this can not be done without a

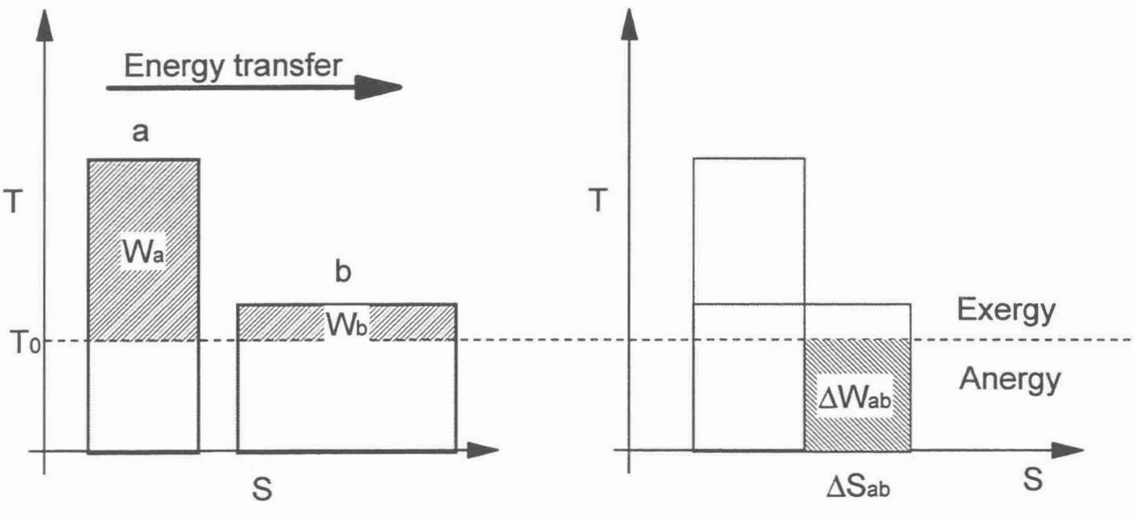

FIG. 1. An area in the T-S diagram has dimension energy. Transfer of thermal energy at a high temperature (a) results in an equal amount of energy (same area) at a lower temperature (b). The transfer of energy does, however, result in an increase in the anergy, i. e. a reduction in the work potential associated with the energy amount.

difference in temperature between waste gas and working fluid. Even if the thermal energy in the waste gas is completely transferred to the working fluid there will be a reduction in temperature, and accordingly in exergy. This is illustrated in Fig. 1. as well and shows that the increase in entropy, ΔS_{ab}, associated with the irreversible heat transfer process directly results in an exergy loss, or loss in ability to perform work:

$$\Delta W_{ab} = \Delta S_{ab} T_0 \quad (2)$$

The temperature at which a defined amount of heat energy is available is strongly related to the exergy and also to the quality, of this energy.

