CASE STUDY ON WASTE-FUELLED GASIFICATION PROJECT GREVE IN CHIANTI, ITALY

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By

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BACKGROUND

Construction of the power station at Greve in Chianti in the early 1990s was funded by the municipalities in the area around Florence, Italy, to recover energy from MSW collected in the same area. In 1988, Termiska Processer AB (TPS) licensed their low-pressure, air-blown, circulating fluidized bed (CFB) gasification process to Ansaldo of Italy. TPS next provided the design of two refuse derived fuel (RDF) pellet gasifiers for a small commercial-scale plant at Loc. Testi, Passo dei Pecorai, Greve in Chianti, Italy. The plant was designed by Studio Ingenaria Ambientale and built by Ansaldo Aerimpianti, and was commissioned in 1992 and turned over to the owner, Servizi Ambientali Area Fiorentina (S.A.F.I.), early in 1993.

In the late 1970s, TPS began development of CFB boilers, and in the mid 1980s turned their attention to CFB gasifiers. The impetus for this work was the high price of fuel oil and the desire in Scandinavia to utilize bark as a fuel in lime kilns. As a consequence, in 1984 TPS embarked on the development of a biomass-fuelled atmospheric pressure gasification system, and constructed a 2 MWt pilot plant gasifier. Although the technology developed by TPS was fairly sophisticated in that it was able to effectively handle a wide range of feedstock types, and was capable of being scaled up in size, the gas produced was heavily contaminated with tarry components that would make its use in gas turbines and engines difficult without gas cleaning. As a result, in 1988 a dolomite tar cracker, cold gas filter, wet scrubber and modified 500 kW diesel engine were developed and added to the pilot plant (Figure 1). As part of the Greve in Chianti project, test work was conducted in the pilot plant gasifier using Italian pelletized RDF as feedstock.

