FERROALLOY OFF-GAS SYSTEM WASTE ENERGY RECOVERY: OPTIONS AND APPLICATIONS

Luther Els[1], Nicole Andrew[2], Thierry Johannes[3], Stacey Noakes[4], Johann Wingard[5]

[1] Resonant Environmental Technologies, Pretoria, South Africa, luther@resonant.co.za
[2] Resonant Environmental Technologies, Pretoria, South Africa, nicole@resonant.co.za
[3] Scientific Design, Edenvale, South Africa, thierry@scienticdesign.co.za
[4] Resonant Environmental Technologies, Pretoria, South Africa, stacey@resonant.co.za
[5] Resonant Environmental Technologies, Pretoria, South Africa, johann@resonant.co.za

This paper critically assesses the various options available for the recovery of waste energy from ferroalloy furnaces, detailing the advantages and disadvantages important in technology selection as well as the effect on the process as a whole.

Semi-open and closed furnaces inherently produce different off-gas streams in terms of volume, temperature, composition and energy content. When planning to utilize this energy for recovery purposes the energy quantity, quality (temperature or exergy and contaminants) and availability (continuous or intermittent) must be carefully considered, as well as the maintenance and operability of the selected recovery equipment.

The following technologies are assessed and compared for open and closed furnaces:

- *Ore and reductant drying.*
- *Heat recovery steam boiler for electricity generation.*
- *Organic Rankine Cycle for electricity generation.*
- *Internal combustion engines for electricity production.*

This paper details technologies and their possible application for waste energy recovery from semi-open and closed furnaces. Actual application data and scenarios from studies and work done are also included in the article.

KEYWORDS: *energy recovery, off-gas, exergy, ORC, steam Rankine, drying*

1 BACKGROUND

The ferroalloy industry in South Africa was founded upon the paradigm of cheap, available energy. As this paradigm shifts and global competitiveness increases innovation is required to retain the leading edge.

Generally, ferroalloy plants are built in locations where energy is inexpensive, leading to waste energy recovery being uneconomical. Therefore, in the past significant amounts of the energy generated by ferroalloy furnaces has been expelled directly to atmosphere. As electricity prices increase energy recovery is becoming an option for improving the economic viability of ferroalloy activities.

Energy recovery is, however, a secondary operation on site and should never take the focus from the main operation which is the production of metal. Energy recovery should therefore only be implemented after an exhaustive study involving a test campaign of the system performance, modeling, comparison of various options and optimization. All possible effects on the main process should also be considered to ensure that there are no adverse effects.

2 CONSIDERATIONS FOR ENERGY RECOVERY

2.1 SITE-SPECIFIC FACTORS

In South Africa and other warmer climates, heat in the form of steam or warm water is not a commodity used for heating of houses and factories. Therefore, in the past significant amounts of the energy generated by ferroalloy furnaces has been expelled directly to atmosphere.

The thermodynamic efficiency of a cycle is affected by the temperature of the heat sink. In South Africa, where ambient temperatures are high and large rivers are not available as a cold heat sink, the thermodynamic efficiencies are lower.

2.2 ENERGY QUANTITY

The amount of waste heat available is the starting point for any energy recovery discussion. As most energy recovery projects are brownfields, the best way to determine the real energy available is through test work on site. A process model should be set up to determine the off-gas energy, verified by the site testing and used to determine the energy for applicable scenarios (1).

For open furnaces, the amount of thermal energy is of concern. This is typically quoted relative to 25 °C or some ambient temperature. For ferroalloy off gases, however, the amount of energy available for energy recovery is limited by the dewpoint of the gas. The gas must be sent to the baghouse at a sufficiently high temperature to safely avoid any condensation in the baghouse. The amount of energy available between the off-gas temperature and the minimum baghouse inlet temperature is therefore the number to be concerned with.

