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UNIVERSIDAD PONTIFICIA

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GRADO EN INGENIERÍA EN TECNOLOGÍAS
INDUSTRIALES

TRABAJO FIN DE GRADO
REPOWERING A CONVENTIONAL THERMAL POWER
PLANT INTO A COMBINED CYCLE POWER PLANT

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Madrid
Julio de 2019

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Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

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Fecha: 12 / 4 / 19

M. ANGEL HERNANDO



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RECONVERSIÓN DE UNA CENTRAL TÉRMICA CONVENCIONAL EN UNA CENTRAL ELÉCTRICA DE CICLO COMBINADO

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Entidad Colaboradora: Técnicas Reunidas.

RESUMEN DEL PROYECTO

Si bien el aumento en las plantas de energía más limpias, incluidas las energías renovables y los ciclos combinados, es evidente, la generación de electricidad a través de combustibles fósiles constituye la mayor parte de la producción de electricidad del mundo. La elección entre centrales térmicas convencionales o centrales térmicas de ciclo combinado dependerá fundamentalmente de la disponibilidad del combustible necesario para cada una de ellas, aunque no es el único factor del que dependerá la elección, ya que, en general, las plantas de potencia de ciclo combinado presentan algunas ventajas sobre las centrales térmicas convencionales y se resumen en las tablas 1 y 2.

	Plantas de Ciclo Combinado	Plantas de carbón
Rendimiento	49%-64%	37%-44%
Inversión	450 €/kW	800-900 €/kW
Tiempo de implantación	2 años	3,5 años

Tabla 1-Comparación genérica, Fuente [*“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”*]

	Plantas de Ciclo Combinado	Plantas de carbón
CO ₂	0.45 kg/kWh	1 kg/kWh
NO _x	≤75 mg/Nm ³	≥200 mg/Nm ³
SO ₂	0	≥200 mg/Nm ³
Cenizas	0	50 mg/Nm ³

Tabla 2-Emissiones contaminantes, Fuente [*“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”*]

En este proyecto, se lleva a cabo un estudio de la reconversión de una central térmica convencional (quema de carbón) en una central eléctrica de ciclo combinado, basada en una turbina de gas (ciclo de Brayton) y una turbina de vapor (ciclo de Rankine).



Figura 1, Ciclo de Brayton y Rankine, Fuente [<http://27.wire.karneval-lastrup.de/diagram-of-the-gas-cycle.html>]

En este trabajo, se examina el Grupo 1 de la Central Térmica Convencional de Litoral de Almería (Carboneras). El grupo 1 tiene una potencia de 576,9MW y se puso en servicio en 1985. Este grupo 1 consta actualmente de: un molino de carbón, una caldera de carbón, una turbina de vapor, un alternador y un condensador. También comparte una chimenea con el grupo 2 que se puso en servicio en 1997.

El combustible actualmente quemado es carbón importado.

Los principales datos del Grupo 1 de la Central Térmica Convencional del Litoral de Almería (Carboneras) son:

GRUPO I

- General
 - Potencia: 576,9.
 - Año de puesta en servicio: 1985.
- Molino
 - Capacidad: 53 t/h.
 - Fabricante: Combustion Engineering.
 - Número: 6.
 - Potencia: 500 kW.
- Caldera
 - Tipo: fuegos tangenciales
 - Fabricante: Combustion Engineering.
 - Altura del calderín: 66,34 m.
 - Flujo principal de vapor: 1679 t/h.
 - Flujo de vapor sobrecalentado: 1525 t/h.
 - Presión inicial de vapor: 176 bar.
 - Presión de vapor sobrecalentado: 41 bar.
 - Temperatura del agua de alimentación: 253 °C.
 - Temperatura de vapor principal: 541 °C.
 - Temperatura de vapor de recalentamiento caliente: 541 °C.
 - Temperatura de vapor de recalentamiento frío: 338 °C.
 - Rendimiento: 89,42%

- Condensador
 - Tipo: doble presión.
 - Líquido refrigerante y origen: Agua de mar de aguas abiertas.
 - Salto térmico: 5 °C.
 - Flujo: 59.530 m³/h
- Turbina
 - Fabricante: Bazán/G.E.E.
 - Potencia máxima: 577 MW.
 - Número de cuerpos: 4.
 - Número de extracciones: 7.
 - Velocidad de régimen: 3000 rpm.
- Alternador
 - Fabricante: General Electric.
 - Potencia: 636 MVA.
 - Tensión de salida: 20 kV.
 - Factor de potencia: 0,9.
 - Corriente nominal del estator: 18.360 A.
 - Refrigeración: Hidrógeno.

Fuente [https://es.wikipedia.org/wiki/Central_t%C3%A9rmica_Litoral_de_Almer%C3%ADa]

En el grupo 1, el ciclo de Rankine aproximado de la turbina de vapor es el siguiente:

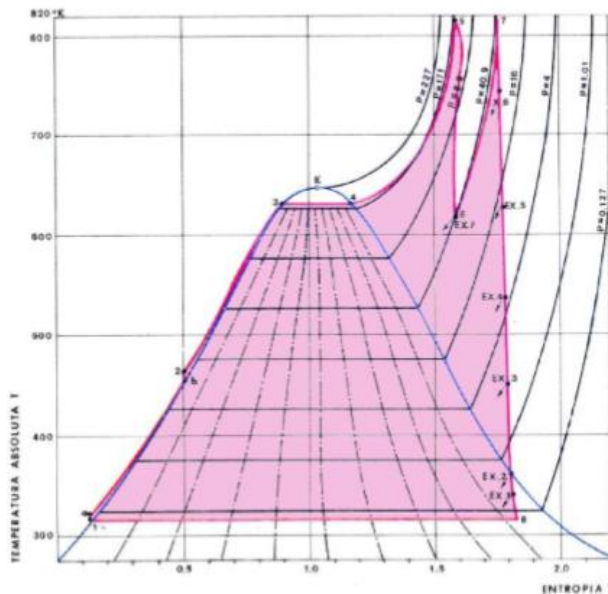


Figura 2, Diagrama T-S aproximado del ciclo termodinámico, Fuente [Unión Fenosa Generación]

El desempeño del grupo 1 de esta planta tiene una eficiencia aproximada del 35% y tiene emisiones significativas de NO_x, CO y CO₂. Las emisiones contaminantes de CO₂ se estimaron entre 2005 y 2007 en casi 7 millones de toneladas. Es cierto que en 2010 se puso en servicio una planta de desulfuración de gas que logró reducir las emisiones en 100.000 toneladas por año.

El presente TFG contempla la sustitución del grupo 1 de la Central Térmica Convencional de Litoral de Almería (Carboneras) por un Ciclo Combinado que consiste en una turbina de gas, una caldera de recuperación de vapor (HRSG), una turbina de vapor y un alternador para lograr un rendimiento de cerca del 64%.

Gracias a la puesta en marcha del gasoducto submarino Medgaz en 2011, con una capacidad de 8 bcm de gas natural por año, el gas natural es un recurso disponible en la provincia de Almería (ver imagen).



Figura 3- Gaseoductos, Fuente [<https://es.wikipedia.org/wiki/Medgaz>]

Datos técnicos del gaseoducto de Medgaz.:

- Capacidad: 8 bcm/año (8 mil millones m³/año).
- Longitud: 210 kilómetros (entre Beni Saf y Almería).
- Diámetro: 24 pulgadas (610 milímetros).
- Máxima profundidad de agua: 2,160 metros.
- Instalaciones de tierra:
 - Estación de compresión (Algeria)
 - Terminal de recepción (Almería, playa de Perdigal).

La composición molar del gas natural sería aproximadamente la siguiente:

Composición de gas	% moles	
		CH ₄ = 89,3
		C ₂ H ₆ = 5,46
		C ₃ H ₈ = 1,38
		iC ₄ H ₁₀ = 0,27
		nC ₄ H ₁₀ = 0,17
		iC ₅ H ₁₂ = 0,06
		nC ₅ H ₁₂ = 0,03
		C ₅ H ₁₄ = 0,09
		N ₂ = 1,55
		CO ₂ = 1,68

Tabla 3, Composición molecular aproximada del Gas Natural, Fuente

[<https://www.enagas.es/stfls/EnagasImport/Ficheros/Comunicacion/Transmission,%20storage%20and%20regasification%20and%20infrastructure%20of%20Enag%C3%A1s%20catalogue.pdf>]

Las centrales de ciclo combinado son un buen complemento del parque de energía renovable existente en España.

Los objetivos del proyecto son la mejora del rendimiento del grupo 1 y la renovación con equipos más modernos y eficientes (se propone una nueva turbina de gas y la sustitución de la caldera existente por una caldera HRSG) y la renovación de la turbina de vapor existente y del alternador. Se reutilizarán algunas de las instalaciones existentes, tales como: la planta de tratamiento de agua, la planta de tratamiento de efluentes y la toma y descarga de agua para agua de refrigeración.

Se logra una reducción significativa de los gases de efecto invernadero, ya que pasaríamos del uso del carbón como combustible del Grupo 1 al uso del gas natural (consulte la tabla 2 de la introducción).

Nuevo equipamiento previsto:

- Turbina de gas
- HRSG
- Turbina de vapor
- Embrague auto-sincronizante
- Alternador con 20kV de salida
- 400kV / 20kV transformador para la conexión con una subestación existente

Utilizando el diagrama de Calor y Balance de masa como base, proporciona la información de PCI del gas natural, la potencia eléctrica de la turbina de gas y los flujos y entalpías correspondientes de cada lugar, diferentes cálculos para cada componente de la Central de Ciclo Combinado se llevan a cabo:

Turbina de Gas:

Los siguientes modelos han sido estudiados en este proyecto:

	General Electric	Siemens	
Ciclo Simple	Modelo	9HA.01	SGT5-8000H
	Frecuencia	50 Hz	50 Hz
	Potencia Ciclo Simple (MW)	446	450
	Heat Rate Neto Ciclo Simple (kJ/kWh, PCI)	8346	<8780
	Rendimiento Ciclo Simple (% , PCI)	43,1%	≈41%
Ciclo Combinado	Configuración de bloque (TGs x TVs)	1x1	1x1
	Potencia neta Ciclo Combinado (MW)	661	665
	Heat Rate Neto Ciclo Combinado (kJ/kWh, PCI)	5674	5695
	Eficiencia neta Ciclo Combinado (% , PCI)	63,5%	61%

Tabla 4- Turbina de gas de GE, modelo 9HA.01, Fuente [<https://www.ge.com/power/gas/gas-turbines/9ha>]

Se realizaron los siguientes cálculos para verificar las características más importantes:

- Eficiencia de la turbina de gas: Potencia eléctrica de la turbina de gas / Energía del Gas Natural = $433580 \cdot 100 / 1004277,4 = 43,18\%$.
- Potencia transferida al eje por la turbina de gas = $0,4318 \cdot 1004277 \cong 433,65$ MW
- Valor HR de la turbina de gas: $1004277,4 \cdot 3600 / 433646 = 8337,2$ kJ/kWh.

El porcentaje de error de estos cálculos con respecto a los calculados en Thermoflow es en cada caso de aproximadamente $0,09\% \ll 1\%$.

HRSO (caldera de recuperación de calor):

La caldera de recuperación de calor es el enlace principal entre el ciclo de gas y el ciclo de vapor. Para lograr una alta eficiencia, se han considerado 3 tambores de presión, tambor de alta presión, tambor de presión intermedia y tambor de baja presión. El HRSO considerado también incluye recalentadores.

La diferencia de temperatura del punto de pellizco, se conoce como Δt_{pp} , y es la diferencia entre la temperatura de los gases de escape en la salida de cada evaporador y la temperatura de vaporización del agua para cada uno de los rangos del tambor entre 5°C y 10°C para obtener una alta eficiencia.

Se realizaron los siguientes cálculos para verificar las características más importantes:

- Los valores de entalpía a la salida de la turbina de gas y de la caldera HRSG se calcularon con la fórmula: $H \left(\frac{\text{kJ}}{\text{kg}} \right) = \left[0,9952 + \frac{92,1 \cdot T_{\text{Chimenea}}(^{\circ}\text{C})}{1000000} \right] \cdot T_{\text{Chimenea}}(^{\circ}\text{C})$.
Por lo tanto, $H_{\text{Turbina de Gas}} = 666 \frac{\text{kJ}}{\text{kg}}$ y $H_{\text{Chimenea}} = 83,4 \frac{\text{kJ}}{\text{kg}}$
- El rendimiento del HRSG: $\eta_{\text{HRSG}} = \frac{Q_{\text{ST}}}{Q_{\text{GT}}}$
$$\frac{\text{Calor contribuido al cuerpo de baja de la tubina de vapor}}{\text{Calor emitido al ciclo por la tubina de gas}} = \frac{138,9 \times 3080}{666 \times 827,4} = 77,6\%$$
- Los correspondientes kW que salen del HRSG como pérdida de energía son:
 $827,4 \times 83,4 = 69005 \text{ kW}$

Turbina de vapor:

Se ha considerado una nueva turbina de vapor que comparte el mismo eje con la turbina de gas, en la configuración 1x1 Single Shaft (SS).

La nueva turbina de vapor tiene cuatro cuerpos y transmite hasta 200 MW de potencia al eje.

En el TFG incluiremos los siguientes planos:

- Tabla genérica de la planta existente.
- Esquema general de la planta de energía de Ciclo Combinado (plano 1).
- Diagramas eléctricos unifilares del nuevo grupo existente. (planos 2, 3 y 4).

Se realizaron los siguientes cálculos para verificar las características más importantes:

- Energía total que la turbina de vapor aporta a los álabes:
 $W = m_{\text{HP}} (h_{\text{HPi}} - h_{\text{HPo}}) + m_{\text{IP}} (h_{\text{IPi}} - h_{\text{IPo}}) + m_{\text{LP}} (h_{\text{LPi}} - h_{\text{LPo}}) - m_{\text{LP}} * W_e$
 $W = 205392,7 \text{ kW}$
- Rendimiento de la turbina de vapor: $W / \text{Energía del gas natural} = 205392,7 * 100 / 1004277,4 = 20,45\%$
- La potencia transferida al eje solo por la turbina de vapor sería:
 $TV_{\text{Potencia eje}} = 0,2045 * 1004277 \cong 205,37 \text{ MW}$.

Condensador:

El objetivo principal era calcular el área de superficie de intercambio que se necesitaría para la condensación:

$$Q = \text{LMTD} \times (U \times A)$$

- LMTD (Diferencia de temperatura media logarítmica) $= \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$. ΔT_A y ΔT_B representan la diferencia de temperatura del condensado y del fluido frío que entra y sale del condensador. So, $\Delta T_A = 0^{\circ}\text{C}$ and $\Delta T_B = 10^{\circ}\text{C}$. Por lo que, $\text{LMTD} = 10$.

- U (coeficiente global de transferencia de calor) es el valor medio entre el rango de 300 y 600 (es decir $450 \frac{\text{hr}}{\text{ft}^2\text{K}} = 2553,5 \frac{\text{W}}{\text{m}^2\text{K}}$) como se muestra en la tabla siguiente:

Condensers		
Cold Fluid	Hot Fluid	Overall U (BTU/hr-ft ² -F)
Water	Steam (pressure)	350 - 750
Water	Steam (vacuum)	300 - 600
Water or brine	Organic solvent (saturated, atmospheric)	100 - 200
Water or brine	Organic solvent (atmospheric, high non-condensables)	20 - 80
Water or brine	Organic solvent (saturated, vacuum)	50 - 120
Water or brine	Organic solvent (vacuum, high non-condensables)	10 - 50
Water or brine	Aromatic vapours (atmospheric with non-condensables)	5 - 30
Water	Low boiling hydrocarbon (atmospheric)	80 - 200
Water	High boiling hydrocarbon (vacuum)	10 - 30

Figura 4- Valores del condensador del coeficiente global de transferencia de calor, Fuente [Unión Fenosa Generación]

- $Q = Q_{IC} - Q_{OC} = 304982,73 \frac{\text{KJ}}{\text{s}}$

Por lo tanto, el área aproximada sugerida de diseño es de 12m².

Planta entera:

La eficiencia de la planta entera de ciclo combinado puede ser calculada de tres maneras distintas:

1. La primera manera es que el rendimiento de la turbina de gas + rendimiento de la turbina de vapor = rendimiento de la planta de potencia: 43,18% + 20,45% = 63,63%. El porcentaje de error con respecto a la eficiencia de 63.15% es del 0.75%.
2. Otra manera de calcular el rendimiento de la planta es por medio del uso de la potencia eléctrica del generador (634781kW): $634781 * 100 / 1004277,4 = 63,20\%$. El porcentaje de error de este valor respecto a la eficiencia 63.15% es 0.079%.
3. La tercera y última forma es con la ecuación: $\eta_{CC} = \eta_{TG} + \eta_{TV} \times \eta_{HRSG} \times (1 - \eta_{TG})$
 $\eta_{CC} = 0,4318 + 0,4318 \times 0,776 \times (1 - 0,4318) = 62,2\%$. El porcentaje de error de este valor con respecto a la eficiencia 63.15% es 1.5%.

Embrague auto-sincronizante:

La turbina de gas arrancará primero.

Una vez que se produce vapor y la turbina de vapor obtiene la velocidad adecuada, se acoplará mediante un embrague de sincronización automática.

Nuevo alternador con 20 kV de voltaje de salida:

Teniendo en cuenta que tanto la turbina de gas como la turbina de vapor transferirán energía al alternador, se considera un nuevo alternador de hasta 650 MW.

Transformadores de generador:

La subestación existente tiene posiciones a 400 kV y a 20 kV.
Se consideran tres transformadores monofásicos de hasta 255 MVA cada uno.

En conclusión, es cierto que algunas empresas de servicios públicos pueden haber contemplado el reemplazo de las centrales eléctricas de carbón en centrales de ciclo combinado. En términos de fuentes disponibles de energía, las reservas probadas de carbón duran alrededor de 200 años, mucho más que el petróleo. Sin embargo, la contaminación de las centrales eléctricas de carbón sigue siendo alta y, por lo tanto, la idea de un ciclo combinado con turbina de gas y turbina de vapor es una buena opción.

La demanda de electricidad sigue creciendo y para satisfacer esta demanda, varios recursos renovables distribuidos (como los parques eólicos y las plantas de energía solar) se han vuelto muy frecuentes. La central térmica de carbón del Litoral de Almería consta de dos grupos, el primero que se puso en marcha en 1985 y el segundo se puso en funcionamiento doce años más tarde en 1997. El gas natural está disponible en Almería desde que se puso en servicio el gasoducto de Medgaz. en 2011 y también hay un gasoducto que conecta la provincia de Almería con la provincia de Murcia (gestionado por la empresa Enagas). Con el fin de aumentar el rango de potencia del antiguo Grupo 1, así como su eficiencia, en este trabajo se propone la sustitución del Grupo 1 por una central de ciclo combinado 1x1 SS. Este ciclo combinado 1x1 SS incluiría una turbina de gas innovadora con una temperatura de encendido (TIT) de 1447 °C y una eficiencia neta de ciclo combinado de hasta el 63.5%. El HRSG incluiría 3 tambores de presión con recalentadores con una temperatura de entrada de 632°C de los gases de escape y una temperatura de salida de los gases que salen del HRSG hacia la chimenea de 83°C.

La turbina de vapor propuesta tiene cuatro cuerpos con una potencia de eje estimada de 206MW que, además de los aproximadamente 434MW de la turbina de gas, da como resultado una potencia de eje combinada de 640MW. El sistema eléctrico propuesto que conecta el nuevo generador a la red consta de tres transformadores de potencia monofásicos IPB (bus de fase aislado), 400kV-20kV.

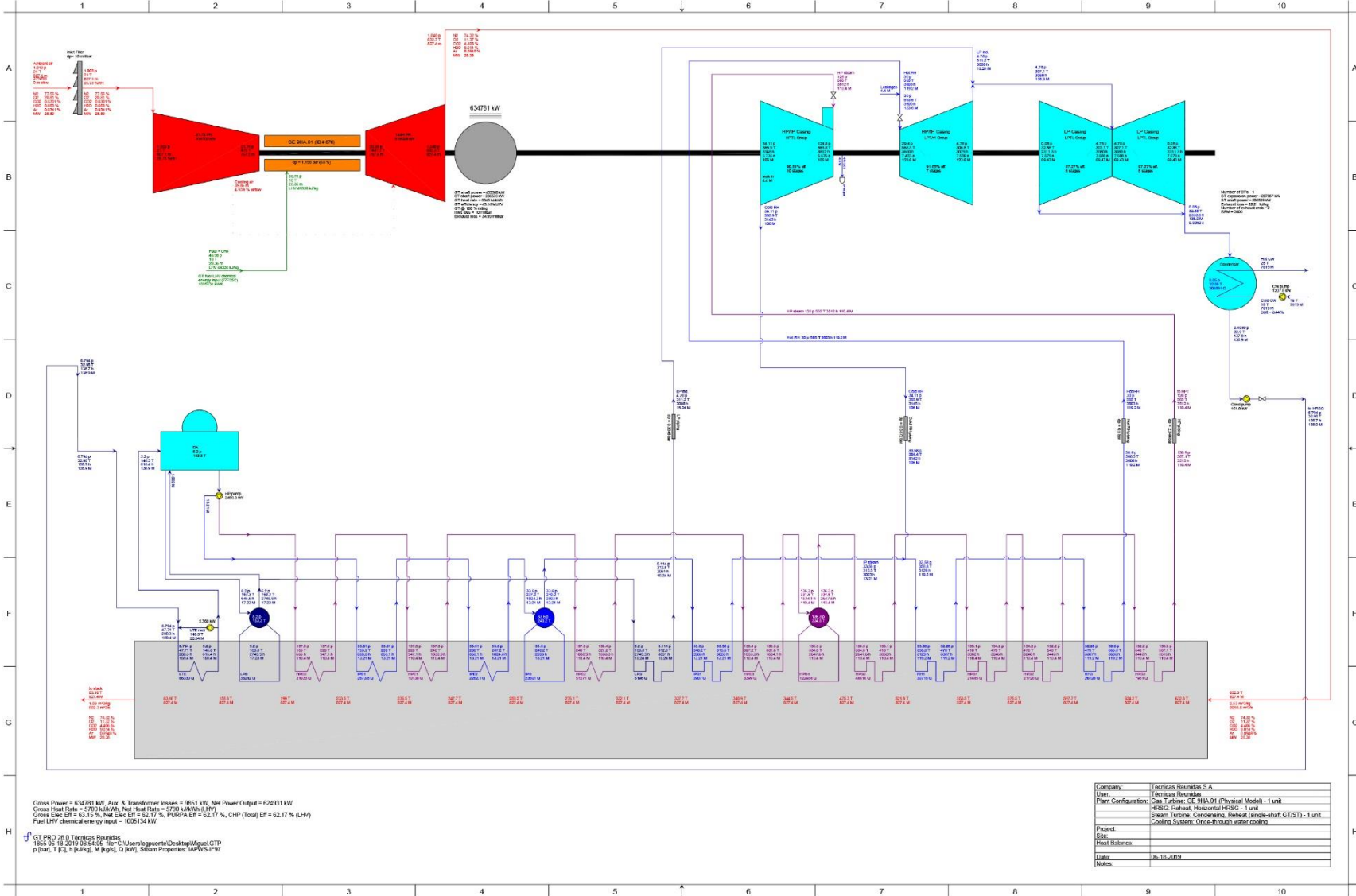
El ciclo combinado 1x1 SS propuesto reduce considerablemente la contaminación en comparación con la del Grupo 1.

Finalmente, para el grupo 2 del Litoral de Almería, que se puso en funcionamiento en 1997, su reemplazo aún no se considera en este trabajo. Sin embargo, la estación de servicio de medición ha sido diseñada para un futuro suministro hipotético al nuevo Grupo 2 y con la posibilidad de: ampliar el espacio para el gasoducto y para la Planta de tratamiento de agua (WTP) existente y la Planta de tratamiento de aguas residuales (WWTP) si es necesario.



Figure 5- Estación de Regulación y Medida, Fuente [Diseño interno]

Balace de Masa y Energía



Gross Power = 634781 kW, Aux. & Transformer losses = 9651 kW, Net Power Output = 624931 kW
 Gross Heat Rate = 5700 kJ/kWh, Net Heat Rate = 5790 kJ/kWh (LHV)
 Gross Cycle Eff = 43.15 %, Net Cycle Eff = 42.17 %, PV/GRCA Eff = 42.17 %, CHP (Total) Eff = 62.17 % (LHV)
 Fuel LHV chemical energy input = 1005134 kW

REPOWERING A CONVENTIONAL THERMAL POWER PLANT INTO A COMBINED CYCLE POWER PLANT

Author: Barriola Arranz, Miguel.

Director: Hernando García, Miguel Ángel.

Collaborating Entity: Técnicas Reunidas.

PROJECT SUMMARY

Although the surge in cleaner power plants including renewable energy and combined cycles is evident, the generation of electricity through fossil fuels constitutes the bulk of the world's electricity production. The choice between conventional thermal power plants or combined cycle thermal power plants will depend fundamentally on the availability of the necessary fuel for each of them, although it is not the only factor on which the choice will depend since, in general, the combined cycle power plants present some advantages over conventional thermal power plants and are summarised in tables 1 and 2.

	Combined cycle power plants	Coal plants
Efficiency	49%-64%	37%-44%
Investment	450 €/kW	800-900 €/kW
Execution time	2 years	3.5 years

Table 2-General comparison, Source [“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”]

	Combined cycle power plants	Coal plants
CO ₂	0.45 kg/kWh	1 kg/kWh
NO _x	≤75 mg/Nm ³	≥200 mg/Nm ³
SO ₂	0	≥200 mg/Nm ³
Ashes	0	50 mg/Nm ³

Table 2-Polluting emissions, Source [“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”]

In this project, a study is carried out of the reconversion of a conventional Thermal Power Plant (burning coal) into a Combined Cycle power plant, based on a Gas Turbine (Brayton Cycle) and a Steam Turbine (Rankine Cycle).



Figure 4, Brayton and Rankine Cycle, Source [<http://27.wire.karneval-lastrup.de/diagram-of-the-gas-cycle.html>]

In this work, Group 1 of the Litoral de Almería Conventional Thermal Power Plant (Carboneras) is examined. Group 1 has a power of 576.9MW and was commissioned in 1985. This group 1 consists, currently, of: a coal mill, coal boiler, steam turbine, alternator and a condenser. It also shares a stack with group 2 that was put in service in 1997.

The fuel currently burnt is imported coal.

The main data of Group 1 of Litoral de Almería Conventional Thermal Power Plant (Carboneras) is:

GROUP I

- General
 - Power: 576.9.
 - Year of commissioning: 1985.
- Mill
 - Capacity: 53 t/h.
 - Maker: Combustion Engineering.
 - Number: 6.
 - Power: 500 kW.
- Boiler
 - Type: tangential fires.
 - Manufacturer: Combustion Engineering.
 - Vessel Height: 66.34 m.
 - Main steam flow: 1679 t/h.
 - Overheated steam flow: 1525 t/h.
 - Initial steam pressure: 176 bar.
 - Pressure of the superheated steam: 41 bar.
 - Feeding water temperature: 253 °C.
 - Main steam temperature: 541 °C.
 - Hot reheated steam temperature: 541 °C.
 - Cold reheated steam temperature: 338 °C.
 - Yield: 89.42%
- Condenser
 - Type: dual pressure.
 - Coolant fluid and origin: Open water seawater.
 - Thermal jump: 5 °C.
 - Flow: 59,530 m³/h
- Turbine
 - Manufacturer: Bazán/G.E.E.
 - Maximum power: 577 MW.
 - Number of bodies: 4.
 - Number of extractions: 7.
 - Speed of regime: 3000 rpm.
- Alternator
 - Manufacturer: General Electric.