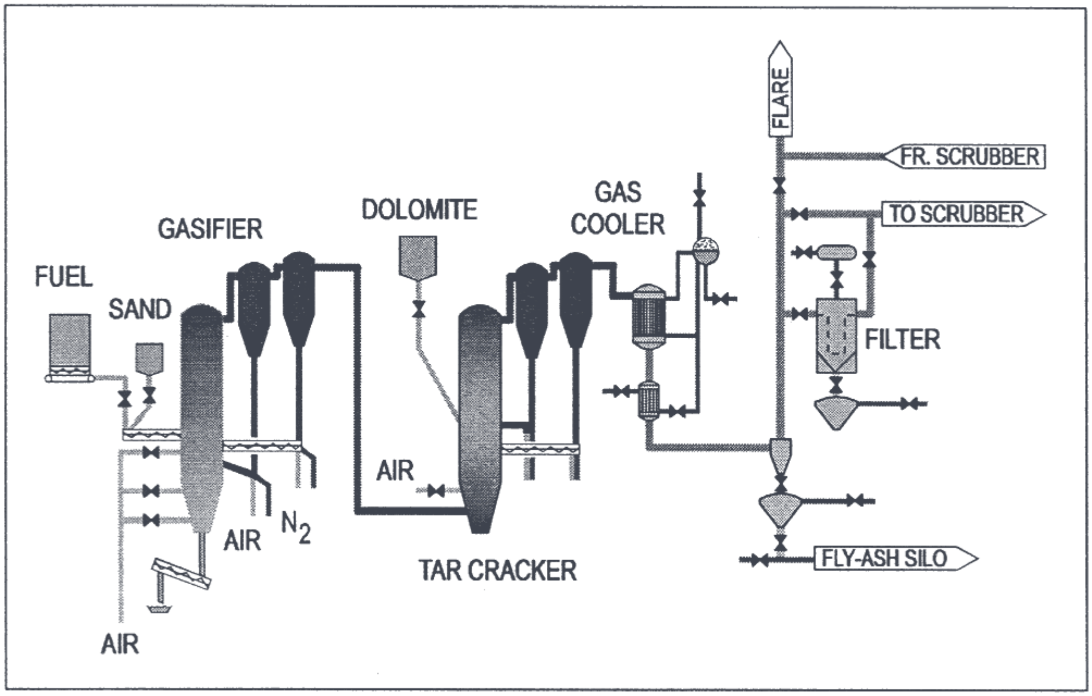

Figure 1. Termiska Processer (TPS) CFB Gasification Pilot Plant

TECHNOLOGICAL DETAILS

Gasification of RDF

Air-blown gasification consists of the conversion, by partial oxidation, of carbonaceous material into a gaseous fuel of low heating value, containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), and some higher hydrocarbons (C_xH_y). The produced gas will also contain nitrogen, water vapour, char particles and ash, tars and oils, and varying quantities of feedstock-specific pollutants such as hydrogen sulphide (H_2S), anhydrous ammonia (NH_3), hydrogen cyanide (HCN) and hydrogen chloride (HCl).

RDF enters the reactor and immediately begins to heat up, as a result of combustion of about 20-30% of the total feed, driving off the moisture. When the temperature rises to 300-500°C, pyrolysis occurs driving off gases and condensable hydrocarbon tars, and leaving a carbonaceous char. Gases and tars react with oxidizing agents to form CO, CO_2 and H_2, increasing the temperature to 800-850°C, which in turn, accelerates gasification of the char. More CO and CO_2 are produced, and hydrogen is generated from the water gas shift reaction ($CO + H_2O = CO_2 + H_2$).

Circulating Fluidized Bed Gasifiers

The Greve plant is equipped with two 15 MWt TPS CFB gasifiers, each with a capacity of 100 t/d of RDF pellets. The TPS technology uses a starved-air gasification process in a combined bubbling and circulating fluidized bed reactor, operating at about 850°C (below the ash melting point) and slightly above atmospheric pressure. Each gasifier is composed of a cylindrical riser, a U-beam conduit for coarse solids separation (by impingement), and a cyclone for finer solids separation. Solids are recycled to the bottom of the bed *via* return legs. All parts are internally lined with refractory to minimize thermal losses and to ensure isothermal conditions are maintained.

Air is used as the oxidizing agent, and silica and/or dolomite sand of 0.3-0.8 mm size is used as the bed material. The bottom section of the bed operates in the bubbling (dense) mode. Primary air is injected upward through the distributor at the bottom of the bed. The air injection rate and internal dimensions are such that gas velocity is lower here, compared to the upper part of the riser. Here, operating temperature is in the range of 700-800°C. RDF, fed in pelletized form by means of a screw conveyor, falls by gravity and is distributed across the dense bed, where the volatiles are released and some fragmentation occurs. Residence time for the larger particles can be quite long, while the finer particles (fragments) are entrained with the sand, and slowly rise to the level where secondary air is injected. This is the boundary between the bubbling (dense) and circulating (fast) bed, and the new influx of air, heat release and particle size reduction increase gas velocity, improving gas/solid mixing. Partial combustion of gaseous species occurs here, increasing the temperature to about 850°C.

This bed expansion causes solid particles to reach the top of the riser and enter the U-beam chamber and cyclone. Separated particles are recirculated to the bubbling bed by means of the return legs, where nitrogen is used as a fluidizing agent to prevent combustion of the hot, ignitable char. Coarse particles from the U-beam chamber are completely recycled; some fine particles from the cyclone are bled off to avoid fine particle enrichment in the bed that would eventually decrease cyclone performance. Bottom ash is discharged by gravity, cooled and conveyed to storage for disposal. Raw gas leaving the cyclone is fed to the combustor/boiler.

Greve in Chianti Combustor/Boiler

The combustor/boiler was purpose-built to accept produced gas from the gasifiers, unlike the Lahti and Zeltweg plants at which the gasifiers were add-ons to existing coal-fired boilers. Design of the boiler had already been undertaken by S.A.F.I. before TPS was involved in the project.