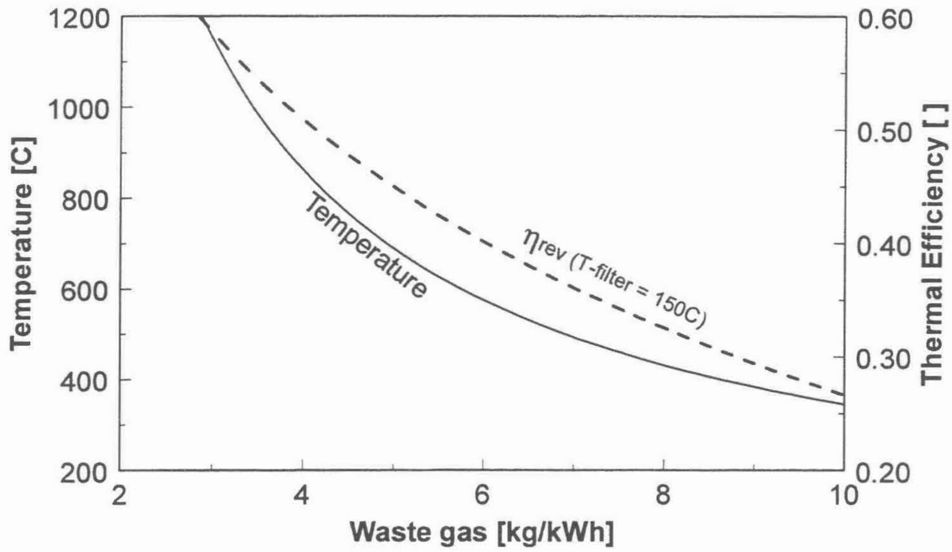

FIG. 2. Effect of amount of waste gas pr energy unit on furnace temperature, and also on the theoretical thermal efficiency of reversible recovery of mechanical energy from the gas. Temperature to the filter is 150^0C. Calculations are based on approximate gas data from a 40 MW semi-closed FeSi furnace./2/

Other Limitations

An important factor that must be considered is also that one does not want to cool the waste gases lower than to approximately 150^0 C before they enter the filter. Lower temperatures may cause severe corrosion problems in the gas filter and the colder parts of the boiler.

FORMS AND USE OF RECOVERED ENERGY

Although electric energy may be reused directly in the ferro alloy production process it is not always evident that the best way to recover energy in this industry is in the form of electricity. In many cases it will be useful to consider energy demands both within the ferroalloy plant itself and in its surroundings to find the best way in which to recover energy. The main questions that must be considered in such cases are connected to the fact that thermal energy demands generally fluctuate with seasonal changes.

Energy quality for the user

Energy quality for the user of energy does not necessarily coincide with the thermodynamic considerations presented earlier. The users very often consider stability and regularity as a main issue and will often demand some kind of guarantee for such qualities.

Thermodynamically speaking, the best way to recover energy available as heat is for heating purposes. Some applications where cooling water from the furnaces or condensers is used in connection with fish farming are technological successes, but this is not always the case from an economic view point. Using the hot furnace gases directly as a heating medium is only done in very special cases, e. g. drying or preheating. Systems involving alternative energy carriers like steam or (pressurised) hot wate rare more common. Energy in this form can not be fully utilised within the ferro alloy plant itself and must accordingly be "exported". Many users in diverse fields (agriculture, fish farming, industry and general heating) use such energy.

Most Norwegian ferro alloy plants are located in smaller communities where the industrial energy customers are scarce and the option then is to convert heat into work and subsequently into electricity to be used on site.

AVAILABLE TECHNOLOGY FOR ENERGY RECOVERY

Although both chemical and thermal energy can be directly converted into electrical energy by various technologies, the practical processes considered here involve some sorts of heat engines. Such processes operate on a thermodynamic heat-engine cycle with limited conversion efficiency. The transformation of heat from combustion or other exothermic

