Proceedings of the GPA-GCC 25th Annual Technical Conference,
Abu Dhabi, UAE, May 09-11, 2017

WHAT HAS YOUR SULPHUR PLANT DONE FOR YOU LATELY?

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ABSTRACT

Sulphur recovery facilities are necessary to meet emissions regulations and are therefore often viewed as a cost of production. However, the sulphur plant is normally a net energy exporter, providing a frequently overlooked benefit to the energy balance of the processing complex. This is because the Claus reaction, which is employed to covert H_2S to elemental sulphur, is exothermic, and the waste heat can be recovered as steam.

This paper will explore the energy benefits of various sulphur recovery technologies. Benchmark key performance indicators (KPIs) will be provided as a guidance to operators on how their sulphur recovery facilities should be performing, from an energy efficiency perspective. A Case Study for a sulphur recovery facility will be presented and energy benefits to the overall processing facility will be explored. Possible options for improving its energy efficiency will also be investigated.

Keywords: *Sulphur recovery, Energy efficiency, Energy balance, Energy KPIs, SO_2 emissions*

NOMENCLATURE

°C	degrees Celsius	kW	kilowatt
°F	degrees Fahrenheit	kWh	kilowatt-hour
ADGAS	Abu Dhabi Gas Liquefaction Co. Ltd.	LHB	lower heating value
AGE	Acid Gas Enrichment	LLP	low low pressure
barg	bar gauge	LP	low pressure
BFD	block flow diagram	m^3	cubic metres
BFW	boiler feed water	MDEA	methyl diethanolamine
BTEX	benzene, toluene, ethylbenzene, xylene	mg	milligram
BTU	British thermal unit	mol%	mole percent
C_1	methane	MP	medium pressure
CO	carbon monoxide	MTPD	metric tons per day
CO_2	carbon dioxide	NGL	natural gas liquids
CW	cooling water	Nm^3	normal cubic metres
DCS	distributed control system	O_2	oxygen
h	hour	OSBL	outside battery limits
H&MB	heat and material balance	P&ID	piping and instrumentation drawing
H_2O	water	PFD	process flow diagram
H_2S	hydrogen sulphide	RF	reaction furnace
HP	high pressure	RGG	reducing gas generator
kmol	kilomole	S	elemental sulphur
KPI	key performance indicator	SA	medium pressure (15 barg)

SH	high pressure (60 barg)
SL	low pressure (4.7 barg)
SO_2	sulphur dioxide
SRE	sulphur recovery efficiency
SRU	sulphur recovery unit
SU	low low pressure (1.1 barg)
S_x	elemental sulphur
TGTU	tail gas treating unit
TRS	total reduced sulphur
UAE	United Arab Emirates
vol%	volume percent
WHB	waste heat boiler
WHE	waste heat exchanger
Δ	change
ΔH	enthalphy of reaction

INTRODUCTION

In late 2014, oil prices plummeted dramatically in the space of just a few months. As shown in Figure 1, around mid-year, the price of oil started dropping rapidly and fell from about $100 per barrel to approximately half of this figure in less than six months. The price suffered additional losses in 2015, falling to a minimum around $25 per barrel, the lowest value in more than 13 years. The price rebounded somewhat in 2016 and now sits at around $55 per barrel (January 2017); however, this is still roughly half the figure enjoyed by the industry during the preceding 5 years.

Low oil price creates both challenges and opportunities for the industry. The challenges are obvious, with threatened economics for new projects and reduced margins on existing production. Those producers who stay focused on achieving success via efficient, cost-effective operations during these challenging times will prosper and thrive when oil price rebounds, allowing for stronger and more profitable operations in the future.

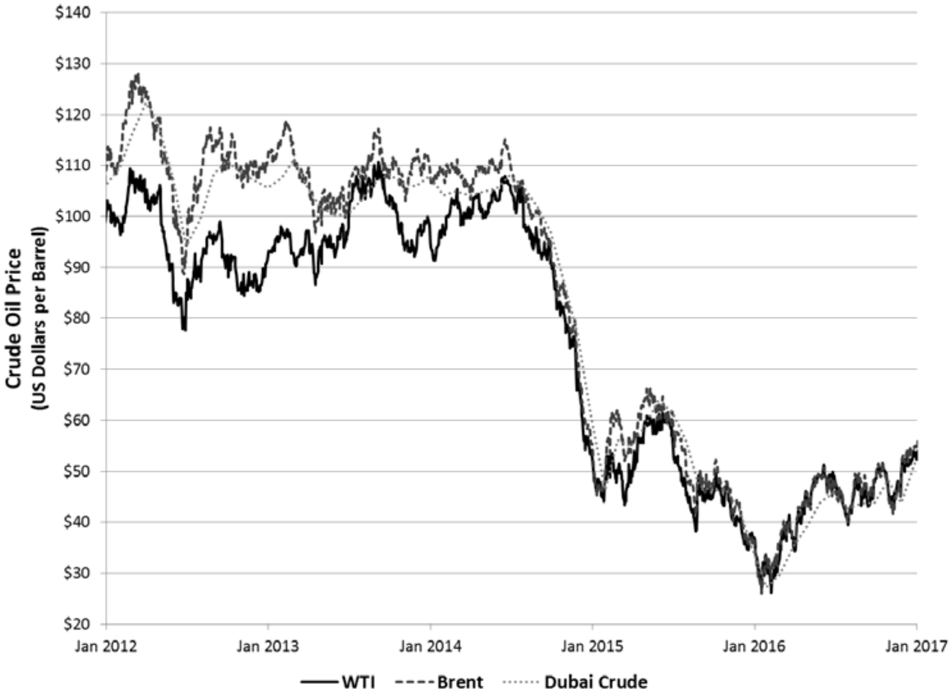

Figure 1. 5-year historical crude oil price [1,2,3]

The sulphur recovery facility within a refinery or gas plant is required to meet SO_2 emissions regulations and is often viewed as a cost of production. However, waste heat from the exothermic Claus reaction is recovered as HP and LP steam, which usually makes the sulphur plant a net energy exporter, supplying needed steam and/or power to the processing complex. For extremely sour gas plants or refineries processing sour crude feedstock, the sulphur plant may be one of the areas of greatest interest for improving energy efficiency and strengthening the economics of production.

As such, the key objectives of this paper are to:

- Identify the top energy producers and consumers in a typical sulphur recovery facility
- Quantify the energy balance and provide benchmark energy performance indicators (KPIs) for a hypothetical Benchmark Plant, across a range of conventional sulphur recovery technologies
- Explore a real world Case Study
- Quantify the potential improvement in energy performance for the Case Study facility through suggested modifications to the existing process operations and equipment

ENERGY PRODUCTION & CONSUMPTION IN THE SULPHUR PLANT

A typical Modified Claus plant is shown in Figure 2. In this well-known process, one third of the H_2S in the acid gas is burned to form SO_2, which then reacts with remaining H_2S to form elemental sulphur, via the exothermic Claus reaction. Key utilities produced/consumed in the process are steam (HP/MP and LP), fuel gas and electrical power. Typically, some form of tail gas treating is required downstream of the sulphur recovery unit (SRU) to satisfy SO_2 emissions regulations, the energy requirements of which can be substantial and will thus be discussed throughout this paper.

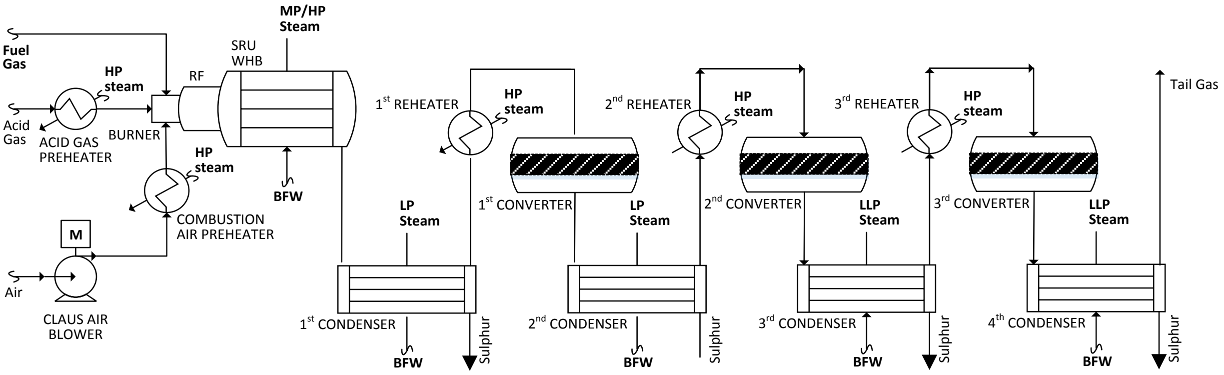

Figure 2. PFD of 3-stage Claus SRU with key utility streams

Steam

The heat of reaction for the exothermic Claus reaction is as indicated in Equations 1-3 [4].

Thermal Section

$$H_2S+\frac{3}{2}O_2 \rightarrow SO_2+H_2O \qquad \Delta H\ @\ 77°\mathrm{F}=-223{,}100\ \ BTU \tag{1}$$

Thermal and Catalytic Reaction Section

$$2H_2S+SO_2 \rightarrow \frac{3}{x}S_x+2H_2O \qquad \Delta H\ @\ 77°\mathrm{F}=-41{,}300\ \ BTU \tag{2}$$

Overall Reaction

$$3H_2S+\frac{3}{2}O_2 \rightarrow \frac{3}{x}S_x+3H_2O \qquad \Delta H\ @\ 77°\mathrm{F}=-264{,}400\ \ BTU \tag{3}$$

As shown in Figure 2, heat released in the process is recovered in the SRU waste heat boiler (WHB) as HP or MP steam, and in the sulphur condensers as LP or LLP steam. In addition to heat released by the Claus reaction, the incinerator produces heat via combustion of fuel gas to achieve temperatures hot enough to ensure complete oxidation of H_2S in the tail gas stream. Incinerators are often equipped with waste heat boilers and/or HP steam superheaters to recover some of this heat and maximize energy efficiency.

Steam consumers in the process include feed gas preheaters and process gas reheaters, all of which typically utilize HP saturated steam. The SRU and incinerator air blowers may also consume HP steam if steam turbine drives are employed. The only continuous LP steam consumer is the reboiler in an amine-based tail gas treatment unit (TGTU).

Overall, the sulphur recovery facility is a net HP or MP steam exporter. It is typically also an LP steam exporter; however, this may not be the case for amine-based TGTUs with extremely high recovery efficiency requirements, which can consume all (or more) of the LP steam produced in the SRU. This is usually not the case unless sulphur recovery efficiency (SRE) significantly exceeds 99.9%.

Fuel Gas

The incinerator is a continuous fuel gas consumer. Fuel gas is burned with excess air and the combustion effluent is mixed with SRU tail gas to achieve a minimum temperature of 650 ^{o}C for nearly complete oxidation of H_2S to SO_2. Sometimes higher temperatures are required to achieve lower limits on CO and/or total reduced sulphur (TRS), up to a maximum of around 815 ^{o}C.