The primary combustion chamber is refractory lined and operates adiabatically. At the top of this chamber, a downward-facing, dual-fluid burner is positioned, consisting of ten raw gas injectors arranged axially around the air injector. The gas injectors are placed at an angle to the axis to impart swirl to ensure mixing. The burner operates at high excess oxygen, which is adjusted by the control system to maintain the flue gas temperature at 1050°C. Natural gas is used as an auxiliary fuel.

The post-combustion chamber is designed as determined by law (DM 503/97) to provide 6% excess oxygen in the flue gas, and a residence time greater than two seconds at a minimum temperature of 850°C (for dioxin destruction). Auxiliary burners (natural gas) and secondary air ports are provided to ensure that temperature restrictions are met. Ammonia (NH_4OH) or urea (NH_2CONH_2) is injected directly into the post-combustion chamber flue gases to reduce nitrogen oxides (NOx) emissions through selective noncatalytic reduction (SNCR).

Exhaust gases enter the radiation section of the boiler, reaching the superheater at a temperature of 650°C, then pass through the convective bank and the economizer, leaving the boiler at 200°C. Superheated steam is generated in the boiler at 380°C and 42 bar, with a design mass flow of 18 t/h to the 6.7 MWe condensing steam turbine.

Environmental Control

Environmental regulations in force stipulate that sulphur dioxide (SO_2) emissions must be reduced to less than 50 mg/Nm^3, while HCl emissions can be no more than 10 mg/Nm^3, both measured at 11% oxygen. To achieve this, a 1-3% (by weight) slurry of hydrated lime (calcium hydroxide, $Ca(OH)_2$) is prepared and injected cocurrently into the flue gas (from the economizer) in a three-stage Research-Cottrell spray dryer absorber. The residence time is sufficient to allow SO_2 and HCl to partially react with the slurry. Downstream of the spray dryer and upstream of a fabric filter (baghouse), more hydrated lime is injected, this time dry. In-duct reaction coupled with further reaction as the flue gases pass through the sorbent in the filter cake on the bag surface, are sufficient to meet the regulated limits. The baghouse also removes fine particulates not captured by the cyclone.

As stated above, dioxins/furans are suppressed in the post-combustion chamber of the boiler, as is NOx (*via* SNCR).

Fuel Preparation, Handling and Feeding

Limited processed RDF pellet supply in early 1995 led to the use of hogged wood or agricultural wastes from time to time, also reducing operating hours of the facility considerably. As a result, new RDF processing facilities were built at Case Passerini, near Florence in mid-1996 to serve the Greve plant. The facility uses standard mechanical processes (primary shear shredding, secondary hammermill shredding, magnetic and eddy current separation, air classification, and fines disc screening) to recover metals and glass, and produce pellets while recycling approximately 25% of the MSW by weight.

At Greve, the RDF pellets are stored in four 80-tonne steel silos. RDF is recovered from the storage silos using a twin-screw reclaimer that digs the waste from the silos and deposits it into a bucket conveyor. From the bucket elevator, the pellets are moved by a screw conveyor running the length of the building, and are discharged into the feed hoppers. RDF is removed from the hoppers with a twin-screw auger/reclaimer, passes through a rotary valve, and then is sent by a chute into the gasifiers.

The process scheme of the Greve in Chianti plant is depicted in Figure 2.