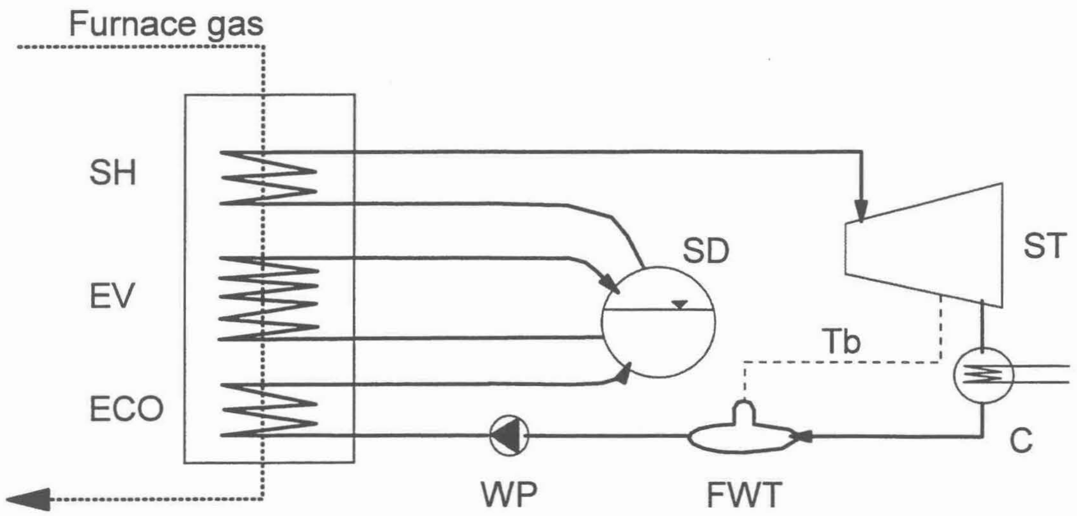

FIG. 3. The Rankine cycle represented by the La Mont design. Main parts are: The boiler with Super Heater (SH), Evaporiser (EV) and Economiser (ECO). Steam Drum (SD). Steam Turbine (ST). Condenser (C). Feed Water Tank (FWT). Water Pump (WP). Pre heating of feed water by Turbine bleed (Tb) is optional.

processes into forms of energy suited for public use covers an enormous field of technology and equally large amounts of money are spent on research and development of new process technology. Not all of these technologies are suited for small scale applications, or they can not handle dusty gas. In this chapter the discussion is concentrated on the conversion of chemical and thermal energy into electricity.

The Rankine cycle - steam boiler and turbine

Considering the case where energy is available in the form large amounts of relatively hot gas, the obvious choice is to pass this gas through a steam boiler and produce hot steam for subsequent use in a steam turbine. Thermodynamically this means that the so-called Rankine cycle will determine the conversion efficiency. The main components in the Rankine cycle are shown on Fig. 3., and the corresponding T-S diagram is given in Fig. 4. The sub processes involved are reversible adiabatic (isentropic) compression (1-2) in the water pump, the reversible isobaric heat addition process in the boiler (2-3), Isentropic expansion in the turbine (3-4) and reversible isobaric heat rejection in the condenser (4-1) completes the cycle. /3/

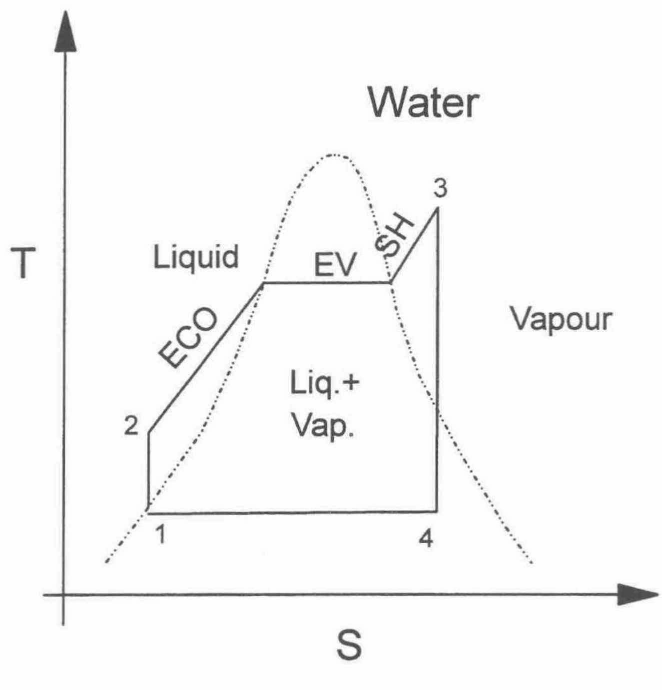

FIG. 4. Rankine cycle T-S diagrams in principle for water: Pump (1-2), Boiler (2-3), Turbine (3-4) & Condenser (4-1). /3/

Performing energy balances over each of the main components according to the general relation:

$$q = \Delta h + w \tag{3}$$

where q = specific heat transfer in the component,
Δh = change in enthalpy across the component, and
w = the thermal equivalent of the specific work done by the component

yield the general expression for the thermal efficiency of the Rankine cycle:

$$\eta_{th} = \frac{w_{net}}{q_{add}} = 1 - \frac{h_4 - h_1}{h_3 - h_2} \qquad (4)$$

An important limitation when using water as the working medium is the moisture content at the turbine exit. Moisture of 10% or more can cause turbine erosion. Generally we will get improved efficiency by increasing the maximum temperature (steam superheat), the maximum pressure and the condenser vacuum. These factors also have the same effect on specific work (net work per mass unit working medium in the cycle). Specific work and the thermal efficiency are the main figures of merit of any thermodynamic cycle. Unfortunately it is only by increasing the maximum temperature that we also get an improvement in moisture. Limitations for this temperature are the material properties in the super heater. /3/

The boiler design for waste gas systems must be carried out with close attention to the large irreversibility introduced through the temperature difference between the furnace gas and the working medium. The limiting factor will be the temperature at the "pinch point", where the gas leaves the evaporator. This is illustrated in Fig. 5. The super heater, evaporator and economiser should be designed to minimise the hatched area in fig. 5 as this will maximise the recovery.