- Power: 636 MVA.
- Output Voltage: 20 kV.
- Power factor: 0.9.
- Stator rated current: 18,360 A.
- Refrigeration: Hydrogen.

Source [https://es.wikipedia.org/wiki/Central_t%C3%A9rmica_Litoral_de_Almer%C3%ADa]

In group 1, the approximate Rankine Cycle of the Steam Turbine is the following:

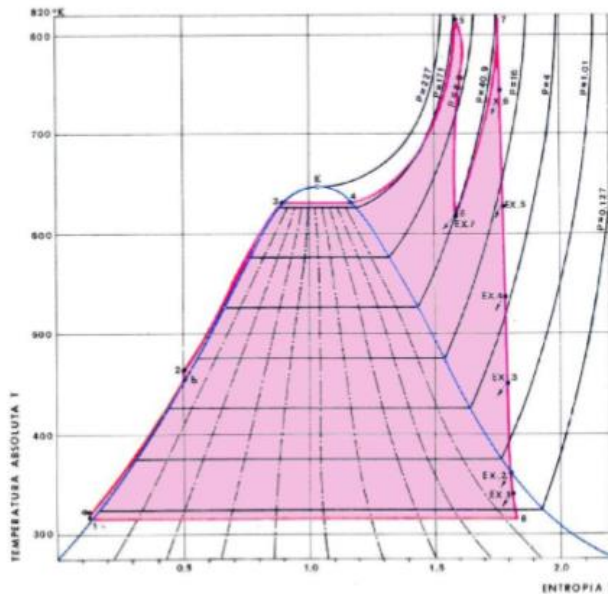


Figure 5, Approximate T-S diagram of the thermodynamic cycle, Source [Unión Fenosa Generación]

The performance of group 1 of this plant has an approximate efficiency of 35% and has significant emissions of NO_x , CO y CO_2 . The pollutant emissions of CO_2 were estimated between 2005 and 2007 by almost 7 million tons. It is true that in 2010 a gas desulphurisation plant was put into service that managed to reduce emissions by 100,000 tons per year.

The present TFG contemplates the replacement of group 1 of the Litoral de Almeria Conventional Thermal Power Station (Carboneras) by a Combined Cycle consisting of a gas turbine, a steam recovery boiler (HRSG), a steam turbine and an alternator to achieve a yield performance close to 64%.

Thanks to the commissioning of the Medgaz submarine gas pipeline in 2011, with a capacity of 8 bcm of natural gas per year, natural gas is a resource available in the province of Almería (see image).



Figure 6- Gas Pipelines, Source [<https://es.wikipedia.org/wiki/Medgaz>]

Technical data Medgaz pipeline:

- Capacity: 8 bcm/year (8 billion m³/year).
- Length: 210 kilometres (between Beni Saf and Almería).
- Diameter: 24 inches (610 millimetres).
- Maximum water depth: 2.160 meters.
- Ground facilities:
 - Compression station (Algeria)
 - Reception Terminal (Almería, Perdigal beach).

The molar composition of Natural Gas would be approximately the following:

Gas composition	% moles	
		CH ₄ = 89.3
		C ₂ H ₆ = 5.46
		C ₃ H ₈ = 1.38
		iC ₄ H ₁₀ = 0.27
		nC ₄ H ₁₀ = 0.17
		iC ₅ H ₁₂ = 0.06
		nC ₅ H ₁₂ = 0.03
		C ₅ H ₁₄ = 0.09
		N ₂ = 1.55
		CO ₂ = 1.68

Table 3, approximate molecular composition of the Natural Gas, Source [<https://www.enagas.es/stfls/EnagasImport/Ficheros/Comunicacion/Transmission,%20storage%20and%20regasification%20and%20infrastructure%20of%20Enag%C3%A1s%20catalogue.pdf>]

Combined cycle power plants are a good complement to the existing renewable energy park in Spain.

The objectives of the project are the improvement of the performance of group 1 and the renovation by more modern and efficient equipment (a new gas turbine is proposed and the replacement of the existing boiler by a HRSG boiler and the renovation of the existing steam turbine and alternator). Certain of the existing facilities will be reused, such as: the water treatment plant, the wastewater treatment plant and the water intake and discharge for cooling water.

A significant reduction in greenhouse gases is achieved, since we would go from using coal as Group 1 fuel to using natural gas (see table 2 of the introduction).

New equipment envisaged:

- Gas turbine
- HRSG (Steam Recovery Boiler)
- Steam turbine
- Self-synchronising clutch
- Alternator with 20kV output
- 400kV / 20kV transformer for connection to an existing substation

Using the Heat and Mass Balance diagram as a basis, which provides: the LHV information of the natural gas, the electrical power of the gas turbine and the corresponding flows and enthalpies of each place, different calculations in each component of the Combined Cycle Power Plant are carried out:

Gas Turbine:

The following models have been studied in this work:

	General Electric	Siemens	
Simple Cycle	Model	9HA.01	SGT5-8000H
	Frequency	50 Hz	50 Hz
	SC Output (MW)	446	450
	SC Net Heat Rate (kJ/kWh, LHV)	8346	<8780
	SC Efficiency (% , LHV)	43.1%	≈41%
Combined cycle	Block Configuration (GTs x STs)	1x1	1x1
	CC Net Output (MW)	661	665
	CC Net Heat Rate (kJ/kWh, LHV)	5674	5695
	CC Net Efficiency (% , LHV)	63.5%	61%

Table 4- GE Gas turbine, model 9HA.01, Source [<https://www.ge.com/power/gas/gas-turbines/9ha>]

The following calculations were carried out to verify the most important characteristics:

- The Gas Turbine efficiency: Electric power of the gas turbine / Natural Gas heat = $433580 \times 100 / 1004277.4 = 43.18\%$.
- The power transferred to the Shaft by the Gas Turbine = $0.4318 \times 1004277 \cong 433.65 \text{ MW}$
- HR performance of the Gas Turbine: $1004277.4 \times 3600 / 433646 = 8337.2 \text{ kJ/kWh}$.

The percentage errors of these calculations with respect to the ones calculated in Thermoflow are in each case approximately $0.09\% \ll 1\%$.

HRS (Heat Recovery Steam Generator):

The heat recovery boiler is the main link between the gas cycle and the steam cycle.

In order to achieve a high efficiency, 3 pressure drums have been considered: high pressure drum, intermediate pressure drum and low-pressure drum. The HRS considered also includes reheaters.

The pinch point temperature difference, which is referred to as Δt_{pp} and is the difference between the exhaust gas temperature at the exit of each evaporator and the water vaporisation temperature for each of the drums ranges between 5°C and 10°C in order to get a high efficiency.

The following calculations were carried out to verify the most important characteristics:

- The enthalpy values at the exit of the gas turbine and of the HRSG were calculated with the formula: $H \left(\frac{\text{kJ}}{\text{kg}} \right) = \left[0.9952 + \frac{92.1 \cdot T_{\text{stack}}(^{\circ}\text{C})}{1000000} \right] \times T_{\text{stack}}(^{\circ}\text{C})$.
Hence $H_{\text{Gas Turbine}} = 666 \frac{\text{kJ}}{\text{kg}}$ and $H_{\text{stack}} = 83.4 \frac{\text{kJ}}{\text{kg}}$
- The HRSG performance: $\eta_{\text{HRSG}} = \frac{Q_{\text{ST}}}{Q_{\text{GT}}} = \frac{\text{Heat contributed to the low-steam turbine cycle}}{\text{Heat given to the cycle by the Gas Turbine}}$
 $= \frac{138.9 \times 3080}{666 \times 827.4} = 77.6\%$
- The corresponding kW that exit the HRSG as useless energy are: $827.4 \times 83.4 = 69005 \text{ kW}$

Steam Turbine:

A new steam turbine sharing the same shaft with the Gas Turbine, in configuration 1x1 SS has been considered.

The new Steam Turbine has four bodies and conveys up to 200 MW of power to the shaft.

In the TFG we will include the following plans:

- General table of existing plant.
- General outline of the proposed Combined Cycle power plant (plan 1).
- Electrical single-line diagrams of the existing plant (plan 2, 3 and 4).

The following calculations were carried out to verify the most important characteristics:

- Total energy the steam turbine gives to the blades:
 $W = m_{\text{HP}} (h_{\text{HPi}} - h_{\text{HPo}}) + m_{\text{IP}} (h_{\text{IPi}} - h_{\text{IPo}}) + m_{\text{LP}} (h_{\text{LPi}} - h_{\text{LPo}}) - m_{\text{LP}} * W_e$
 $W = 205392.7 \text{ kW}$
- Efficiency of the steam turbine: $W / \text{Natural Gas Heat} = 205392.7 * 100 / 1004277.4 = 20.45\%$
- The power transferred to the Shaft only by the ST would be:
 $ST_{\text{Shaft Power}} = 0.2045 \times 1004277 \cong 205.37 \text{ MW}$.

Condenser:

The main objective was to calculate the surface area of exchange that would be needed for the condensation:

$$Q = \text{LMTD} \times (U \times A)$$

- LMTD (Logarithmic mean temperature difference) $= \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$. ΔT_A and ΔT_B represent the temperature difference of the condensate and of the cold fluid that enter and leave the condenser. So, $\Delta T_A = 0^{\circ}\text{C}$ and $\Delta T_B = 10^{\circ}\text{C}$. Therefore, $\text{LMTD} = 10$.

- U (global coefficient of heat transfer) is the medium value between the range of 300 and 600 (i.e. $450 \frac{\text{hr}}{\text{ft}^2\text{K}} = 2553.5 \frac{\text{W}}{\text{m}^2\text{K}}$) as shown in the following table:

Condensers		
Cold Fluid	Hot Fluid	Overall U (BTU/hr-ft ² -F)
Water	Steam (pressure)	350 - 750
Water	Steam (vacuum)	300 - 600
Water or brine	Organic solvent (saturated, atmospheric)	100 - 200
Water or brine	Organic solvent (atmospheric, high non-condensables)	20 - 80
Water or brine	Organic solvent (saturated, vacuum)	50 - 120
Water or brine	Organic solvent (vacuum, high non-condensables)	10 - 50
Water or brine	Aromatic vapours (atmospheric with non-condensables)	5 - 30
Water	Low boiling hydrocarbon (atmospheric)	80 - 200
Water	High boiling hydrocarbon (vacuum)	10 - 30

Figure 4- Condenser values for the global coefficient heat of transfer, Source [Unión Fenosa Generación]

- $Q = Q_{IC} - Q_{OC} = 304982.73 \frac{\text{KJ}}{\text{s}}$

Hence the area suggested to be designed is approximately of 12m²

Whole Plant:

The efficiency of the whole combined cycle power plant can be calculated in three different ways:

1. The first way is that the performance of the gas turbine + performance of the steam turbine = performance of the power plant: 43.18% + 20.45% = 63.63%. The percentage difference of this value with respect to the efficiency 63.15% is 0.75%.
2. Another way of calculating the plant's performance, is using the electrical power of the generator (634781kW): $634781 * 100 / 1004277.4 = 63.20\%$. The percentage difference of this value with respect to the efficiency 63.15% is 0.079%
3. The third last form is with the equation: $\eta_{CC} = \eta_{GT} + \eta_{ST} \times \eta_{HRSG} \times (1 - \eta_{GT})$
 $\eta_{CC} = 0.4318 + 0.4318 \times 0.776 \times (1 - 0.4318) = 62.2\%$. The percentage difference of this value with respect to the efficiency 63.15% is 1.5%

Self-synchronising clutch:

The Gas Turbine will start first.

Once steam is produced and the Steam Turbine gets the appropriate speed, it will be coupled by means of a self-synchronising clutch.

New alternator with 20 kV voltage output:

Considering that both the Gas Turbine and the Steam Turbine will transfer power to the Alternator, a new alternator of up to 650 MW is considered.

Generator Transformers:

The existing substation has bays at 400 kV and at 20 kV.
Three Single-Phase Transformers of up to 255 MVA each are considered.

In conclusion, it is true that some utilities may have contemplated the replacement of coal power plants into combined cycle power plants. In terms of available sources of energy proven coal reserves are estimated to last for about 200 years, much longer than oil. However, the pollution of coal power plants is still high and, therefore, the idea of a combined cycle with gas turbine and steam turbine is a good option.

Electricity demand continues to grow and in order to meet this demand, several distributed renewable resources (such as wind farms and solar power plants) have become very frequent. The coal thermal power plant of Litoral de Almería consists of two groups, the first one which was commissioned in 1985 and the second one was put into operation twelve years later in 1997. Natural gas is available in Almería since Medgaz gas pipeline was put into service in 2011 and there is also a gas pipeline connecting Almería province with Murcia province (run by the company Enagas). In order to increase the power range of the old Group 1 as well as its efficiency, the replacement of Group 1 into a 1x1 SS combined cycle power plant is proposed in this work. This 1x1 SS combined cycle would include an innovative gas turbine with a firing temperature (TIT) of 1447°C and a combined cycle net efficiency of up to 63.5%. The HRSG would include 3 pressure drums with reheaters with an inlet temperature of 632°C of the exhaust gases and an outlet temperature of the gases that exit the HRSG towards the stack with 83°C.

The proposed steam turbine has four bodies with an estimated shaft power of 206MW which in addition to the approximate 434MW of the gas turbine results in a combined shaft power of 640MW. The proposed electrical system connecting the new generator to the grid consists of IPB (isolated phase bus) three single-phase power transformers, 400kV-20kV.

The proposed 1x1 SS combined cycle reduces considerably the pollution compared with that of the existing Group 1.

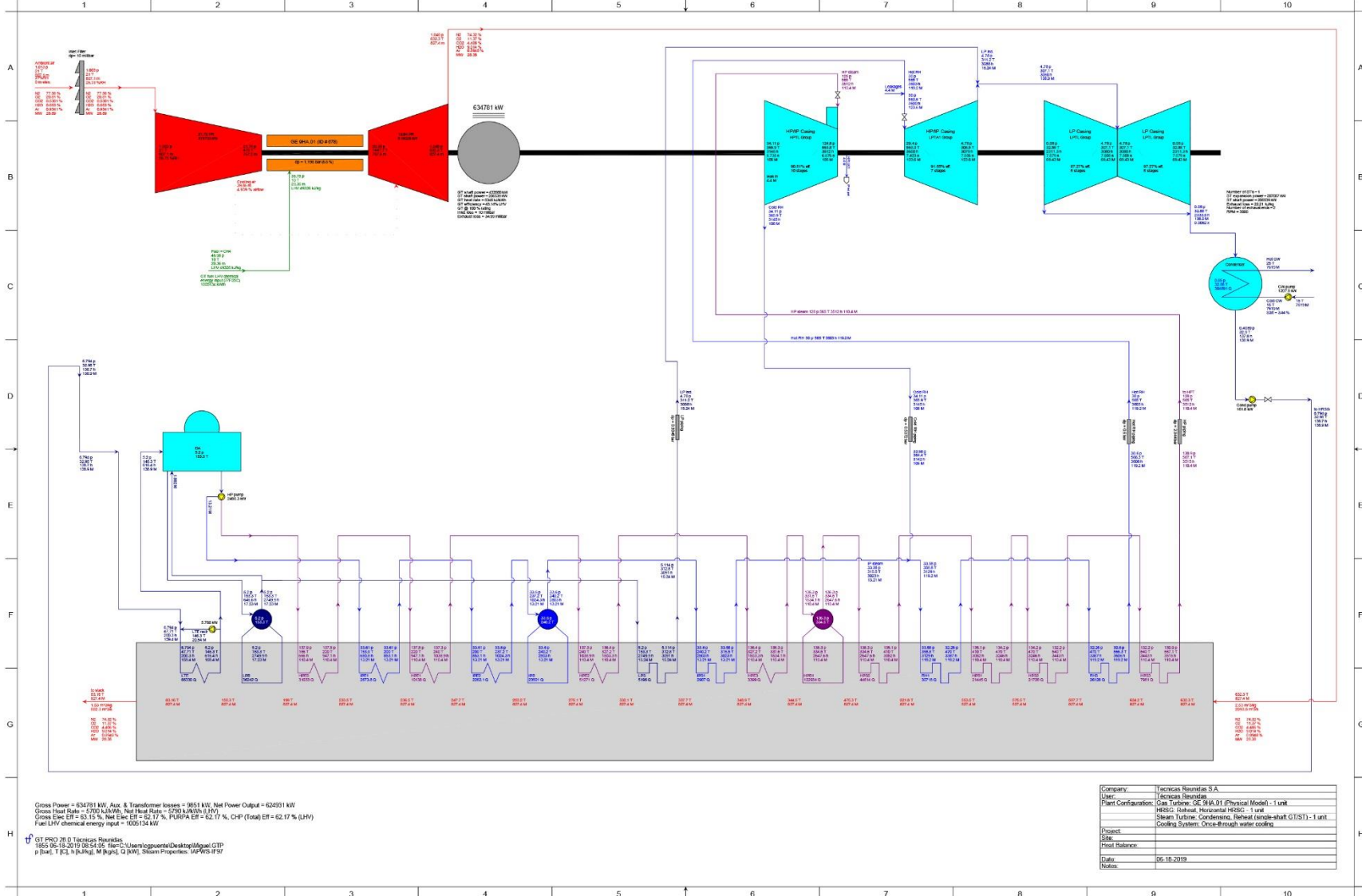
Finally, for group 2 of the Litoral de Almería, as it was put into operation in 1997, its replacement is still not considered in this work. However, the Metering Gas Station has been designed for a hypothetical future supply to the new Group 2 with the possibility of expanding the space for the

gas pipeline and for the existing Water Treatment Plant (WTP) and the Wastewater Treatment Plant (WWTP) if necessary.



Figure 5- Natural Gas Metering Station, Source [Internal design]

Heat and Mass Balance



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0- LIST OF ABBREVIATIONS

- BCM: Billion cubic metre
- GRP: Glass reinforced plastic
- IPB: Isolated phase bus system
- OLTC: On load taps changer
- BIL: Basic impulse insulation level
- TSO: Transmission System operator, company in charge of operating the 220 kV and 400 kV grids.
- REE: Red Eléctrica de España, Transmission System Operator (TSO) in Spain.
- G1: Group 1, including turbine and alternator of a Thermal Power Plant. In this work, it refers to Group 1 of Central Litoral de Almería (Carboneras).
- G2: Group 2, including turbine and alternator of a Thermal Power Plant. In this work, it refers to Group 2 of Central Litoral de Almería (Carboneras).
- ONAN: Oil Natural Air Natural. It applies to the cooling of transformers, when the flow of both oil and air is natural convection.
- ONAF: Oil Natural Air Forced.
- OFAF: Oil Forced Air Forced.
- LV: Low voltage, usually below 1 kV or 1000 V.
- MV: Medium voltage. In this work, 6.3 kV and 20 kV.
- EHV: Extremely High Voltage. In this work, 400 kV.
- HRSG: Heat Recovery Steam Generator.
- HP: High pressure. In this work, the HP drum is at approximately 130 bar.
- IP: Intermediate pressure. In this work, the IP drum is approximately 28 bar.
- LP: Low pressure, in this work, the LP drum is approximately 5 bar.
- RH: Reheater
- SH: Superheater
- NG: Natural Gas
- GT: Gas Turbine
- ST: Steam Turbine
- LSB: Last-stage buckets
- TIT: Turbine Inlet Temperature
- TOT: Turbine Outlet Temperature
- SS Clutch: Self-synchronizing clutch.
- SWG: Switchgear. In this work it refers mainly to the 6.3 kV Switchgears
- PURPA: Public Utilities Regulatory Policies, Act of 1978.
- IAPWS-IF97 (International Association for the Properties of Water and Steam)

1-INTRODUCTION

1.1-History

The growth of the world energy demand is unstoppable. To the increase associated with the developed countries must be added the correspondent increase in demand of the developing countries, such as China, whose needs and energy requirements are growing rapidly day by day and at a much more intense pace than those of the countries that are considered to be developed.

The energy panorama of the first quarter of the century (2000 to 2025) is and will be very different from that pertaining to the last quarter of the twentieth century; Energy competition will be fierce with the launch of new, more efficient energy conversion systems on the market.

The generation of electricity through fossil fuels constitutes the bulk of the world's electricity production. The choice between conventional thermal power plants or combined cycle thermal power plants will depend fundamentally on the availability of the necessary fuel for each of them, although it is not the only factor on which the choice will depend since, in general, the combined cycle power plants present some advantages over conventional thermal power plants and summarised in tables 1 and 2.

	Combined cycle power plants	Coal plants
Efficiency	49%-64%	37%-44%
Investment	450 €/kW	800-900 €/kW
Execution time	2 years	3.5 years

Table 1-General comparison, Source [“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”]

	Combined cycle power plants	Coal plants
CO ₂	0.45 kg/kWh	1 kg/kWh
NO _x	≤75 mg/Nm ³	≥200 mg/Nm ³
SO ₂	0	≥200 mg/Nm ³
Ashes	0	50 mg/Nm ³

Table 2-Polluting emissions, Source [“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”]

The configuration of the energy market will depend a lot on the availability and cost of fossil fuels. In the twentieth century, the most commonly used fuel was coal. Nowadays natural gas is by far the fuel of choice, if its availability and its price allow it, due to its lower polluting emissions and its low transport and storage costs. Thence, in those countries where the availability of natural gas as a fuel is higher than that of coal, it is a coherent option to opt for the construction of combined cycle thermal power plants.

The structure of generation costs tells us that the decisive factor of investments for the future will be the cost of fuel and this, together with the environmental considerations related to CO₂ emissions and their management, will determine the continuity or not of investments in combined cycles.

	Combined cycle power plants (400 MW)	Coal plants (700MW)
Fuel	71%	55%
Investment	18%	37%

Table 3- Cost structure of the kWh, Source [“Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”]

1.2-Presentation of the project

In this work, we study group 1 of the Litoral de Almería Conventional Thermal Power Plant (Carboneras) that has a power of 576.9MW and which was put in service in 1985. This group 1 consists, currently, of: coal mill, coal boiler, steam turbine, alternator and condenser. It shares a stack with group 2 that was put in service in 1997.

The present work consists in the renewal of group 1 since in 2025, it will be 40 years old and it is a recommended period for its replacement by a Combined Cycle consisting of a gas turbine and steam turbine (i.e. 1x1 configuration). The process will be carried out, firstly, by taking advantage of group’s 1 existing equipment and components and eventually installing new components, like a Gas Turbine, to achieve its conversion into a combined cycle (repowering).

As a result, a recovery and a modernisation of the facilities is achieved. An increase in the power generated is provoked without the need to resort to new spaces and, a dismantling procedure is avoided by prolonging the useful life of the existing equipment and facilities.

The idea of the project comes from Técnicas Reunidas with the intention to have available in the thermal department different alternatives about its facilities, which can serve for potential future developments and as internal memory of the company and can be used for the traineeship of its employees.

The project is focused on a present and probably constant future scenario, the substitution of thermal power plants for combined cycle power plants.

1.3- Coal and Combined Cycle Thermal Plants

It consists of a general description of the components and operation of a conventional thermal power plant and of a combined cycle. Comparisons will also be done between different configurations of combined cycles.

1.4- Design of the project

There is a report of the current state of the Litoral de Almería power. Hence a remodelling of the turbine is therefore available to adapt it to a combined cycle. This is done through different statistical approaches after studying the thermal balances provided by Técnicas Reunidas of the thermal power plant.

There is technical data available as to Gas Turbines, HRSGs, Steam Turbines, including the following manufacturers:

- GE
- Siemens
- ABB

We are going to focus on group 1 since it is the older of the two existing groups (since it was put in service in 1987) and whose technical characteristics are reflected in the following section:

GROUP I

- General
 - Power: 576,9.
 - Year of commissioning: 1985.
- Mill
 - Capacity: 53 t/h.
 - Maker: Combustion Engineering.
 - Number: 6.
 - Power: 500 kW.
- Boiler
 - Type: tangential fires.
 - Manufacturer: Combustion Engineering.
 - Vessel Height: 66,34 m.
 - Main steam flow: 1679 t/h.
 - Overheated steam flow: 1525 t/h.
 - Initial steam pressure: 176 bar.
 - Pressure of the superheated steam: 41 bar.
 - Feeding water temperature: 253 °C.
 - Main steam temperature: 541 °C.
 - Hot reheated steam temperature: 541 °C.
 - Cold reheated steam temperature: 338 °C.
 - Yield: 89,42%
- Condenser
 - Type: dual pressure.
 - Coolant fluid and origin: Open water seawater.
 - Thermal jump: 5 °C.

- Flow: 59.530 m³/h
- Turbine
 - Manufacturer: Bazán/G.E.E.
 - Maximum power: 577 MW.
 - Number of bodies: 4.
 - Number of extractions: 7.
 - Speed of regime: 3000 rpm.
- Alternator
 - Manufacturer: General Electric.
 - Power: 636 MVA.
 - Output Voltage: 20 kV.
 - Power factor: 0,9.
 - Stator rated current: 18.360 A.
 - Refrigeration: Hydrogen.

It is well known that the current design of group 1 of the plant consists, in summary, of a coal mill, a boiler, a steam turbine, a condenser and an alternator following a Rankine cycle.

1.5- Environmental Impact

A study is made of the pollution produced by the plant at different levels and is compared with a compilation of the current legislation on pollution.

1.6- Conclusions

Technical calculations, later on, showing efficiencies of the new solution considering the combined cycle of gas turbine, an HRSG, steam turbine.

Moreover, comments on the percentage reduction in the greenhouse gases achieved, since we would go from using coal as group 1 fuel to using natural gas. A detailed description of the new TTP (Thermal Power Plant) gas natural metering station is shown in section 4.2 including a future gas pipe available for the replacement of group 2.

2- COAL THERMAL PLANTS

2.1- Description of a thermal power plant

The operation of a conventional thermal power plant is similar regardless of the fossil fuel it uses (be it coal, natural gas or oil) to produce electrical energy. The internal energy (calorific value) of fossil fuels is used to transmit energy inside a boiler to a piping system through which water circulates and turns into steam, this causes a transformation in mechanical energy to move the blades of the turbine which in turn moves the rotor of the alternator (producing electrical energy).