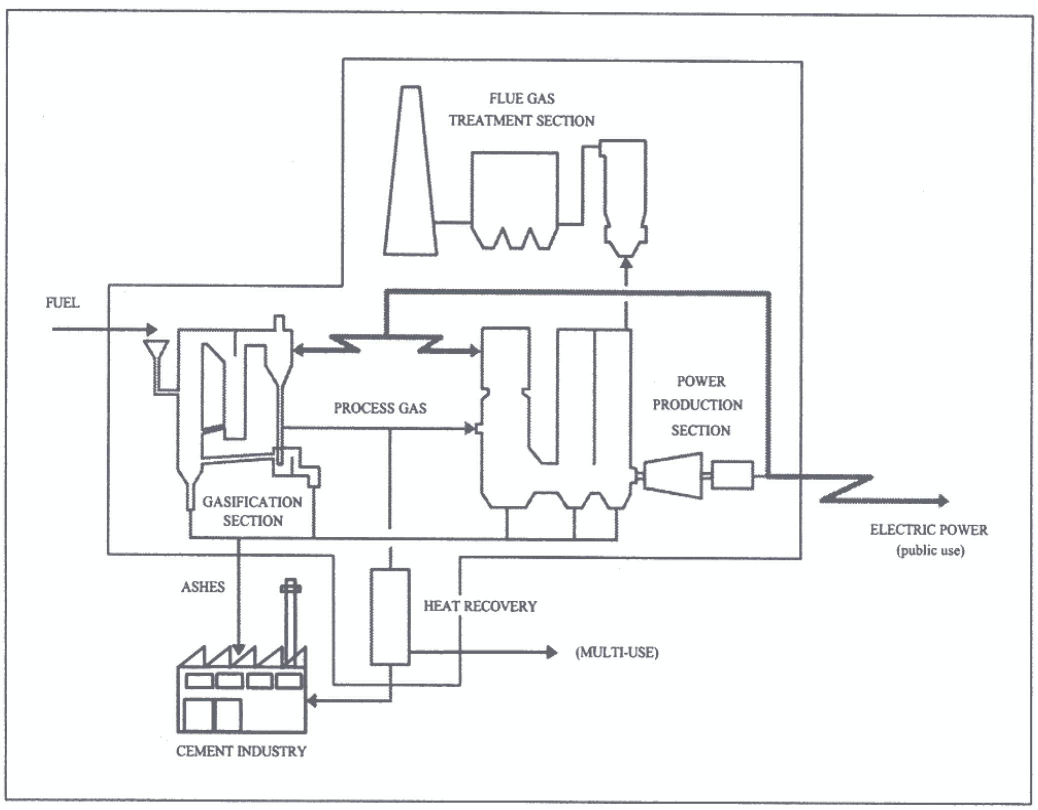

Figure 2. Process Scheme of Greve in Chianti RDF Gasification Plant, Italy

Innovative Features at Greve in Chianti

The plant at Greve in Chianti is comprised of two gasifiers (only one is shown in Figure 2). These gasifiers are used alternately to feed the single boiler. However, produced gas in excess of that required by the boiler (and gas from the second gasifier, when required) is cooled to 400°C but not cleaned, and transported (by pipeline) a short distance to a nearby cement plant, operated by SACCI. Here, the produced gas is used as fuel for the cement kiln. The SACCI plant also uses the ash and spent lime from the Greve plant, in return providing fresh lime for the scrubber.

Present economics favour electricity generation from the produced gas; however, the gas sales option provides a measure of operational flexibility while ensuring that the supply of RDF pellets can be effectively utilized.

FUEL/GAS CHARACTERISTICS

As stated above, RDF is produced and pelletized at a specialized plant in Case Passerini (TPS does not normally supply fuel preparation, but fuel characteristics are clearly important to the gasification process, thus the pilot-scale work on ‘design’ pellets). The pelletized RDF feed specifications for the Greve in Chianti plant are as follows:

- Diameter 10-15 mm
- Length 50-150 mm
- Bulk density 500-700 kg/m^3 (31-42 lb/ft^3)
- Net calorific value (LHV basis) 17.2 MJ/kg (7 380 Btu/lb)
- Volatile matter 71.1 percent
- Moisture (typical) 6.5 percent
- Fixed carbon 11.4 percent
- Sulphur 0.5 percent
- Chlorine 0.4-0.6 percent
- Total noncombustibles 11 percent

Table 1 presents the raw gas composition, *i.e.*, actual values of the gas that is fed either to the boiler or the SACCI cement kiln.