In some facilities which process lean acid gas, continuous fuel gas co-firing may be employed in the SRU burner to achieve temperatures high enough for BTEX destruction. Other methods for increasing furnace temperature such as acid gas enrichment (AGE) or oxygen enrichment are preferred, as they reduce the risk of soot deposition and/or fire in the downstream catalyst beds, as well as minimizing the process gas flow through the facility, thereby minimizing the size of equipment and piping. Nevertheless, fuel co-firing is not an uncommon practice for increasing furnace temperature.

In older facilities, fuel gas is sometimes consumed in SRU fired reheaters; however, most modern SRUs utilize indirect HP steam reheaters to avoid the concerns mentioned above for fuel co-firing in the SRU burner. Most modern amine-based TGTUs employ preheating with HP saturated steam upstream of the hydrogenation reactor. However, for facilities that are not equipped with a hydrogen source, reducing gas generators (RGGs) are often installed. In an RGG, fuel is combusted sub-stoichiometrically to produce reducing gas; the exhaust gas is then mixed with the SRU tail gas to achieve sufficient temperature for the hydrogenation and hydrolysis reactions to occur in the downstream reactor. RGGs result in increased energy consumption (vs. TGTU steam preheaters) due to fuel consumption in the burner and also result in increased process gas flow through all equipment downstream of the RGG.

Overall, the sulphur recovery facility is a net fuel gas importer. All SRUs require continuous fuel firing in the incinerator; however, facilities which employ continuous fuel firing in the SRU burner, reheaters and/or TGTU RGG may require significantly more fuel consumption than units which do not.

Electric Power

The Claus and incinerator blowers are the primary electric power consumers in a sulphur recovery facility, when these machines are equipped with motor drivers. Other power consumers include air-cooled heat exchangers and pumps. In hot climates and/or when extremely high sulphur recovery efficiency is required, refrigeration may be required for solvent and quench water cooling in the TGTU.

Overall, the sulphur recovery facility is a net power importer. Facilities which employ amine-based tail gas treating may utilize significantly more power than those which do not, due to additional air cooled exchangers, pumps and possible refrigeration utilized in those facilities.

ENERGY PERFORMANCE COMPARISON OF SULPHUR RECOVERY TECHNOLOGIES

The overall impact of the various utility producers and consumers described above is that the sulphur recovery facility is typically a net energy exporter, although the quantity of energy exported can vary greatly depending on the type of tail gas treating technology employed. In some cases, the facility may actually need to import energy, when very high sulphur recovery efficiency is required, negating the energy benefits of the Claus process. To illustrate this, a hypothetical 1,000 MTPD sulphur recovery train has been considered, over a range of sulphur recovery efficiencies, which will be referred to as the Benchmark Plant. Considering that most refineries produce rich acid gas (H_2S > 85 mol%) and most gas plants produce relatively lean acid gas (40-50 mol% H_2S), a median concentration of 60 mol% is assumed. Feed gas flow and composition for the hypothetical plant are provided in Table 1.

Table 1. Feedstock for hypothetical 1,000 MTPD sulphur recovery train (Benchmark Plant)

	mol%	**kmol/h**
Component		
H_2S	60%	1,300
CO_2	30%	650
Hydrocarbon (as C_1)	1%	22
H_2O	9%	195
Total	100%	2,167
Temperature, °C	54	
Pressure, barg	0.69	

To compare relative energy balances for varying recovery efficiencies, simulations were generated, over a range of tail gas treating technologies and plant configurations. The following SRE cases were explored.

A. **97% SRE** – 97% recovery is based on a conventional 3-stage Claus unit.
B. **99.0% SRE** – 99.0% recovery is based on a sub-dewpoint process (2-stage Claus + 2 sub-dewpoint reactors), although it should be noted that a direct oxidation process would achieve similar SRE and energy balance.
C. **99.3% SRE** – 99.3% recovery is based on a 2-stage Claus unit + TGTU (MDEA). This SRE is just beyond the upper limit of an achievable guarantee value for sub-dewpoint and direct oxidation processes; therefore, it was investigated as the entry point for an amine-based TGTU.
D. **99.9% SRE** – 99.9% recovery is based on a 2-stage Claus unit + TGTU (MDEA).
E. **150 mg SO_2/Nm^3 (MDEA)** – The World Bank Standard case (99.98% SRE) is first investigated based on a 2-stage Claus unit + TGTU with generic solvent (MDEA).
F. **150 mg SO_2/Nm^3 (Proprietary Solvent)** – The World Bank Standard case (99.98% SRE) is investigated utilizing a more selective solvent in the TGTU and corresponding positive energy impact; thus, this case is based on a 2-stage Claus unit + TGTU with proprietary solvent.

Process flow diagrams for the six cases are provided in Figures 3-6.