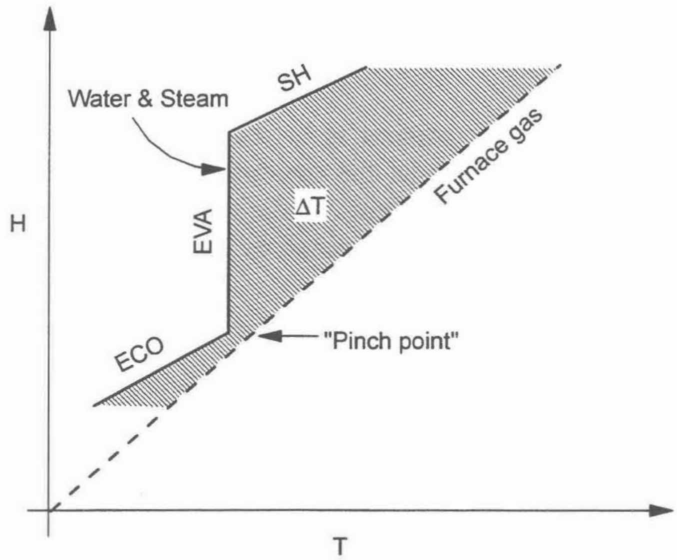

FIG. 5. Temperature difference between gas and working fluid in boiler. The temperature difference is a direct illustration of the irreversibilities introduced in the heat exchanging.

Several different solutions could be used to change this (different working fluid, splitting the evaporation in a two-pressure system, etc.), but most of them lead to complicated changes in the system and are expensive. One possibility could be to introduce a gas turbine in the system.

<u>The Brayton cycle - gas turbine</u>

This cycle involves the same thermodynamic processes as the Rankine cycle, but uses a (non condensing) gas as the working medium (see Fig 6). The fuel in the open cycle must be free from dust and can only be used on clean furnace gas.

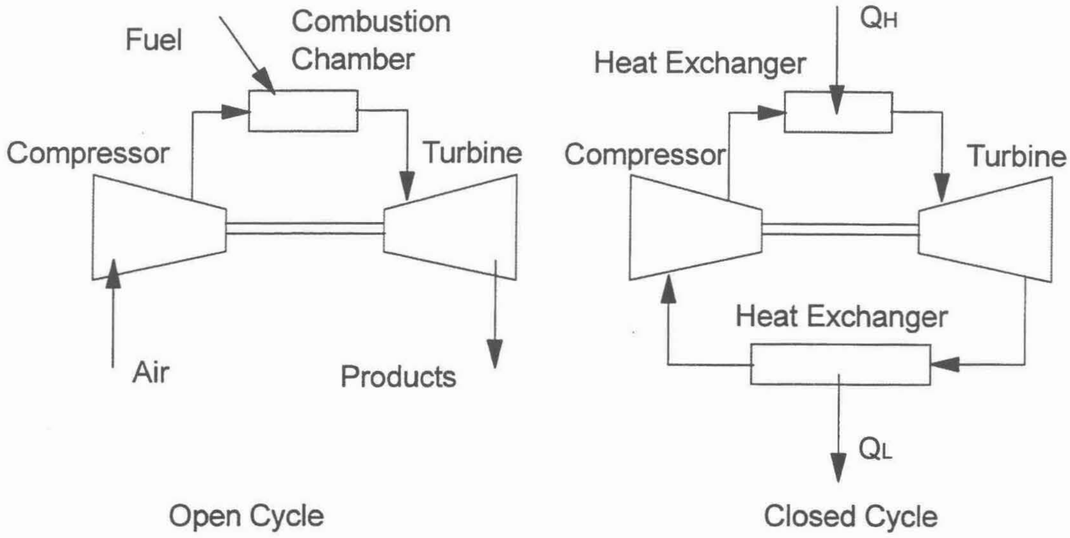

FIG. 6. The Brayton cycle that can be of the open or closed type as indicated. Energy is supplied through combustion in the open cycle or by heat exchange in the closed cycle. The working medium in the open cycle is the combustion products, while noble gases are often used in the closed cycle. /3/