Table 1. Typical Produced Raw Gas Composition at Greve in Chianti

Component	**Volume %**	**% of Heating Value**
CO_2	15.65	Nil
N_2 + Ar	45.83	Nil
CO	8.79	34.9
H_2	8.61	22.5
CH_4	6.51	12.8
C_xH_y	4.88	29.7
H_2S	48.61 ppm	0.05
H_2O	9.48	Nil
Other	0.14	N/A
Total	**100.00**	**7.53 MJ/Nm^3 (202 Btu/Sft^3)**

In addition, approximately 50 g/Nm^3 of fine char particles (10-100 microns) and 75 g/Nm^3 of tars are entrained in the produced gas.

PERFORMANCE

Environmental

Tables 2 and 3 present air emissions data, as measured in stack testing at Greve. As is obvious from the numbers, the plant is capable of meeting all EU regulations and US EPA New Source Performance Standards (NSPS). Wastewater is produced in the scrubber system, and blowdown streams occur for the boiler and cooling tower. Pilot test data suggest that these wastewater streams can be treated adequately in a biological system or with activated carbon filters.

Table 2. Air Emissions Data—Greve in Chianti Plant

Pollutant	Measured Emissions Rates		Greve Regulatory Limits	
	11% O_2	**7% O_2**	**11% O_2**	**7% O_2**
CO, mg/Nm^3	2.5-5	1.8-3.6	50	35
Particulates, mg/Nm^3	3-7	2-5	10	7
HCl, mg/Nm^3	0.5-2	0.4-1.4	30	21
HF + HBr, mg/Nm^3	< 0.1	< 0.1	2	1.4
SO_2, mg/Nm^3	5-15	3.6-10	100	71
Heavy Metals, mg/Nm^3	2.2	1.6	*	*
PCBs, $\mu g/Nm^3$	0.163	0.116	100	< 100
NOx, mg/Nm^3	200-300	140-214	300	214
PCDD/PCDF, ng/Nm^3	13.1	9.3	2 860	2 040

*See Table 3

Table 3. Heavy Metals Emissions Data—Greve in Chianti Plant

Metal	Measured Value, mg/Nm^3	Italian Regulatory Limit, mg/Nm^3
Lead (Pb)	0.005 (maximum)	3
Cadmium (Cd)	< 0.0004	0.1
Mercury (Hg)	0.008-0.05	0.1

Mass and Energy Balances

Since commissioning in 1993, the plant has operated for 5 000 h, generating electricity for 4 500 h (production of 6 200 MWh). In addition, about 4 million Nm^3 of cooled gas was supplied to the cement plant. Conversion efficiency of the gasifiers has varied between 85% and 95%, on a throughput of 2-3.9 t/h of RDF pellets. Various sources have placed the overall electrical efficiency of the Greve in Chianti plant, as it existed in 1997, between 18% and 20%. This was due to a number of problems (discussed below) that resulted in an expensive retrofit. Because communication with the plant was difficult after the renovations, no new data are available. Instead, mass and energy balances are presented here (Figure 3) for a TPS system based on the Greve RDF pellets as feedstock, and TPS's extensive pilot-scale test results.

Figure 3 depicts a high-efficiency combined cycle system. In a combined cycle, the cleaned produced gas from the gasifier is combusted in a gas turbine producing electricity, and the hot combustion gases from the gas turbine exhaust then flow through a heat recovery steam generator (HRSG) to produce steam that generates more electricity in a steam turbine/generator. Thus, in Figure 3, feed of 387 t/d of RDF produces 25.7 MWe from the gas turbine and a further 17.0 MWe from the steam turbine. Power requirements include 7.3 MWe to compress the clean produced gas to be fed into the gas turbine, and a further 1.7 MWe needed for other equipment. This yields net power output of 33.7 MWe, and a remarkable efficiency of 39% on a higher heating value basis. Of course, this value must be reduced by the energy required to reduce the mass of the original MSW by 30% and pelletize the resulting RDF. (This value has not been reported in the available literature.)