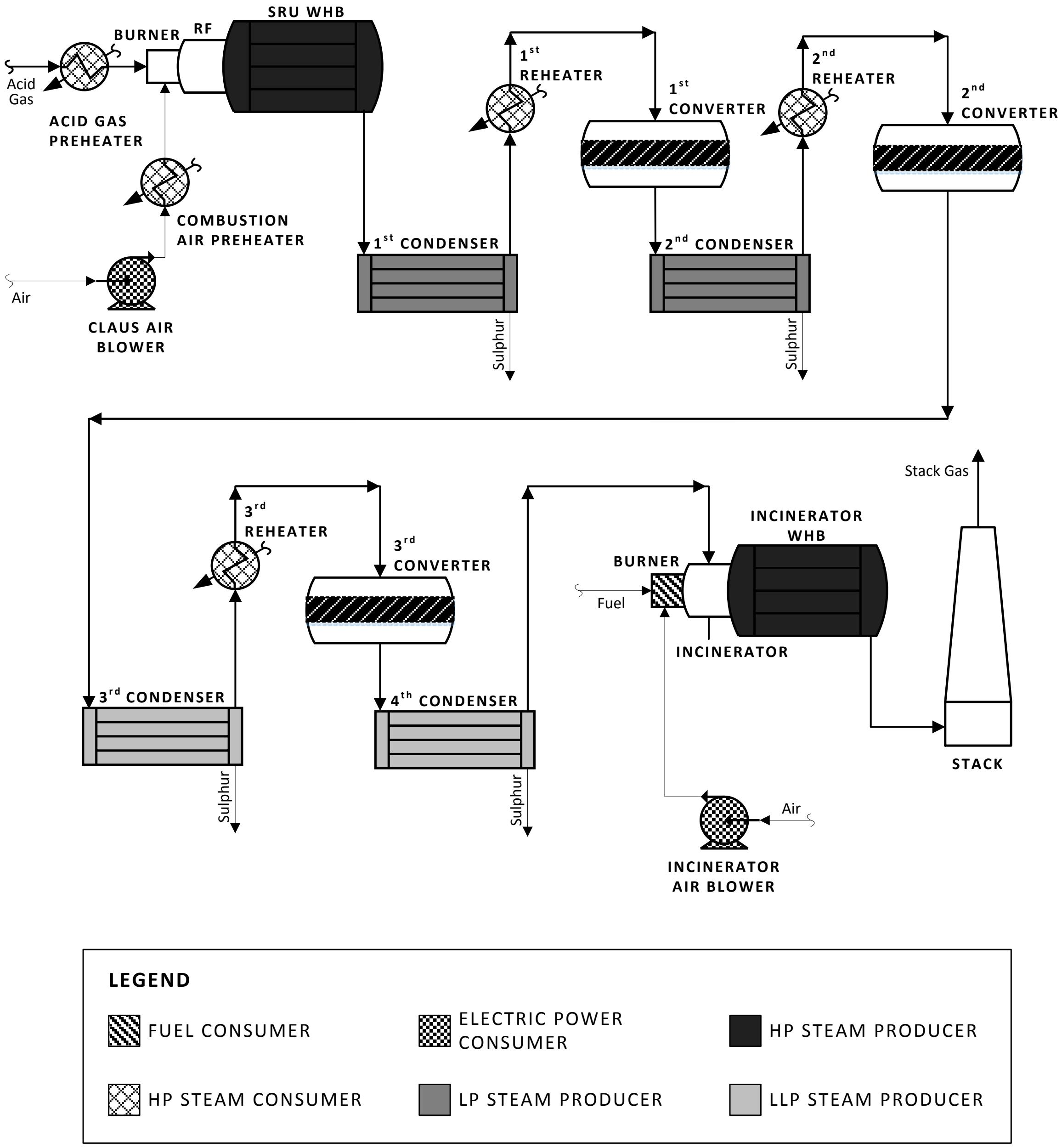

Figure 3. PFD for Benchmark Plant Case A

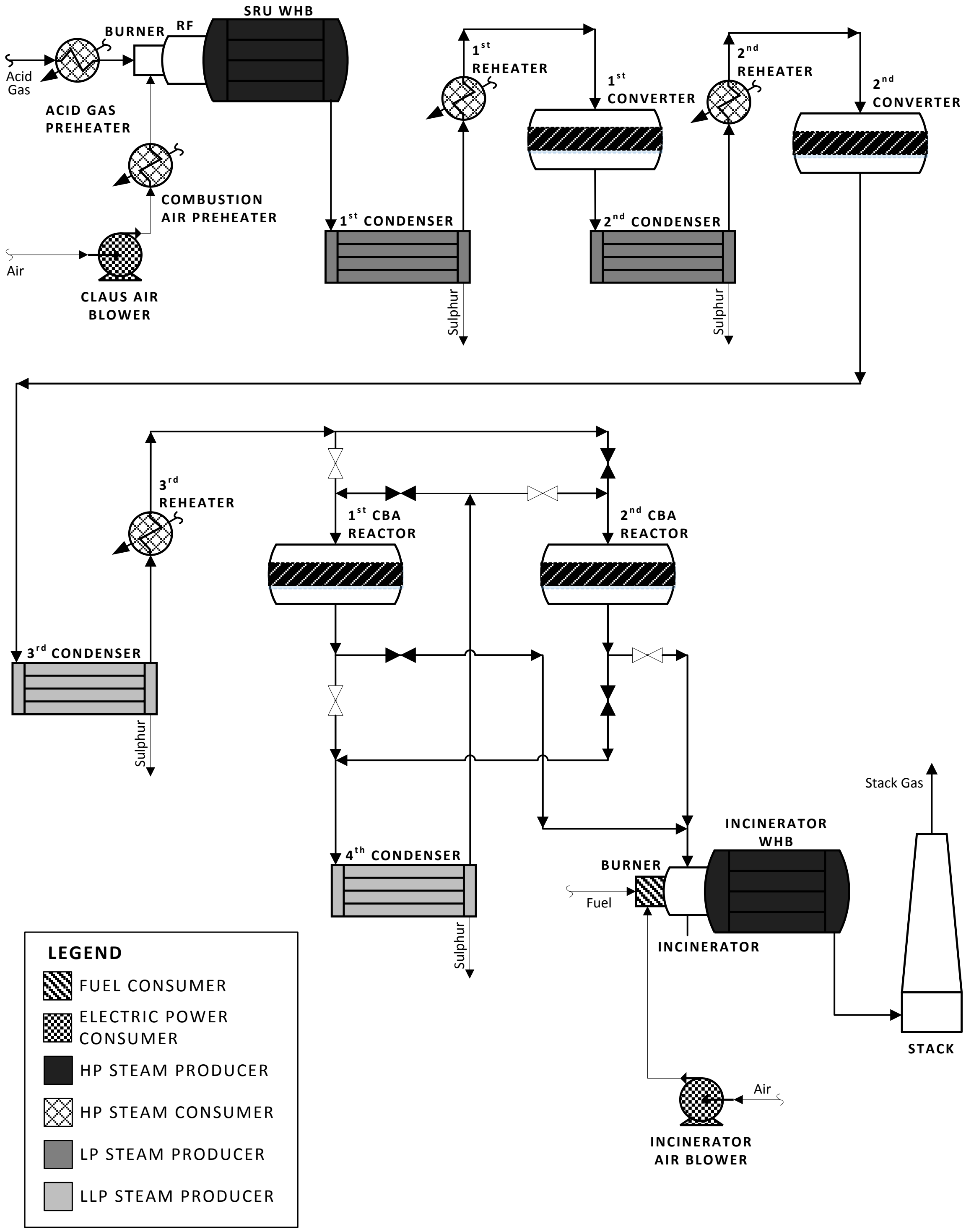

Figure 4. PFD for Benchmark Plant Case B

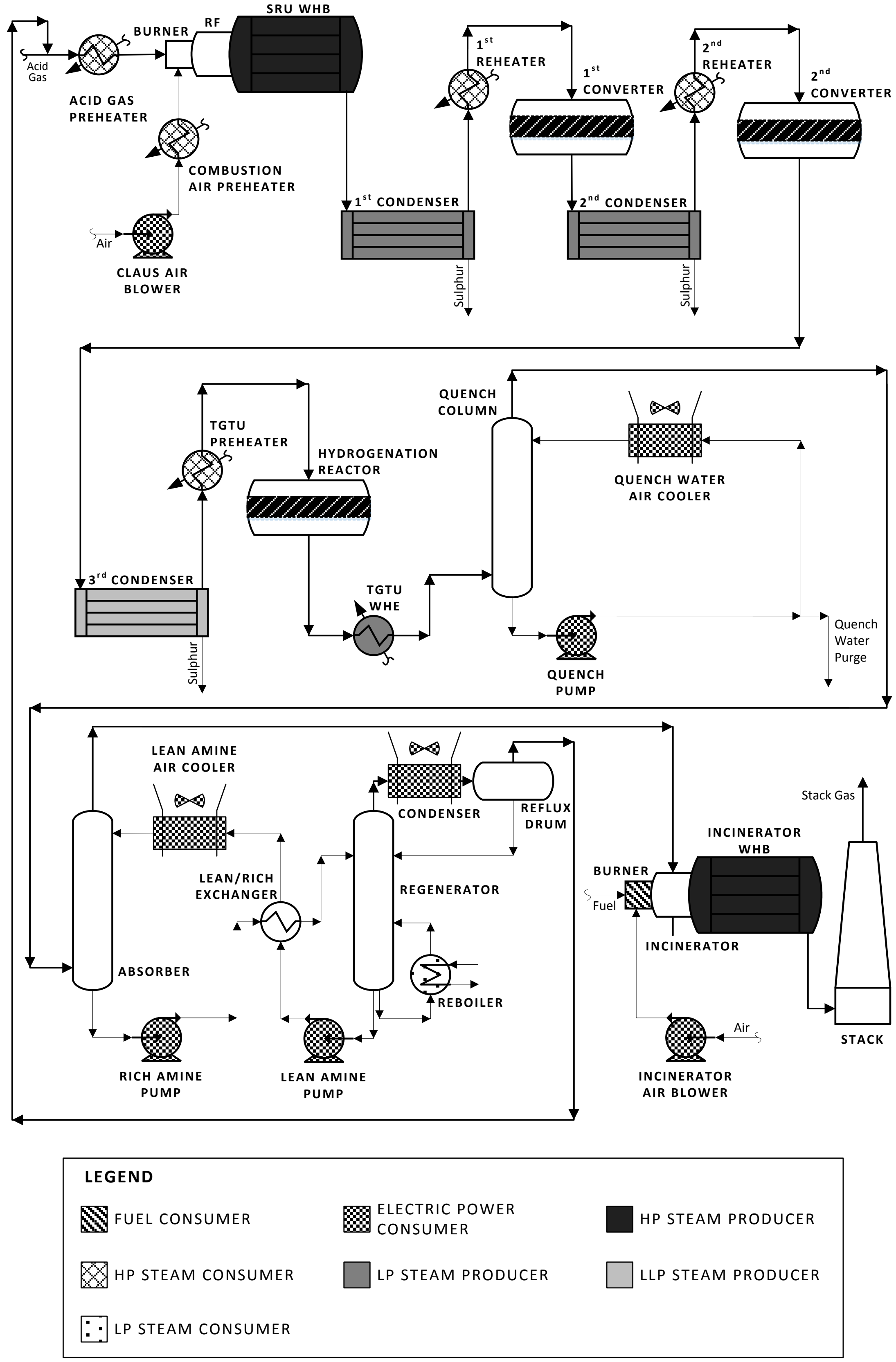

Figure 5. PFD for Benchmark Plant Cases C and D

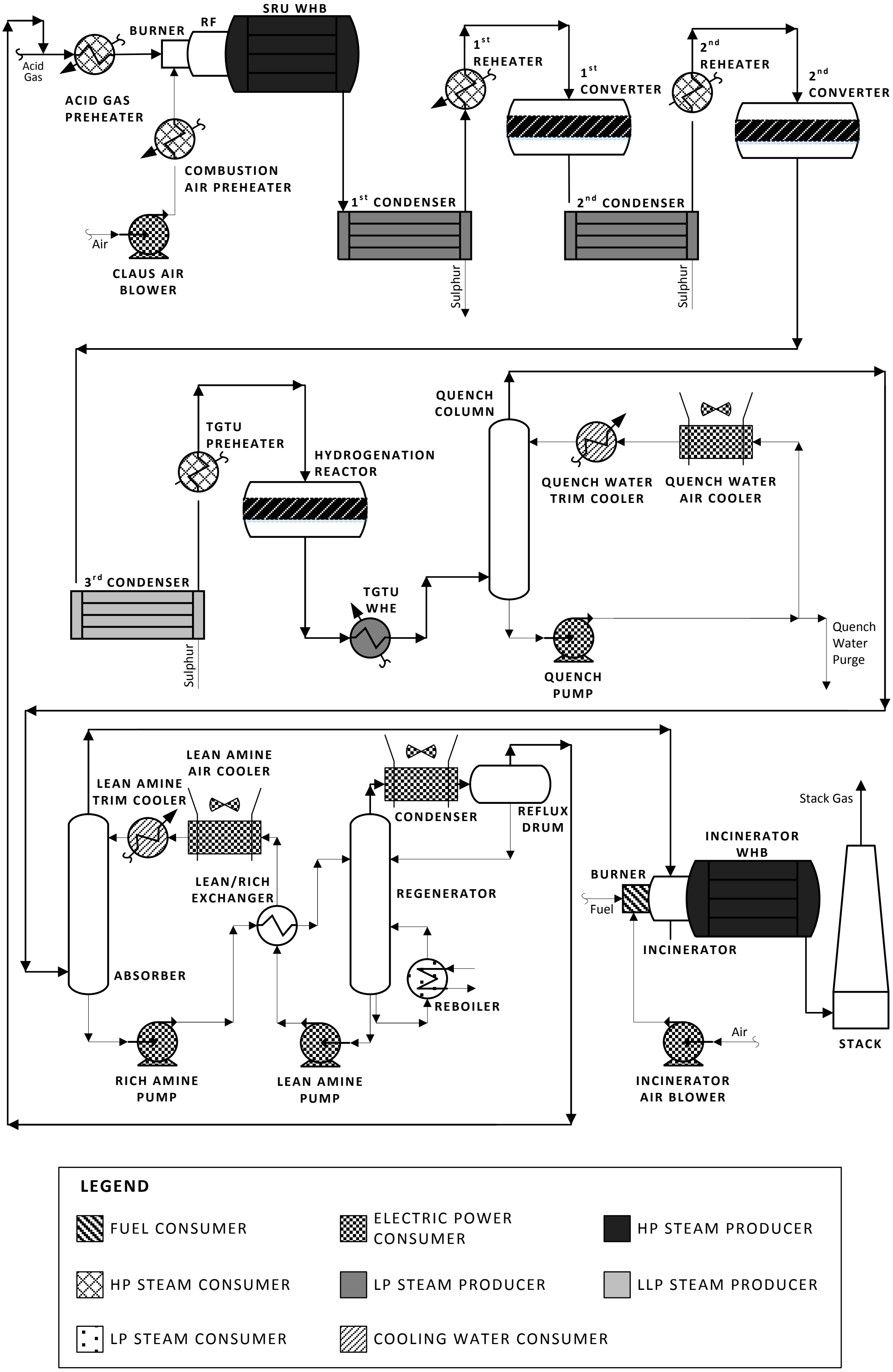

Figure 6. PFD for Benchmark Plant Cases E and F

A standard set of design parameters was employed for all cases to allow relative comparison on a consistent basis. Key design features are aimed at optimizing energy efficiency, as follows:

- Sulphur Recovery Unit
  - Air-only operation, without fuel co-firing
  - Motor-driven Claus air blowers
  - HP saturated steam (40 barg) produced in SRU WHB
  - 2 Claus beds (3 for 97% SRE case) with promoted activated alumina catalyst
  - 2 additional sub-dewpoint beds for 99.0% SRE case
  - LP steam (3.5 barg) produced in 1st & 2nd sulphur condensers
  - LLP steam (1.0 barg) produced in 3rd & 4th sulphur condensers
  - HP saturated steam (40 barg) consumed in SRU preheaters and reheaters

- Amine-based Tail Gas Treatment Unit
  - HP saturated steam (40 barg) consumed in preheater
  - Low temperature hydrogenation catalyst (232 °C inlet temperature)
  - LP steam (3.5 barg) produced in TGTU WHE
  - Lean solvent temperature of 50 °C for all except Cases E and F, which was reduced to 40 °C to achieve ultra-high SRE (air cooling to 50 °C with CW trim cooling)
  - LP steam (3.5 barg) consumed in regenerator reboiler
  - Solvent circulation rate for Case F assumed as 50% of Case E to approximate proprietary solvent [5]

- Incinerator
  - Operated at 815 °C (upper limit, required for achieving <5 mg/Nm^3 TRS)
  - 2% excess O_2 in stack gas
  - Fuel fired (LHV of 8,953 kcal/Nm^3)
  - Motor-driven incinerator air blowers
  - HP saturated steam (40 barg) produced in incinerator WHB
  - No sulphur pit ejector routed to incinerator

Key process parameters were compared for the range of SRE cases, as summarized in Table 2.