2.3 ENERGY QUALITY

2.3.1 Exergy

The law of conservation of energy holds that energy cannot be destroyed or created, only transferred from one state to another. Exergy, however, is a measure of how much work can be obtained from a particular amount of energy relative to its environment and is by nature destroyed in any spontaneous process. Exergy optimisation can therefore be used to improve overall energy efficiency. The total exergy of a substance is the sum of its physical exergy, including thermal exergy, pressure or dynamic exergy and mixing exergy; and chemical exergy. Exergy is the maximum amount of work available when an energy carrier is brought into a state of thermodynamic equilibrium with the environment in a reversible manner. The actual amount of energy available will always be less than the exergy due to the irreversibility of actual processes (2).

The thermal exergy can be derived from the Carnot efficiency. Carnot efficiency assumes a constant temperature of the hot source, whereas the exergy takes into account the decrease in temperature of the heat source as it is brought into equilibrium with its environment by calculating the integral as follows:

$$E = \int_{T_0}^{T} \frac{T - T_0}{T} dQ = (H - H_0) - T_0(S - S_0) = \Delta H - T\Delta S \qquad (1)$$

The thermal exergy therefore is calculated in the same way as the Gibbs free energy, except that the reference state, 0, is always the natural environment.

From this it follows that any cooling of the off-gas will result in irreversible exergy destruction and a loss in the efficiency of any subsequent heat recovery system. Material limitations, however, mean that the off-gas must be cooled, especially on furnaces where the off-gas temperature is in excess of 1 500 °C. Figure 1 shows the results of an analysis performed on a small ferromanganese furnace off-gas to compare the exergy destruction by air dilution and by water cooling.

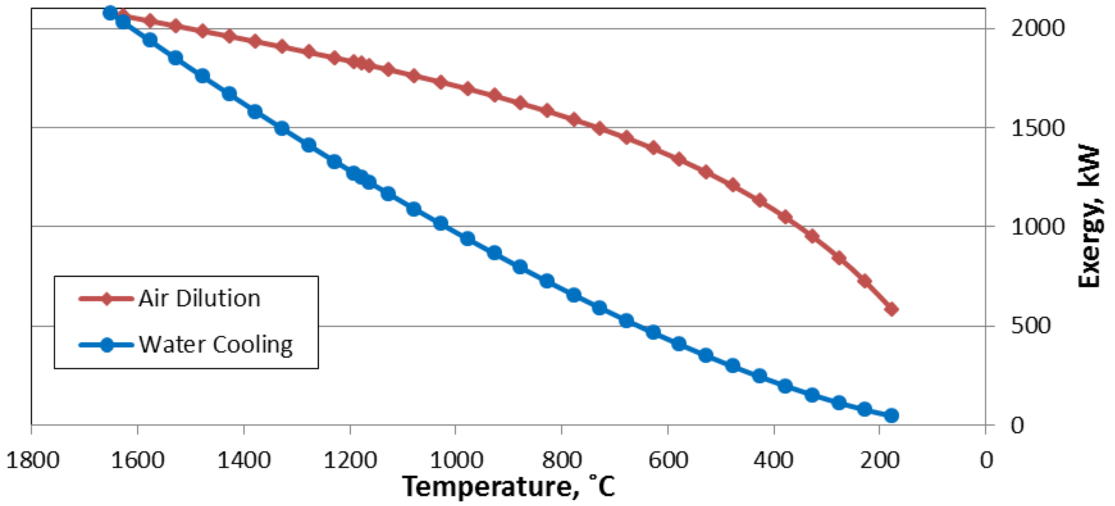


Figure 1: Exergy decrease during off-gas cooling by air dilution compared to water cooling

Figure 1 shows that air dilution is more efficient thermodynamically than water cooling. It also shows that the exergy destruction with temperature for air dilution is not that significant above 600 °C, below this temperature, however, the exergy destruction is more severe. This trend bodes well for energy recovery as commercially available heat exchangers can handle 600 °C.