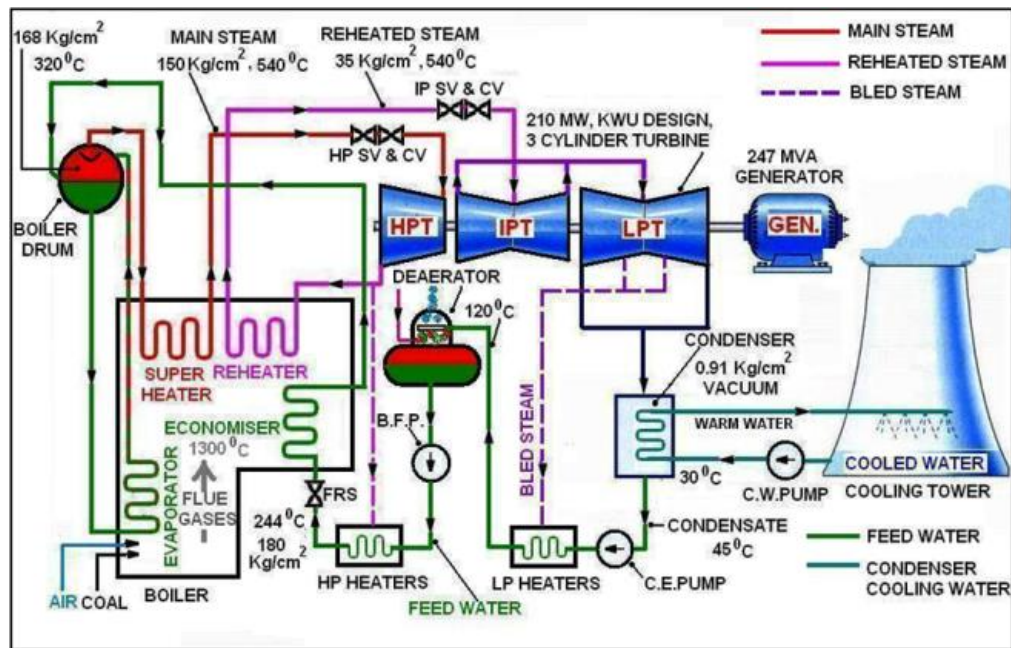


Figure 1- Coal Based Thermal Power Plant, Source [<http://electrical-engineering-world1.blogspot.com/2015/02/typical-coal-fired-thermal-power-station.html>]

The combustion steam produced by the combustion of fossil raw materials, which takes place in the boiler, is introduced into the high-pressure turbine body, where there is a high temperature and pressure. Subsequently the steam coming from the output of the high-pressure turbine is sent back to the boiler and thus reheated where it acquires high pressures and temperatures again. The superheated steam is conducted to the body of the medium pressure turbine. Ultimately, the steam extracted from the medium pressure turbine, which still retains useful properties, is taken to the low-pressure turbine body. The steam existing in the low-pressure area of the turbine does not have usable qualities and is therefore taken to the condenser where conditions of very low pressure (vacuum) and temperature (40°C) exist. Here, when entering in contact with tubes (that transport water of circulation of a lake, river or sea) the vapour condenses into liquid water, beginning the thermodynamic cycle again.

The water is then preheated through pre-heaters that obtain their energy due to extractions coming from the different turbine bodies. It is in this stage where the deaerator is, in order to eliminate the oxygen that may exist in the water flow.

2.2- Thermodynamic Cycle

The cycle of the thermal power plants corresponds to the Rankine cycle and is the technological application of the Carnot cycle for the case that the motor fluid is a condensable fluid and during its evolution there are phase changes. In a simplified way, and for the basic cycle, the evolution of the fluid follows the following stages:

- A stage of expansion of the fluid in vapor phase, carried out in the steam turbine, and as isentropic as possible.
- At the outlet of the steam turbine, a transfer of residual heat from the steam (and its passage to the liquid phase) under constant pressure in a device called a condenser.
- One or several stages of elevation of the fluid pressure. The process is carried out with pumps and outside the zone of phase change.
- A stage of heat input at constant pressure. The fluid performs a pre-heating step in the liquid phase, a phase change process and a subsequent rise of the steam temperature to decrease the humidity in the steam in the later stages of expansion of the turbine.

The basic structure of a water-steam cycle in its simplest version, as well as the evolution of the fluid in the h-s and T-s diagrams, are schematized in figures 2.7 and 2.8 respectively.

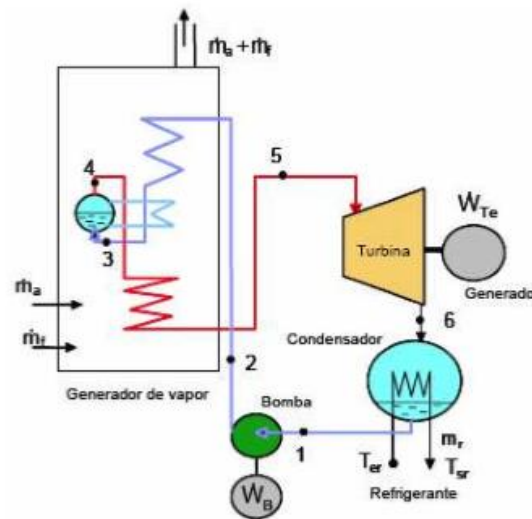


Figure 2. Basic Rankine cycle, Source [Unión Fenosa Generación]

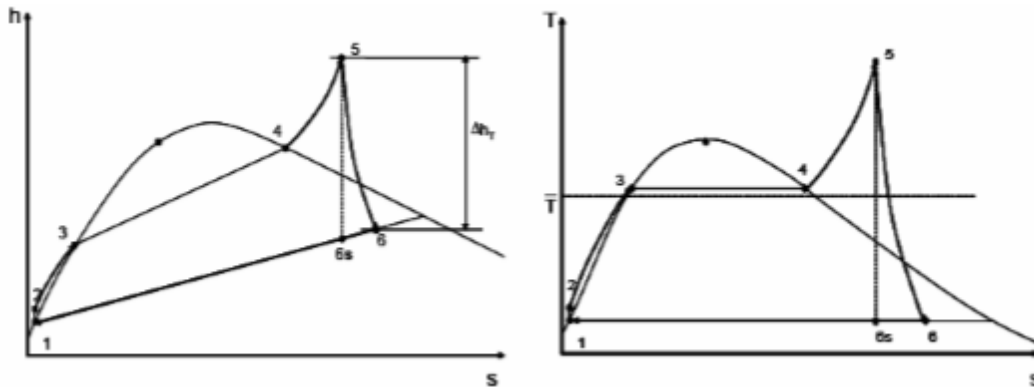


Figure 3- Diagrams h-s and T-s of a basic Rankine Cycle, Source [Unión Fenosa Generación]

2.3- Components

2.3.1-Air preheaters

A heat exchanger whose mission is to recover part of the heat contained in the combustion gases. The latter are at the output of the economiser at a high temperature, in the order of 250 to 300 ° C. The limitation of the use of the heat energy of the gases is imposed by the dew point, which depends mainly on the type of fuel and the excess of admitted air. The dew temperature (that is approximately between 110 and 150 ° C) is the one that corresponds to the appearance of condensations in the gases, giving rise to depositions of sulfuric acid that destroy, by corrosion, the metallic parts of the gas circuits.

2.3.2-Boiler

It is one of the most important elements of the thermal power. It is the place where the transformation of water into a liquid state occurs.

2.3.2.1- Economiser

The economiser is a coil located in the gas output stream of the boiler, usually between the reheater and the air preheater. The entering water, after passing through the high-pressure preheaters, circulates inside the coil before entering the vaporisation zone. The gases that reach the economiser still have a considerable temperature and transmit heat by convection to the coil which, in turn, is cooled by the supply water, which will therefore heat up.

The temperature of the water at the exit of the economiser is very close to the saturation point that corresponds to the pressure of the vaporisation zone.

The economiser carries out two missions:

- Reduce the losses in the chimney by taking advantage of the residual heat of the gases.
- Get the water to reach the vaporisation zone at an already high temperature.

2.3.2.2- Boiler drum

It is positioned in the water-steam circuit, it is a component that mixes the liquid phase and the vapour phase of the generator water.

Inside are devices that achieve a separation between liquid water and steam. In addition, a water plane whose level is maintained at a constant value for the same vaporisation regime is established in the boiler drum. Above this water plane, there is the saturated steam, which is released to the super heater by means of separators and dryers, located in the upper part of the boiler drum.

There are different types of boiler drums available depending on the capacity and characteristics of the boiler drum, such as the situation and arrangement of the connections with the various pipes, and the devices contained inside of them, such as: screens, separators, etc.

2.3.2.3- Super heater

The super heaters are simple heat exchangers in the form of heat coils, located in the stream of combustion gases. Their arrangements can differ in order to maximise the heat of the combustion gases.

The steam coming from the boiler drum, is first passed through the super heater where it reaches the maximum temperature. It is then sent through the main steam pipe to the high-pressure body of the turbine.

The super heater receives heat mainly by radiation, being in a zone of the boiler where the temperatures are very high. It should be noted that the super heater also receives heat by convection of the combustion gases.

In the boilers, the maximum steam temperature is limited to 600°C. This limit is imposed by the resistance conditions of the metals that make up the boiler and the steam turbine.

2.3.2.4- Re heaters

Re heaters receive heat primarily by convection. Its construction is analogous to that of super heaters and is also located in the flue gas stream. They can be a single section or divided into different sections. The super heater receives the expanded steam in the high-pressure turbine (cold superheated steam), raises its temperature again to the maximum and as hot superheated steam goes to the medium pressure body.

2.3.3- Steam Turbine

The steam turbine is a thermal machine where the energy of the steam (enthalpy) is transformed into mechanical energy of rotation in the axis of the turbine. The steam, with high enthalpy, reaches the turbine with a high pressure and temperature and, in it, undergoes a large expansion with a large temperature decrease. The enthalpy of the steam at it exits from the turbine is much smaller than that at its entrance. The difference between these enthalpies is, practically, the energy that the turbine has transformed into

useful mechanical energy of rotation. During its expansion, the mass of vapour acquires kinetic energy, at the expense of the corresponding decrease in its enthalpy.

The turbine has two main parts the rotor and stator. In the rotor are the mobile organs, where the kinetic energy of the steam is transformed into mechanical energy of rotation, which is transferred to the axis, to which they are solidary. In the stator are the fixed organs, which are responsible for directing the steam. In particular, the stator is composed of two other fundamental parts: a framework and a cylinder. The framework is the cover of the turbine, and the function of the cylinder is to prevent the escape of steam into the atmosphere and act as a support for the fixed organs.

The shaft of the turbine is supported on the bearings by means of an area called the wrist. This area is perfectly balanced and polished, and sometimes hardened, to reduce friction with the bearing. Two types of oil are applied for its use. One is lubrication oil and the other is the shaft lift oil in order to inject high pressure oil into the lower part of the bearing and so separate the rotor slightly before operating the turbine.

The classification of the steam turbines can be done following: the steam performance, the number of bodies and of their alignment and according to the direction of movement of the steam in relation to the axis of the turbine.

At the entrance of the turbines, the paddles are small, and they increase in size as the steam advances through them. Specifically, in group 1 of Litoral de Almería, the turbine has a high-pressure part, here, the vapour pressure is the highest and it is where the greatest effort is produced on the axis; so, the turbine paddles are small. The medium pressure turbine receives the steam that comes from the high-pressure turbine after being reheated; and in the low-pressure turbine there are large paddles due to the lower vapour pressure. Of all the turbines that work in a thermal power station, a certain quantity of steam is extracted, which is then taken to the preheater to increase the temperature of the water before being introduced into the boiler, and thus avoid a great thermal shock and increase the performance of the plant.

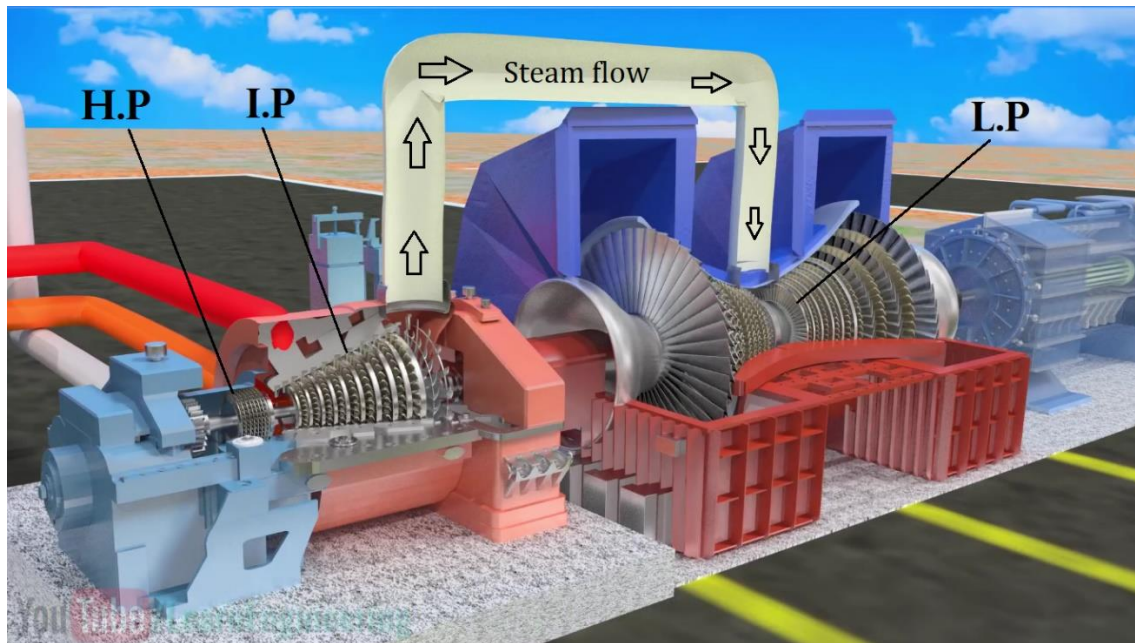


Figure 4- Steam Turbine of Tandem-Compound, Source [<https://i2.wp.com/mechstuff.com/wp-content/uploads/2018/01/steam-turbine.png>]

2.3.4- Alternator

The electric generator is a rotary machine consisting of rotor and stator.



Figure 5- Alternator, Source [<http://www.directindustry.es/fabricante-industrial/rotor-estator-alternador-229533.html>]

The axis of the rotor of the generator is coupled to that of the turbine rotor, so that the generator receives mechanical energy from the turbine for its rotation. The coupling is usually direct, and both axes rotate at the same speed. In large turbo generators the coupling is usually rigid, by means of flanges and screws.

The generators of the turbo groups of thermal power plants are alternators, that is, they generate alternating current. The operating principle of the alternators is magnetic induction. The rotor is powered by a continuous current generator called an exciter. This

current circulates through the windings of the rotor, originating in it magnetic poles. As the rotor rotates, driven by the turbine, the magnetic fields of these poles are cutting stator windings (induced) and induce in them an electromotive force or alternating voltage that is manifested in the terminals of the alternator. This voltage, when the terminals are connected to the network, results in an alternating current as well.

The active electrical power generated by the alternator is proportional to the product of this voltage and this intensity. For this power to be generated, it is necessary that the rotor rotates by the drive of the turbine. The mechanical power that the turbine must transmit to rotate the rotor at the desired speed, which is equivalent to the resistance that the rotor opposes to the rotation, is proportional and slightly higher than the electrical power supplied by the stator.

It should be noted that the mechanical power of the turbine is automatically adjusted by the regulator to the load demanded from the alternator. Let's consider the case that there's an increase of the load that the network demands from the generator, which will cause its rotor to resist rotation and as the steam flow in the turbine has not changed, it will not have the power to maintain the same speed of rotation. Consequently, the speed of rotation of the group will decrease and this will actuate the pilot valve and opening, in short, the steam control valves. Then, the steam admission will be adjusted to the turbine so that it has enough power to move the alternator rotor at normal speed.

2.3.5- Condenser

In the condenser, the steam coming from the low-pressure turbine is transformed into liquid water. It has two tubular plaques at each end and its body is composed of steel. Between these plaques it contains a large bundle of brass or alloy tubes. Cooling water comes from these pipes, from some nearby natural reserve, which is circulated through a circulation pump.

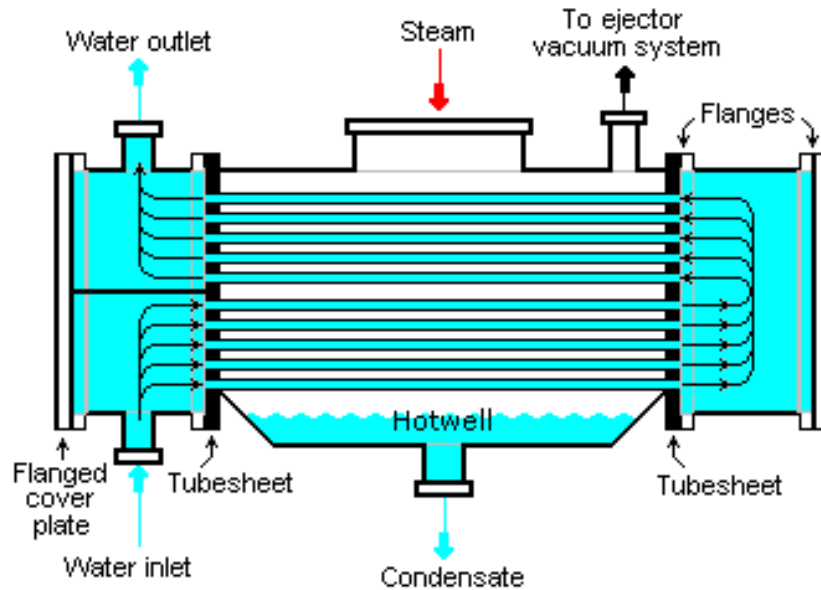


Figure 6-Condenser, Source [<http://albem.energy/>]

When the steam meets the pipes, through which the cooling water circulates, condenses and is deposited in the well located in the lower part of the condenser. By means of an extraction pump, the water that is deposited in the well is sucked up and put back into circulation by sending it back to the boiler through the preheaters. If the flow rate of available cooling water is insufficient, the circulation water at the condenser outlet is sent to an atmospheric coolant, this water would again serve to condense the steam in the condenser.

The air that is introduced into the condenser is sucked by means of vacuum pumps, located above the condenser.

2.3.6- Pumps

Its function is to move fluids, transforming mechanical energy into hydraulic energy. The pumps transport fluids through pipes. Being in between the pipe, they suck (overpressure) on the one hand and drive (depression) on the other, providing the energy necessary for the displacement of the fluid. In short, the pump transports a fluid from a point of low pressure to one of a higher pressure.



Figure 7- Pump, Source[<http://iechristmastrees.org/ex/>]

2.3.7- Deaerator

Its function is to eliminate oxygen from the feed water that goes to the boiler to avoid an important corrosion in the circuit, called pitting effect. It consists of a cylindrical container through which water enters inside it through the top part and then it falls on the trays that distribute it in the form of fine rain throughout the deaerator, and through whose lower part enters the extraction steam. When the water and steam are in counter current, the heat exchange takes place, condensing the steam and transferring its condensation heat to the water.

In the water-steam circuit there are some areas subjected to vacuum, that is, at pressures below atmospheric, and in them it is inevitable that air from outside enters through valve packings. On the other hand, dissolved air also enters the circuit in the supply water through the condensate reservoir tank.

It is necessary to keep the oxygen levels very low since it could cause a rapid oxidation of the steam circuit. The deaerator does this by basically contacting two streams of saturated liquid water with pure steam. The oxygen in the saturated liquid stream passes into the pure steam stream.

2.3.8- Water circulating system

2.3.8.1- Closed circulating system

The circulation water is necessary to remove the heat from the cycle, taking it to the environment through an open circuit, so that the water is taken, for example, from the

sea, which is usual in plants on the coast, and after passing through the condenser, it returns to the sea for discharge.

Normally, in the case of a plant close to a natural water reserve, a closed circulating system is available, so that the heat from the water, which passes through the condenser, can be extracted in a tower, and once it has happened, it returns to the condenser. Small replenishments must be made due to the water losses in the towers (water that escapes into the air) and to the purges necessary to maintain the quality of the water. The towers can be natural or forced draft. In case of natural draft, the water is passed through a special filling that breaks the water into very thin drops to facilitate the evacuation of heat. The draft is natural due to the configuration of the tower. The drawback is the size of the tower and its visual contamination. In the case of forced draft, the operation is similar, but the draft is achieved by fans with electric motor.

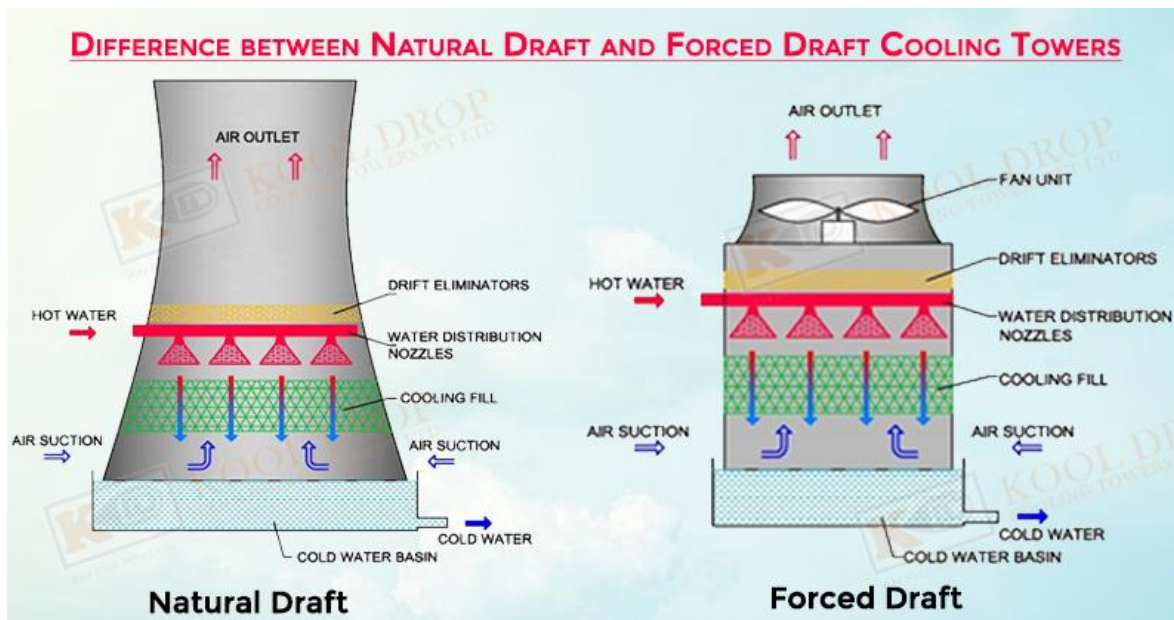


Figure 8-Natural draft vs Forced draft, Source

[<https://www.scoop.it/topic/kooldrop/p/4101917673/2018/09/25/difference-between-natural-draft-and-forced-draft-cooling-towers>]

1. Ventilators
2. Raft
3. Risers



Figure 9- Cooling tower, Source [Curso Introducción de Técnicas Reunidas]

2.3.8.2- Air condenser



Figure 10- Air Condenser (ACC), Source [Curso de Introducción de Técnicas Reunidas]

When we are in locations where water is a scarce resource and where it is not in adequate quantities to condense the exhaust steam from our steam turbine, we can use other means such as the air-condenser. In this case, the exhaust steam from the steam turbine passes through a collector directly to be condensed by means of air moved by fans.

2.3.8.3- Open circulating system

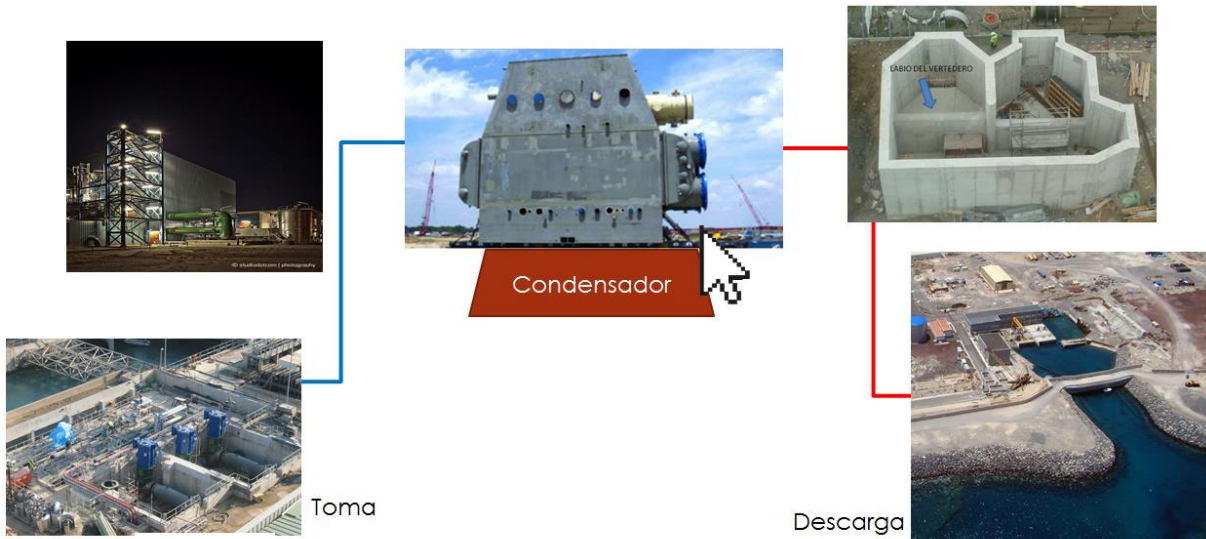


Figure 11- Open cooling circuit, Source [Curso de Introducción de Técnicas Reunidas]

When the plant is to be in the vicinity of a river or in the vicinity of the sea or in a place where water is not a problem and can be found in high quantities, the best configuration is an open cooling circuit. Here, the water is taken from a tank by means of some pumps, it is then sent to the condenser where the condensation of the steam turbine exhaust gasses takes place.

From there, the waste products, are sent to a landfill and a discharge to the sea. In this case, we will have to consider the environmental conditions of hot water emission to the river or sea.

2.3.8.4- Balance of different cooling systems

In the following image, there is a summary of the different technologies seen to design the cold cooling systems. From the advantages and disadvantages of application of each of these technologies, we can choose the most convenient configuration for the type of site of the future.



Pros



Cons




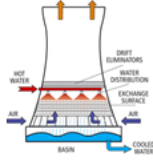
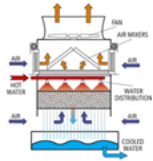
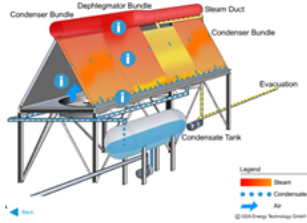
	 Pros	 Cons	
Open cycle	<ul style="list-style-type: none"> Most efficient system. 	<ul style="list-style-type: none"> Use of river/sea water. AT (EIA) 	
Natural draft cooling tower	<ul style="list-style-type: none"> Efficient. 	<ul style="list-style-type: none"> Visual impact. Needs refilling of water. 	
Forced draft cooling tower	<ul style="list-style-type: none"> Little visual impact. 	<ul style="list-style-type: none"> Less efficient than natural draft cooling tower. Needs refilling of water. 	
Air cooled condenser	<ul style="list-style-type: none"> Useful in places with unavailability of water. 	<ul style="list-style-type: none"> Lowest efficient system. 	

Table 4- Cooling Systems, Source [Curso de Introducción de Técnicas Reunidas]

3- COMBINED CYCLE POWER PLANTS

3.1- General description of a combined cycle

The configuration of a combined cycle is that of a thermodynamic configuration that contains at least two or more power cycles, where different motor fluids are used (one whose working fluid is water vapour and another whose working fluid is a gas, product of combustion or burning). The goal is to find the combination of these two power cycles because it provides a higher yield than we could get from any of them independently. In general, the cycles are composed of a lower cycle and a higher cycle. The higher cycle is considered the first cycle by which heat energy is delivered. The lower cycle is what is called the second process, which operates at a lower temperature and receives the residual heat from the upper cycle.

In order to optimise the use of heat in the upper temperature range and to reduce the harmful impact on the environment, returning the residual heat to the lowest possible temperature, the engine fluid of the configuration is carefully selected of the global process. Normally, a heat exchanger is used to couple the upper and lower cycles.

It is a steam cycle (which contains a steam turbine and carries out a Rankine cycle) and a gas cycle (which contains a gas turbine and carries out a Brayton cycle) combined that compose, generally, a combined cycles. Between the cycles there are certain differences:

Firstly, the gas cycle is a high temperature cycle. Its entrance temperature is between 1100°C and 1200°C, while the temperature at which the heat is released to the environment is 500°C. In this cycle the gases resulting from combustion can either: Be taken advantage of and transmit their energy to the steam cycle (in case of being part of a combined cycle), or be expelled to the outside in which case the cycle is considered an open cycle.