Table 2. 1,000 MTPD Benchmark Plant process parameters

CASE	**A**	**B**	**C**	**D**	**E**	**F**
SRE	**97%**	**99.0%**	**99.3%**	**99.9%**	**99.98%**	**99.98%**
Stack Gas SO_2 (kmol/hr)	38.95	12.97	9.04	1.24	0.28	0.28
Stack Gas CO_2 (kmol/hr)	870.6	885.7	845.4	850.6	851.2	851.2
Total Stack Gas Flow (kmol/hr)	8,012	8,134	6,176	6,188	6,189	6,189
Amine Circulation (m^3/hr)	---	---	176	264	1,026	513

ENERGY BALANCE FOR BENCHMARK PLANT

Thermal energy production/consumption figures for the top producers and consumers in the Benchmark sulphur recovery facility are summarized in Table 3, for each of the cases studied. For electric power consumers, the equivalent thermal energy consumption is calculated based on electricity generation with a nominal thermal to electric energy conversion efficiency of 40%.

It is observed that as SRE increases, energy export decreases, and the facility reverts from net energy export to import at ultra-high recovery efficiency (Case E), primarily due to LP steam consumption for MDEA solvent regeneration in the TGTU. When a highly-selective proprietary solvent is employed (Case F), LP steam consumption is reduced substantially, making the facility closer to energy-neutral.

Table 3. Energy balance by top utility producers/consumers for Benchmark Plant (kW)

CASE	**A**	**B**	**C**	**D**	**E**	**F**
SRE	**97%**	**99.0%**	**99.3%**	**99.9%**	**99.98%**	**99.98%**
HP STEAM PRODUCERS						
SRU WHB	+53,921	+54,044	+55,256	+55,586	+55,561	+55,561
Incinerator WHB (815°C)	+40,460	+40,615	+30,379	+30,424	+30,429	+30,429
HP STEAM CONSUMERS						
Acid Gas Preheater	-3,994	-3,994	-3,994	-3,994	-3,994	-3,994
Combustion Air Preheater	-3,271	-3,279	-2,900	-2,916	-2,918	-2,918
1st & 2nd SRU Reheaters	-7,376	-7,210	-7,604	-7,638	-7,678	-7,678
3rd SRU Reheater	-2,352	-1,350	---	---	---	---
TGTU Reactor Preheater	---	---	-4,382	-4,401	-4,423	-4,423
LP/LLP STEAM PRODUCERS						
1st & 2nd Sulphur Condensers	+19,544	+19,620	+20,255	+20,353	+20,431	+20,431
3rd Sulphur Condenser	+4,954	+4,092	+5,282	+5,307	+5,329	+5,329
4th Sulphur Condenser	+2,677	+4,185	---	---	---	---
TGTU Hydrogenation WHE	---	---	+3,592	+3,609	+3,622	+3,622
LP STEAM CONSUMERS						
Regenerator Reboiler	---	---	-12,266	-18,610	-86,820	-43,410
MP/LP FUEL CONSUMERS						
Incinerator Burner	-43,838	-47,147	-38,261	-39,426	-39,572	-39,572
MAJOR ELECTRIC POWER CONSUMERS						
Claus Air Blowers	-3,546	-3,556	-4,681	-4,706	-4,711	-4,711
Quench Pumps	---	---	-175	-175	-175	-175
Amine Pumps	---	---	-194	-295	-1,137	-568
Quench Water Air Cooler	---	---	-239	-358	-1,387	-692
Lean Amine Air Cooler	---	---	-159	-246	-641	-320
Regenerator Ovh’d Condenser	---	---	-145	-236	-1,375	-688
Incinerator Air Blowers	-575	-578	-458	-458	-458	-458
MAJOR COOLING WATER CONSUMERS						
Quench Water Trim Cooler	---	---	---	---	-17,366	-8,683
Lean Amine Trim Cooler	---	---	---	---	-9,937	-4,969
ENERGY BALANCE						
Net Energy Import/Export	+56,603	+55,443	+39,306	+31,819	-67,191	-7,889
Comparison to Case A (Net Δ)	---	-2%	-31%	-44%	-219%	-114%

The energy balances for the various cases are summarized by unit operation in Table 4 and Figure 7. These balances clearly illustrate that the SRU is always a net energy exporter whose energy production remains fairly constant, even for Case B, which employs a non-amine-based tail gas treating technology to achieve higher SRE. It is the amine-based TGTU that is responsible for increasing energy consumption as SRE increases.

Highly-selective solvents can offer reductions in LP steam and solvent cooling requirements but the overall impact of the TGTU on sulphur recovery energy production is still significant. The world average sulphur recovery efficiency for new plants is around 99.9% (Case D), which results in a 44% energy penalty on the standalone Claus plant, as shown in Tables 3 and 4. Despite its detrimental impact on the overall SRU/TGTU energy balance, the amine-based tail gas treating process is currently the only conventional technology available for achieving guaranteed SRE in excess of about 99.3%.

Table 4 also shows that incinerator energy consumption increases slightly as SRE increases, simply due to a reduced quantity of H_2S in the tail gas. This results in lower tail gas heating value and therefore greater fuel requirements, although the overall impact is marginal.

Table 4. Benchmark Plant energy balance by processing unit (kW)

CASE	**A**	**B**	**C**	**D**	**E**	**F**
SRE	**97%**	**99.0%**	**99.3%**	**99.9%**	**99.98%**	**99.98%**
SRU	+60,557	+62,552	+61,614	+61,992	+62,020	+62,020
TGTU	---	---	-13,968	-20,712	-119,610	-60,307
INCINERATOR	-3,953	-7.110	-8,340	-9,460	-9,601	-9,601
NET	+56,603	+55,443	+39,306	+31,819	-67,191	-7,889

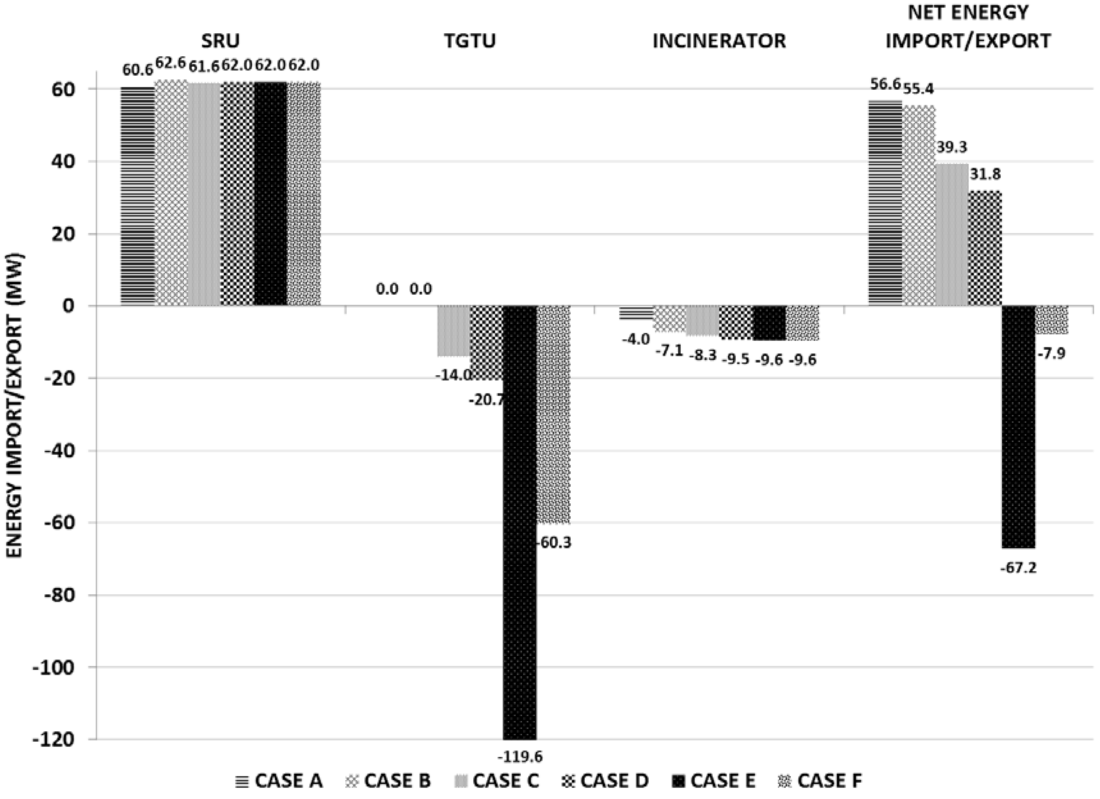

Figure 7. Benchmark Plant energy balance by processing unit

ENERGY KEY PERFORMANCE INDICATORS (KPIs) FOR BENCHMARK PLANT

The net energy balance figures provided in Tables 3 and 4 are converted to “thumb rule” targets that can be used to assess a sulphur recovery facility’s energy performance, as provided in Table 5 and Figure 8. These key performance indicators (KPIs) can be utilized by operators to evaluate whether their facilities are operating in accordance with best energy efficiency standards. While such metrics may not have been viewed as particularly important previously, the authors are observing an increasing trend of operators wishing to make the best use of the sulphur recovery unit’s energy benefits. As a result, SRU/TGTU energy efficiency is being increasingly evaluated and scrutinized, particularly for those sour facilities with relatively large sulphur recovery requirements.

Table 5. Energy performance KPIs for Benchmark Plant

CASE	**A**	**B**	**C**	**D**	**E**	**F**
SRE	**97%**	**99.0%**	**99.3%**	**99.9%**	**99.98%**	**99.98%**
kWh per Metric Ton of ‘S’ Produced	+1,400	+1,434	+949	+764	-1,612	-189
kWh per Nm^3 H_2S in Acid Gas Feed	+1.94	+1.90	+1.35	+1.09	-2.31	-0.27