2.3.2 Contaminants

The main problem with off-gas heat is that it is dirty. Sticky dusts foul up heat exchangers and can be very difficult to remove. Sulphur compounds and water vapour increase the dewpoint and are extremely corrosive if the off-gas temperatures drop below this limit. Technology specific contaminants are discussed later.

2.4 ENERGY AVAILABILITY

It is important to take note in economic calculations that the system will most likely run at below design conditions more often than above. Accurate testing, modeling and statistical analysis can ensure that effective assessment of energy availability is done.

2.5 MAINTENANCE AND OPERABILITY

South Africa has a shortage of skilled labour. This can make the implementation of complex systems difficult and this should be taken into account during the equipment selection and design phase. It is also important to remember to consider the maintenance that is required for the selected system.

3 TECHNOLOGIES

3.1 ORE AND REDUCTANT DRYING

The first option for energy recovery is direct use of the heat. Drying of feed materials is one of the most efficient and economical ways of converting off-gas heat into energy savings in the furnace.

3.1.1 Closed Furnaces

Closed furnace off-gas heat recovery to drying is well established and has been implemented successfully on ferro-alloy smelters in South Africa. Typically the off-gas is cooled and cleaned through scrubbers and subsequently burned as fuel in a dryer. Typical operational constraints are:

- Burner system clogging due to dust, tars and moisture if the gas scrubbing is not efficient.
- Hazards related to CO gas in the plant.
- Co-firing of furnace off-gas and natural gas or a light fuel oil may be required depending on the furnace off-gas energy, this adds to the cost and complexity of the burner system.

3.1.2 Open Furnaces

Open furnaces are less sensitive to feed moisture content as the water is driven off in the feed hoppers or on the surface of the bed by the energy released from the combustion reactions. The thermal energy available in the off-gas from open furnaces is still a significant quantity of energy. Open furnace off-gas can, therefore, be used to dry closed furnace feed if there are a number of furnaces on site. There are three ways of transferring the energy from the off-gas to the dryer:

1. <u>Indirect heat exchange to a fluid medium</u>

Indirect heat transfer by means of a working fluid requires the off-gas to be passed through a waste heat boiler or thermal oil pack and in order to generate steam or hot thermal oil. The hot medium is in turn used to preheat drying air through a second heat exchanger. The temperature of the pre-heated air is typically limited to between 180°C and 250°C.

2. <u>Gas to air heat exchanger</u>

In a gas to air heat exchanger, ambient air is preheated in a counter current heat exchanger with the furnace off-gas. Gas to gas heat exchange coefficients are typically low, resulting in poor efficiencies, typically 50% to 55%, resulting in a large heat exchanger construction which can be uneconomical.

In the case of drying ore, a furnace off-gas temperature of 500°C would result in a dryer inlet temperature of approximately 250°C which calls for a larger dryer and associated dust handling equipment than would be the case at a higher inlet temperature.

The main advantage of indirect heat exchangers is that the air supplied to the dryer is clean of dust and potentially corrosive substances. The following challenges are introduced though:

- Complex construction and expensive materials.
- Can be physically large.
- High potential of fouling and abrasion on the furnace gas side.
- Filtration capacity is required for furnace and drier off-gas.

In ore drying, the dryer inlet temperature can be as high as 700°C, thus this method of recovering heat provides only 25%-35% of the energy to the dryer. The balance needs to be provided by a supporting fuel. When drying reductant, the dryer inlet temperature is typically lower (250°C-350°C) and thus the recovered heat can provide from 50% to 100% of the heat required.

3. Direct contact drying

In direct contact drying, the furnace off gas is used directly in the dryer. Unless dictated by specific site or process constraints, this method is the most cost effective. Another advantage of the direct contact drying method is that the off-gas dust handling equipment (typically a bag filter) remains the same capacity.

The temperature of the off gas is critical to the viability of the project. The higher the temperature, the smaller the drying installation and associated gas treatment plant.