The most interesting aspect in our context is to use a gas turbine as the top process in a combined-cycle system. In such systems the gas-turbine discharge is used as input to the boiler in the steam cycle for the open systems. In the closed system the gas is heated in a heat exchanger that could be parallel to the super-heater in the boiler.

Low temperature systems

There are a number of companies that have constructed systems for power generation that operate with fairly high efficiencies even on low temperature (<300^{0}C) heat sources like terrestrial heat. The best known company is probably ORMAT Turbines of Israel that has delivered several thousand installations, mostly up to 1.2 MW per unit. Traditionally such systems are using organic media (ORC) as working fluids (R22, R113, R114, R115), which in the later years have had decreasing popularity because they are known as potential ozone depleting agents (CFCs). Development of new media with less harmful properties, however, makes this an option still. /1/

CURRENT STATE IN INDUSTRY

The general situation for this industry is constantly changing, partly due to continuous discussions on how to best utilise the Norwegian energy reserves and at the same time comply with the environmental issues.

Energy used and potential recovery - an overview

As can be seen from Table II it should be possible to recover about 13% of the total electric energy used in the ferro alloy industry in the form of "recycled" electric energy. Presently

TABLE II Overview of present status /1, 4/

	Plant	Electrical energy used [GWh/year]	Possible recovery [GWh/year]		Actual recovery [GWh/year]	
			Electrical energy	Thermal energy	Electrical energy	Thermal energy
Si-metal	Fiskaa	500	70	85		
	Holla	250	33	50		1
	Meraker	500	60	80		
		1,250	163	215		1
Fe-Si	Bjølvefossen	550	55	95	35	
	Bremanger	720	90	130		
	Finnfjord	420	106	85		
	Hafslund	530	75	104		23
	Holla	270	50	54		
	Ila-Lilleby	280		120		120
	Rana Metall	700	275	175		
	Salten	890	125	163		40
	Thamshavn	580	80	98	80	
		4,940	856	1,024	115	183
Fe-Si-Mn	PEA[1]	500		200		200
	Sauda[1]	850		300		
	Øye	500	80	50	80	16
		1,850	80	550	80	216
Fe-Cr	Elkem Rana[1]	360		140		
Total		8,400	1,099	1,929	195	400

[1] Gas (partly) used as fuel or syn-gas

about 18% of this potential is actually recovered. The figures for thermal energy are when referring to the same base, a potential of 23% and actual recovery is 21% of the potential.

Presently energy is recovered as electricity at three different plants, and two of these are presented below. The energy recovering system of the third, Bjølvefossen, was presented by Grong at the ILAFA Congress in 1978 /5/. The thermal recovery system at Ila-Lilleby in Trondheim is also briefly described.

Elkem - Thamshavn

In the early seventies the Thamshavn plant had one furnace for production of ferrosilicon and with a power consumption of approximately 20 MW. Due to governmental regulations it was necessary to install gas cleaning equipment at the plant. The cost of gas cleaning would be relatively high at a plant of this size, and it was decided to increase the capacity by a factor of 3 by installing a new 40 MW furnace. This decision was made in 1978 and included an energy