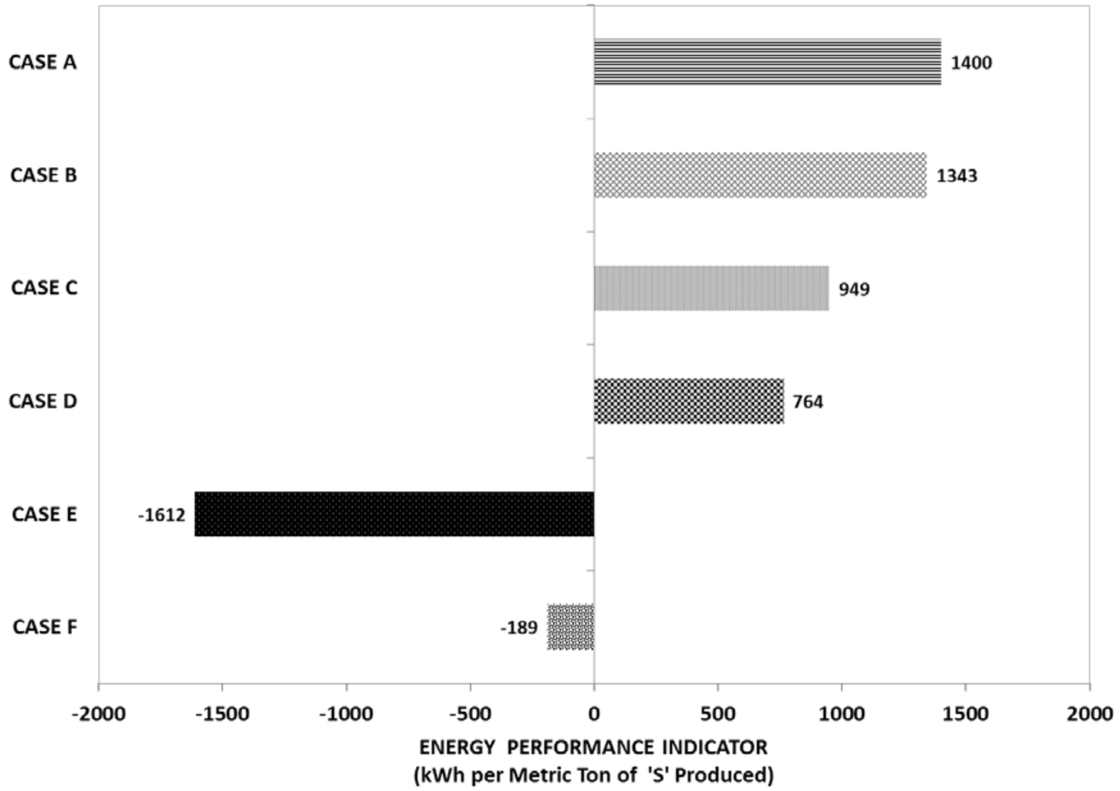

Figure 8. Energy performance KPIs for Benchmark Plant

It is important to keep in mind specific feed conditions and plant design configuration when applying this information. A different configuration, feedstock and/or operating philosophy can lead to significant variations in KPIs, as we will see in the Case Study which follows. For example, a plant which is equipped with an incinerator WHB can generate up to 40% more HP steam than one that is not, as illustrated in Table 3. Some other examples that can lead to widely varying KPIs include fuel gas co-firing in the SRU, the use of an RGG in the TGTU, installation of low-temperature catalyst in the TGTU and TGTU solvent chilling requirements, to name a few.

CASE STUDY – SULPHUR RECOVERY FACILITY IN THE MIDDLE EAST

To illustrate the potential energy enhancements that can be gained by scrutinizing plant operation to ensure efficient operation, a specific Case Study is presented for a sulphur recovery facility in the Middle East. A fully optimized configuration of the facility's existing hardware is also investigated to estimate the maximum energy benefit that may be realized through equipment modifications.

Case Study Facility Description

Abu Dhabi Gas Liquefaction Company Ltd. (ADGAS) operates a gas liquefaction plant on Das Island in Abu Dhabi, UAE, consisting of three NGL fractionation trains, Trains 1, 2 and 3, which process an average of 8 million tons of associated and non-associated gases per year. Train 3 includes a sulphur recovery unit, SRU-3, which was originally a 3-stage split-flow Claus process when it was first commissioned in 1994. In October 2006, a SUPERCLAUS® selective oxidation stage was added to the unit to increase the specified SRE from 97% to 99.0%. SRU-3 has a design capacity of 504 MTPD of sulphur and processes lean acid gas with 30 – 35 mol% H_2S. A simplified block flow diagram of the unit is presented in Figure 9.

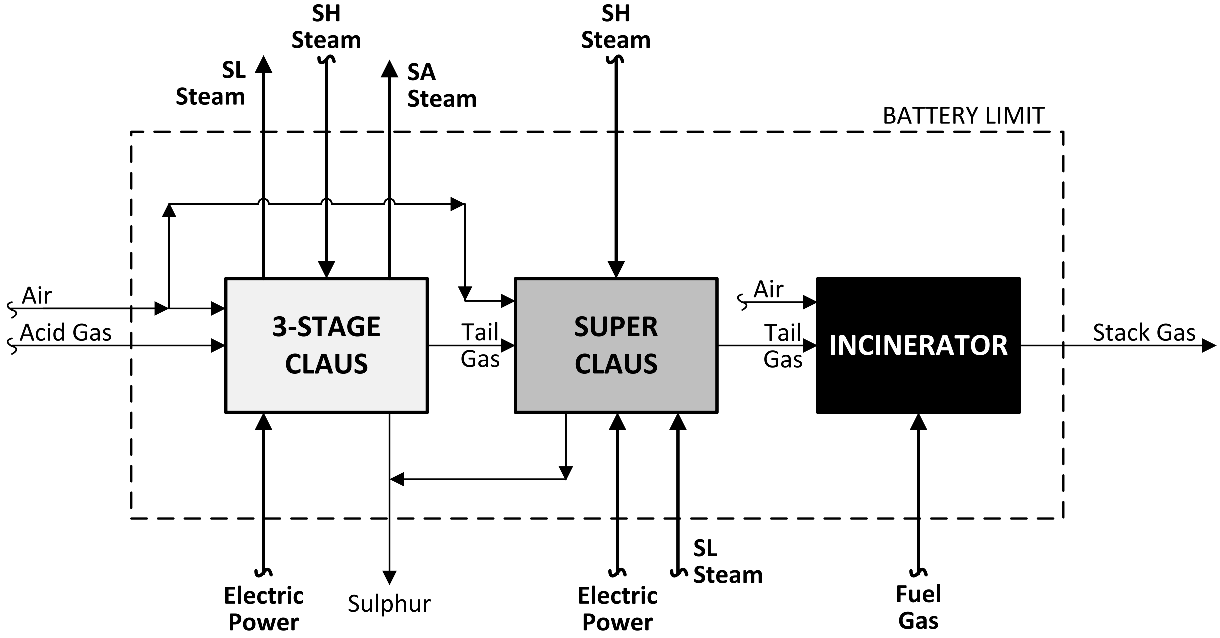

Figure 9. Case Study utility block flow diagram

SRU-3 recovers waste heat as medium pressure (SA) saturated steam and low pressure (SL) saturated steam. Superheated high pressure (SH) steam is imported from OSBL for process preheating and reheating duties. Electric power is required to operate the Claus air blower motor and the low low pressure (SU) steam condenser fans, while fuel gas is consumed for thermal oxidation of the tail gas in the natural draft incinerator. The top utility producers and consumers in SRU-3 are identified in the process flow diagram provided in Figure 10. These users account for more than 97% of the unit's absolute energy production/consumption as calculated in Table 6.

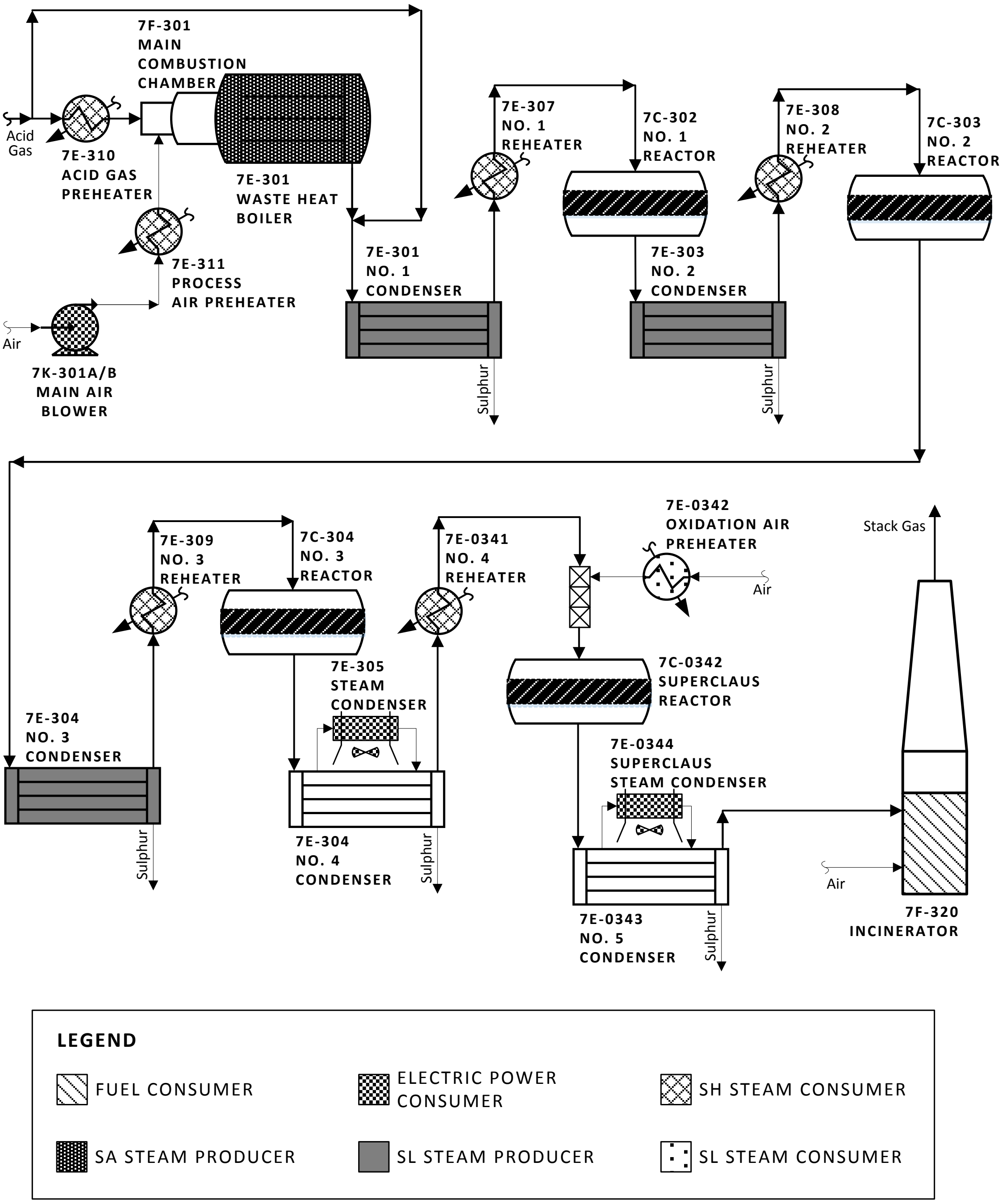

Figure 10. Case Study process flow diagram

Table 6. Case Study top utility users

Utility	**Equipment Number**	**Equipment Item**	**Producer / Consumer?**	**Percent of Absolute Utility Production / Consumption**	**Weight**
SH Steam (60 barg, superheated to 434 °C)	7E-307	No. 1 Reheater	Consumer	100%	0.37
	7E-308	No. 2 Reheater	Consumer		
	7E-309	No. 3 Reheater	Consumer		
	7E-0341	No. 4 Reheater	Consumer		
	7E-310	Acid Gas Preheater	Consumer		
	7E-311	Process Air Preheater	Consumer		
SA Steam (15 barg, saturated)	7E-301	Waste Heat Boiler	Producer	100%	0.35
SL Steam (4.7 barg, saturated)	7E-302	No. 1 Condenser	Producer	91.7%*	0.21
	7E-303	No. 2 Condenser	Producer		
	7E-304	No. 3 Condenser	Producer		
	7E-0342	Oxidation Air Heater	Consumer		
Fuel Gas	7F-320	Incinerator	Consumer	100%	0.23
Electric Power	7K-301A/B	Main Air Blower	Consumer	82.6%**	0.05
	7E-306	Steam Condenser	Consumer		
	7E-0344	SUPERCLAUS Steam Condenser	Consumer		
Percent of Absolute Energy Production/Consumption				**97.5%**	

**Remaining 8.3% of SL steam consumption is from the sulphur degassing/holding pit*
***Remaining 17.4% of electric power consumption is from the sulphur degassing and transfer pumps*

Case Study Methodology and Basis

The primary purpose of the Case Study is to evaluate the energy performance of SRU-3 at current operating conditions and identify gaps for energy efficiency improvement. To begin, a range of consecutive days was identified during which the acid gas feed conditions (flow rate and composition) to the unit were considered to be most typical of normal operation. Daily DCS operating data for the time period were provided. The day during which the feed conditions were stable and closest to the design conditions was selected as the representative operating condition (20 December 2016).