Secondly, the steam cycle is a closed cycle with internal combustion and of a low temperature (the maximum temperature reached is around 550°C, although its heat emission is at room temperature).

From a practical point of view, it would be advantageous to use the residual heat, produced by the combustion process in the gas cycle, to use it in the steam cycle as a source of heat. Here is a diagram of the operation of a combined cycle power plant:

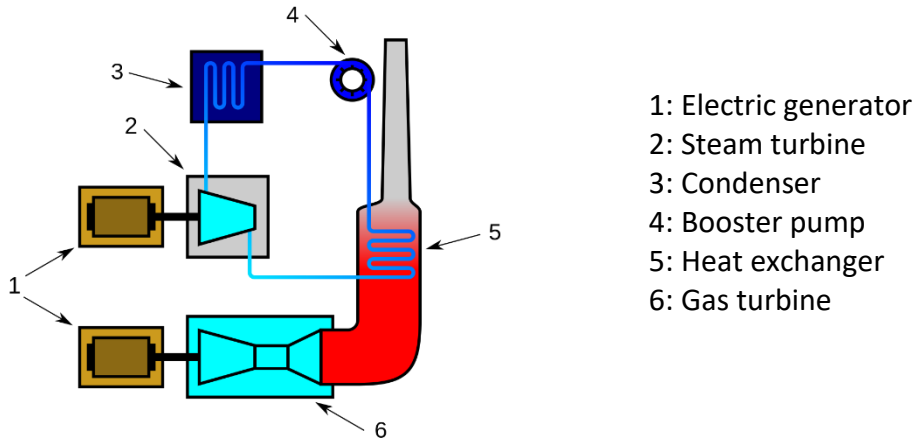


Figure 11-General scheme of a combined cycle, Source [<https://sites.google.com/site/omarinstgn/5-1-turbina-de-gas-de-cycle-obert>]

The combination of the gas cycle with the steam cycle would entail changes in the characteristics of both power cycles. A typical installation of a combined cycle is like the one shown (figure 10), and it consists of:

- Gas turbine
- Heat recovery boiler (HRSG)
- Steam turbine

Many of the components of a combined cycle power plant are common to those used in a conventional thermal power plant. Therefore we will deal with the new elements that appear in the combined cycle, since the rest have already been studied in the previous section.

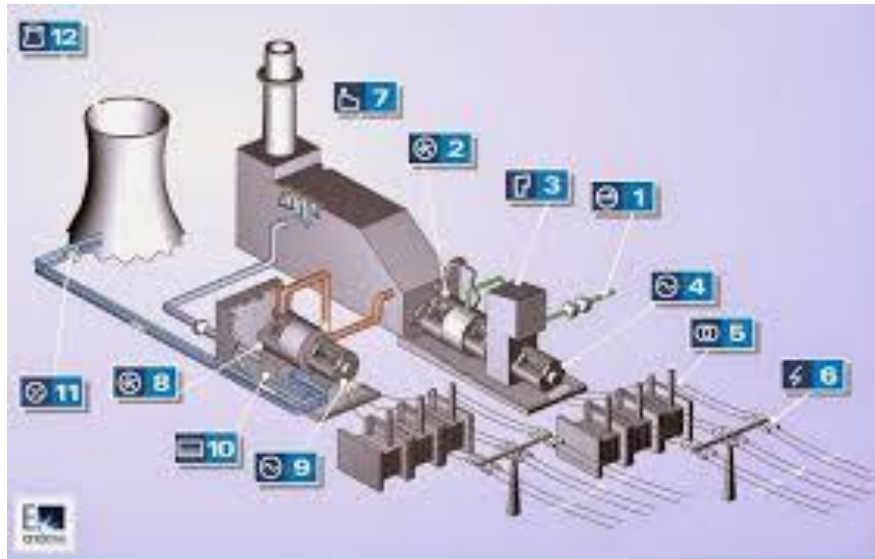


Figure 12- Operation of a combined cycle power plant, Source [https://github.com/KaliNuska/Curso_2015-2017/blob/master/Tecnologia_Industrial/Esquema%20centrales%20convencionales.md]

1. Natural gas is transported to the plant through a gas pipeline and passes through the Regulation and Measurement station. In it, the calorific value (quantity and quality) of the gas entering the plant is measured and, in addition, impurities are removed from the gas. Likewise, the pressure is regulated adapting it to the operation of the Gas Turbine (said pressure is usually between 30atm and 40 atm).
2. Gas turbine. The turbine transforms the enthalpy of the gases into mechanical energy of rotation, activates the air compressor and the alternator. Air is sucked through the compressor that it then introduces into the combustion chamber at high pressure and where the natural gas is combusted. The compressor has a variable number of stages (currently there are normally 18) and they depend on the model of the gas turbine. The ratio of compression of compressors are nowadays normally 16:1.
The gases resulting from this combustion are at high pressure and temperature (between 500 and 600 °C) and they transfer their internal energy to the turbine blades that transmit their rotary motion to the alternator.
3. House of Filters. It contains a series of filter batteries where the air sucked into the compressor is cleaned to remove the unwanted particles it carries
4. Alternator. Its function is to convert the mechanical energy of rotation of the turbine into electrical energy. The conversion is possible since the alternator is coupled to the Gas Turbine and is moved by it.
5. Transformer. Its function is to increase the voltage of the Electric Power generated in the alternator (which is between 6 and 20kV) up to the voltage of the transport network (132.220 or 440kV).

6. Electrical network. The electricity network transports the electricity generated in the power stations to the points of consumption. The networks have a high degree of meshing, as well as interconnections, as in the case of the Spanish Electricity Network with the networks of other countries.
7. Recovery boiler. Here, there is a transmission of energy, by the gas turbine's exhaust gas, to the water that passes through the pipes located in the boiler, transforming it into steam, which will be directed to the steam turbine.
8. Steam turbine. In this component, the internal energy of the steam of the boiler is transformed into mechanical energy of rotation when it moves the blades turning the turbine. This turbine is coupled to an alternator. In this case, unlike a conventional thermal power plant, it operates at lower pressure and, as the work of the heaters is now done in the boiler, it has no extractions.
9. Alternator. Explanation in the section 2.3.4.
10. Condenser. Explanation in the section 2.3.5.
11. Bomb. Explanation in the section 2.3.6.
12. Cooling tower. Explanation in the section 2.3.8.1.

3.2- Thermodynamic cycle

In a combined cycle, the cycles that are coupled are a Rankine steam cycle and a Brayton gas cycle. From the Rankine cycle we have talked before, we need to analyse how the Brayton cycle works. The Brayton cycle is the simplest cycle with which gas turbines work.

The evolution that follows the fluid of the system is shown in diagram h-s (Figure 11) and basically consists of the following stages:

- A compression stage, performed by the compressor, as isentropic as possible.
- A stage of heat input at constant pressure.
- An expansion stage, performed in a turbine, as isentropic as possible.
- A stage of heat transfer at constant pressure.

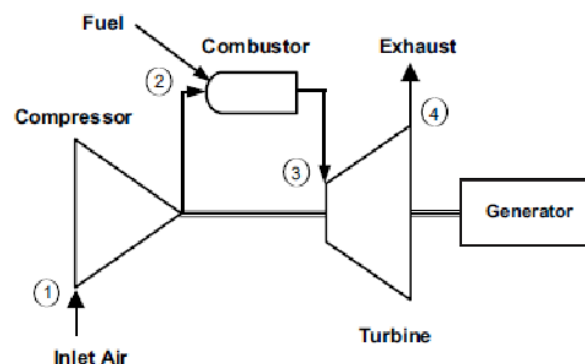


Figure 13-Gas turbine simple cycle, Source [<https://wiringdiagramdefiant.herokuapp.com/post/process-flow-diagram-gas-turbine/>]

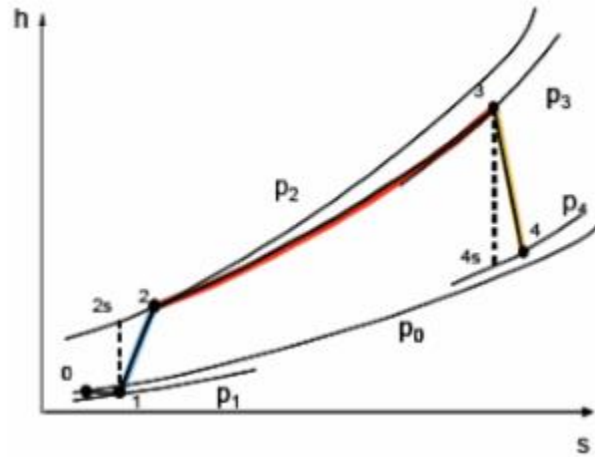


Figure 14-Simple cycle Gas Turbine, h-s diagram, Source [Unión Fenosa Generación]

As it was explained previously, the exhaust gases of the gas turbine of the Brayton cycle, which still contain a large amount of thermal energy, are conducted through a heat exchanger where they give most of their energy to the connected Rankine cycle. Thus, the steam is produced under optimum conditions and is then introduced into the corresponding steam turbine. In this way the exhaust gases coming from the gas turbine are used to give energy in the form of heat to the Rankine cycle with which the steam turbine operates. As a result, this system makes a more efficient use of fuel.

3.3- Components

As mentioned previously, given that conventional thermal plants and combined cycles share most of the same components, in this section we will only describe those new components of a combined cycle that don't form part of a conventional thermal plant.

3.3.1-Gas Turbine

The gas turbine has two missions in a combined cycle:

- Operating an alternator so that it can produce electrical energy. The alternator is coupled to the turbine with a direct connection to its shaft, which normally rotates at a speed of 3000 rpm (50Hz).
- Produce exhaust heat that is then used as heat supplied to the steam cycle.

The turbine allows to transform the enthalpy of the combustion gases, coming from the combustion chamber, by its expansion in mechanical rotation energy. Then, the desired electrical energy is produced when the gas turbine drives the generator. As in the cases

of combined cycle, it is sought to bring the exhaust gases to a heat recovery in order to obtain an additional production of electricity.

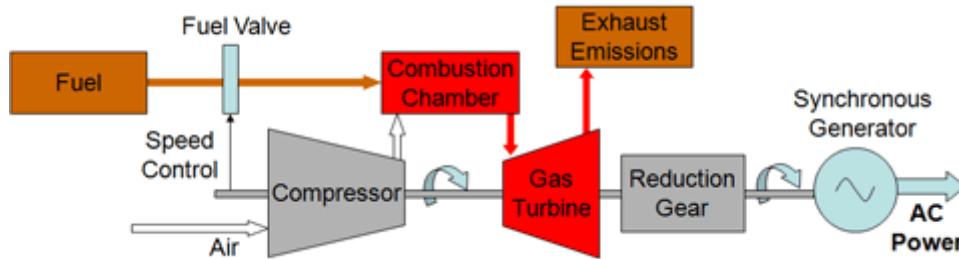


Figure 15- Gas Turbine configuration, Source [<https://finditword.wordpress.com/2015/12/04/power-stations/>]

The most important component in the gas cycle is the Gas Turbine, which consists of a compressor, a combustion chamber and a turbine.

The simple process of gas turbines is as follows:

1. **Air compression.** The air enters the compressor where it undergoes a compression process prior to the contribution of the thermal state, which will increase the thermal performance of the cycle. In this stage, the air pressure is increased.
2. **Combustion in the combustion chamber.** Once compressed, the air enters the combustion chamber, where fuel is continuously supplied. The combustion reaction is performed by a spark plug that is removed as soon as the process is self-maintained.
3. **Expansion of exhaust gases.** The exhaust gases from the combustion process come out at high temperature and enter the turbine. Within it, they undergo a process of expansion, causing mechanical energy in the axis of the turbine. It should be noted that part of this mechanical energy is used to drive, also, the compressor (usually represents more than 50% of the work generated). The rest is the mechanical work that can be used in the gas turbine.
4. **Expulsion of gases.** These gases are taken to a recovery boiler where they are used in a steam cycle.

There are two types of configurations to choose from: the one-axis or the two-axis. The assembly of an axis is so named because the compressor and the turbine are connected to the same axis. This configuration is usually used in cases where the turbine must operate under fixed conditions of speed and load, as it happens, for example, in the peak plants.

In the following figure, the assembly of a double-axis gas turbine is shown:

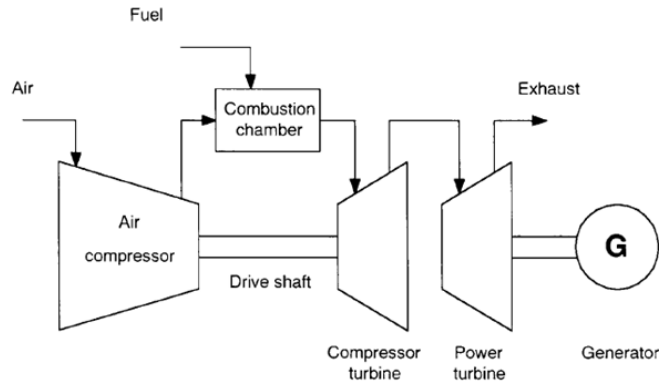
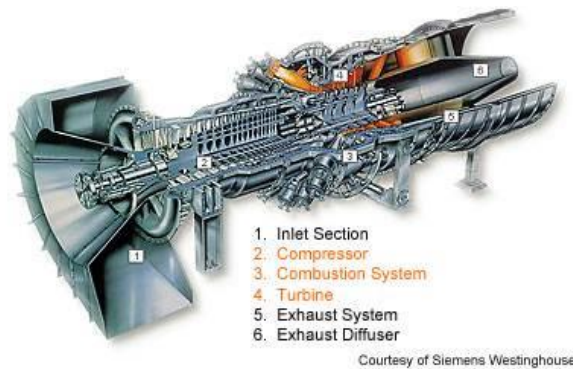


Figure 2.4 Two-shaft gas turbine.

Figure 16- Gas Turbine double axis configuration, Source [<https://www.green-mechanic.com/2017/07/what-is-single-shaft-turbine-and-double.html>]

For these cases, a greater importance is given to the flexibility of operation (case for automotive, rail, etc.). In these assemblies there are two turbines with different functions. The turbine connected to the compressor by a single axis, develops the power necessary for its operation, while the other turbine is the one that provides the useful power of the gas turbine.

The gas generator is the assembly that includes the compressor, the combustion chamber and the turbine in mono axis with the compressor. The second turbine is the power turbine. This system, being a mechanically independent gas generator, is more interesting than the single axis at the level of flexibility and, in addition, it provides a greater performance against load variations.



Courtesy of Siemens Westinghouse

Figure 17-Principal components of a Gas Turbine, Source [<https://www.energy.gov/fe/how-gas-turbine-power-plants-work>]

3.3.1.1- Turbine

In the stages of the turbine the transformation of the thermal energy of the gases into mechanical rotation energy of the shaft takes place.

Each stage of the turbine is made of a crown of fixed paddles mounted on the stator and a crown of moving paddles mounted on the rotor. As the vapour passes through the fixed paddles, the fluid accelerates (thanks to a narrowing of the available passage area) while there's also a decrease in the static pressure. Subsequently, as it passes through the mobile paddles, the fluid gives part of its moving motion, thus producing useful mechanical work.

In this way, the direction of the flow always goes in the favourable direction of the pressure gradient, being a more stable process than the diffusion of the flow that takes place in the stages of the compressor. Therefore, the jump of pressures in the stages of the turbine can be higher without losses in efficiency, allowing fewer stages in the turbine.

A critical aspect in the performance of the gas turbine is the temperature of the inlet gases. Investigations of materials and configurations have been carried out to raise the intake temperature to the turbine without damaging the structure of the materials. One approach in terms of design has been the cooling of the turbine blades, for which three groups have been designed: cooling by air, by steam or by liquid.

The investigations of liquid refrigeration have not been very successful, not even in its variant of natural or forced circulation. We run into the impossibility of eliminating corrosion because of the difficulty of channelling the coolant inside the paddles.

Air cooling systems have turned out to be more positive. The temperature of the paddle can be reduced by 200-300°C using a small percentage of the total air flow through the compressor. These values allow the temperature of the blades to increase to almost 1500°C. One of the procedures used is the cooling by transpiration, in which the air circulation is mounted at high pressure through the inside of the blade and through some orifices made on the external faces of the same, thus achieving a double effect: cooling of the paddle wall uniformly and the formation of a protective film that protects the outer surface of the hot gas stream, thus reducing heat transfer to the paddle.

An alternative solution for the cooling of the blades was introduced by General Electric in the H series of turbines, which consists of a closed circuit of steam cooling that is obtained from the recovery boiler. This eliminates the derivation of part of the air from the compressor through the blades of the turbine, increasing the performance of the combined cycle.

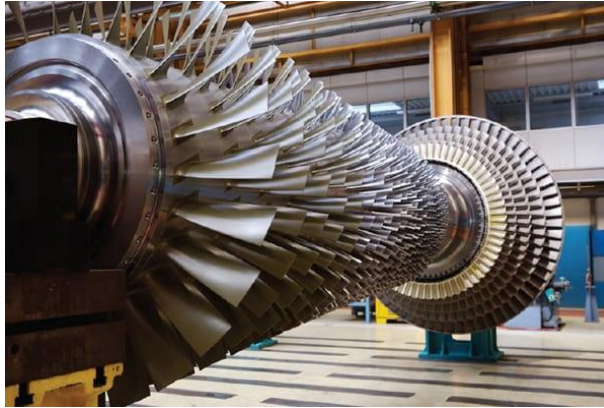


Figure 18-Gas Turbine, Source [<http://wallsviews.co/ge-gas-turbine-spare-parts/>]

3.3.1.2- Compressor

The purpose of the compressor is to increase the pressure of the air received from the air intake system. The inlet air, once it is dry and clean, is brought to the compressor, where it is compressed by the succession of mobile and fixed paddles (also known as the compressor stage). The air accelerates through the rotating paddle crown and then decelerates in the fixed paddle crown, so that the kinetic energy received in the rotor is transformed into static pressure. This procedure is repeated as many times as necessary until the desired compression ratio is reached (in other words, until the desired pressure increase is achieved).

In this path, the air flow always passes through an adverse pressure gradient and the more complex the design of the compressor is, the higher the desired compression ratio must be. The process is based on a series of diffusions in the rotor paddles and in the stator paddles. As there is a decrease in the relative speed (although the absolute speed in the rotor increases) there is also diffusion in the crown of mobile paddles.

To avoid irreversibility's, the variation of area must be limited during the diffusion of the fluid through its passage through the paddles. This implies that the pressure increase that can be achieved in one stage of the compressor is limited to a value much lower than the expansion ratio that can be achieved in a turbine stage (the compression ratio depends on the manufacturer, but is generally between 12 and 25 bar). For this reason, a single turbine stepping has enough power to move several stages of the compressor, and that is why the turbo-groups of the compressor have several stages much higher than those of the turbine.



Figure 19- MS9001FB Turbine, Source [<http://docplayer.net/65195738-Ge-energy-gas-turbine-and-combined-cycle-products.html>]

The compressors usually have a row of regulating vanes at the entrance (inlet guide vanes: IGV's) that regulate the inlet flow to improve the performance of the system when it does not operate in the nominal condition, and thus, limits the air flow when the rotation speed is less than the nominal.

The compressors have a considerable variation of the size of the blades in the part of admission and discharge of the air, especially when the compression ratio is high, since when compressing, the density is increased. When the compressor operates at loads different from the nominal one, it is possible that in the last stages there will be reflows. To avoid this, blow-off valves can be used from a control system to eliminate excess air flow.

3.3.1.3- Combustion chamber

The combustion chamber is place where the chemical reaction between the fuel and the oxidiser takes place.

Since that in the working conditions of a gas turbine, and especially when the fuel is natural gas, the combustion is practically complete, the energy supplied by the fuel will almost coincide with the lower calorific value of the same.

The design of this element is more difficult than the rest of equipment and components due to its difficulty to make a theoretical treatment of them. That is why the development of computational calculation systems for fluid dynamics has been a breakthrough in this matter since, before, it was done through experimental methods of trial and error.

The combustion in a gas turbine is a continuous process in which the fuel is burned, at constant pressure, with the air provided by the compressor. The combustion reaction is self-sustaining, and an ignition source, like a spark plug, is required to start the reaction.

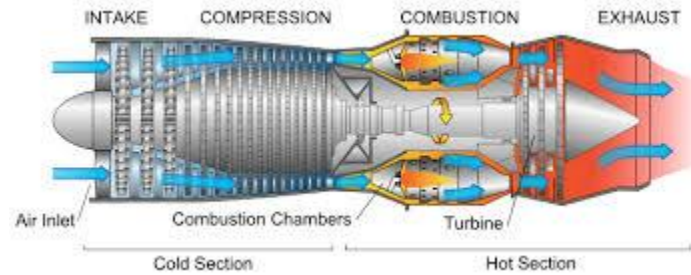


Figure 20-Combustion chamber of a gas turbine, Source [<https://www.pinterest.fr/pin/24277285469731789/>]

The combustion chambers are formed by two "layers":

- Flame tube. It is the internal envelope whose mission is to withstand high temperatures. It is in this volume where combustion occurs.
- Pressure envelope, whose mission is to act as a pressure barrier. It is the external envelope.

3.3.2- Heat Recovery Steam Generator (HRSG)

The heat recovery boiler is the main link between the gas cycle and the steam cycle

A typical heat recovery boiler is the one shown in the following image:



Figure 21- Heat Recovery Boiler, Source [Unión Fenosa Generación]

The designs of the recovery boilers have been evolving. Depending on the use, from a single level of pressure, to more complex systems with three levels of pressure with: reheating zones, burning of supplementary fuel, NO_x control equipment and condensation preheating to recover the maximum possible heat of the escape gas. The boiler could also supply the process steam at an intermediate pressure to a transformer or chemical plant.

At the outlet of the gas turbine, the exhaust gases have a temperature high enough to be used to generate steam in the heat recovery boiler HRSG (Heat Recovery Steam Generator). The transmission of heat that takes place is the convection, differing from a conventional boiler in which the radiation has a very important weight.

It is possible to maximise the performance of the assembly (gas turbine and recovery boiler) due to the optimal exhaust temperature of the gases.

The optimal design of a boiler must meet the following requirements:

- The heat transfer rate must be high.

- The pressure drops in the recovery boiler must be very small to avoid losses of power and performance in the gas turbine.
- Low temperatures of the combustion gases must be avoided to prevent them from reaching the spray temperature and causing corrosion.
- High pressure variations should be allowed during starts.

As the only mechanism of heat transmission in the boiler is convection, it is difficult to meet the first two points. For the first point to be met, it is necessary that the gases circulate at high speeds so that the heat transfer coefficient is high enough, which would lead to high load losses and, on the contrary, to the breach of the second requirement. The only way to meet both requirements simultaneously is by having boilers whose tubes have a small diameter.

3.4- Configurations of a combined cycle

There are many different configurations for a Combined Cycle Gas Turbine (CCGT) power plant. Typically, each gas turbine (GT) is associated with a particular HRSG, and multiple HRSGs supply steam to one or more steam turbines. For instance, at a plant in a 2x1 configuration, two GT/HRSG trains supply to one steam turbine; there can also be 1x1, 3x1 or 4x1 arrangements. The steam turbine is adapted to the number and capacity of supplying GTs/HRSGs.

3.4.1- Main configurations

SS configuration

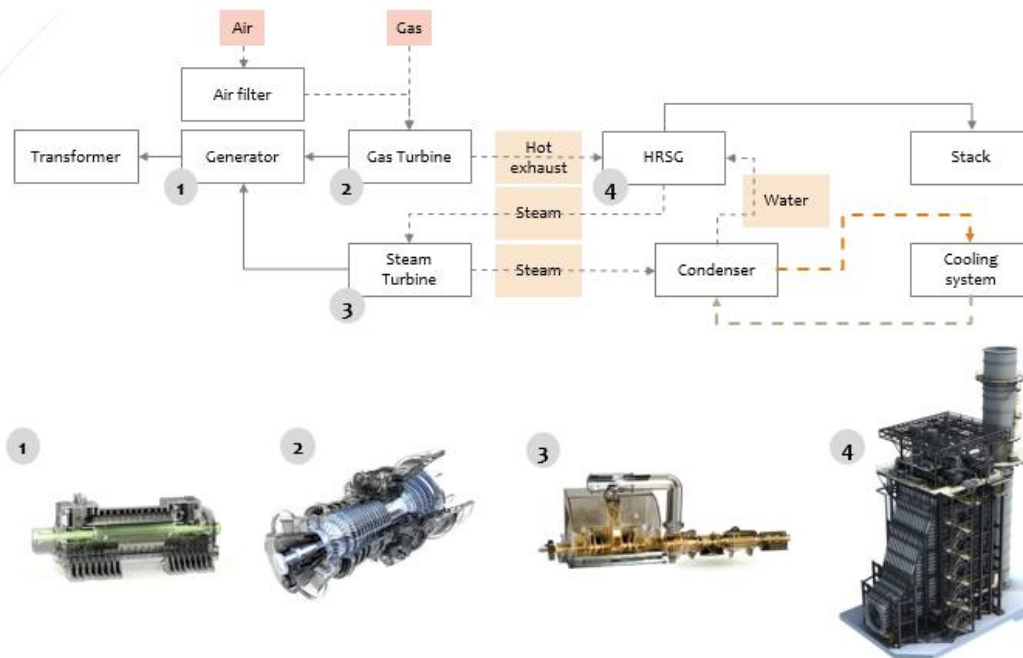


Figure 22 – SS configuration, Source [Curso de introducción de Técnicas Reunidas]

In this configuration, there is only one gas turbine, one boiler and one steam turbine. The steam turbine and the gas turbine are connected on a single axis to a single generator that produces the electrical energy that is exported to the grid.

Advantage

-Presents very compact solutions for the power we can obtain.

Disadvantages

-Flexibility. If you have the gas turbine running, you should also have the steam turbine in operation, so the operating ranges of this type of plants are not as wide as in other cases.