3.1.3 Ore Drying

Ore drying is common at many ferroalloy smelters in South Africa. The drying technologies of choice are:

- Rotary dryers.
- Static fluidised bed dryers.

Dryer inlet temperatures for ore are in the range of 600 to 700°C. In most instances, the dryers are directly fired using closed furnace off gas as fuel or by burning coal in fluidised bed combustors (FBC). The use of coal fired fluidised bed combustors is limited to rotary dryers where the dryer exhaust fan draws in the hot gases from the FBC into the rotary dryer (induced draught).

In a static fluidised bed, the hot gases need to be pressurised in order to fluidise the bed of material inside the dryer. This requires a relatively high pressure (6 – 10 kPa).

The fans required to fluidise at high temperature present the following challenges:

- Large, expensive units.
- Large electrical drives are required in order to be able the start-up in cold condition.
- Inefficient designs due to the propensity for the impeller to build-up fine dust from the hot gas resulting in out-off balance operation.
- Wear from the dust laden gas (these fans run at high speed).

For these reasons, static fluidised beds are fired using furnace off-gas through a burner, with natural gas or oil for start-up or back-up. In normal operation, the dryers operate on furnace off gas exclusively. This design allows the fluidizing fan to be a cold, clean air unit. Heat recovery on fluidized bed dryers is therefore limited to closed furnace operations, using furnace off-gas and has been implemented very successfully.

Open furnace heat recovery is best achieved by using the hot furnace off gas directly into a rotary dryer.

Factors to be taken into account in evaluating these systems are:

- Space constraints (rotary dryers tend to be larger than a typical fluidized bed).
- Distance between the furnace and the dryer (hot duct installation).
- The effect of furnace dust being recycled to the furnace through the drying circuit.

Figure 2: A Rotary drier and its off-gas cleaning system

3.1.4 Reductant Drying

Drying of the reductant stream is generally aimed at improving material handling and blending. It is not as common as ore drying for the following reasons:

- The process is potentially hazardous: risk of combustion or explosion.
- It is a much smaller stream and thus the impact of the heat recovery from drying is less significant to the furnace operation.
- Drying of friable reductant causes attrition and the generation of fines which can cause losses due to entrainment in the furnace gas stream.

To mitigate the fire/explosion risk, drying is carried out at a much lower temperature of 250 to 280 °C. As reductants come in various sizes (0-25 mm) and forms, the use of static fluidized beds is not recommended. Large diameter rotary dryers can lead to excessive product attrition.

Vibrating fluidised bed dryers do not require the same high pressure fans as static units as fluidisation is achieved mainly by the vibrating action of the bed. The lower operating temperature is also easier on the fluidising fans, thus direct heat recovery is possible. However, dust laden air from the furnace off gas can lead to plugging of the fluidising plate or nozzles and thus in this type of dryer, an indirect heat recovery method would be advisable.

In order to benefit from the direct contact drying method, using the furnace off-gas, a flash dryer can be used. The advantages of such a dryer are as follows:

- Smaller foot print and thus easier to integrate in the vicinity of the furnace (less ducting and associated heat losses).
- Short contact time between the material and the hot gas, reducing the fire/explosion risk
- At any point in time, there is only a small amount of material in the dryer, again reducing the risk of fire/explosion.
- Lay-out permitting, the dryer can be utilized as a pneumatic conveyor to the reductant feed bin.

A flash dryer can generate a certain amount of fines due to the attrition of the reductant, this needs careful consideration. Also the use of a flash dryer, essentially a pneumatic dryer, is limited to fine particles (< 5 mm).

When drying a combustible product, a scrubber is recommended over a bag filter to clean the drier off-gas. If a bag filter is preferred, the use a spark detection/dousing system is compulsory. A reductant drier off-gas temperature is usually in the range of 100 °C. If an open furnace off-gas were to be used directly in the drier, condensation of sulphur compounds at this temperature would be likely. It is therefore recommended to use stainless steel in the lower temperature regions of the scrubber to prevent corrosion.