Note that the additional cleanup equipment in Figure 3—a dolomite catalytic tar cracker, fabric filter baghouse, wet scrubber and H_2S removal—are required because the gas turbine has very strict restrictions on particulate matter, alkalis, sulphur compounds, *etc*. On the other hand, this will ensure that plant emissions levels, *e.g.*, sulphur, NOx and particulates, mercury and dioxins, will be extremely low, capable of meeting present and future regulations.

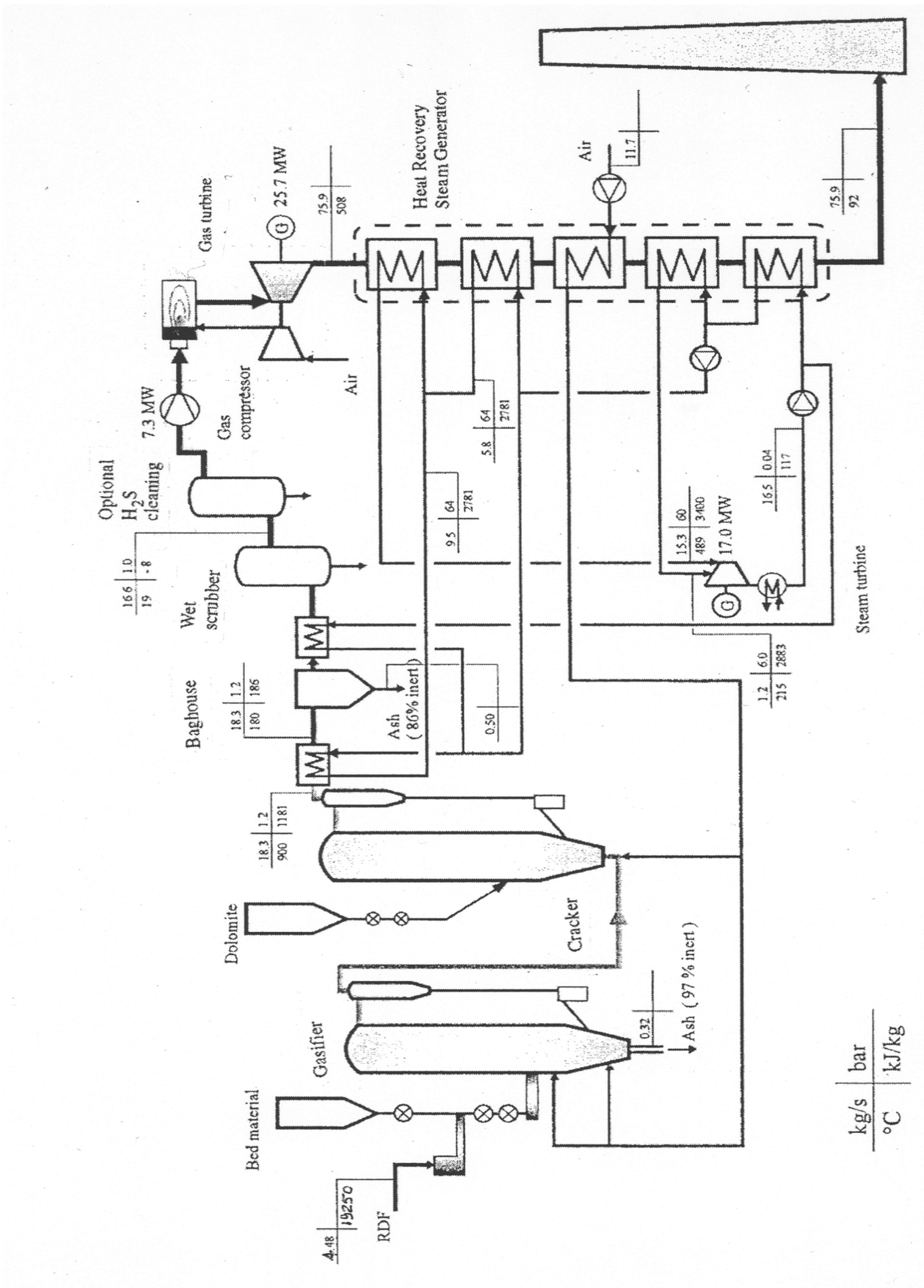

Figure 3. Greve in Chianti (Conceptual) Mass/Energy Balance

Problems/Solutions

Although the plant at Greve in Chianti has operated with some success since 1993, fouling of the boiler has caused significant reduction in operational availability of the plant. As a result, the steam turbine has been operated at 30-50% of its nominal rating of 6.7 MWe, and the resultant loss of electricity production has had a negative effect on the economics of the plant.