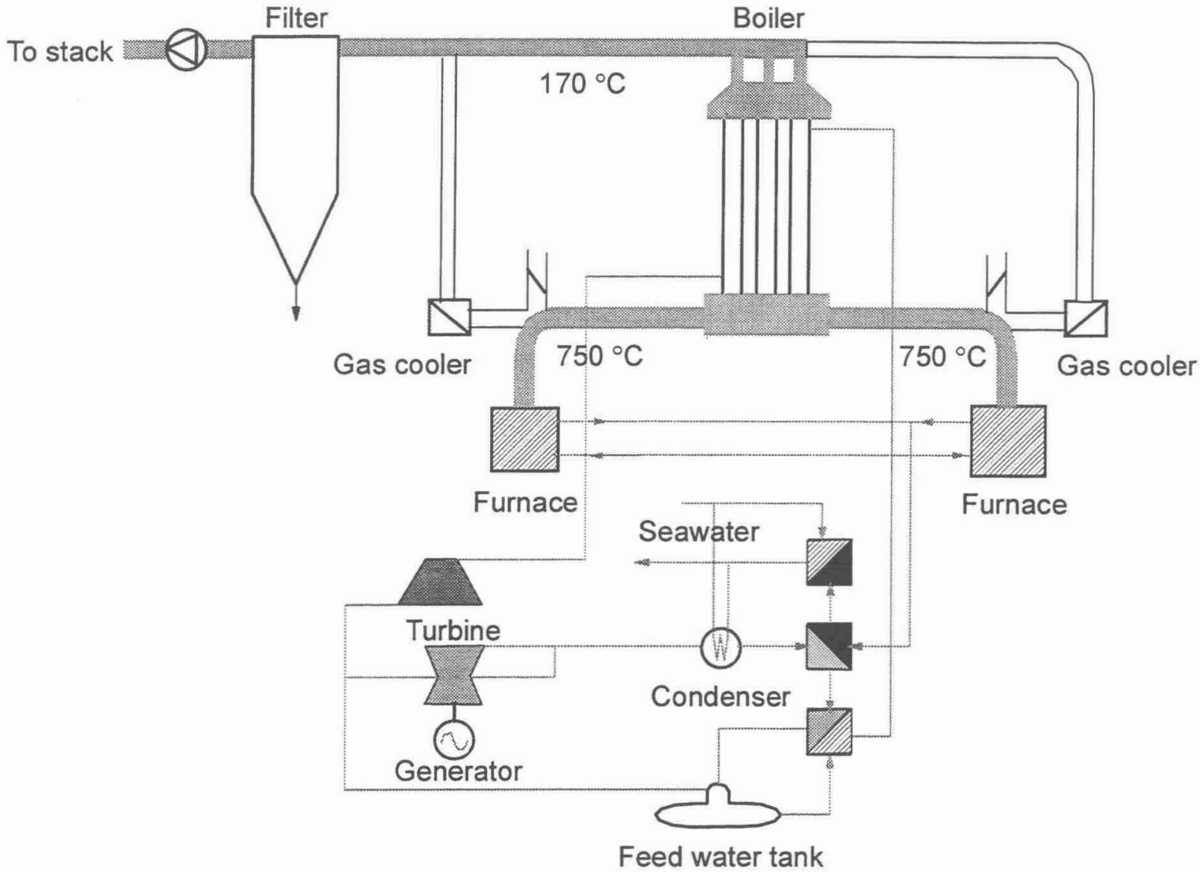

FIG. 7. Schematic diagram of the energy recovery system at Elkem Thamshavn /6/

recovery plant and adaptation of the existing furnace to this. The new furnace has been in operation since 1981 and the reconstruction of the old furnace as well as the energy recovery plant was completed the year after. The waste heat boiler was constructed as a fluid-bed boiler, where sand particles according to theory are supposed to keep the heating surfaces clean and increase the heat transfer pr unit area. This was indeed the case, but the wear of the heating surfaces was also extremely high, and this principle was abandoned in the summer of 1983 and was reconstructed to shot-cleaning. This new boiler was in operation in April 1986. It was necessary to install separate gas coolers due to this delay of the energy recovery plant, but also to meet the new governmental requirement of 96% availability for the gas cleaning system. The resulting system of these 8 years of development is shown in figure 7. The normal operation loads of the two furnaces are 20.5 and 43.5 MW and they are semi-closed Elkem furnaces. Production capacity of the plant is 65000 TPY of granulated and refined 75% ferro silicon. The heat recovery system was constructed by ABB Miljø (Norsk Viftefabrikk AS) /6/.