The net energy balance for the unit was then calculated by process simulation using ProTreat® software for each of the following cases:

Design Case	Simulation based on design operating conditions, as given in the process design documentation (design basis, as-built PFDs and P&IDs, H&MBs, equipment datasheets, utility summaries, etc.)
Actual Case	Simulation based on daily average DCS data for the selected representative operating condition
Expected Case	Simulation based on optimized energy performance of the existing hardware at the selected representative operating condition
Fully Optimized Plant	Simulation based on a fully optimized configuration of the unit, via modifications to the existing hardware, at the selected representative operating condition

Parameters for the key feed and product streams for each of the above simulations are provided in Table 7.

Table 7. Case Study key process parameters

	Design	**Actual**	**Expected**	**Fully Optimized Plant**
Acid Gas Feed (Nm^3/h)	47,313	39,893	39,893	40,000
Acid Gas Bypass (%)	50	53	53	50
Acid Gas H_2S Content (mol%)	31.25	34.27	34.27	35.00
Sulphur Production (MTPD)	504	466	466	477

For this type of study, it would be preferable to conduct a dedicated performance test to collect consistent operating data; however, in the absence of that possibility, existing DCS data were relied upon. Some assumptions had to be made to simulate current actual performance, and operational and hardware modifications were applied to simulate expected and fully optimized performance, respectively.

The following assumptions were applied to the Design Case simulation to approximate current plant performance and produce the Actual Case simulation:

- Acid gas composition based on feed gas H_2S analyzer (AI0001) daily average reading
- Air composition based on design H&MB
- Fuel gas composition based on sample analysis taken 20-Dec-2016
- Plant DCS data matched (as close as possible), except where measured values were obviously incorrect

The following changes were applied to the Actual Case to achieve optimal energy performance with the existing hardware and produce the Expected Case simulation:

- Stack gas O_2 content reduced by approximately 3.5 mol%, to a value of 2.0 mol%
- Outlet temperature of No. 2 Reheater reduced by 10 °C to achieve a sulphur dewpoint margin of 15 °C
- Outlet temperature of No. 3 Reheater reduced by 25 °C to achieve a sulphur dewpoint margin of 15 °C

The changes applied to the existing hardware configuration to produce the Fully Optimized Plant are summarized in Table 8.

Table 8. Configuration comparison between existing plant and Fully Optimized Plant

	Existing Plant	**Fully Optimized Plant**
UTILITY PARAMETERS		
SH Steam (*imported from OSBL*)	60 barg, superheated to 434 °C	-
HP Steam	-	40 barg, saturated
SA Steam	15 barg, saturated	-
SL Steam	4.7 barg, saturated	
SU Steam	1.1 barg, saturated	-
EQUIPMENT CONSIDERATIONS		
Main Air Blower	Electric motor drive	Steam turbine drive (superheated HP steam)
SRU WHB	Produces SA steam	Produces HP steam
Sulphur Condensers	SL steam produced in No. 1, 2 and 3 Condensers; closed loop steam production / condensation in No. 4 and 5 Condensers	SL steam produced in No. 1, 2 and 3 Condensers; BFW preheating in No. 4 and 5 Condensers
Incinerator Air Blower Drive	N/A (natural draft)	Steam turbine drive (superheated HP steam)
Incinerator WHB	No	Yes; produces HP steam

The most significant differences between the existing plant and the Fully Optimized Plant are as follows:

1. **HP steam** – SRU-3 imports 60 barg (SH) steam from OSBL, which is unique as sulphur recovery facilities are typically net high pressure steam exporters. SH steam must be imported because medium pressure (SA) steam at only 15 barg is produced in the SRU WHB. In the Fully Optimized Plant, the SRU WHB produces 40 barg (HP) steam, which can be used in the process preheaters, reheaters and steam turbines, thereby eliminating the need for imported SH steam.

2. **Incinerator WHB** – the Fully Optimized Plant includes a WHB downstream of the incinerator to recover more waste heat as 40 barg (HP) steam.

3. **BFW preheating** – in the Fully Optimized Plant, waste heat from the No. 4 and 5 Condensers is used to preheat BFW instead of generating low low pressure (SU) steam, increasing energy conservation and eliminating the use of electric power for the operation of the steam condenser fans.

4. **Steam turbine-driven air blowers –** in the Fully Optimized Plant, the Main Air Blower is made more energy efficient by changing from an electric motor drive to a steam turbine drive. A steam turbine-driven Incinerator Air Blower is also included in the Fully Optimized Plant, as the addition of the Incinerator WHB is only possible with a forced-draft Incinerator.

The thermal energy production/consumption of the top utility users in SRU-3 was calculated for the different simulation cases. For electric power consumers, a thermal to mechanical energy conversion efficiency of 40% was used. Table 9 presents the net energy balance for the simulation cases.

Table 9. Energy balance by top utility producers/consumers for Case Study (kW)

		Design	**Actual**	**Expected**	**Fully Optimized Plant**
SH/HP STEAM CONSUMERS					
7E-307	No. 1 Reheater	-1,782	-1,291	-1,290	-1,308
7E-308	No. 2 Reheater	-1,310	-1,423	-1,133	-1,138
7E-309	No. 3 Reheater	-793	-1,481	-768	-773
7E-0341	No. 4 Reheater	-2,800	-1,549	-1,548	-1,559
7E-310	Acid Gas Preheater	-2,482	-1,958	-1,958	-2,083
7E-311	Process Air Preheater	-2,081	-1,701	-1,698	-1,780
	Main Air Blower Steam Turbine	---	---	---	-962
	Incinerator Air Blower Steam Turbine	---	---	---	-831
SA/HP STEAM PRODUCERS					
7E-301	SRU WHB	+23,609	+20,011	+19,976	+24,979
	Incinerator WHB	---	---	---	+13,469
SL STEAM PRODUCERS					
7E-302	No. 1 Condenser	+4,316	+4,448	+4,446	+4,458
7E-303	No. 2 Condenser	+7,314	+6,656	+6,783	+6,694
7E-304	No. 3 Condenser	+2,549	+2,326	+2,478	+2,467
SL STEAM CONSUMERS					
7E-0342	Oxidation Air Heater	-50	-36	-36	-32
FUEL GAS CONSUMERS					
7F-320	Incinerator	-15,860	-22,198	-13,705	-13,101
ELECTRIC POWER CONSUMERS					
7K-301A/B	Main Air Blower	-3,049	-2,964	-2,955	---
7E-306	Steam Condenser	-32	-38	-30	---
7E-0344	SUPERCLAUS Steam Condenser	-37	-20	-34	---
NET ENERGY IMPORT/EXPORT		**+7,511**	**-1,217**	**+8,528**	**+28,501**

For comparison, the figures in Table 9 are converted to energy performance KPIs in Table 10 and Figure 11. As typically expected, SRU-3 is designed to be a net energy exporter. However, the Actual Case determines that the unit is almost energy neutral at current operating conditions. If operating conditions are adjusted as demonstrated in the Expected Case, it may be possible to exceed the energy export of the Design Case by more than 20%; however, this is still only about one third of the potential energy export from the Fully Optimized Plant, for reasons which are explored in the more detailed discussion of major utility producers/consumers that follows.

The energy performance KPI of the Fully Optimized Plant can be cross-referenced against Benchmark Plant Case B, which has the same SRE. The net energy export in the Fully Optimized Plant is identical to Benchmark Plant Case B (1,434 kWh/Ton S), although this will not be the case for all plants with 99.0% SRE, as differences in feed gas composition, equipment configuration, etc. will impact the energy balance. The Fully Optimized Plant is actually equipped with a more optimized configuration than the Benchmark Plant, and thus its KPI should be superior. However, due to a lower acid gas H_2S concentration, the KPI is reduced.

Table 10. Energy Performance KPIs for Case Study (kWh per Metric Ton of 'S' Produced)

Utility	**Design**	**Actual**	**Expected**	**Fully Optimized Plant**
SH/HP Steam	-535	-484	-432	-525
SA/HP Steam	+1,123	+1,031	+1,029	+1,934
SL Steam	+672	+690	+704	+683
Fuel Gas	-755	-1,143	-706	-659
Electric Power	-148	-156	-156	0
NET	**+357**	**-63**	**+439**	**+1,434**
Comparison to Design Case (Net Δ)	**---**	**-118%**	**+23%**	**+301%**

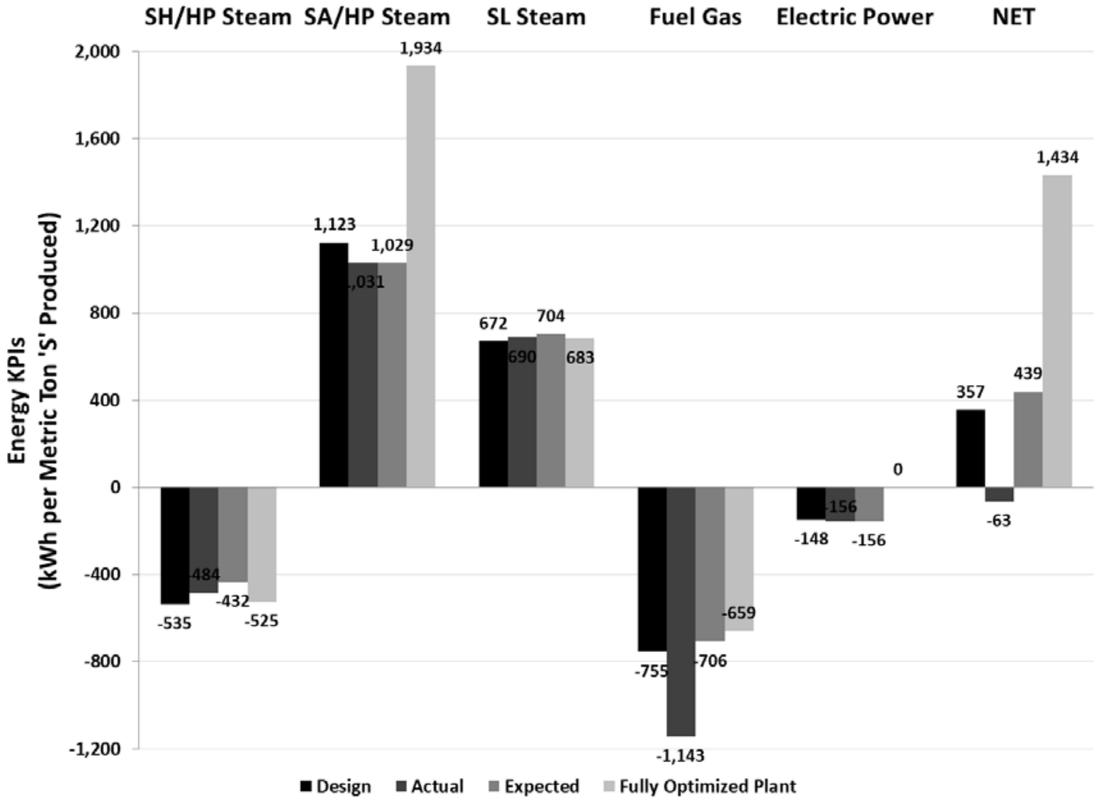

Figure 11. Energy performance KPIs for Case Study

Figure 12 illustrates high pressure steam consumption KPIs by major equipment (SH steam at 60 barg for Design, Actual and Expected Cases; HP steam at 40 barg for Fully Optimized Plant).