Boiler fouling, the main technical problem experienced during the period 1993-1997, has resulted from large quantities of carbon particulates (50-80 g/Nm^3) and condensible tars (70-80 g/Nm^3) in the produced gases which, when combusted in the boiler, coat the tube surfaces. To correct this situation and bring the plant back to profitability, a two-phase remediation program was undertaken.

Phase I involved overhauling the boiler to increase total surface area available for heat transfer, and modification of the internal surfaces and pathways to avoid low gas velocities in the boiler. As a result, in the period August 1997-February 1998 (7 months) boiler availability increased by 70% and almost 50% of the previous loss in efficiency was recovered (to 85%). Table 4 summarizes operating results for this period.

Table 4. Operating Results after Boiler Modifications (August 1997-February 1998)

Gasifier operating hours	3 700
Boiler operating hours	3 300
Steam production	13-15 t/h
Steam turbine operating hours	2 100
Steam efficiency	2 800 kJ/kg steam
RDF converted to gas	9 000 t
LHV of RDF	17.16 MJ/kg
Electrical energy generated	3.4 GWh
Gas supplied to cement works	3 900 000 Nm^3

As can be seen from Table 4, production of gas for the cement works in this period almost equalled that during the first four years of operation, while electricity production was about one-half (3.4 *vs.* 6.2 GWh).

Further performance improvements and increased capacity were possible only if an advanced gas cleaning system and a second boiler were installed (Phase II). Late in 1997, the European Commission's THERMIE Programme agreed to provide M€1.5 of the total cost of Phase II of M€9.7, and modifications began in 1998. Partners in the renovation included the Comune di Greve, S.A.F.I., Ansaldo S.p.A. (Italy), Ansaldo Volund R&D (Denmark), and Schumacher (Germany). Green Land Reclamation (UK) and Tavolini (Italy) acted as consultants.

Phase II involved installation of a second combustion line (a new boiler with a capacity of 3.1 MWe) and a complete upgrading of the gas cleaning system. Gas cleaning involves: a first deduster (centrifugal cyclone); a high-temperature acid gas/dechlorination unit (injection of limestone at 800ºC); a second deduster (axial centrifugal cyclone); cooling; and ceramic filters. A bypass line after the first deduster allows maintenance to be performed on the system without taking the boilers off line. Table 5 summarizes the inputs and outputs from the new cleaning system.

Table 5. New Gas Cleanup System Results

Parameter	**Gas Input**	**Gas Output**
Flowrate, Nm^3/h	3 000-5 000	Up to 4 500
Temperature, ºC	< 850	> 550
Dust content, g/Nm^3	50-80	< 1
Chlorine removal efficiency, %	--	> 75
Dust removal efficiency, %	--	> 90

With this gas cleanup system and new boiler in place, the existing steam turbine/generator set can now be fully loaded. This will allow a greater proportion of the produced gas to be converted to electricity (rather than being sold to the cement works), allowing the plant to be more profitable. In addition, the already excellent environmental performance of the plant will be improved. At this level of gas cleanup, the option exists for installation of a gas turbine (combined cycle) to boost efficiency and electricity output considerably.