1X1 CONFIGURATION

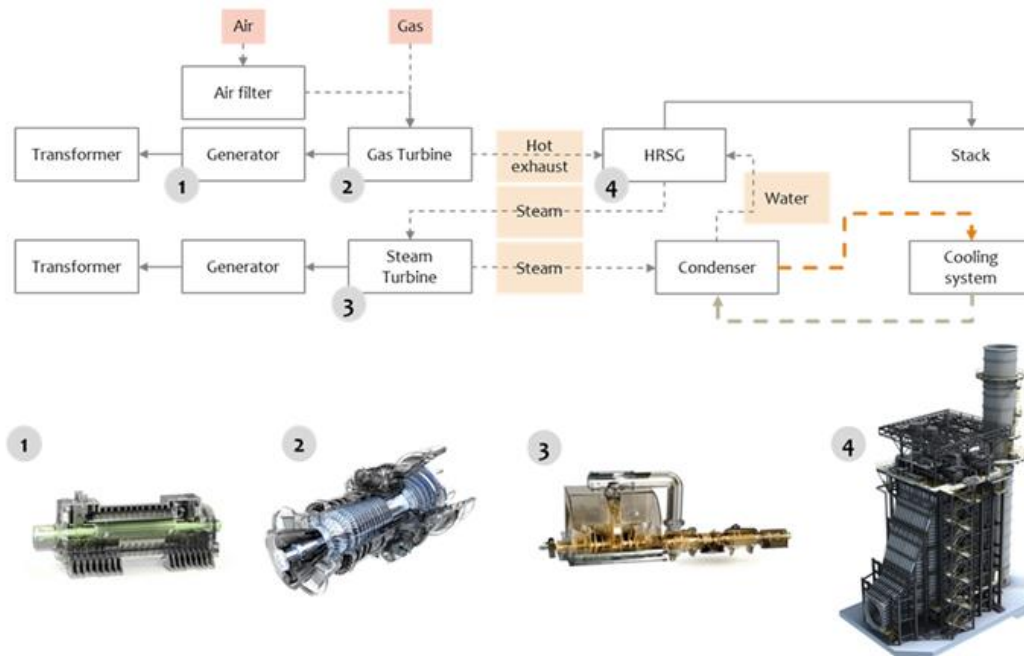


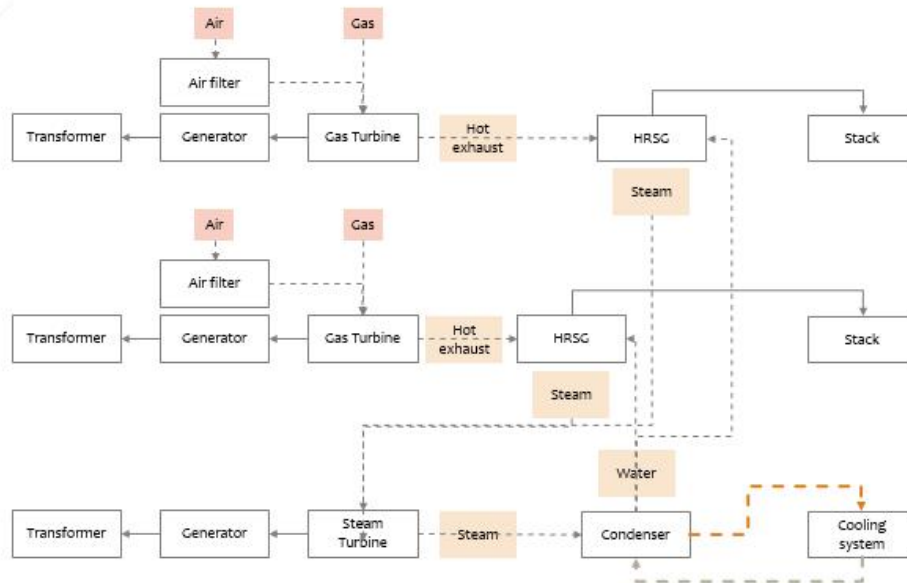
Figure 23– SS with clutch, Source [Curso de introducción de Técnicas Reunidas]

As in the SS, there is only one gas turbine, one boiler and one steam turbine. Unlike the SS, they are not coupled to the same axis and do not use the same generator. Each has its own independent generator. This gives the flexibility to use the cycle as an open cycle only with the production of the gas turbine, but having to put two generators, the investment cost is higher than in the SS as a consequence.

Considering the 1x1 single shaft configuration, we have two possible solutions to arrange the alternator:

1. **Alternator in the centre:** If the steam turbine remains at one end of the shaft, it is possible to uncouple it during start-up and shutdown of the plant. For this to occur, a complex clutch is required.
2. **Alternator at the end:** In this case the steam turbine cannot be uncoupled, because it is between the gas turbine and the alternator, so an auxiliary boiler would be needed so as not to turn the steam turbine in vacuum.

2X1 CONFIGURATION



Basadas en 2 GT



Figure 24 – 2x1 configuration, Source [Curso de introducción de Técnicas Reunidas]

In this configuration we have two gas turbines coupled to two boilers that send the steam produced to a single steam turbine.

Advantage

-Great flexibility and a very high power operation range since we can work with a single gas turbine, with 2 gas turbines, with only one gas turbine and its steam production to the steam turbine or, in the case of maximum power output, with two gas turbines sending steam to the steam turbine.

3X1 CONFIGURATION

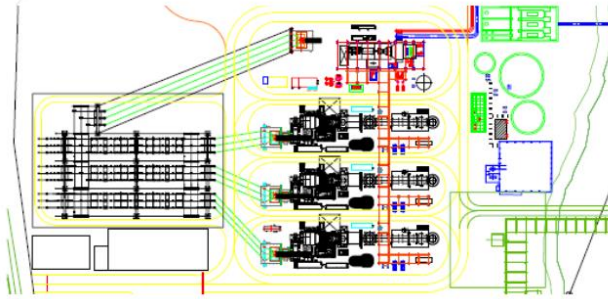


Figure 25 – 3x1 configuration, Source [Curso de introducción de Técnicas Reunidas]

They give us the maximum flexibility and can be used well: Very large gas turbines to achieve very high powers with this configuration or very small gas turbines that give greater flexibility. In any case, in this configuration, we will have three gas turbines with three boilers that produce a steam that is sent to a single steam turbine.

3x1 + planta LNG

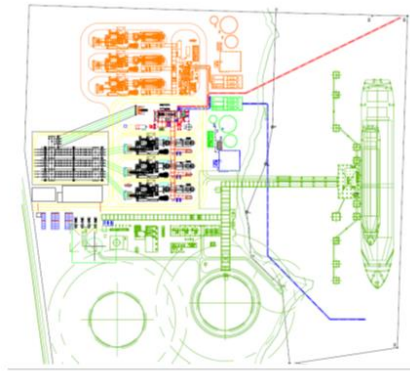


Figure 26- 3x1 + planta LNG, Source [Curso de introducción de Técnicas Reunidas]

It is not very usual, but it is interesting in the face of maximum energy efficiency and facing the interests Técnicas Reunidas, since it works in both fields.

We have a conventional 3x1 but the heat that comes from the condensation of the exhaust steam from the turbine is used for the gasification of the LNG stored in the tanks, with which the efficiency of both plants, working together both the regasification plant and the cogeneration, is as high as it can be.

4X1



Figure 27 – 4x1 configuration, Source [Curso de introducción de Técnicas Reunidas]

In this configuration, there are four gas turbines and four boilers that generate steam for a single steam turbine. Maximum flexibility or high power can be achieved as a function of the individual power of each of the gas turbines.

5X2

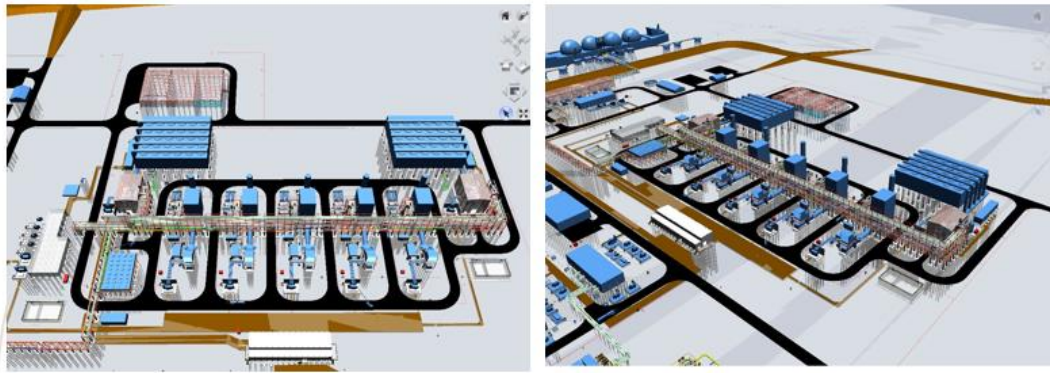


Figure 28 – 5x2 configuration, Source [Curso de introducción de Técnicas Reunidas]

They are not very common in the world of energy, but depending on the needs of the customer or the plant to be fed, the number of gas turbines and steam turbines can be combined, trying to achieve maximum flexibility and maximum production that are requested.

3.4.2- Configuration 1x1 Single-Shaft vs Multi-Shaft

Single-Shaft (SS) denotes where the gas turbine and steam turbine share one generator and are connected on one shaft. Multi-shaft (MS) refers where the gas turbine(s) and generator(s) are separate from the steam turbine and its generator. 1x1 denotes that there is one gas turbine supplying steam energy to one steam turbine.

To generate power and most cogeneration applications, single shaft is the lowest cost integrated solution when compared to a 1x1 Multi-shaft configuration.

If we consider the case of a power plant that produces an output power of around 400 MW, the most convenient option is a 1x1 configuration because, in case of other configurations, smaller gas turbines with worse performance should be used.

If we take into consideration the concept of cost associated with the SS of the previous section, as an insight, the primary driver to lower cost of the SS with respect to a MS is the need to purchase and install one less generator, associated electrical bus, step up transformer, high yard connection, power train foundation and building.

In a more precise manner, the SS configuration has a lower generation cost associated for the following reasons in particular:

- By having common equipment (alternator, main transformer, lubrication of turbines, etc.), there is a lower cost per kW installed.
- It has better performance in the transformation of mechanical energy to electrical energy which leads to a lower cost of fuel per kWh generated.
- The operating and maintenance cost per kWh generated is similar in both configurations.

However, it is worth noting that a MS configuration also has certain advantages with respect to an SS configuration: An SS occupies more space physically speaking, which may entail vibration problems and require the design of very complex closures; MS configurations have more operation flexibility; the MS configuration can be started to function in two phases so that, over a period of 12 months, if needed, the gas turbine can be available in an open cycle.

In addition, it must be stated that given certain circumstances, certain plant requirements and constraints may result as an impediment to support the application of a SS solution. In some cases, certain impediments can be that plant output and peak output demands exceed SS capabilities.

In conclusion, considering the advantages and the drawbacks, the safest and most economic option is the SS.

3.4.3- Configuration 1x1 vs Configuration 2x1

A case of comparison between these two configurations with the same power (of around 900MW). For this, a 2x1 will be compared with two 1x1 units.

In this case, the 2x1 configuration entails a lower generation cost given that:

- Configuration elements of a 2x1 are less expensive than the configurations of a 1x1 hence there's a lower cost per kW.
- The cost of maintenance and use per kWh generated is lower.

In favour of the 1x1 configuration: its construction and commissioning time is more malleable, has a slightly higher availability and it's also worth noting that the cost of fuel per kWh is the same for both configurations.

3.4.4- Configuration costs

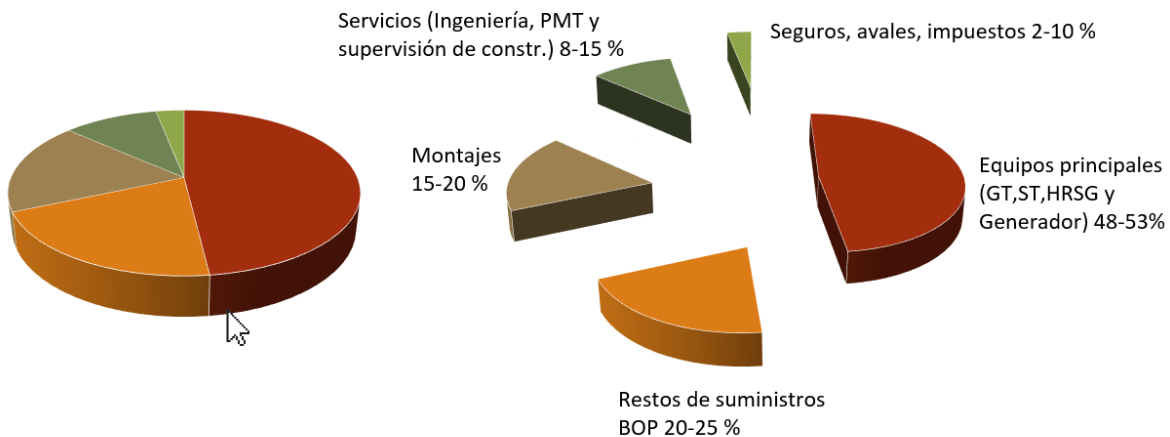


Figure 29 – Configuration costs, Source [Curso de Introducción de Técnicas Reunidas]

In terms of costs, we can break down the combined cycle projects in the items shown above. Considering these levels as a reference, which can vary depending on the location, chosen configuration, etc. Thus, we can say that the cost of the “main equipment” (red) together with the cost of the other block of “supplies remains” (orange) are the most important factors to consider when approximating the cost and price factor of the combined cycle plant.

3.5- Combined Cycle vs Classic Thermal Power Plant

The advantages of combined cycles compared to classic thermal power plants are the following:

1. **Better energy efficiency.** In net values, expressed as a percentage with respect to the LHV, the combined cycles have between 55% and 60% while the classic thermal power plants have between 35% and 40%.
2. **Lower atmospheric emissions.** Especially CO₂, reduces from 850 g per kWh of the classic thermal power plants to 350 g.

3. **Lower water consumption.** It has less need for refrigeration than that of a thermal power plant. For a 350 MW power plant, the water consumption of a combined cycle is $381 \frac{m^3}{h}$ compared to $766 \frac{m^3}{h}$ for conventional thermals.
4. **Low specific investment cost.** For each kWh the cost of a combined cycle is around 450€ and 600€ when the cost of thermal power plants exceeds 1000€, which is largely due to its low installation cost. The equipment of the thermal power plant is usually modular equipment that is pre-installed in the factory (so the construction time is short). For the rest of the equipment (such as the gas turbine or the steam turbine), since only its interconnection is necessary, they are transported directly to the assembly site. All in all, the equipment is more expensive, but the final cost is lower.
5. **High degree of automation.** This reduces the fixed cost of operation. Compared to the 5€ per kW per year of the combined cycles, the classic thermal power plants have an approximate cost of 30€ per kW per year.
6. **High flexibility and availability of operation.** In a combined cycle thermal plant, the load variations are fast, and, in addition, you can operate both base load and partial load. Moreover, boot times are very short, being able to boot frequently.
7. **Location closer to consumption.** It has a greater degree of modularization and low space requirement. Considering the construction of a 400MW power plant, in the case of a combined cycle, it would only need a land of $100000m^2$ for its construction, while a classic thermal power plant would need $260000m^2$.

4- PLANT DESIGN

4.1- Existing thermal power station (characteristics of group G1)

The Thermal Power Plant Litoral de Almería is located beside of the sea, in the municipality of Carboneras and is owned by Endesa. It uses coal as fuel.

The plant is composed of two groups, the G1 group was put into service in 1985 and the G2 group was put into service in 1997.

This project studies the existing group G1, whose main characteristics are the following.

Source [https://es.wikipedia.org/wiki/Central_t%C3%A9rmica_Litoral_de_Almer%C3%ADa]

General

	Group 1
Type of group	Coal
Power per group (MW)	576.9
Year commissioned	1985
Fuel	Import coal

Mill

	Group 1
Capacity (t/h)	53
Manufacturer	Combustion Engineering
Number	6
Power (kW)	500

Boiler

	Group 1
Type of boiler	Tangential fires
Manufacturer	Combustion Engineering
Steam drum height (m)	66.34
Main steam flow (t/h)	1,679
Reheated steam capacity (t/h)	1,525

Initial vapour pressure (bar)	176
Reheated steam pressure (bar)	41
Feeding water temperature (°C)	253
Initial steam temperature (°C)	541
Hot reheated steam temperature (°C)	541
Cold reheated steam temperature (°C)	338
Boiler situation	Outdoor
Performance (%)	89.42

Filters

	Group 1
Electrostatic filters	2 units, 4 fields, 5 zonas
Characteristics by groups	20 electric fields
Gas flow (m³/h)	1,574,608
Performance (%)	99.83

Condenser

	Group 1
Type of condenser	Dual pressure
Coolant fluid and origin	Sea water in open circuit
Thermal jump (°C)	5
Exchange surface (m²)	28,743
Flow (m³/h)	59,530
Pressure in condenser (mbar)	38.10

Steam Turbine

	Group 1
Manufacturer	Bazán/G.E.E.
Maximum Power (MW)	577
Number of bodies	4
Number of extractions	7
Pressure in the condenser (mbar)	38.10
Speed of regime (r.p.m.)	3000

Alternator

	Group 1
Manufacturer	General Electric
Number of poles, rpm	2 poles, 3000 rpm
Power (MVA)	636
Terminal voltage (kV)	20
Power Factor	0.9
Nominal intensity of the stator (A)	18,360
Stator cooling	Hydrogen
Frequency (Hz)	50
Type of excitement	Alternator-Alterrex

Network connection transformers

	Group 1
Number and Type of transformer	3 single-phase core-type transformers
Manufacturer	Westinghouse
Unitary power (MVA)	209.5
Total power (MVA)	628.5
Transformation relation	400/20 kV
Load regulation	Yes

Group G1 of the Power Plant has a maximum power of 577 MW.

For the evacuation of the energy produced by the power plant, there is a 20/400 kV substation connected to the national network of REE (Red Eléctrica de España).

4.1.1- Location and environmental conditions

The municipality of Carboneras, in the province of Almería, has the following average atmospheric conditions:

- Ambient Temperature: 21 °C
- Atmospheric Pressure: 1.022 mbar (a)
- Relative Humidity: 53%

The geographical characteristics of Carboneras are the following:

- Latitude: 36° 59 '50' 'N
- Length: 1° 53 '36' 'O
- Altitude above sea level: 6 m

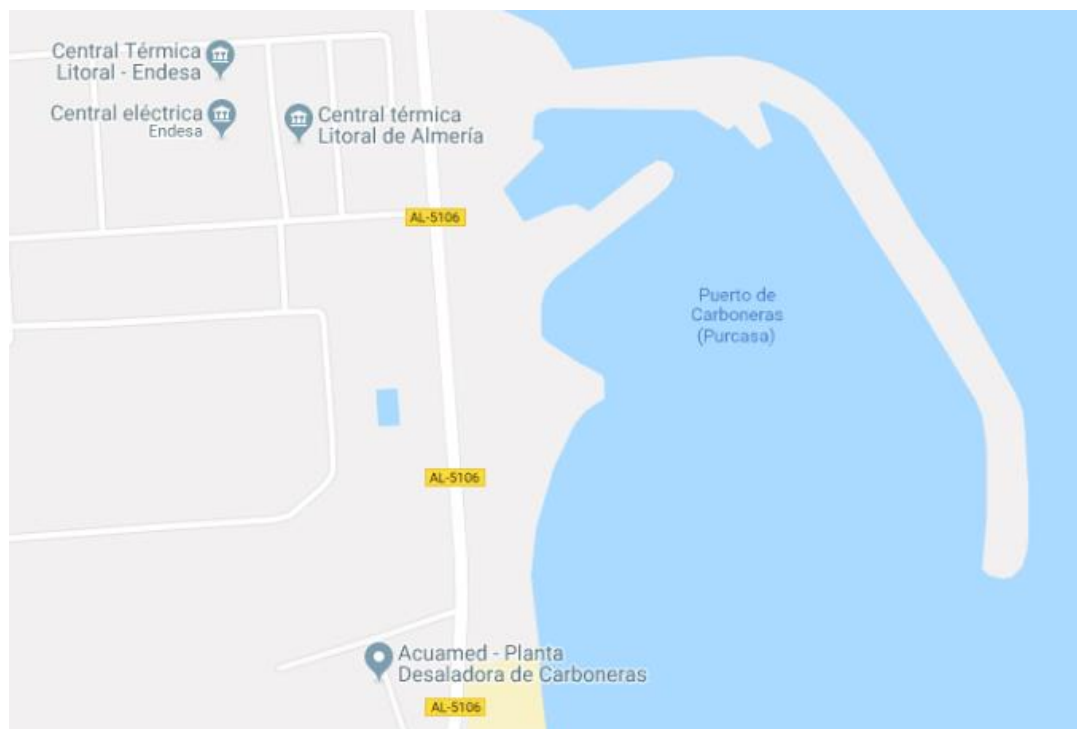


Figure 29- Litoral de Almería (Carboneras), Source [Google Maps]

You can access the Litoral de Almería Thermal Power Plant on the AL-5106 road from Agua Amarga (TM Níjar).

4.1.2- Group G1 steam turbine and thermodynamic cycle

The steam turbine of the G1 of the thermal power plant corresponds to the Rankine cycle, with extractions, of four bodies, with reheating, condensation, multistage, horizontal axis and axial steam flow.

The steam turbine of the G1 has 577 MW of rated power on the plate and rotates at 3.000 r.p.m.

The nominal conditions of the main steam at the inlet are 176 bar at 541°C. The discharge pressure is 38 mm Hg abs. The turbine is formed by four bodies; one of high, one of medium and two of low pressure, being these last two of double flow and discharge to its corresponding section of condenser by the inferior part.

The steam leaves the high-pressure section and returns to the boiler to be reheated. The thermodynamic cycle approximated in diagram T (absolute temperature) - S (entropy) is the one represented in the following figure:

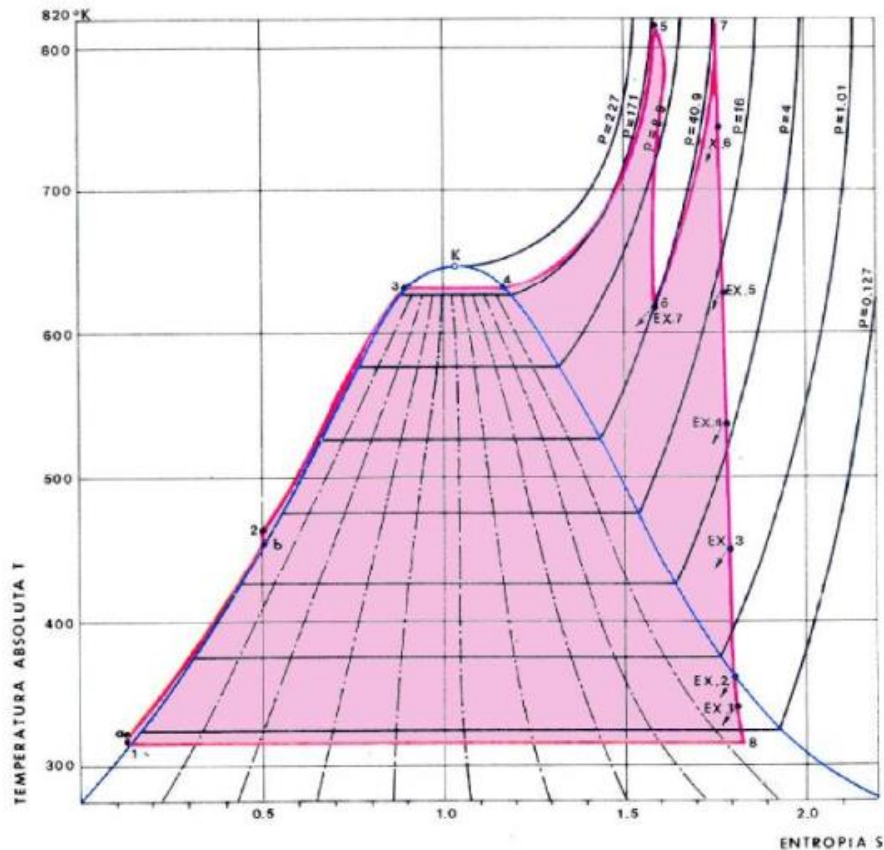


Figure 30 – Approximate T-S diagram of the thermodynamic cycle, Source [Unión Fenosa Generación]

4.1.3- Group G1 alternator and network connection transformers

The existing G1 Group steam turbine alternator is from General Electric, up to 636 MVA nominal apparent power and has 2 poles. The nominal generation voltage is 20 kV and 50 Hz frequency. The cooling of the stator is carried out by hydrogen.

The Group G1 alternator is connected to the Network through three single-phase core-type transformers manufactured by Westinghouse, of 209.5 MVA each. The apparent total power of these three single-phase transformers is 628.5 MVA.

The cooling of the three single-phase transformers is done with forced circulation of oil and air (OFAF, Oil Forced Air Forced).

These three single phase transformers are connected in delta on the alternator side through copper bus ducts. The EHV (extremely high voltage) windings are connected to the grid substation in a star with the neutral grounded.

4.1.4- Condenser and auxiliary pumps

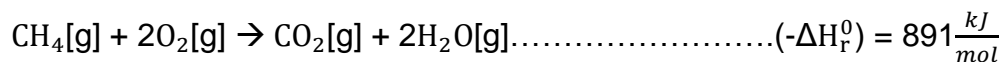
To produce the condensation of steam that comes out completely expanded from the steam turbine from the low-pressure section, seawater steam (open cycle) is used as a cold focus of the steam cycle by means of sea water pumps. The thermal jump is 5°C.

The pressure in the condenser is 38.10 mmHg. The incondensable gases are extracted by vacuum pumps and sent to the atmosphere.

There is also a condensate pump that carries the flow of water through the preheaters, passing through the deaerator, to a pump responsible for pushing the water to the boiler.

4.2- Natural Gas Metering Station

The main component of natural gas is methane. Its combustion is an exothermic reaction with oxygen that results in CO₂ in the liquid state (due to the high temperatures that occur during the reaction, evaporates) and energy. This is the reaction:



For our project, a new Natural Gas Metering Station will be considered for the supply of the Gas Turbine.

A study has been done to make a branch connection from the already existing gas pipeline Almería-Lorca-Chinchilla to the Thermal Power Plant Litoral de Almería (Carboneras).

The data corresponding to the existing gas pipeline Almería-Lorca-Chinchilla are taken from Enagas website and are the following:

Gas pipeline	Stretch	Start date	Diameter	Pressure	Length (km)
Almería - Lorca - Chinchilla	Almería-Lorca	2009	42	80 bar	127,45
	Connection Lorca	2009	20"	80 bar	40,21
	Lorca-Chinchilla	2009	42"	80 bar	168,03

Table 4- Natural Gas Pipeline Almería-Lorca-Chinchilla, Source [https://www.medgaz.com/medgaz/pages/nota_prensa_29-eng.htm]

This gas pipeline is connected to the Medgaz submarine gas pipeline, coming from Algeria, which was commissioned in 2011 and which has a capacity of 8 bcm of Natural Gas per year.



Source [<https://es.wikipedia.org/wiki/Medgaz>]

Technical data Medgaz pipeline:

- Capacity: 8 bcm/year (8 billion m³/year).
- Length: 210 kilometers (between Beni Saf and Almería).
- Diameter: 24 inches (610 millimetres).
- Maximum water depth: 2.160 meters.
- Ground facilities:
 - Compression station (Algeria)
 - Reception Terminal (Almería, Perdigal beach).

The Natural gas Metering Station shall include the following elements:

- Natural Gas pipeline: A 24" steel pipeline to supply Gas to the Gas Turbine.
- Emergency shutdown valves.
- Pig receiver.
- Nitrogen bottles rack.