Compared to the Design Case, the energy consumed by the Acid Gas Preheater is lower in the other simulation cases due to a higher H_2S content in the acid gas (34-35 mol% vs. 31.3 mol%), which reduces its specific heat capacity. The energy consumed by the Process Air Preheater is also reduced due to a preheat temperature that is lower than design.

The higher acid gas H_2S content in the Actual Case increases temperatures throughout the unit above design values and generally lowers the energy required for process gas reheating. Energy consumption in the No. 2 and No. 3 Reheaters can be further reduced in the Expected Case and Fully Optimized Plant by reducing reheat temperatures to achieve sulphur dewpoint margins of 15 °C.

The major difference between the Fully Optimized Plant and the existing plant is the addition of the steam turbine-drive combustion and incinerator air blowers, which results in an additional 90 kWh/Ton S of high pressure steam energy consumption. However, this is offset by an energy savings of 150 kWh/Ton S from eliminating the electric motor-drive combustion air blower.

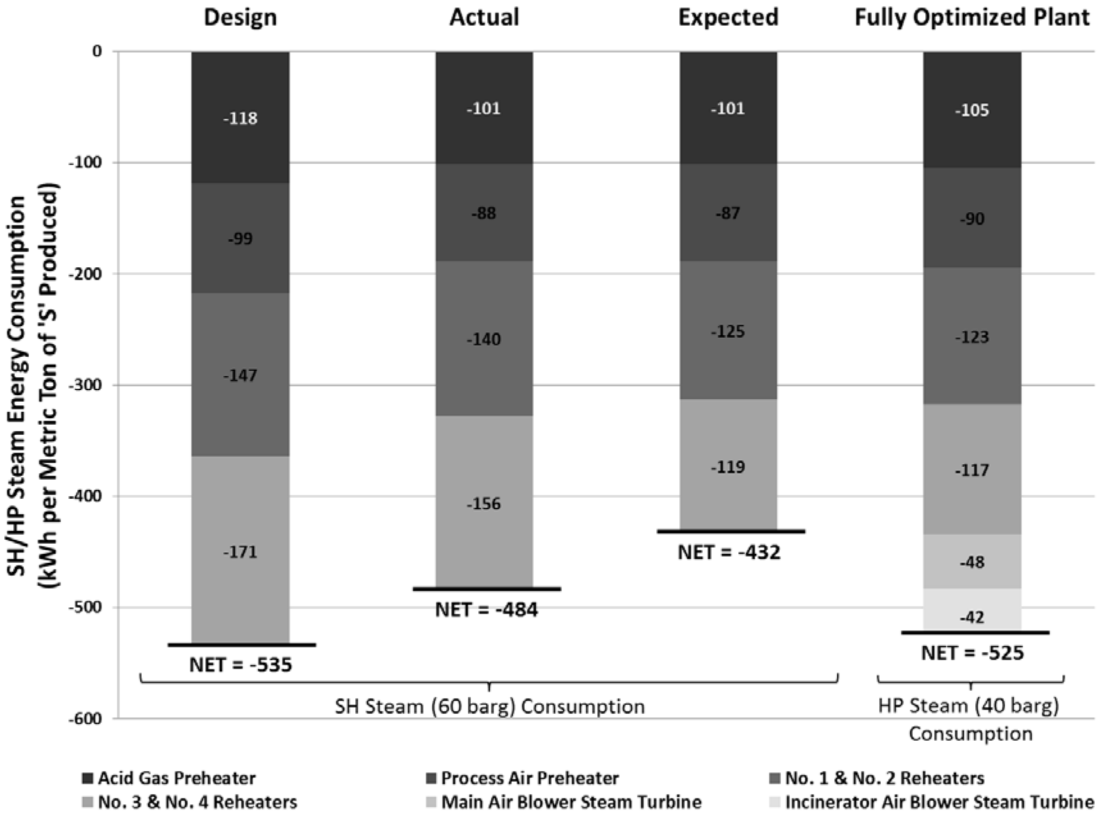

Figure 12. SH/HP steam energy consumption for Case Study

Figure 13 illustrates medium/high pressure steam production KPIs by major equipment (SA steam at 15 barg for Design, Actual and Expected Cases; HP steam at 40 barg for Fully Optimized Plant).

At current operating conditions, heat recovery in the SRU WHB is not significantly different from design, with minor variations due to differences in acid gas composition and amount of acid gas bypass. In the Fully Optimized Plant, approximately 200 kWh/Ton S of additional waste heat is recovered by converting the No. 4 and No. 5 Condensers from low low pressure steam producers to BFW preheaters. This energy benefit is realized in the SRU WHB, where the use of preheated BFW results in additional steam production. This modification also eliminates the minor consumption of electric power energy in the steam condenser fans.

The true energy value of the SRU WHB in the Fully Optimized Plant, which recovers waste heat as high pressure steam rather than medium pressure steam, is not fully captured in Figure 13. Unlike 15 barg steam, 40 barg steam can be used in the process preheaters/reheaters and thereby eliminate the need to import 60 barg steam from OSBL. It could also be superheated and used in steam turbine-drive air blowers or electric generators.

High pressure steam production is significantly increased in the Fully Optimized Plant compared to the existing plant by introducing a WHB downstream of the incinerator to recover additional waste heat as 40 barg steam. This addition increases high pressure steam production by approximately 54%.

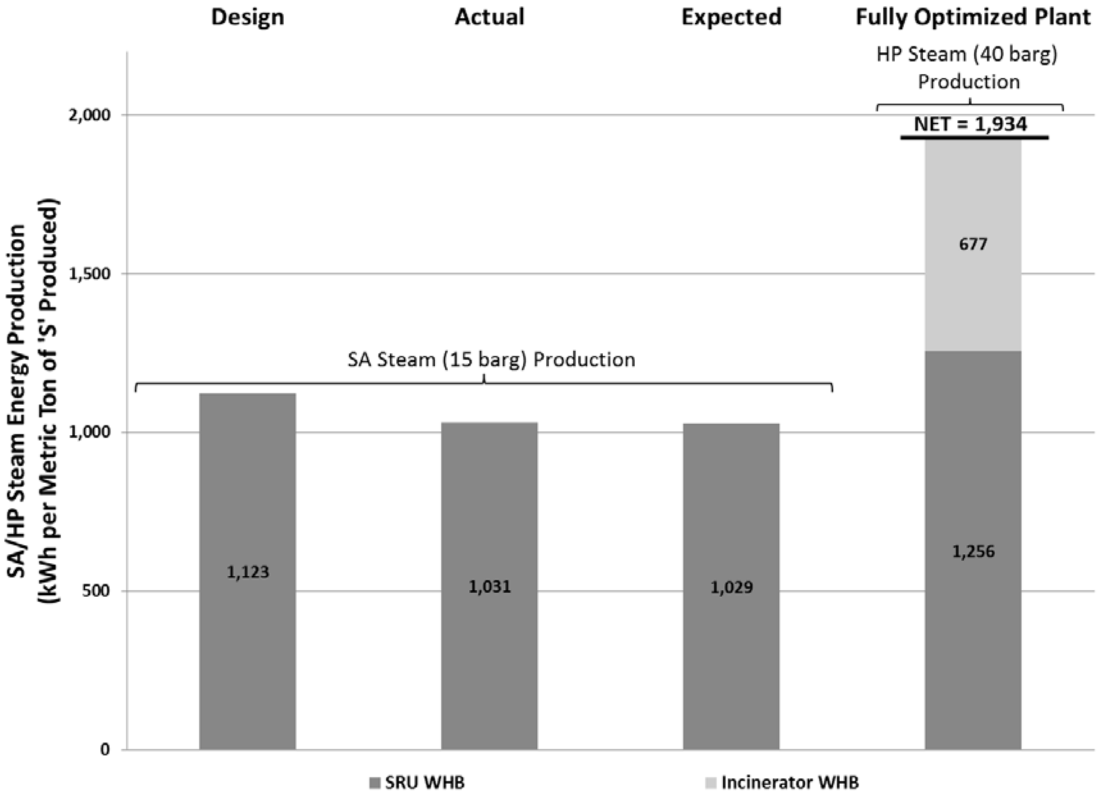

Figure 13. SA/HP steam energy production for Case Study

Figure 14 illustrates low pressure steam KPIs by major equipment and shows that there is no significant difference in energy production/consumption between the various simulations, with minor variations due to differences in acid gas composition and amount of acid gas bypass.