CAPITAL, OPERATING AND MAINTENANCE COSTS

Capital cost of the original plant configuration was US$20 million (approximately M€20). The added cost of the second boiler and advanced cleanup system was M€9.7. For a fully loaded steam turbine/generator (6.7 MWe), and assuming 5% plant auxiliary power requirement (0.335 MWe) for net electrical output of **6.365 MWe**, this is equivalent to a specific capital investment of:

29 700 000/(6 700 – 335) = **€4 666/kW** (approximately **US$4 666/kW**)

This is a very high figure; however, there are two mitigating considerations. First, if the initial boiler had been designed and sized correctly, and if minimal gas cleaning had been added originally, the total cost would have been less than the eventual cost of what has turned out to be a patch job. Second, the cost includes a spare gasifier, which will be necessary to fully load a gas turbine/steam turbine combined cycle configuration, should this direction be pursued in the future.

As no operating and maintenance costs are available for the renovated Greve in Chianti plant, two available cost estimates for TPS combined cycle plants, similar to that depicted in Figure 3, will instead be presented here.

The first estimate is from TPS itself, for a plant consisting of two CFB gasification systems, and a combined cycle (gas and steam turbine). Capacity of this plant is 1 200 t/d of unpelletized RDF (from 1 600 t/d of MSW), and gross electricity generation is 74.5 MWe. Fuel preparation requires 1.4 MWe, while auxiliary power requirements (mainly to compress the gas feed for the gas turbine) use another 12.4 MWe, leaving a net output of **60.7 MWe**. Capital cost of this plant (1996 US dollars) is $170.7 million, for a specific capital investment of **$2 812/kW**. Annual gross O&M is $35.6 million, and electricity sales (at $0.04/kWh) generate $16.3 million annually. Net O&M of $19.3 million translates into a net cost for waste disposal of **$38.91/t of MSW**.

The second study comes from the US National Renewable Energy Laboratories (NREL) for a plant at the Weyerhauser Mill in New Bern, NC. In this feasibility study, the TPS-designed cogeneration, combined cycle plant would gasify 63.7 t/h of wood wastes to produce **33.8 MWe** net and 98 MWt of high- and low-pressure steam for use in the plant. Capital cost of this plant, as a retrofit, is US$ 102.1 million (1995 US dollars), yielding a specific capital investment (electricity only) of **US$3 020/kW**. Total annual O&M costs are US$4.69 million, for a gross waste disposal cost of **US$9.35/t**. (Note that this figure is based on 90% plant annual capacity factor, and does not include credit for the value of generated electricity or steam).

NREL has also estimated the cost of larger greenfield plants (without cogeneration) to examine the economies of scale. For a **59 MWe** plant, specific capital investment was **US$1 750/kW**, and net electricity generation efficiency was calculated as 30% (HHV basis). A plant producing **100 MWe** could be built for **US$1 535/kW**. While these figures look good on paper, a plant generating 100 MWe would require more than 1.5 million t/a of wood waste. At these quantities, the cost of acquiring and transporting waste fuel would soon render the plant uneconomical to operate.

CONCLUSIONS

The Greve in Chianti RDF gasification plant is an example of coupling a promising new technology with an old warhorse, producing a mediocre result. Throughout the project's spotty history, no problems have been reported with the CFB gasifier, not even the usual (for this technology) fuel feeding concerns. However, developers chose to couple the gasifier to an inefficient, poorly (under)designed, yet conventional, gas boiler, doubtless unheeding of advice from TPS about gas cleaning. As a result, overall efficiencies of 18-20% have been reported, a far cry from the almost double efficiency values obtained at Lahti. Worse still, the boiler fouling problems encountered at the plant were serious enough that the steam turbine/generator had to be seriously derated, and availability was uneconomically low as a consequence. To save the plant and the initial investment, the owners put up another 50% in capital expenditure to renovate the plant to what it should have been in 1993.

We know that these renovations/additions were completed at some point in 2000. Since that date, however, no papers or reports of substance have come from the plant, and all attempts at communication with Comune di Greve personnel have been fruitless. This lack of openness suggests that perhaps the renovations did not perform as expected.

Whatever the outcome of the project, the flawless performance of the CFB gasifiers in supplying RDF-derived gas to the boiler and cement plant stands as a testament to the efficacy of this equipment and technology.

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