- Flowmeters, pressure and temperature indicators and transmitters.
- Analyser shelter.
- Water Supply pipe: A 28" GRP (Glass reinforced plastic) pipeline is estimated.
- Water Return pipe: A 24" GRP (Glass reinforced plastic) pipeline is estimated

The following images show the projected Metering Station:

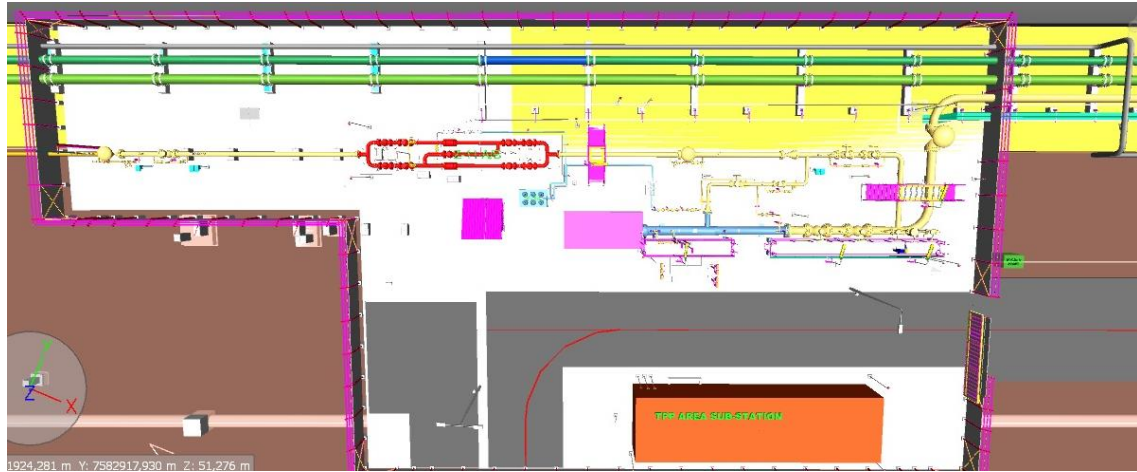


Figure 31- Aerial view of the Metering Station, Source [Internal design]



Figure 32- Side view of the Metering Station, Source [Internal design]

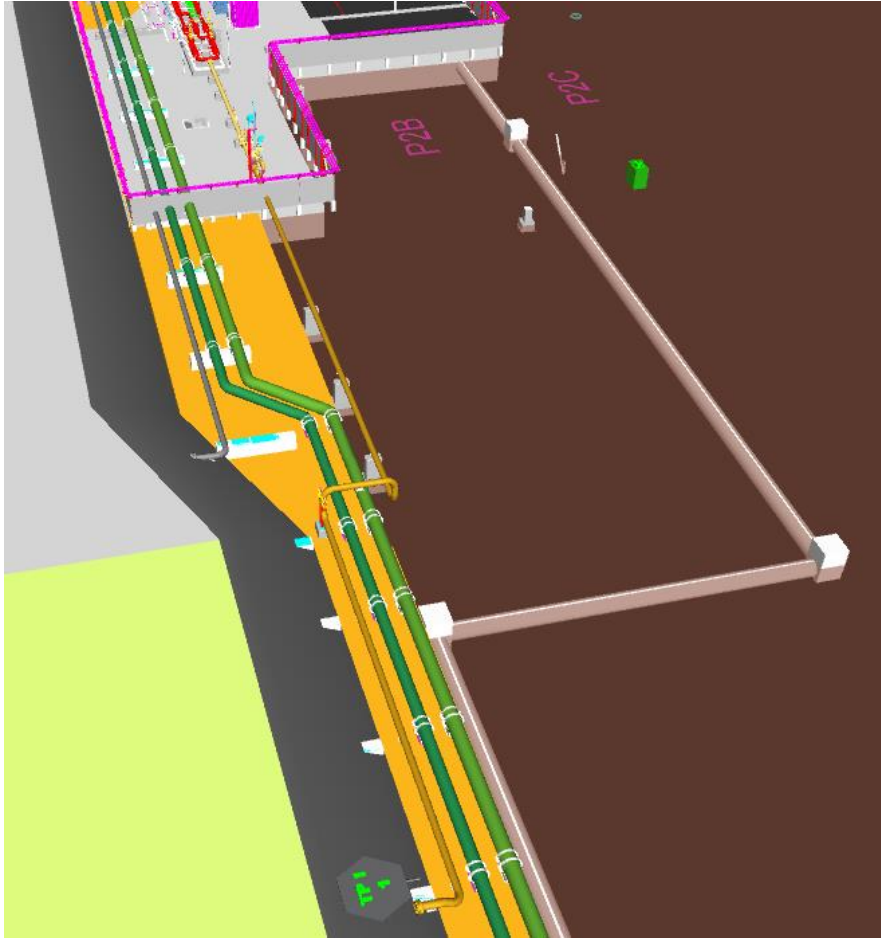


Figure 33- Natural Gas delivery, Source [Internal design]

4.3- Description of the proposed Combined Cycle

The proposed combined cycle consists mainly of a gas turbine, a steam turbine, a self-synchronising clutch, an electrical generator, and a HRSG.

Both the turbines and the generator are coupled in a Single Shaft configuration with the electrical generator in between.

An official Heat and Mass Balance was done with the use of the Thermoflow program. In order to use the program, certain parameters of the cycle had to be introduced, which were the following:

- **The atmospheric temperature** at which the air was going to be sucked in through the inlet filter.
- **The composition of the Natural Gas** supply.
- **The inlet temperature of the exhaust gas into the HP body of the steam turbine.** This temperature is normally about 30°C less than the inlet temperature of the exhaust gas into the HRSG. It is also possible to introduce the inlet pressure instead of the inlet temperature. As a matter of fact, it is very convenient to have the highest inlet temperature

(or pressure) as possible because in this way it is possible to increase the power plant's performance to its maximum ability, this can be seen with the Carnot efficiency:

$$\eta(\%) = 1 - \frac{T_{\text{Cold}}}{T_{\text{Hot}}} * 100\%$$

However, a balance must be made between the maximum inlet temperature (i.e. T_{Hot}) and the cost associated. It is also worth noticing that rather only the inlet temperature to the IP body can be introduced instead of the inlet temperature of the HP body given that both bodies are made of the same material.

- **The outlet pressure of the LP body of the turbine.** It is intended to leave this pressure as close as possible to the vacuum point to ensure the maximum expansion of the steam. This variable is dependent on the power of the ST (Steam Turbine) as well as on the size of the condenser. According to the following equation:

$$Q = \text{LMTD} * (U * A)$$

- $\text{LMTD} = \frac{\Delta T_A - \Delta T_B}{\ln(\frac{\Delta T_A}{\Delta T_B})}$. Logarithmic mean temperature difference. The detailed study of the temperature profile of any of the fluid currents in the exchanger shows a logarithmic evolution. It is used to determine the force that drives heat transfer in flow systems. ΔT_A and ΔT_B represent the temperature difference of the condensate and of the cold fluid that enter and leave the condenser. ΔT_B is maintained fixed (25°C - 15°C). ΔT_A will be zero because the steam that enters the condenser undergoes a change of phase (to liquid water) at constant temperature.
- U ($\frac{W}{m^2K}$) global coefficient of heat transfer. The value of U is inside a range for a given cold and hot fluid. In this case, the range of interest is the one in the second row given that the cold fluid is water and the hot fluid is steam, which can be considered to be in a vacuum as it leaves the LP body at 0.05 bar \approx 0 bar.

Condensers		
Cold Fluid	Hot Fluid	Overall U (BTU/hr-ft ² -F)
Water	Steam (pressure)	350 - 750
Water	Steam (vacuum)	300 - 600
Water or brine	Organic solvent (saturated, atmospheric)	100 - 200
Water or brine	Organic solvent (atmospheric, high non-condensables)	20 - 80
Water or brine	Organic solvent (saturated, vacuum)	50 - 120
Water or brine	Organic solvent (vacuum, high non-condensables)	10 - 50
Water or brine	Aromatic vapours (atmospheric with non-condensables)	5 - 30
Water	Low boiling hydrocarbon (atmospheric)	80 - 200
Water	High boiling hydrocarbon (vacuum)	10 - 30

Figure 33- Condenser values for the global coefficient heat of transfer, Source [Unión Fenosa Generación]

- $Q = m_{LP} (h_{CI} - h_{CO})$. With m_{LP} the mass flow in the exit of the LP body, h_{CI} the enthalpy in the input of the condenser and h_{CO} the enthalpy in the output of the condenser.

As a result, the variables Q, U and LMTD are constants and so for a given value of T_A and T_B and thus for LMTD, there's a certain size of condenser associated.

- **The number of pressure levels of the HSRG.** To a certain extent, this parameter is not an absolute necessity but rather a technical-economical decision. For the given circumstances, a big cycle (i.e. a power plant with a power production higher than 100MW) needs an HRSG with three pressure levels to increase the power plant's efficiency and thus be able to benefit from economies of scale in an energetic sense.
- **Single-Shaft configuration (i.e. SS) or MM (Multi-Shaft configuration).** In this case, a SS was favourable since it saved the cost of another generator.
- **The drum pressures.** The values of the three drum pressures were unnecessary the introduced because once all the previous parameters were stated, the program automatically proportionated a margin of what the pressures could be. In a real situation, it is the supplier who takes the decision of what margin to choose instead of the client or the company.

Furthermore, a process calculation section will be done in all the components as a measure of comparison with the scheme of the Flow Diagram. Amongst other things, the component's efficiency will be verified through calculation (with the Heat and Mass Balance in page 94) along with the component's Heat Rate (HR).

Heat rate is a term commonly used in power stations to indicate the power plant efficiency. The heat rate is the inverse of the efficiency: a lower heat rate is better.

$$\text{Heat Rate} = \frac{\text{Thermal Energy In}}{\text{Electrical Energy Out}}$$

The unit of HR is typically expressed as Btu/kWh. It generally indicates the amount of fuel required to generate one unit of electricity

The steam tables used for all the calculations will be IAPWS-IF97 (International Association for the Properties of Water and Steam).

4.3.1- Gas turbine

The proposed gas turbine is model 9HA.01 from GE with the following main characteristics:

		General Electric
Simple Cycle	Model	9HA.01
	Frequency	50 Hz
	SC Output (MW)	446
	SC Net Heat Rate (kJ/kWh, LHV)	8346
	SC Efficiency (% , LHV)	43.1%
Combined cycle	Block Configuration (GTs x STs)	1x1
	CC Net Output (MW)	661
	CC Net Heat Rate (kJ/kWh, LHV)	5674
	CC Net Efficiency (% , LHV)	63.5%

Table 4- GE Gas turbine, model 9HA.01, Source [<https://www.ge.com/power/gas/gas-turbines/9ha>]

The firing temperature (TIT) is approximately 1447°C and the exhaust gas temperature (TOT) is approximately 632°C.

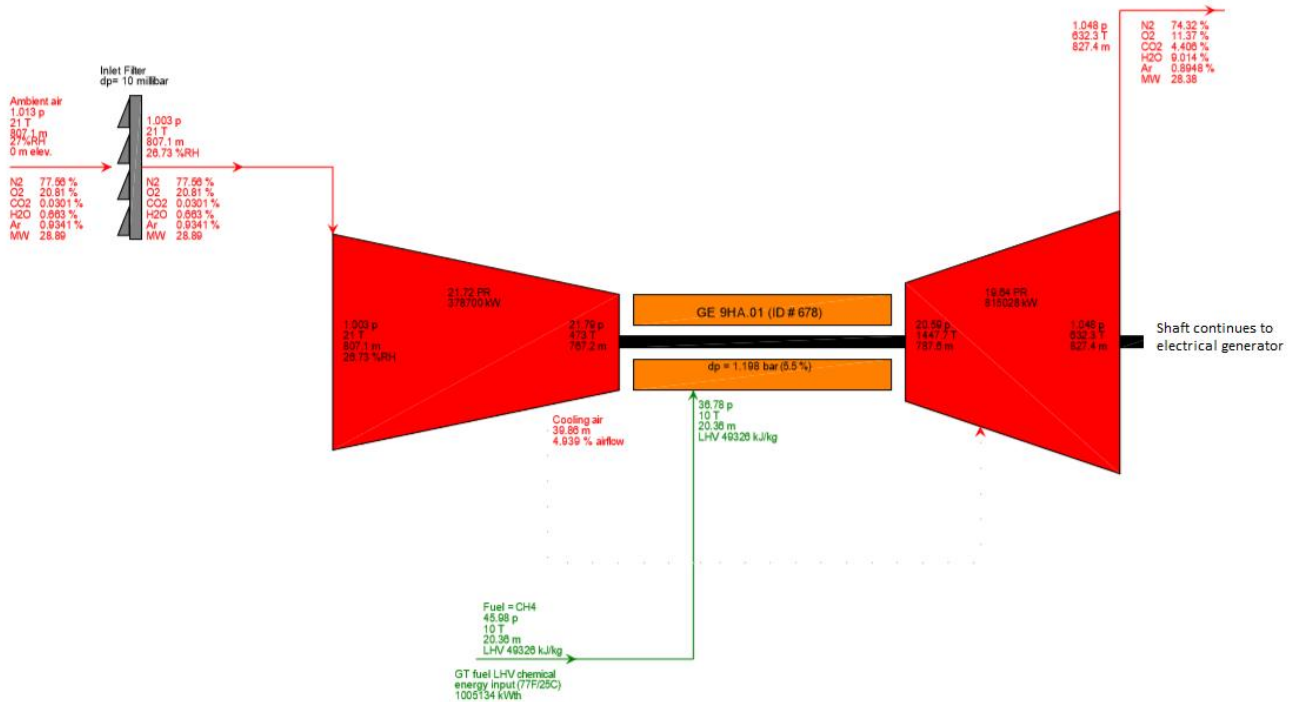


Figure 33- Gas turbine of the Combined Cycle, Source [Internal design, Flow Diagram]

The air intake system provides the compressor with enough dry and clean air to withstand the combustion process and the cooling requirements of the thermal block. The approximate values of pressure and temperature at the inlet of the compressor are: 1 bar and 21°C respectively.

The air is then compressed, as it goes through the compressor, in such a way that it enters the combustion chamber at, roughly, 27.79 bar and 473°C with an approximate mass flow of $767 \frac{\text{Kg}}{\text{s}}$.

It is in the combustion chamber where the mixture takes place between the compressed air and the continually present, natural gas (that enters the combustion chamber at about 10°C, 46 bar and with a $20 \frac{\text{Kg}}{\text{s}}$ mass flow). To ignite the combustion, a simple spark plug is needed until the process is self-maintained.

The combustion products are then introduced into the inlet of the gas turbine at about 1448°C and, roughly, at the same pressure as before, 21 bar with an increased mass flow of $788 \frac{\text{Kg}}{\text{s}}$. At the outlet of the turbine, the conditions of the exhaust gas are of around 1 bar and 632°C. It is also worth noting that the mass flow is now $827 \frac{\text{Kg}}{\text{s}}$. The reason for this is that, to the previous mass flow, an airflow stemming from the compressor is added in

order to reduce the working temperature of the paddles in the turbine and thus increase their life expectancy.

Finally, the exhaust gas leaves the gas turbine, in the conditions previously stated, with a composition of a variety of gases of which Nitrogen and Oxygen have the highest compositions (74.32% and 11.37% respectively).

Process Calculations:

The **Incoming Air** has the following approximate composition:

N ₂	77.56%
O ₂	20.81%
CO ₂	0.03%
H ₂ O	0.66%
As	0.93%

The **Molar Weight** (MW) can thus be calculated as follows:

$$MW_{\text{incoming_air}} = 0.7756 * 28 + 0.2081 * 32 + 0.0003 * 44 + 0.0066 * 18 + 0.0093 * 39.9 = 28.89$$

The **Exhaust Gases** going out the GT has the following approximate composition:

N ₂	74.32%
O ₂	11.37%
CO ₂	4.406%
H ₂ O	9.014%
As	0.8948%

$$MW_{\text{exhaust_gases_GT}} = 0.7432 * 28 + 0.1137 * 32 + 0.04406 * 44 + 0.09014 * 18 + 0.0089 * 39.9 = 28.38$$

The **Pressure Ratio** (PR) of the Air Compressor is:

$$PR_{\text{AirCompressor}} = \frac{21.79}{1.003} = 21.72;$$

The **Pressure Ratio** (PR) of the Gas Turbine (GT) considering incoming pressure divided by outgoing pressure is:

$$PR_{\text{GT}} = \frac{20.59}{1.048} = 19.64;$$

The Enthalpy (kJ/kg) of the Exhaust Gases going out the Gas Turbine (GT) can be calculated considering the temperature of the Exhaust Gases, T_{GT} , which is 632.3 °C:

$$H_{GT} \left(\frac{\text{kJ}}{\text{kg}} \right) = \left[0.9952 + \frac{92.1 \cdot T_{GT} (^{\circ}\text{C})}{1000000} \right] \cdot T_{GT} (^{\circ}\text{C}) = 666 \frac{\text{kJ}}{\text{kg}};$$

The flow of Exhaust Gases as per Heat and Mass Balance in page 94 is 827.4 kg/s.

The corresponding kilowatts (kW) are: $827.4 \frac{\text{kg}}{\text{s}} \cdot 666 \frac{\text{kJ}}{\text{kg}} = 551120 \text{ kW};$

In the Combustion Chamber, compressed air reacts with Natural Gas at 36.78 bar and 10°C (see Heat and Mass Balance in page 94).

The **Lower Heating Value (LHV)** of the Natural Gas is approximately 49326 kJ/kg. The flow of Natural Gas entering the Combustion Chamber is 20.36 kg/s.

The heat generated by natural gas (kW) is: $Q_g = 20.36 \frac{\text{kg}}{\text{s}} \cdot 49326 \frac{\text{kJ}}{\text{kg}} = 1004277 \text{ kW};$

As an informative note, it should be noted that in the Heat and Mass Balance of the plant, the value of the chemical energy of the fuel is 1005134 kW. This is because the program, Thermoflow, tabulates the ASME standard to 25 °C of the LHV value of natural gas.

The efficiency of the gas turbine is calculated as follows:

$$Q_g = 1004277.4 \frac{\text{KJ}}{\text{s}}$$

The electric power of the gas turbine is 433580 kW

Thus, the performance of the gas turbine is $433580 \cdot 100 / 1004277.4 = 43.18\%$.

The gross power transferred to the Shaft only by the GT would be:

$$GT_{\text{Shaft_Power}} = 0.4318 \cdot 1004277 \cong 433646 \text{ kW} = 433.65 \text{ MW}.$$

The HR performance is the inverse of the calculated efficiency, which is $1004277.4 \cdot 3600 / 433646 = 8337.2 \frac{\text{KJ}}{\text{kWh}}$.

Comparing the previous calculated values with the ones calculated in Thermoflow it is observable that the percentage difference is in each case approximately 0.09 % << 1%, which is negligible.

4.3.2- HRSG

The exhaust gases coming out of the Gas Turbine are used to boil the water and heat the steam in the HRSG (Heat Recovery Steam Generator), as per Heat and Mass Balance in page 94.

The exhaust gases have an approximate temperature of 632 °C and the composition is as follows:

- Nitrogen (N₂): 74.3%
- Oxygen (O₂): 11.4%
- CO₂: 4.4%
- Water steam (H₂O): 9%

The **HRSG** is the link between the GT and the steam cycle.

The **HRSG** is made up of several heat exchangers for feed water heating, water vaporisation and steam superheating while at the same time cooling the GT exhaust.

If the **HRSG** had only one pressure Drum, the Heat and Mass Balance would be the following:

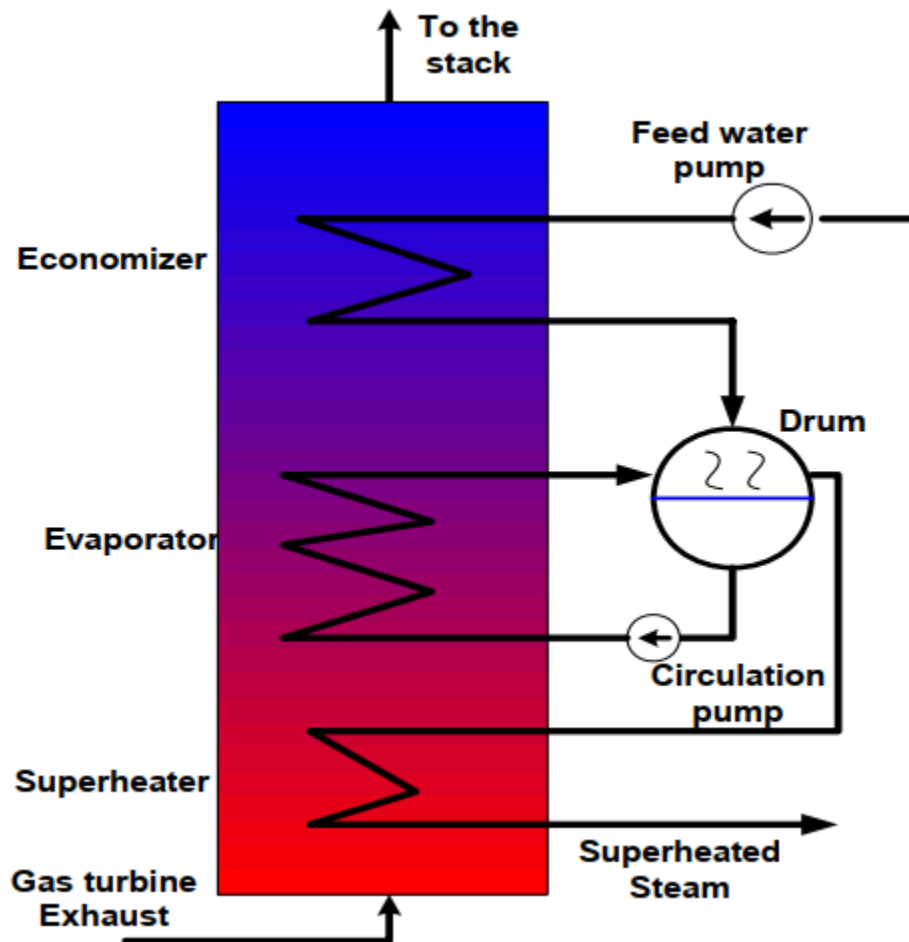


Figure 34- HRSG diagram of one pressure drum, Source

[http://www.energy.kth.se/compedu/webcompedu/WebHelp/S1_Heat_and_Power_Technology/B4_Commercial_Combined_Cycles/C2_Heat_Recovery_Steam_Generators/49_3_Single_Pressure_HRSG.htm]

In the ECO (Economiser), low value heat from the exhaust gas is used to heat the pressurised feed water.

In the EVAP (Evaporator), medium value heat from the exhaust is used to boil the pressurised feed water.

In the SH (Superheater), high value heat from the exhaust is used to superheat the steam and conducting it to the ST.

The three main steps of the heat recovery are represented in the following illustration:

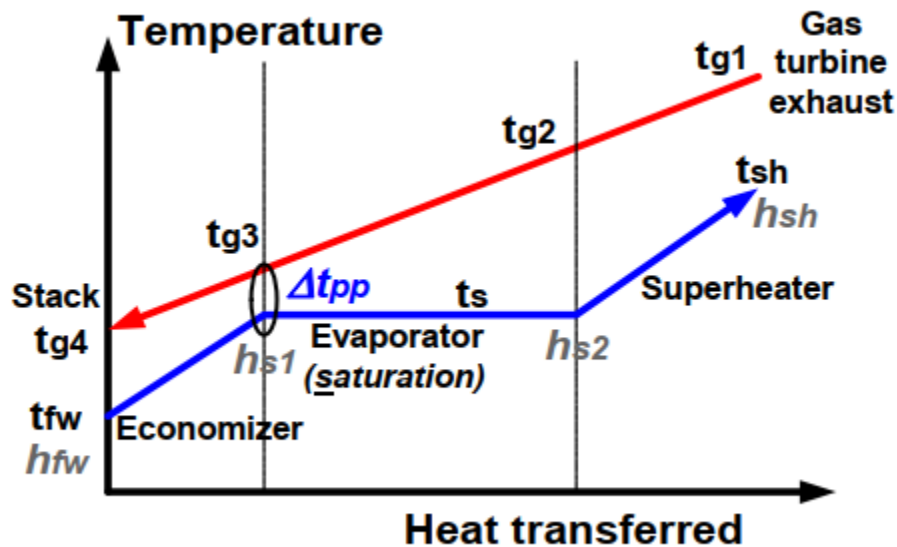


Figure 35- Temperature-Heat transferred diagram, Source

[http://www.energy.kth.se/compedu/webcompedu/WebHelp/S1_Heat_and_Power_Technology/B4_Commercial_Combined_Cycles/C2_Heat_Recovery_Steam_Generators/49_3_Single_Pressure_HRSG.htm]

The Δt_{pp} is usually referred to as pinch point temperature difference and is an important parameter of HRSG design. This difference, which equals to $tg_3 - ts$, is the difference between the exhaust exiting the evaporator and the temperature of the water evaporation. The water evaporation takes place at constant temperature and at the pressure prevailing in the drum.

The aim of introducing the pinch point temperature difference is to avoid a temperature cross, where ts is bigger than tg_3 .

The larger the temperature difference of the two media, - exhaust gas and water/steam, the lower the efficiency of the heat exchange and thus less heat is recovered.

The lower the heat recovery and thus the efficiency, the higher the exit temperature of the exhaust to the stack.

In this study three pressure drums have been considered in order to increase the efficiency of the HRSG.

The considered flow of exhaust gases in this study has been $827 \frac{Kg}{s}$, which corresponds to a volumetric flow of $2093 \frac{m^3}{s}$ with a specific volume of $2.53 \frac{m^3}{kg}$.

The following heat exchangers have been considered within the HRSG, as per Heat and Mass Balance in page 94:

- HPS3: First High Pressure SH.
- RH3 (IP): First Intermediate Pressure Reheater
- HPS2: Second High Pressure SH.
- HPS1: Third High Pressure SH.
- RH1 (IP): Second Intermediate Pressure Reheater
- HPS0: Fourth High Pressure SH.
- HPB1: High Pressure EVAP
- HPE3: First High Pressure ECO
- IPS1: Intermediate Pressure SH
- LPS: Low Pressure SH
- HPE2: High Pressure ECO
- IPB: Intermediate Pressure EVAP
- IPE2: Intermediate Pressure ECO
- HPE1: High Pressure ECO
- IPE1: Intermediate Pressure ECO
- HPE0: High Pressure ECO
- LPB: Low Pressure EVAP
- LTE: Low Pressure ECO

HPS3: First High Pressure Superheater (SH):

The exhaust gas enters with a temperature of 632°C and exits HPS3 with a temperature of 627°C.

The Steam enters HPS3 with a temperature of 540 °C and exits HPS3 with a temperature of 567°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	632	540
Outgoing Temperature (°C)	627	567

RH3 (IP): Intermediate Pressure Reheater:

The exhaust gas enters RH3 (IP) with a temperature of 624°C and exits RH3 (IP) with a temperature of 598°C.

The Steam enters RH3 (IP) with a temperature of 470 °C and exits RH3 (IP) with a temperature of 566°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	624	470
Outgoing Temperature (°C)	598	566

HPS2: Second High Pressure Superheater (SH):

The exhaust gas enters HPS2 with a temperature of 598°C and exits HPS2 with a temperature of 575°C.

The Steam enters HPS2 with a temperature of 470 °C and exits HPS2 with a temperature of 540°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	598	470
Outgoing Temperature (°C)	575	540

HPS1: Third High Pressure Superheater (SH):

The exhaust gas enters HPS1 with a temperature of 575°C and exits HPS1 with a temperature of 553°C.

The Steam enters HPS1 with a temperature of 410 °C and exits HPS1 with a temperature of 470°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	575	410
Outgoing Temperature (°C)	553	470

RH1 (IP): Second Intermediate Pressure Reheater:

The exhaust gas enters HPS1 with a temperature of 554°C and exits HPS1 with a temperature of 522°C.

The Steam enters HPS1 with a temperature of 359 °C and exits HPS1 with a temperature of 470°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	554	359
Outgoing Temperature (°C)	522	470

HPS0: Fourth High Pressure SH:

The exhaust gas enters HPS1 with a temperature of 522°C and exits HPS1 with a temperature of 475°C.

The Steam enters HPS1 with a temperature of 335 °C and exits HPS1 with a temperature of 410°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	522	335
Outgoing Temperature (°C)	475	410

HPB1: High Pressure EVAP:

The exhaust gas enters HPS1 with a temperature of 475°C and exits HPS1 with a temperature of 345°C.

The Steam enters HPS1 with a temperature of 332°C and exits HPS1 with a temperature of 335°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	475	332
Outgoing Temperature (°C)	345	335

The Δt_{pp} or pinch point temperature difference for the High Pressure EVAP is approximately $345 - 335 = 10^\circ\text{C}$.

HPE3: First High Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 345°C and exits HPS1 with a temperature of 341°C.