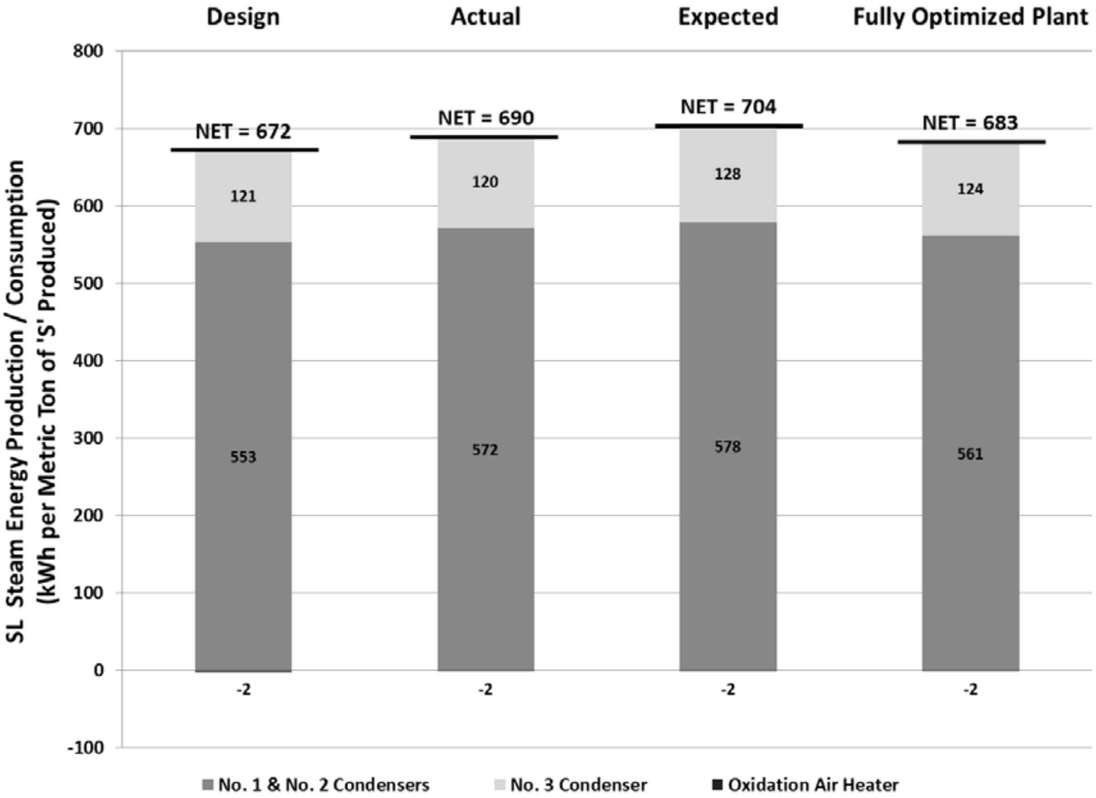

Figure 14. SL steam energy production/consumption for Case Study

Figure 15 illustrates fuel gas KPIs for the incinerator, which is the only continuous fuel gas user in the unit.

In current operation, fuel gas consumption is significantly higher than design due to an increased flow of air to the incinerator, resulting in an estimated stack gas O_2 content of 5.5 mol%. In the Design Case, the stack gas O_2 content is specified at 1.0 mol%, a target that is difficult to meet based on regional and historical sulphur recovery facility operating experiences. Therefore, in the Expected Case and Fully Optimized Plant, fuel gas consumption is reduced by maintaining the stack gas O_2 content at a more reasonable value of 2.0 mol%, although even this may be difficult to achieve with a natural draft-type incinerator.

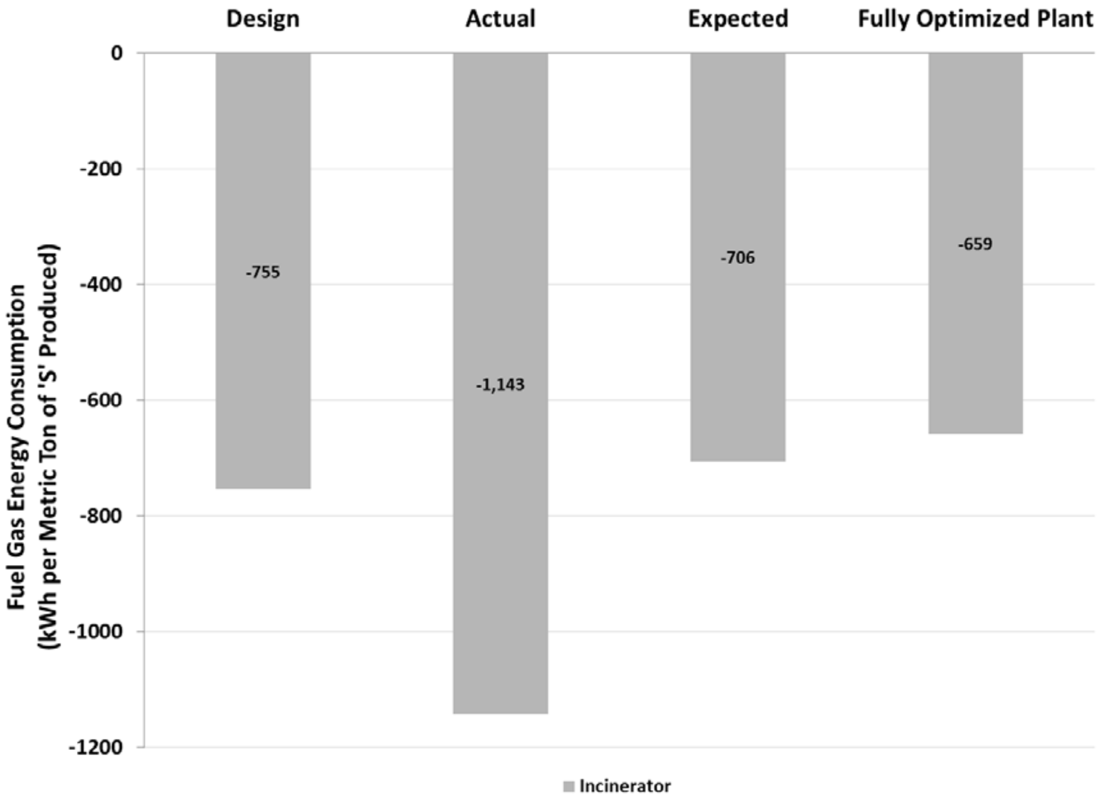

Figure 15. Fuel gas energy consumption for Case Study

Figure 16 illustrates electric power KPIs, in terms of thermal energy equivalent, by major equipment. A thermal to mechanical energy conversion efficiency of 40% is assumed.

The only significant electric power consumer in the unit is the Main Air Blower. The blower, which regulates air flow with inlet guide vanes, is less energy efficient at lower loads. Hence, more electric power is consumed per ton of sulphur production in the Actual and Expected Cases, compared to the Design Case, as the unit is operating at only 84% of design capacity.

In the Fully Optimized Plant, the major electric power consumers are eliminated by replacing the electric motor-drive air blower with a steam turbine-drive air blower and by converting the No. 4 and No. 5 Condensers from low low pressure steam producers to BFW preheaters.

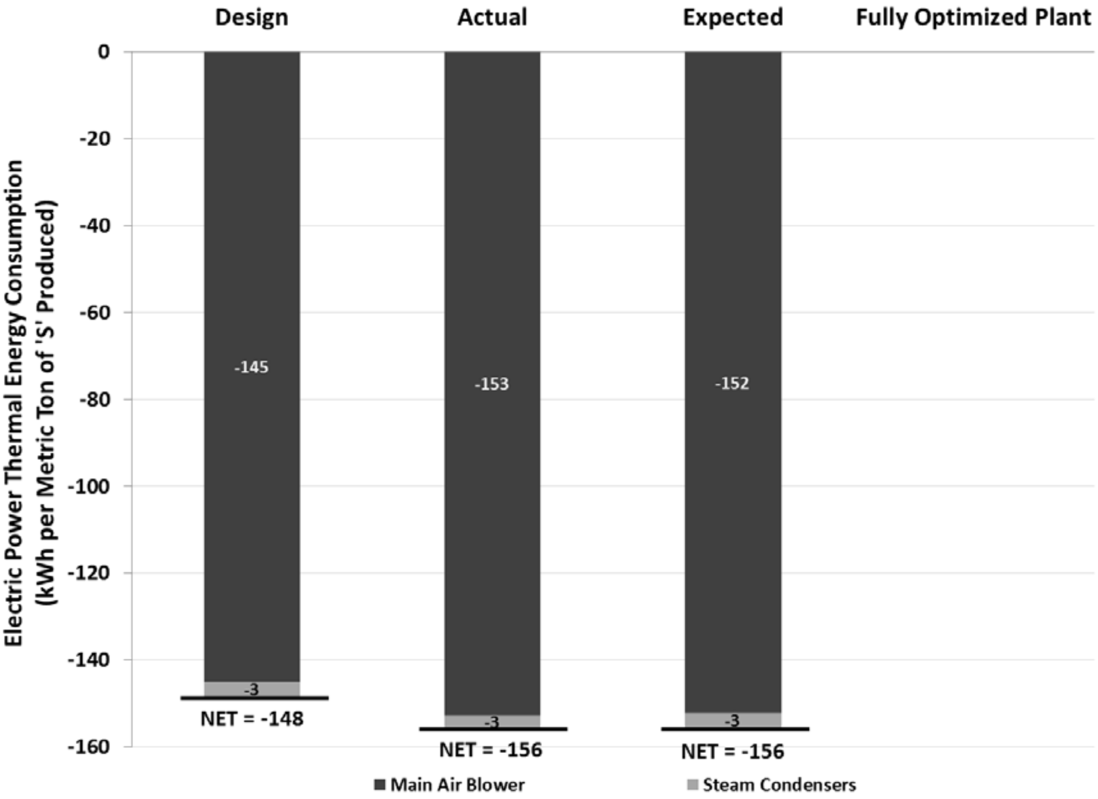

Figure 16. Electric power thermal energy consumption for Case Study

Case Study Summary

The key operational changes listed below can be implemented in the Case Study plant to convert it from a net energy consumer (Actual Case) to a net energy producer (Expected Case), without implementing any hardware changes.

A1. Reduce fuel consumption in the incinerator by reducing excess air
A2. Reduce high pressure steam consumption in the second and third reheaters by reducing the reheat temperatures to achieve sulphur dewpoint margins of 15 ^{o}C

It should be noted that the above recommendations are based on theoretical performance of the unit only. It is possible that there are equipment limitations that will prevent these changes from being implemented. For example, a stack gas O_2 content of 2.0 mol% or less may be difficult to maintain with a natural draft incinerator. Additionally, tight control on sulphur dewpoint margins may prove difficult if the calculation is not built into the DCS for continuous monitoring.

If the Case Study plant were modified to approximate the Fully Optimized Plant energy performance KPIs, the following hardware changes would need to be implemented:

B1. Modify unit to produce 40 barg steam in the SRU WHB and use this steam in the preheaters and reheaters
B2. Install incinerator WHB to recover waste heat as 40 barg steam; a steam turbine-drive incinerator air blower would also be required to support the forced-draft incinerator design
B3. Replace electric motor-drive combustion air blower with a steam turbine-drive blower
B4. Convert low low pressure steam generating sulphur condensers to BFW preheaters

It should be noted that the above modifications could be quite substantial in the existing facility and could even introduce operational and maintenance problems if not carefully designed and implemented. A cost-benefit analysis would need to be carried out for each of the above recommendations to determine whether the benefits of implementing the modification would justify the cost. Such a study has not been performed.

CONCLUSIONS

Sulphur recovery facilities provide significant energy benefits and should be leveraged to their fullest potential via astute design and optimized operation, deliberately focused on energy conservation. This is especially important in the current climate of low oil price and reduced margins. Above 99.0% SRE, conventional tail gas treating technologies can significantly erode energy benefits provided by Claus SRUs. However, tail gas treating technologies designed to achieve 99.0% SRE, such as SUPERCLAUS® and sub-dewpoint, preserve the energy benefits of the SRU, as illustrated by the Benchmark Plant Case B and Case Study presented in this paper. Unfortunately, most new facilities require SRE in excess of 99.0%, necessitating amine-based tail gas treating and resulting in a significant negative impact on the energy balance of the facility.

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