3.2 STEAM RANKINE CYCLE

Tubatse Ferrochrome, located in Steelpoort, South Africa, produces ferrochrome in 6 open electric arc furnaces. A project is in the construction phase to modify the gas cleaning system and install six boilers, with a power generating plant. Furnace off-gas parameters were tested and a process model developed to evaluate the project feasibility (1). The proposed layout is illustrated in Figure 3.

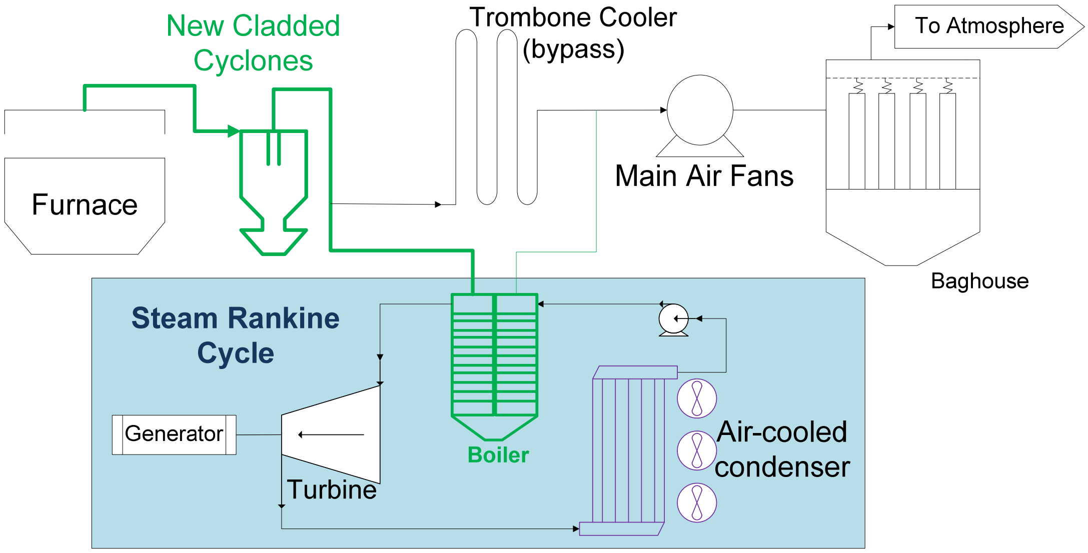


Figure 3: PFD for Steam Rankine Integration of one furnace with off-gas system at Tubatse

The total off-gas from the furnaces is approximately 1 000 000 Nm^3/h at a temperature of 500°C, with steam generation of 150 t/h and turbine installed capacity of 30 MW.

3.3 ORGANIC RANKINE CYCLE

An energy recovery feasibility study was performed at a ferrochrome furnace in South Africa. An Organic Rankine Cycle was recommended as an energy recovery option for the following reasons:

- A wide operating range. The turbine is designed to follow load changes at a constant speed. This means the off-gas need not be moderated to the detriment of metal production.
- Systems are designed with automatic start up procedures and simple efficient control which makes them easy to operate, also ORCs operate at lower pressures than steam boilers therefore boiler operators are not required.