The Steam enters HPS1 with a temperature of 327°C and exits HPS1 with a temperature of 332°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	345	327
Outgoing Temperature (°C)	341	332

IPS1: Intermediate Pressure SH:

The exhaust gas enters HPS1 with a temperature of 341°C and exits HPS1 with a temperature of 338°C.

The Steam enters HPS1 with a temperature of 240°C and exits HPS1 with a temperature of 316°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	341	240
Outgoing Temperature (°C)	338	316

LPS: Low Pressure SH:

The exhaust gas enters HPS1 with a temperature of 338°C and exits HPS1 with a temperature of 332°C.

The Steam enters HPS1 with a temperature of 153°C and exits HPS1 with a temperature of 313°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	338	153
Outgoing Temperature (°C)	332	313

HPE2: High Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 332°C and exits HPS1 with a temperature of 276°C.

The Steam enters HPS1 with a temperature of 240°C and exits HPS1 with a temperature of 327°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	332	240
Outgoing Temperature (°C)	276	327

IPB: Intermediate Pressure EVAP:

The exhaust gas enters HPS1 with a temperature of 276°C and exits HPS1 with a temperature of 250°C.

The Steam enters HPS1 with a temperature of 237°C and exits HPS1 with a temperature of 240°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	276	237
Outgoing Temperature (°C)	250	240

The Δt_{pp} or pinch point temperature difference for the Intermediate Pressure EVAP is approximately $250 - 240 = 10^{\circ}\text{C}$.

IPE2: Intermediate Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 250°C and exits HPS1 with a temperature of 248°C .

The Steam enters HPS1 with a temperature of 200°C and exits HPS1 with a temperature of 237°C .

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	250	200
Outgoing Temperature (°C)	248	237

HPE1: High Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 248°C and exits HPS1 with a temperature of 237°C .

The Steam enters HPS1 with a temperature of 220°C and exits HPS1 with a temperature of 240°C .

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	248	220
Outgoing Temperature (°C)	237	240

IPE1: Intermediate Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 237°C and exits HPS1 with a temperature of 234°C .

The Steam enters HPS1 with a temperature of 154°C and exits HPS1 with a temperature of 200°C .

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	237	154
Outgoing Temperature (°C)	234	200

HPE0: High Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 234°C and exits HPS1 with a temperature of 199°C.

The Steam enters HPS1 with a temperature of 156°C and exits HPS1 with a temperature of 220°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	234	156
Outgoing Temperature (°C)	199	220

LPB: Low Pressure EVAP:

The exhaust gas enters HPS1 with a temperature of 199°C and exits HPS1 with a temperature of 158°C.

The Steam enters HPS1 with a temperature of 153°C and exits HPS1 with a temperature of 153°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	199	153
Outgoing Temperature (°C)	158	153

The Δt_{pp} or pinch point temperature difference for the Low Pressure EVAP is approximately $158 - 153 = 5^\circ\text{C}$.

LTE: Low Pressure ECO:

The exhaust gas enters HPS1 with a temperature of 158°C and exits HPS1 with a temperature of 83°C.

The Steam enters HPS1 with a temperature of 48°C and exits HPS1 with a temperature of 146°C.

	Exhaust Gas	Water/Steam
Incoming Temperature (°C)	158	48
Outgoing Temperature (°C)	83	146

At this point, the exhaust gases exit the HRSG with the same mass flow of $827 \frac{\text{Kg}}{\text{s}}$, which corresponds to a volumetric flow of $852 \frac{\text{m}^3}{\text{s}}$ with a specific volume of $1.03 \frac{\text{m}^3}{\text{kg}}$.

Process Calculations:

The expression by which the heat exchange efficiency is obtained between the gas turbine exhaust gases and the water-steam circuit as it passes through the heat recovery boiler is as follows:

$$\eta_{\text{HRSG}} = \frac{Q_{\text{ST}}}{Q_{\text{GT}}}$$

Where:

η_{HRSG} : Performance of the HRSG

Q_{ST} : Heat contributed to the low-steam turbine cycle

Q_{GT} : Heat given to the cycle by the Gas Turbine

$$\eta_{\text{HRSG}} = \frac{427812}{551120} * 100 = 77.6\%$$

The Enthalpy (kJ/kg) of the Exhaust Gases coming out the HRSG and entering the stack can be calculated considering the temperature of the Exhaust Gases, T_{stack} , which is 83.16°C:

$$H_{\text{stack}} \left(\frac{\text{kJ}}{\text{kg}} \right) = \left[0.9952 + \frac{92.1 \cdot T_{\text{stack}}(^{\circ}\text{C})}{1000000} \right] \cdot T_{\text{stack}}(^{\circ}\text{C}) = 83.4;$$

Assuming the flow of Exhaust Gases to be 827.4 kg/s, the corresponding kW that exit the HRSG as useless energy are:

$$827.4 \frac{\text{kg}}{\text{s}} \times 83.4 \frac{\text{kJ}}{\text{kg}} = 69005 \text{ kW};$$

Therefore, the amount of energy that is used eventually in the vapour cycle is 551120kW – 69005kW = 482,115kW.

4.3.3- Steam turbine

The proposed steam turbine is model D-650 from GE. It is composed of four bodies: a high-pressure casing, a medium pressure casing and two low-pressure casing.

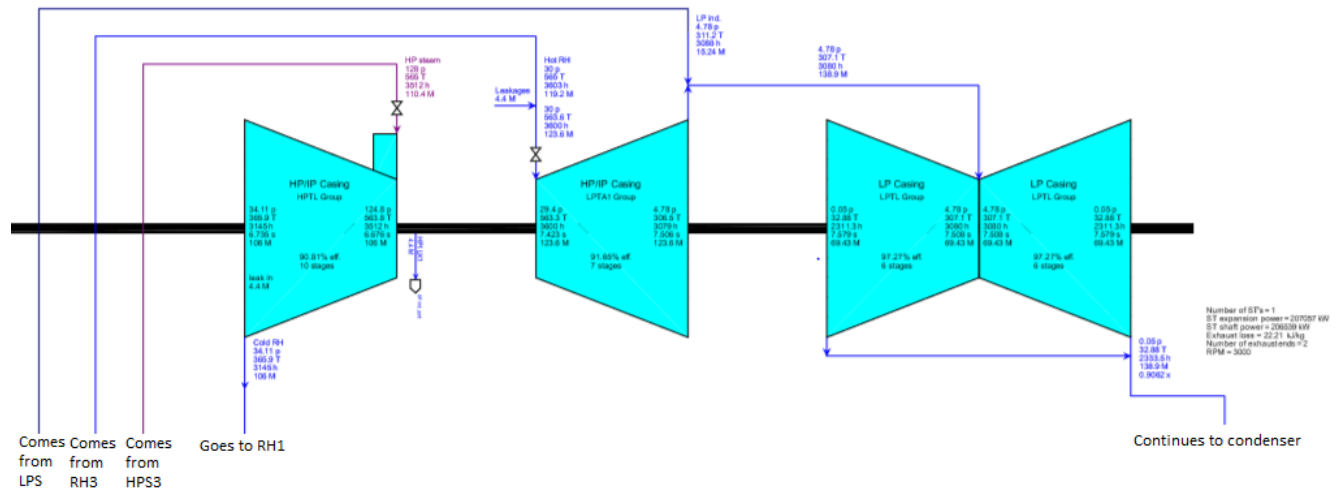


Figure 35- Steam turbine Combined Cycle, Source [Internal design, Flow Diagram]

The steam, with highest enthalpy value ($3512 \frac{\text{KJ}}{\text{Kg}}$), reaches the turbine with its highest value of pressure (128 bar) and temperature (565°C) and, in it, undergoes a large expansion (leaving the high-pressure casing at 34 bar) and with a much lower temperature (366 °C).

The medium pressure turbine receives the steam that comes from the high-pressure turbine after being reheated in the RH1 (Intermediate pressure reheater) the conditions at which the reheated steam enters the medium-pressure casing are 30 bar and 564°C. Again, the steam undergoes another process of expansion (with a decrease of its temperature of roughly 260 °C) and when it leaves the medium-pressure body it is mixed with heated steam that comes from the LPS (Low pressure superheater) and as a result the new, mixed, steam that enters the low-pressure body has a temperature of 307°C and a pressure of approximately 5 bar.

In this stage, the entering steam undergoes its last process of expansion (with about 270 °C decrease in its temperature) in the two low-pressure casings and it is then conducted towards the condenser with a very low pressure (0.05bar) and temperature (33°C) where the steam is transformed into liquid water.

There is a further analysis of the values of the variables of operation of the steam turbine: the flow (m), the pressure (P), the temperature (T) and the enthalpy (H) obtained from the thermal balance of the combined cycle at 100% in operating mode.

The relation between the output pressure of the intermediate pressure (IP) turbine with respect to the input pressure is 0.16. For the high-pressure body (HP), the relationship is 0.27. Experts indicate that the maximum thermal efficiency of an ideal combined cycle

with reheating is obtained when the quotient between the outlet pressure and the inlet pressure is between 0.15 and 0.35.

Process Calculations:

We proceed to calculate the power of the turbine through the first principle of thermodynamics.

$$\frac{dE}{dt} = Q - W + m (h_i - h_o) + m \left(\frac{1}{2} C_i^2 - \frac{1}{2} C_o^2 \right) + m (gZ_i - gZ_o)$$

Q = Heat

W = Work

m = Mass flow

h_i = Input enthalpy

h_o = Outlet enthalpy

C_i = Inlet velocity

C_o = Outlet velocity

Z_i = Inlet height

Z_o = Outlet height

Let us assume as correct the approximate idea that the turbines have an isothermal process, both the output and input speed is the same and the height difference between inputs and outputs is identical too.

The total energy that the steam gives to the turbine blades (W) will be:

$$W = m_{HP} (h_{HPi} - h_{HPo}) + m_{IP} (h_{IPi} - h_{IPo}) + m_{LP} (h_{LPi} - h_{LPo}) - m_{LP} * W_e$$

$$m_{HP} = 110.4 \frac{\text{Kg}}{\text{s}}$$

$$h_{HPi} = 3512 \frac{\text{KJ}}{\text{Kg}}$$

$$h_{HPo} = 3145 \frac{\text{KJ}}{\text{Kg}}$$

$$m_{IP} = 123.6 \frac{\text{Kg}}{\text{s}}$$

$$h_{IPi} = 3600 \frac{\text{KJ}}{\text{Kg}}$$

$$h_{IPo} = 3080 \frac{\text{KJ}}{\text{Kg}}$$

$$m_{LP} = 138.9 \frac{\text{Kg}}{\text{s}}$$

$$h_{LPi} = 3080 \frac{\text{KJ}}{\text{Kg}}$$

$$h_{LP0} = 2333.5 \frac{\text{KJ}}{\text{Kg}}$$

$$W_e = \text{Exhaust loss} = 22.21 \frac{\text{KJ}}{\text{Kg}} * 138.9 \frac{\text{Kg}}{\text{s}}$$

$$W = 205392.7 \text{ kW}$$

In section 4.3.1, the power generated by the gas cycle was calculated to be = $Q_g = 1004277.4 \frac{\text{KJ}}{\text{s}}$.

It is now possible to calculate the performance of the steam turbine as a stand-alone unit: $205392.7 * 100 / 1004277.4 = 20.45\%$.

Considering an efficiency of the ST (Steam Turbine) as a stand-alone unit of 20.45%, the gross power transferred to the Shaft only by the ST would be:

$$ST_{\text{Shaft Power}} = 0.2045 \times 1004277 \cong 205374.65 \text{ kW} = 205.37 \text{ MW}.$$

As a result, the efficiency of the whole combined cycle power plant can be calculated. In fact, there are three ways to conclude that the plant's performance is roughly 62.17% as it is indicated in the Flow Diagram.

1. The first way is that the performance of the gas turbine + performance of the steam turbine = performance of the power plant: $43.18\% + 20.45\% = 63.63\%$. The percentage difference of this value with respect to the efficiency 63.15 %, is 0.75%
2. Another way of calculating the plant's performance, is using the electrical power of the generator (634781kW): $634781 * 100 / 1004277.4 = 63.20\%$. The percentage difference of this value with respect to the efficiency 63.15 % is 0.079%.
3. $\eta_{CC} = \eta_{GT} + \eta_{ST} \times \eta_{HRSG} \times (1 - \eta_{GT})$
 $\eta_{CC} = 0.4318 + 0.4318 \times 0.776 \times (1 - 0.4318) = 62.2\%$. The percentage difference of this value with respect to the efficiency 63.15 % is 1.5%.

As it is observable the calculations have a percentage difference that is very small to take into consideration.

4.3.4- Condenser

The condenser works in an open circulating system and it contains cooling water (of about 15 °C) from the Mediterranean Sea that is pumped in by extraction pumps and that, after it absorbs the steam's heat, it is returned to the sea at 25°C. When the steam meets the pipes, through which the cooling water circulates, condenses and is deposited in the well located in the lower part of the condenser. By means of a condensate pump, the water that is deposited in the well is sucked up and put back into circulation by sending it back to the boiler at approximately 33°C and 0.4bar.

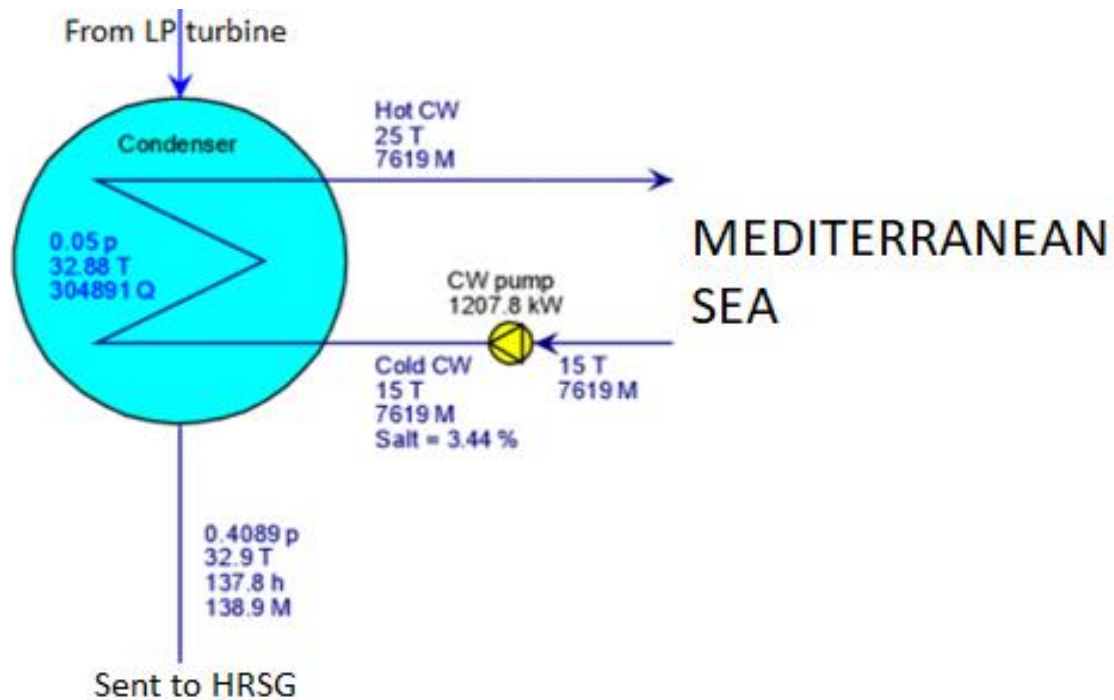


Figure 36- Condenser Combined Cycle, Source [Internal design, Flow Diagram]

Process Calculations:

The thermal load of all the connections that reach the condenser at full load is calculated:

- The output of the 2 bodies of low pressure of the steam turbine (taking into account a mass flow of $138.9 \frac{\text{Kg}}{\text{s}}$ and an enthalpy of $2333.5 \frac{\text{KJ}}{\text{Kg}}$).

$$Q_{IC} = 138.9 \frac{\text{Kg}}{\text{s}} * 2333.5 \frac{\text{KJ}}{\text{Kg}} = 324123.15 \frac{\text{KJ}}{\text{s}}$$

- The output of the condenser (considering a mass flow of $138.9 \frac{\text{Kg}}{\text{s}}$ and an enthalpy of $137.8 \frac{\text{KJ}}{\text{Kg}}$).

$$Q_{OC} = 138.9 \frac{\text{Kg}}{\text{s}} * 137.8 \frac{\text{KJ}}{\text{Kg}} = 19140.42 \frac{\text{KJ}}{\text{s}}$$

(Thermal load in the condenser in $\frac{\text{KJ}}{\text{s}}$ at full load) = $Q_{IC} - Q_{OC} = 304982.73 \frac{\text{KJ}}{\text{s}}$.

The calculated value only has a 0.03% percentage difference with respect to the value shown in the Flow Diagram.

As mentioned previously, the formula needed to calculate the dimension of the condenser is the following:

$$Q = \text{LMTD} * (U * A)$$

- The temperature profiles of the fluids are not constant. An approximate temperature diagram is shown on the condenser's heat exchanger:

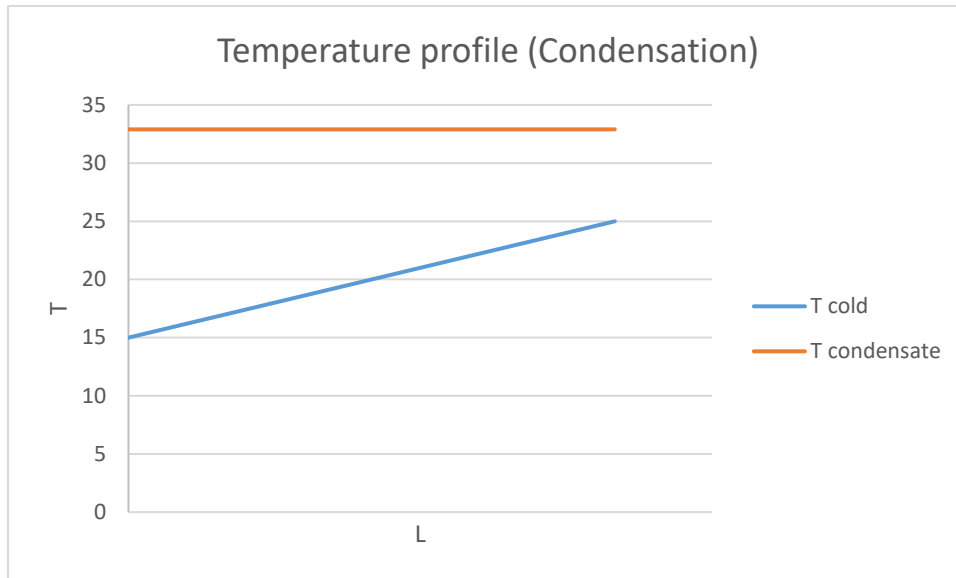


Figure 36- Temperature diagram heat exchanger, Source [Internal Design, Excel]

- $$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

$$\Delta T_A = 32.9^\circ\text{C} - 32.9^\circ\text{C} = 0^\circ\text{C}$$

$$\Delta T_B = 25^\circ\text{C} - 15^\circ\text{C} = 10^\circ\text{C}$$

$$LMTD = 10.$$

- U is considered to be the medium value between the range of 300 and 600 $\frac{\text{hr}}{\text{ft}^2\text{K}}$ (i.e. $450 \frac{\text{hr}}{\text{ft}^2\text{K}} = 2553.5 \frac{\text{W}}{\text{m}^2\text{K}}$).

- $Q = 304982.73 \frac{\text{KJ}}{\text{s}}$.

In conclusion, the value of A is calculated to be: $A = 12\text{m}^2$

4.3.5- Combined Cycle performance

The common shaft must be rotating slowly (less than 1 rpm) for several hours. This phase is called the vibrating phase. It is done to avoid deformation and arching, caused by the weight of the shaft or the temperature, which can produce imbalances and more vibrations, or even the blocking of the axis itself.

The boot process starts when the operator presses a start button on the control system. As soon as the process begins, the acceleration of the gas turbine begins. In the moment, the generator works as an engine, feeding on the electrical network. To achieve a soft start, a frequency inverter is used, which controls the speed of the generator accurately.

First, a gas sweep is made in the turbine, to clean any gas bag in the turbine. During this sweep, the turbine runs at 500 rpm for 5-10 minutes. Once the sweep is done, the turbine increases its speed and increases certain critical speeds (like the resonance frequency) in which the level of vibrations in the bearing increases considerably.

At a certain speed (normally above 50% of the rated speed), gas begins to enter the burners. If the burners ignite properly, the combustion gases start to push the turbine blades. As the turbine increases its speed, the generator pushes less and the exhaust gases more and more and when the speed is about 2500rpm the generator is disconnected and the combustion will become the only responsible for the drive of the rotor.

The graph below shows the response of the Combined Cycle when it is operated. It offers a high operational flexibility with the ability to offer highly efficient steady state operations and rapid deliveries of power to the grid.

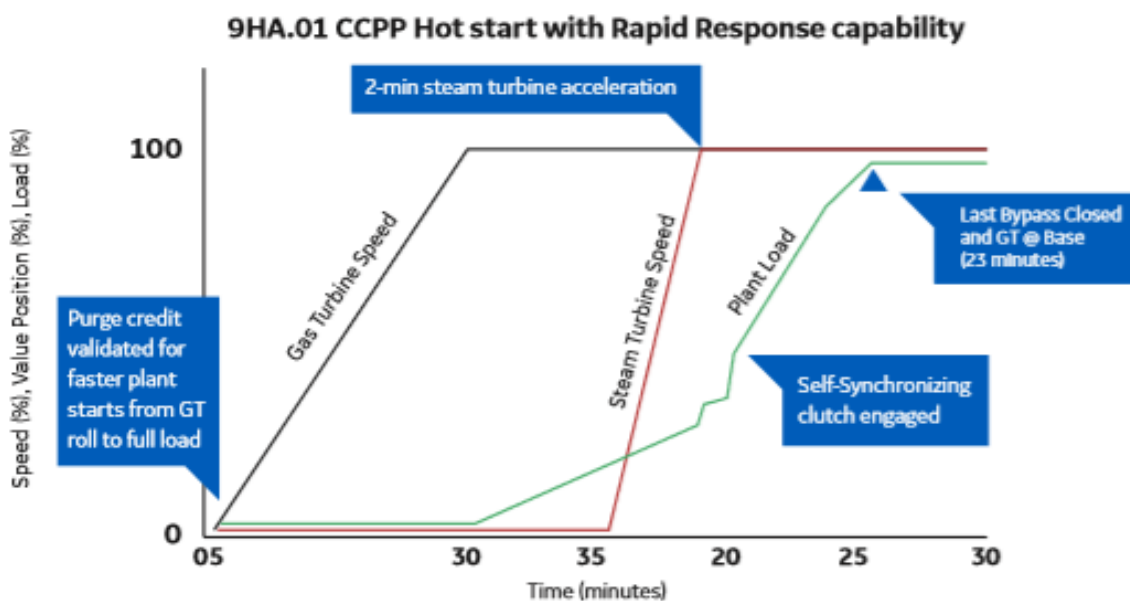


Figure- 37 9HA.01 CCPP Response capability, Source [https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/White%20Paper/gea32885-bouchain-whitepaper-final-aug-2016.pdf]

As it is observable, given the inflexibility that a SS configuration entails, the use of a shaft allows a better flexibility for extreme cases such as a breakdown of any key component of the steam cycle, for example, because in this case the plant can still operate using the GT in an open circuit.

It takes the GT roughly 23 minutes to reach its nominal operative speed at full load. As it increases its operational ability, the GT exhaust gases get the HRSG functioning and into approximately 35 minutes of the start of the process, the steam turbine begins to function and has a 2-minute acceleration to start to operate at its nominal speed.

Once both components operate at nominal speed (3000 rpm), they can be synchronised by engaging the clutch. This automatically regulates the frequency, voltage and phase shift of the voltage curve of the generator and the electrical network. When the generator and network voltage curves coincide fully, the generator switch is closed, and the generated electric power is exported to the network through the main transformer.

4.3.6- Electrical System

4.3.6.1- Main Electrical System

The Electrical System of the proposed new Group 1 shall consist of the new 20 kV Generator, the Isolated Phase Bus System (IPB) connecting the Generator to the Generator Transformers, - which shall be three Single-Phase Core Type Transformers -, and the main Auxiliary Systems.

The following illustration depicts these electrical elements:

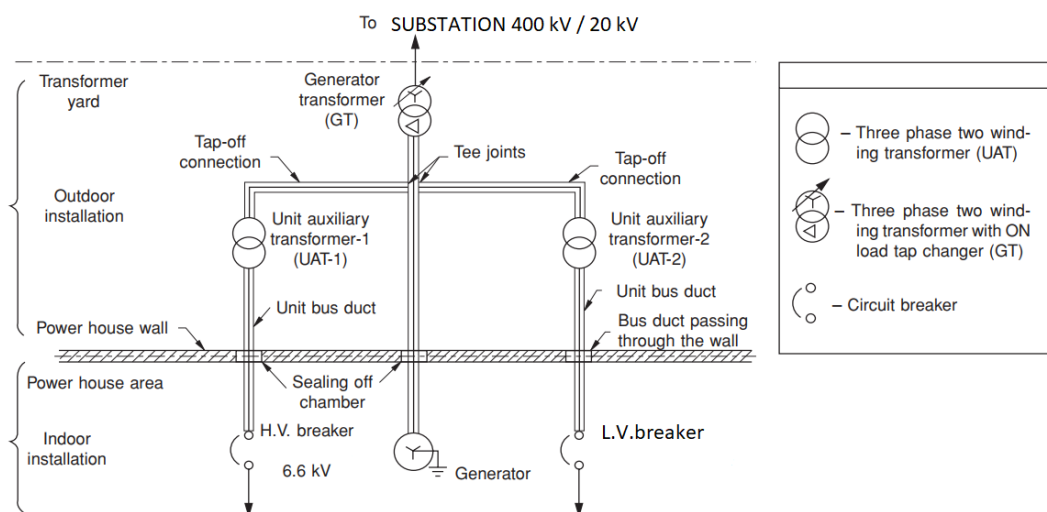


Figure 38- Electrical elements of the substation, Source [<http://www.electricalengineering-book.com/pdf/chapter-498842.pdf>]

4.3.6.1.1- New Generator G1

The new Generator G1 shall be designed for 650 MW of real power, considering the joint operation of the new Gas Turbine and Steam Turbine (see sections 4.3.1 and 4.3.3).

The apparent power assuming $\cos\phi=0.85$ is:

$$S(\text{MVA}) = \frac{P(\text{MW})}{0.85} \approx 765;$$

The Generator nominal output voltage shall be 20 kV.

The Generator nominal output current can thus be calculated:

$$I(\text{kA}) = \frac{S(\text{MVA})}{\sqrt{3} \cdot U(\text{kV})} = \frac{765}{\sqrt{3} \cdot 20} \cong 22.11;$$

This large nominal current of 22110 Amps will flow from the new Generator G1 to the Generator Transformers and will then be injected onto the Grid. The electrical connection from the new Generator G1 to the Generator Transformers shall be made with an Isolated Phase Bus system (IPB).

4.3.6.1.2- Main Isolated Phase Bus (IPB) System run

The calculated nominal current in previous item is a very large current and therefore an Isolated Phase Bus System with continuous or bonded enclosures must be specified.

The enclosure shall be constructed of non-magnetic material, generally aluminium, in view of its low cost and weight compared to copper. The nonmagnetic material eliminates hysteresis and eddy current losses in the enclosure.

The Main IPB run shall connect the Generator G1 to the 20 kV side of the Single-Phase Generator Transformers and shall be dimensioned for at least 22.1 kA nominal current.