The boiler produces superheated steam at approximately 460 ^{0}C and 50 bar. This is fed to a multi-stage reaction turbine with an operating effect of ~13 MW. The back pressure is 0.05 bar. The boiler has three separate sections, each with 4 economisers, 2 evaporators and 2 super heaters. One section can be taken out of operation and the plant does not have to be shot completely down during maintenance periods. The originally calculated recovery was 110 GWh/year /6/, but the actual production has been less. This is due to several interlinked

TABLE III. Gross Energy Balance of the Thamshavn Plant 1994 /8/

PROCESS ENERGY		TJ	GWH	%	% of el. input
Input:	Electrical	1577	438	49	100
	Fix C	971	270	30	62
	Volatiles	688	191	21	44
Output:	Chemical Energy in FeSi	1409	391	44	89
	Enthalpy of hot FeSi	134	37	4	8
	Cooling Water Loss	371	103	11	24
	Waste Gas Loss	1083	301	33	69
	Recovered Electrical Energy	240	67	7	15

factors. Important factors are lower energy in the off gas and lower gas temperature than assumed at the design stage in order to avoid gas channel clogging /7/.

Full production presently corresponds to ~80 GWh/year, while last year it was down at 67 GWh/year as seen in Table III. The reason for this was reduced alloy production due to market situation and accordingly lower energy input over the year. The electrical energy represents approximately half of the energy input, and energy contained in the product together with recovered energy similarly is about half of the energy output. Even with energy recovery the losses in the waste gas represent one third of the energy output.

Tinfos - Øye Smelteverk

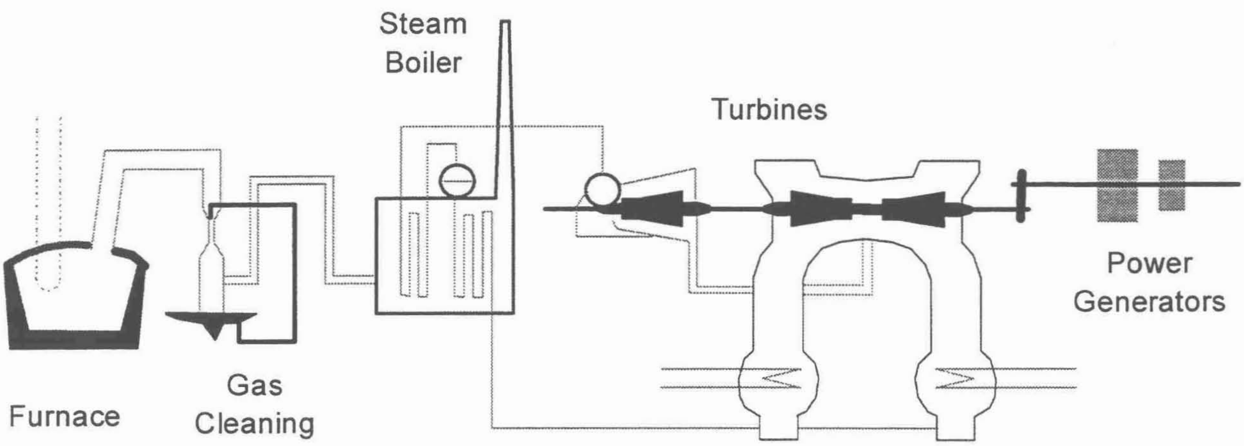

FIG. 8 Principal design of gas handling and energy recovery system at Øye Smelteverk /9/

The main product from Øye Smelteverk is silicomanganese, and this is produced in two closed furnaces with a load of 30 MW each. The gas consists mainly of CO and is cleaned in a scrubber system before it is combusted with air in the steam boiler. The steam (35-40 tons/h) is fed to a set of high pressure and low pressure turbines. Energy recovery is ~70 GWh/year, corresponding to 13.5 % of the electrical energy input. /9/

Ila & Lilleby

The location of this plant in Trondheim made it possible to choose an alternative strategy, namely to produce pressurised hot water for district heating. This energy is sold to nearby industrial customers at a price corresponding to 70% of fuel oil. This corresponds to a rate of interest on the investments in the same order as bank rates giving a pay back time of 6 to 9 years. Plans exist now for connecting this heat recovery system with the municipal system, a factor that has been beneficiary in negotiating power prices.