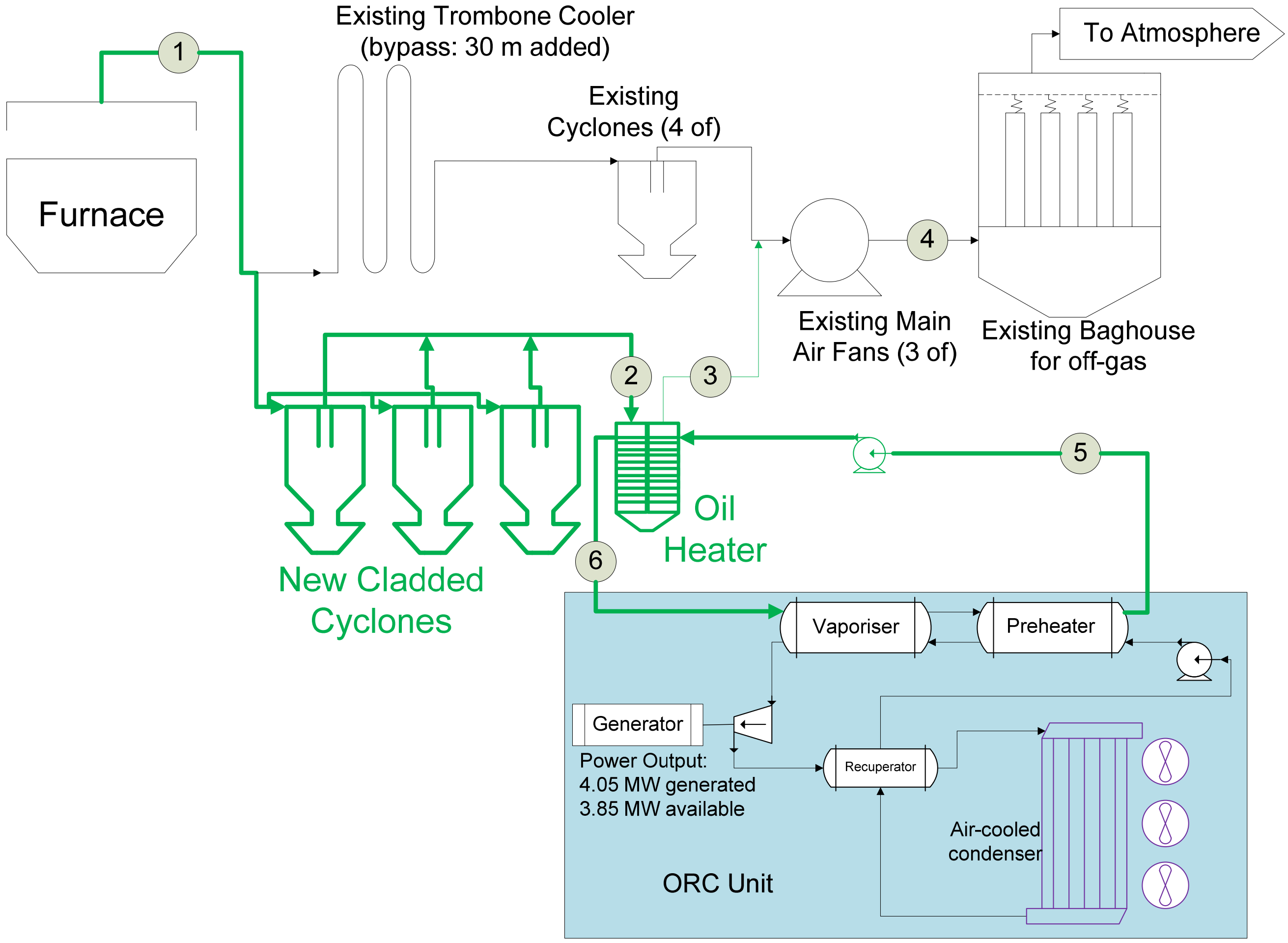
An ORC makes use of a lower boiling working fluid than a traditional steam boiler, which allows for lower temperature heat recovery. Different working fluids are available for different temperatures; however at lower temperatures the efficiency is reduced. Heat can be recovered from sources at temperatures as low as 100°C.

The ORC system had to be integrated with the existing system. The following modifications were suggested:

- Reduce water cooled ducting on the furnace off-takes to increase off-gas temperature and energy.
- Replace all off-gas ducting up to the heat exchanger with cladded 3CR12.
- The bypass case was then considered and the trombone was no longer capable of cooling the higher temperature off-gas so a trombone extension was needed.
- Installation of three high temperature insulated 3CR12 cyclones to remove large particulate matter and prevent abrasion in the oil heater.
- Placement of the air-cooled condensers on top of the ORC unit to reduce footprint.

The oil heater was considered to be the most critical and technically risky component of the whole system. The heat exchanger was designed for the following conditions:

- Gas velocities of 25 m/s to maximize heat transfer without causing significant abrasion.
- Oil velocities of more than 2 m/s to prevent hot spots which would lead to oil degradation.
- Minimal pressure drop on the off-gas side to reduce the load required by the fans.



Stream Number	1	2	3	4	5	6
Stream Description	Off Gas	Into Oil Heater	After Oil Heater	Into Baghouse	Oil into heater	Oil out of heater
Mass flow (kg/h)	200000	200000	200000	200000	211785	211785
Normal Flow (Nm3/h)	154483	154484	154483	154483		
Volume Flow (Am3/h)	562045	555169	302389	274056	253.6	253.6
Temperature (°C)	570	550	170	150	280	105
Pressure (kPa)	86	85	84	88.5		
Energy (MW)	32.7	31.1	8.2	7.1		

Figure 4: PFD of an ORC heat recovery option for an open ferrochrome furnace

3.4 INTERNAL COMBUSTION ENGINES

Hernic Ferrochrome operates four closed ferrochrome furnaces, rated from 37 to 78MVA. The application of gas engines was evaluated during a bankable feasibility study and results of test work reported (1). The engines required a much lower dust concentration at the inlet than the tested current scrubber emission; a secondary filter therefore had to be incorporated in the gas conditioning system, which also allowed for tar and sulphur removal. The equipment layout is illustrated in Figure 5.

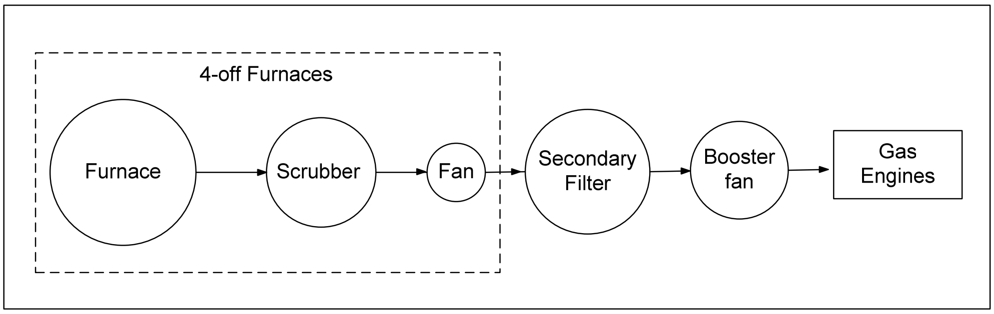


Figure 5: Process layout – closed furnaces to gas engines

In addition to ensuring that contaminants (dust, tars, etc) are within engine specifications, engine selection also has to be done based on measured gas analysis. Fuel parameters of importance are carbon monoxide (CO) and hydrogen (H_2). Based on statistical analysis of the combined four furnace operation, 16 engines were selected with a combined utilization of 88.4% and an average power generation rate of 24 MW.

4 CONCLUSIONS

Thermodynamically, air dilution is the most efficient means of cooling furnace off-gas to manageable temperatures and direct heat recovery in a drier is the most efficient means of recovering heat.

Unbiased evaluation of various off-gas energy recovery options is essential to determine the most optimum solution on a site specific basis. Careful attention must be paid to site integration of energy recovery systems to ensure that the primary focus, metal production, is not affected and all safety considerations are included.

1. *Process Modelling and Testing Methods for Evaluating Ferroalloy Furnace Off-gas Waste Energy.* **Els, L, Andrew, N and Noakes, S.** Almaty : INFACON XIII, 2013.
2. **Sato, S.** *Chemical Energy and Exergy.* s.l. : Elsevier Science and Technology Books, 2004.