Energy recovered amounts to 35 GWh/year or 12 - 15% of the consumption of electrical energy in the plant. The recovered energy replaces oil in most cases and has thereby reduced the emission of SO_2 in Trondheim by 10-20 % and that of CO_2 by 1%.

THE FUTURE

As is seen by the survey presented here the potentials for energy recovery are not exhausted in the Norwegian ferro alloy industry. From an economic point of view investments in this type of recovery plants are not bad, but the returns on investments may not be high enough to justify such investments.

A technological development, especially on gas turbines, has taken place during the past years /1, 3, 4/. Projects looking into these possibilities show that it may be possible to increase the present production of recovered electrical energy with 50 to 90% relative to the present levels by using gas turbines as top system in combination with a Rankine cycle /4/. Many combinations are possible, but generally it will be favourable to use an open cycle gas turbine in closed furnace operations and closed cycle gas turbine in the case of semi closed furnaces. In the latter case very high thermal efficiencies may be obtained provided that ammonia is used as working fluid in the closed cycle gas turbine and water in the Rankine cycle. Using ammonia in the bottom system as well will lower the thermal efficiency, but will increase the range of operation regarding energy content of the gas. On the other hand, the resulting system will be complicated and will also lead to high investment costs. Provided that the gas is clean, the open cycle will generally provide the best economics when only energy recovery is considered.

CONCLUSION

The general conclusions are that technologically complicated solutions should be avoided, but on the other hand, a solution that is well integrated with the process as well as with its surroundings is invariably better than solutions undividedly concentrated on the heat losses. Energy recovery is presently in operation in various systems in the ferroalloy industry and has performed satisfactory for many years. Only small changes in future energy availability /10/ and environmental issues or regulations /11/ may be sufficient to change the economical importance of such systems significantly.

REFERENCES

1. Arild Olsbu et. al.: "Industrial *Energy Technology"* Survey report for The Royal Norwegian Research Council (NTNF), Oslo, June 1989 *(In Norwegian)*
2. B. Magnusson, Jens Ottersen: *"Principles and Practical Issues connected with Energy Recovery from a Ferrosilicon Plant"* Division of Thermodynamics, NTH-Norwegian Institute of Technology, and Holla Smelteverk 1978 *(In Norwegian)*
3. A. W. Culp Jr.: *"PRINCIPLES OF ENERGY CONVERSION"* McGraw-Hill, Tokyo, Int. Student Edition, 1985, [ISBN 0-07-014892-9] pp 300-371
4. Oddbjørn Haug: *"Effective Use of Energy in the Energy-intensive Industry"* M. Sc. Thesis, Division of Thermal Energy, NTH-Norwegian Institute of Technology, Trondheim; May 11, 1989 *(In Norwegian)*
5. T. Grong: *"Energy Recovery from Electric Ferrosilicon Furnace Waste Gas"* ILAFA - Ferroalloy Congress, Acapulco, Mexico May 14 - 18, 1978
6. *"Electricity Production by Heat Recovery at a Ferrosilicon Plant"* CADDET (Centre for the Analysis and Dissemination of Demonstrated Energy Technology) 2B.H02.001.89.NO/RESULT 25, IEA/OECD, The Netherlands, 1989
7. S.T. Johansen et. al.: *"Clogging of ferrosilicon off gas channels at high temperatures"*, Smelter Process Gas Handling and Treatment TMS pp 7-18, 1992
8. S. M. Haarsaker: Personal Communication, Elkem Thamshavn, March 1995
9. M. Bruno, K. Festøy: *"Experiences in Manganese Alloy Production at Tinfos, Øye Smelteverk, Norway 1974 - 1991"* 50th Electric Furnace Conference Proceedings - Atlanta Meeting, November 10-13, 1992, Iron & Steel Society of AIME, pp 67-74
10. T. Lindstad: *"Ferroalloy Production. Energy, Emissions and Reclamation of Dust and Energy"*. Environment Northern Seas Conference, Report Vol. 4, pp 127-141, Stavanger (1991)
11. T. Lindstad, L Kolbeinsen: *"Ferroalloys Production and the Environment"* Paper presented at Metal Bulletin's 10th International Ferro-Alloys Conference, Barcelona November 6 -8, 1994