The following illustration shows a cross section of two of the three phases involved.

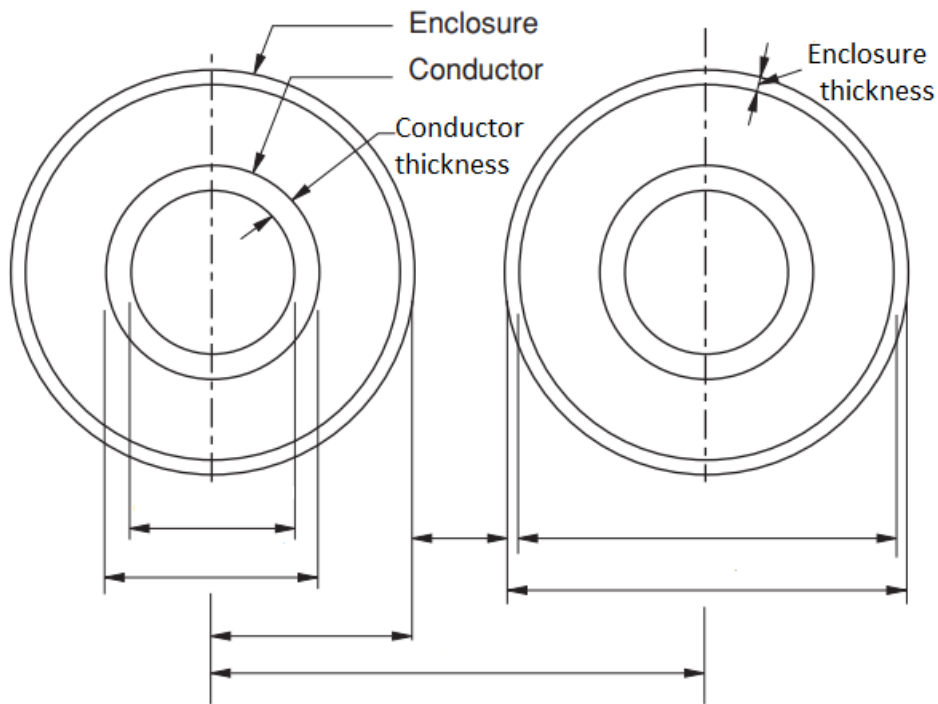


Figure 39- Cross section of the three phases, Source [<http://www.electricalengineering-book.com/pdf/chapter-498842.pdf>]

The conductors of each phase are housed in a separate non-magnetic metallic enclosure to isolate them completely from each other with the following objectives:

- Elimination of Phase-to-Phase faults.
- Elimination of the proximity effect (extra forces and heating) by providing a magnetic shielding to the supporting and metallic structures in the vicinity.
- Reduction of the proximity effects between the main current-carrying conductors of the adjacent phases to almost zero due to magnetic shielding and large centre spacing.
- Complete protection for operating personnel from high touch or step voltages across the enclosure and the metallic structures caused by parasitic currents.

Tubular conductors provide the most efficient system for current carrying, particularly large currents. The current density is maximum at the skin (surface) of the conductor and falls rapidly towards the core (see illustration).

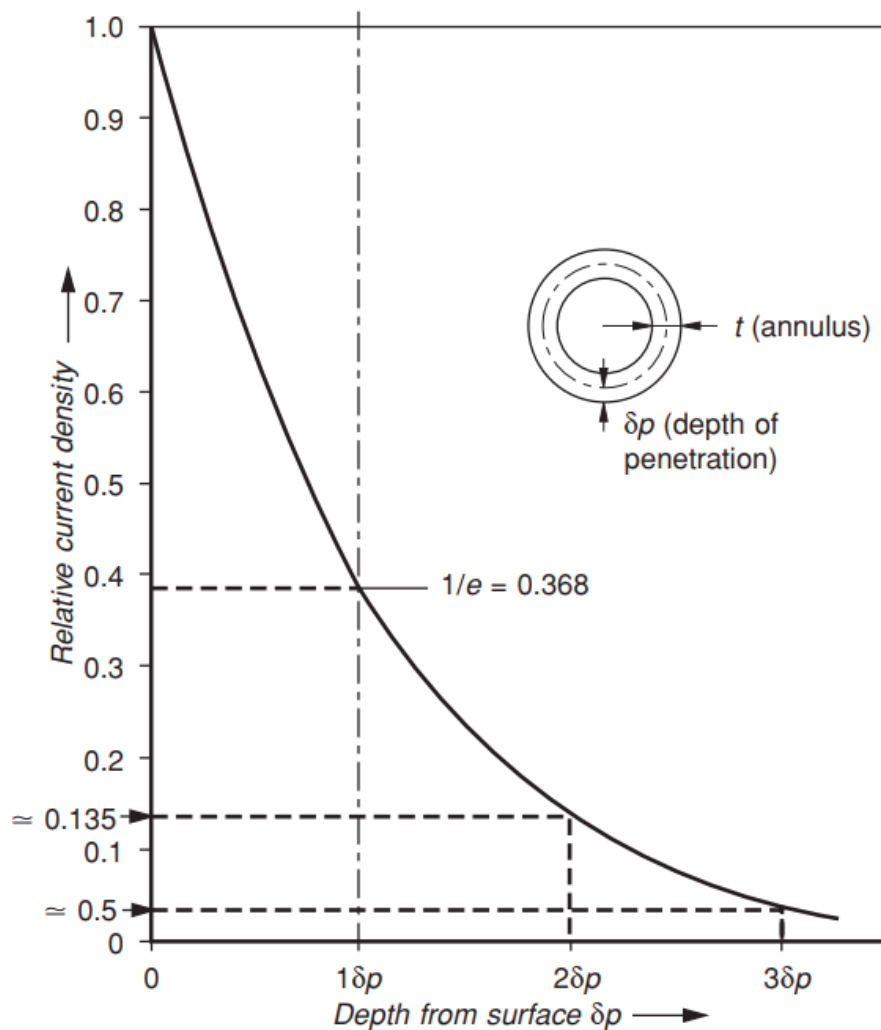


Figure 40- Current density vs Depth from surface, Source [<http://www.electricalengineering-book.com/pdf/chapter-498842.pdf>]

It is proved that around 90% of the total current is concentrated in an area with a depth δp from the surface of the conductor. δp usually referred to as depth of penetration. The higher the frequency, the smaller the depth of penetration δp . This effect is well known as skin effect.

Each enclosure is cross connected with the enclosure of the other phases at both ends of the installed bus duct run permitting longitudinal flow of induced currents through the length of the enclosure and return through the enclosure of the other phases.

The following illustration shows the disposition of the conductor and enclosure currents as well as the magnetic fields involved.

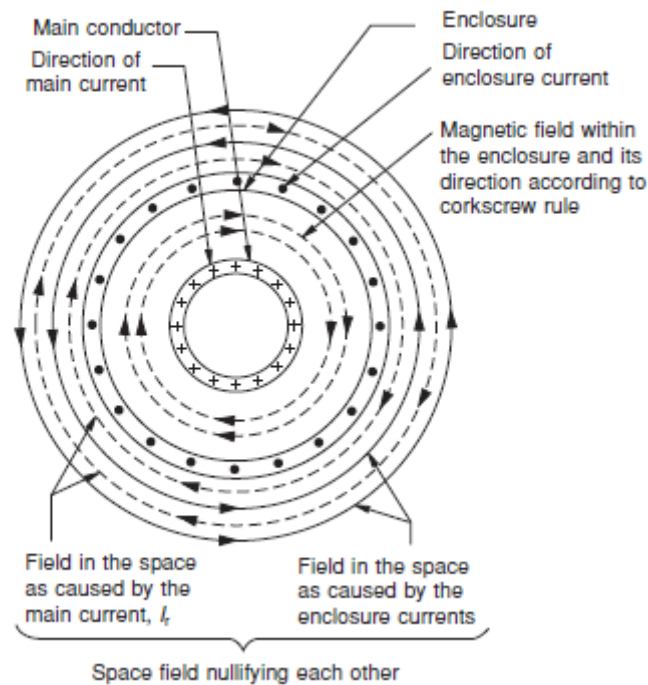


Figure 41- Enclosure currents and magnetic fields, Source [<http://www.electricalengineering-book.com/pdf/chapter-498842.pdf>]

For better shielding it is essential that bonding is carried out at the bends and tap-offs or where it passes through a wall. Where bonding is not possible, the supports and the enclosure must be adequately reinforced to sustain electrodynamic forces, especially during a fault.

The enclosure must also be insulated electrically from the rest of the plant by rubber bellows. For a better flow of circulating currents, grounding of the enclosure shall be done only at one point. The ground bus shall be provided some distance away from the enclosure to remain unaffected by the fault currents.

4.3.6.1.3- Generator Single-Phase Transformers

Each Single-Phase Transformer shall be able to supply one third of the total calculated power, which is 765 MVA.

In this work, we shall estimate the power of each Single-Phase Generator Transformer as follows, considering a reference ambient temperature of 40°C:

- 230 MVA with 55°C average temperature rise of windings insulation.
- 255 MVA with 65°C average temperature rise of windings insulation (OFAF). If such large power is required, both the oil pumps and the air fans of the Transformer shall be on.

On the Generator side, the nominal line voltage is 20 kV and the Transformer's windings shall be connected in Delta (Δ).

On the EHV (Extremely High Voltage) side, which is the Grid or substation side, the windings of the three Generator Transformers shall be connected in Star and the neutral grounded.

The vector group of the assembly of the three Generator Transformers shall be Ynd11, and the voltage ratio 400 kV / 20 kV.

The short-circuit impedance shall be less than 16%.

The Basic-Impulse Insulation level (BIL) withstand of the windings, which corresponds to the standard 1.2/50 μ s lightning impulse, as well as the highest voltage system are represented in the following table:

	400 kV side Grid side	20 kV side Generator side
Highest voltage system (r.m.s 50 Hz)	420 kV	24 kV
Lightning impulse withstand (1.2/50 μ s crest values)	1175 kV	145 kV

Table 5- Basic-Impulse Insulation level (BIL), Source [<http://www.electricalengineering-book.com/pdf/chapter-498842.pdf>]

4.3.6.2- Main Auxiliary Services

4.3.6.2.1- Auxiliary Distribution Transformers

The main Auxiliary Transformers considered in this work are drawn on page 95-97 and are the following:

- 5000 kVA Transformer to supply the 6.3 kV Switchgear. This 20 kV/6.3 kV Transformer is ONAN, oil-immersed, vector group Dy11 and is supplied on the primary side by Single-Core 12/20 kV copper cables. On the 6.3 kV side three Single-Core 6/10 kV copper cables connect this Transformer to the 6.3 kV Switchgear. Each of these 6/10 cables has 240 mm² of cross section. The calculated output current at the 6.3 kV side of the Transformer is;

$$I(\text{Amps}) = \frac{S(\text{kVA})}{\sqrt{3} \cdot 6.3(\text{kV})} = \frac{5000}{1.73 \cdot 6.3} \approx 458$$

- 630 kVA Transformer to supply the main 400 V Switchgear. This 20 kV/0.4 kV Transformer is ONAN, oil-immersed, vector group Dyn11 and is supplied on the primary side by Single-Core 12/20 kV copper cables. On the low voltage side three Single-Core 0.6/1 kV copper cables connect this Transformer to the 400 V Switchgear. The calculated output current at the low voltage side of the Transformer is;

$$I(\text{Amps}) = \frac{S(\text{kVA})}{\sqrt{3} \cdot 0.4(\text{kV})} = \frac{630}{1.73 \cdot 0.4} = 910.4$$

4.3.6.2.2- Electrical Switchgears

The following main Switchgears have been considered.

- 20 kV Switchgear. This Switchgear shall have at least one incoming cell, one measuring cell (not represented in drawing on page 95) and the following outgoing cells;
 - Outgoing cell to 20 kV/6.3 kV Transformer. This cell shall include sectionaliser switch, automatic circuit breaker and grounding disconnecter with the corresponding inter-lock.
 - Outgoing cell to 20 kV/0.4 kV Transformer. This cell shall include sectionaliser switch, automatic circuit breaker and grounding disconnecter with the corresponding inter-lock.

- 6.3 kV Switchgear Motor Control Centre (MCC). This Switchgear shall have one incoming Circuit Breaker and at least the following outgoing cells;
 - Outgoing cell to **HP Pump**. This cell shall supply and protect the outgoing line to HP Feed Pump, with a 2400 kW rating. The corresponding average current to this HP Feed Pump Motor is 244 Amps approximately. Three Single-Core 6/10 kV, 95 mm² copper cables shall be laid from the Switchgear to the Motor.
 - Outgoing cell to **Cool Water Pump (CW Pump)**. This cell shall supply and protect the outgoing line to Condensate Pump, with a 1200 kW rating. The corresponding average current to this Condensate Pump Motor is 122 Amps approximately. Three Single-Core 6/10 kV, 50 mm² copper cables shall be laid from the Switchgear to the Motor.

- 400 V Switchgear. This Switchgear be responsible for the supply of the motors rated below 210 kW and shall also supply lighting circuits as well as convenience outlets. The main low voltage motors supplied by this Switchgear are;
 - Condensate Pump Motor: This outgoing line shall be protected by a 630 A- Circuit Breaker. The corresponding average current to this IP Feed Water Pump Motor is 270 Amps approximately. The calculated voltage drop for a 50 m long route from the Switchgear to the motor is 0.66% considering three 240 mm² copper cables, as per drawing on page 97.
 - Recirculation Water Pumps. There shall be several recirculation water pumps. In this work an average rating of 5.5 kW has been considered for each recirculation water pump. The corresponding average current to each Recirculation Water Pump Motor is 10.2 Amps approximately. The calculated voltage drop for a 25 m long route from the Switchgear to the motor is 0.48% considering three 4 mm² copper cables, as per drawing on page 97.

4.3.6.2.3- Water pumps

According to the Flow diagram, there are the main following pumps to be considered:

- **Cool Water Pump.** This pump makes the cool water flow to the Condenser. The estimated electrical power is 1200 kW. The motor of this pump is supplied at 6.3 kV.
- **HP Feed Pump.** This pump feeds water to the high pressure and intermediate pressure drums in the HRSG. The estimated electrical power is 2400 kW. The motor of this pump is supplied at 6.3 kV.
- **Condensate Pump.** This pump makes the water flow from the Condenser to the LP Economizer in the HRSG. The estimated electrical power is 160 kW. The motor of this pump is supplied at 400 V.
- **Recirculation Water Pumps.** There shall be several recirculation pumps. The estimated power of a recirculation pump is 5.5 kW. The motor of this pump is supplied at 400 V.

4.3.7- Pollution

The Carboneras thermal power station emits daily, according to the PRTR (Registro Estatal de Emisiones 2017), the following greenhouse gases: 2,211 kg of CO per day, 17,888 kg of NO_x and 12,611,111 kg of CO₂ per day, in addition to: Arsenic, mercury, sulfur, zinc, cadmium, copper, nickel and lead (particulate matter). These emissions have converted this plant in the third most polluting thermal power plant in Spain. Far from decreasing, its emissions have increased by 14.3% in 2018, reaching 6.27 million tons of CO₂ per year.

As a possible location for the new Group1, the existing coal mill area of Group1 is proposed, which reduces the environmental impact as well as the better facility for procedures and licenses.

The 9th Article of the Facilities subject to the integrated environmental authorisation, of the Royal Legislative Decree 1/2016, of December 16, on Integrated Prevention and Control of Pollution, states that the repowering of certain thermal plants with a thermal power of more than 50 MW must undergo the process of obtaining the Integrated Environmental Authorisation.

Specifically, point 1.a) of Article 12 of the Royal Legislative Decree 1/2016 of December 16, on Integrated Prevention and Control of Pollution, requests the documentation required to obtain the corresponding Municipal License of Classified Activities for which the Regulation of Unhealthy, Unhealthy, Harmful and Dangerous Activities is approved, or in the autonomic provisions that result from application.

In the Royal Legislative Decree 1/2016 of December 16, of Integrated Prevention and Control of Pollution, it is established in Annex 1 a classification of categories of facilities

and activities in relation to the Integrated Environmental Authorization procedure. According to the classification, the repowered thermal power plant is applied within the group as it is a combustion plant with a thermal power of more than 50 MW, where the combustion of fossil fuels takes place.

The substitution of group 1 for the proposed Combined Cycle 1x1 would be an improvement for the environment in terms of emissions. Natural gas is an energy that until now has been presented as one of the most efficient and clean and is progressively displacing conventional power plants that use other fossil fuels, which damage the environment much more.

4.3.7.1- Atmospheric impact

A combined cycle has a lower environmental impact. For the configuration that we have chosen, a 1x1 SS, and taking as reference a cycle with the same configuration that is in operation, we have the following information:

Existing coal emissions, Group 1 and Group 2:

	Coal
CO (kg/day)	2,211
NO _x (kg/day)	17,888
CO ₂ (kg/day)	12,611,111
Particulate matter (Hg, As, S, Zn, Cd, Cu, Ni, Pb)	more or less 1 kg/day

Table 6- Existing coal emissions Group 1 and Group 2, Source [http://www.prtr-es.es/informes/fichacomplejo.aspx?Id_Complejo=3191]

Theoretical emissions of the new Group 1 of the exhaust gases that go from the HRSG to the stack:

	Natural Gas Fuel
N ₂ (%)	74.32
O ₂ (%)	11.37
CO ₂ (%)	4.406
H ₂ O (%)	9.014
A _r (%)	0.8948

Table 7- Theoretical emissions of the exhaust gases from the HRSG, Source [Heat and Mass Balance of this project]

The above table corresponds to the emissions shown in the Flow diagram. The actual emissions also contain NO_x and SO_x and are as follows:

CO (kg/day)	664
NO _x (kg/day)	419
CO ₂ (kg/day)	886,111
SO _x (kg/day)	24

Figure 8- Actual emissions of the exhaust gases from the HRSG, Source [http://www.prtr-es.es/informes/fichacomplejo.aspx?Id_Complejo=3191]

4.3.7.2- Acoustic impact

In Royal Decree 1367/2007, of October 19, which develops Law 37/2003, of November 17, of Noise, regarding acoustic zoning, quality objectives and acoustic emissions.

The noise quality objectives for noise applicable to existing urbanized areas are indicated as the noise emission limit values applicable to port infrastructures and to collected activities.

According to the Royal Decree, the objective of acoustic quality is understood as the set of requirements that, in relation to noise pollution, must be met at a given time in a given space, including the limit values of emission. And by limit value of emission, the value that should not be exceeded and that if it is overcome requires foreseeing or applying measures to avoid such overcoming. The limit values may vary depending on the acoustic emitter (noise from road traffic, rail or air, industrial noise, etc.), the environment or the different vulnerability to noise pollution of population groups; they can be different from an existing situation to a new situation (when the acoustic emitter changes, or the use given to the environment).

4.3.7.3- Impact of water consumption and discharges

The combined cycle thermal power plants capture water for proper operation. The refrigeration of the re-powered plant will be done in the existing open circuit with seawater.

The thermal power plant, that has been upgraded, in its open circuit cooling will use the existing intake and discharge infrastructures as well as the cooling pumps of the current thermal power station.

The seawater will be pumped through GRP conduction for the cooling of the condenser. This heated water will be discharged back to the sea at an enough distance from the catchment to avoid recirculation of hot water.

The environmental impact of the cooling circuit of a plant will be minimal. It consists of the total thermal energy from the thermodynamic cycle of the steam turbine and the cooling of other auxiliary equipment of the Power Plant, which is evacuated to the sea and dispersed by the marine environment.

4.3.7.4- Applicable Legislation

The legislation applicable to air pollution is in Royal Decree 22/12/2017 number 1042/2017, which defines the rules on the limitation of emissions to the atmosphere of certain pollutants from large combustion plants.

The Royal Decree is also affected by:

- Development, in certain aspects referring to thermoelectric plants, by Order 1/7/2011.
- Article 4 has an addition and Annex III has been partially replaced by Royal Decree 20/3/2004 number 430/2004.
- The Royal Decree 23/12/2017 in its article 2, when defining combustion installation, explicitly excludes gas turbines.

Likewise, there is the following European legislation regarding environmental impact:

- Directive 1999/30 / CE of the Council of 03/22/99 on evaluation and management of the environmental air quality.
- Proposal for a Council Directive amending Directive 88/609 / EC on the limitation of emissions to the atmosphere of certain pollutants from large combustion plants (98 / c 300/04), submitted by the Commission on 8/31/98.
- IPPC Directive (Royal Legislative Decree 1/2016).
- Directive 2010/75 / EU. Limitation of GIC atmospheric emissions.
- Directive 2003/35 / CE (Resolution of 14/12/2016 of the Ministry of the Environment) National caps of emission SO₂, NO_x, VOC and NH₃.

Kyoto Protocol (decision 406/2009 / CE) Directive 2009/29 / EC on trade in greenhouse gas emission rights.

Combined cycle power plants use clean fuels such as natural gas, which, compared to conventional electric generation facilities, achieves a significant reduction in liquid effluents and pollutants.

Seawater from the open circuit cooling system will not be subjected to any previous treatment, minimizing the production of contaminated effluents.

The characteristics of industrial effluents in combined cycle power plants, unlike other industrial processes, are no necessity to have complex treatment facilities.

Effluents can be grouped into four categories, for collection and treatment separately:

1. Effluents produced from the process (for example rejects of the demineralization system, purge of boilers).
2. Cooling water.

3. Effluents with residues.
4. Sanitary Waters.

Moreover, there are two more differentiations for effluents, the ones which must be treated and the ones that don't have to:

1. **Cooling effluent that does not require treatment.** It is not contaminated and is characterised by being the same as sea water, although with a higher temperature due to the cooling of the condenser.
2. **Industrial effluent of the plant that will undergo treatments.** It contains sanitary waters, effluents from the process and other effluents that may contain oily residues.

5- CONCLUSION

It is true that some utilities may have contemplated the replacement of coal power plants into combined cycle power plants. In terms of available sources of energy proven coal reserves are estimated to last for about 200 years, much longer than oil. However, the pollution of coal power plants is still high and, therefore, the idea of a combined cycle with gas turbine and steam turbine is a good option.

Electricity demand continues to grow and in order to meet this demand, several distributed renewable resources (such as wind farms and solar power plants) have become very frequent. The coal thermal power plant of Litoral de Almería consists of two groups, the first one which was commissioned in 1985 and the second one was put into operation twelve years later in 1997. Natural gas is available in Almería since Medgaz gas pipeline was put into service in 2011 and there is also a gas pipeline connecting Almería province with Murcia province (run by the company Enagas). In order to increase the power range of the old Group 1 as well as its efficiency, the replacement of Group 1 into a 1x1 SS combined cycle power plant is proposed in this work. This 1x1 SS combined cycle would include an innovative gas turbine with a firing temperature (TIT) of 1447°C and a combined cycle net efficiency of up to 63.5%. The HRSG would include 3 pressure drums with reheaters with an inlet temperature of 632°C of the exhaust gases and an outlet temperature of the gases that exit the HRSG towards the stack with 83°C.

The proposed steam turbine has four bodies with an estimated shaft power of 206MW which in addition to the approximate 434MW of the gas turbine results in a combined shaft power of 640MW. The proposed electrical system connecting the new generator to the grid consists of IPB (isolated phase bus) three single-phase power transformers, 400kV-20kV as described in 4.3.6.

The proposed 1x1 SS combined cycle reduces considerably the pollution compared with that of the existing Group 1 as indicated in the section 4.3.7.

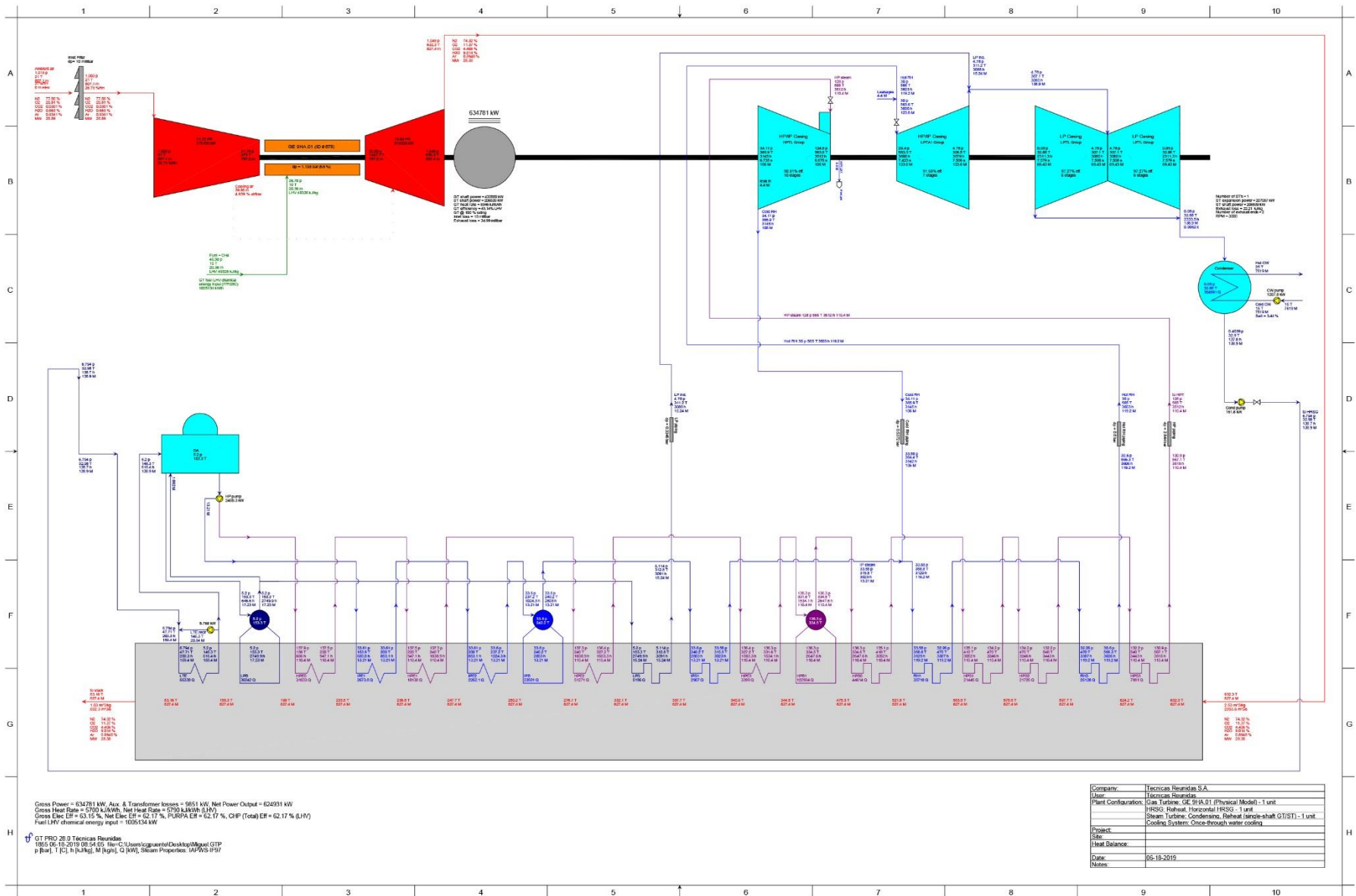
Finally, for group 2 of the Litoral de Almería, as it was put into operation in 1997, its replacement is still not considered in this work. However, the Metering Gas Station has been designed for a hypothetical future supply to the new Group 2 with the possibility of expanding the space for the gas pipeline and for the existing Water Treatment Plant (WTP) and the Wastewater Treatment Plant (WWTP) if necessary.

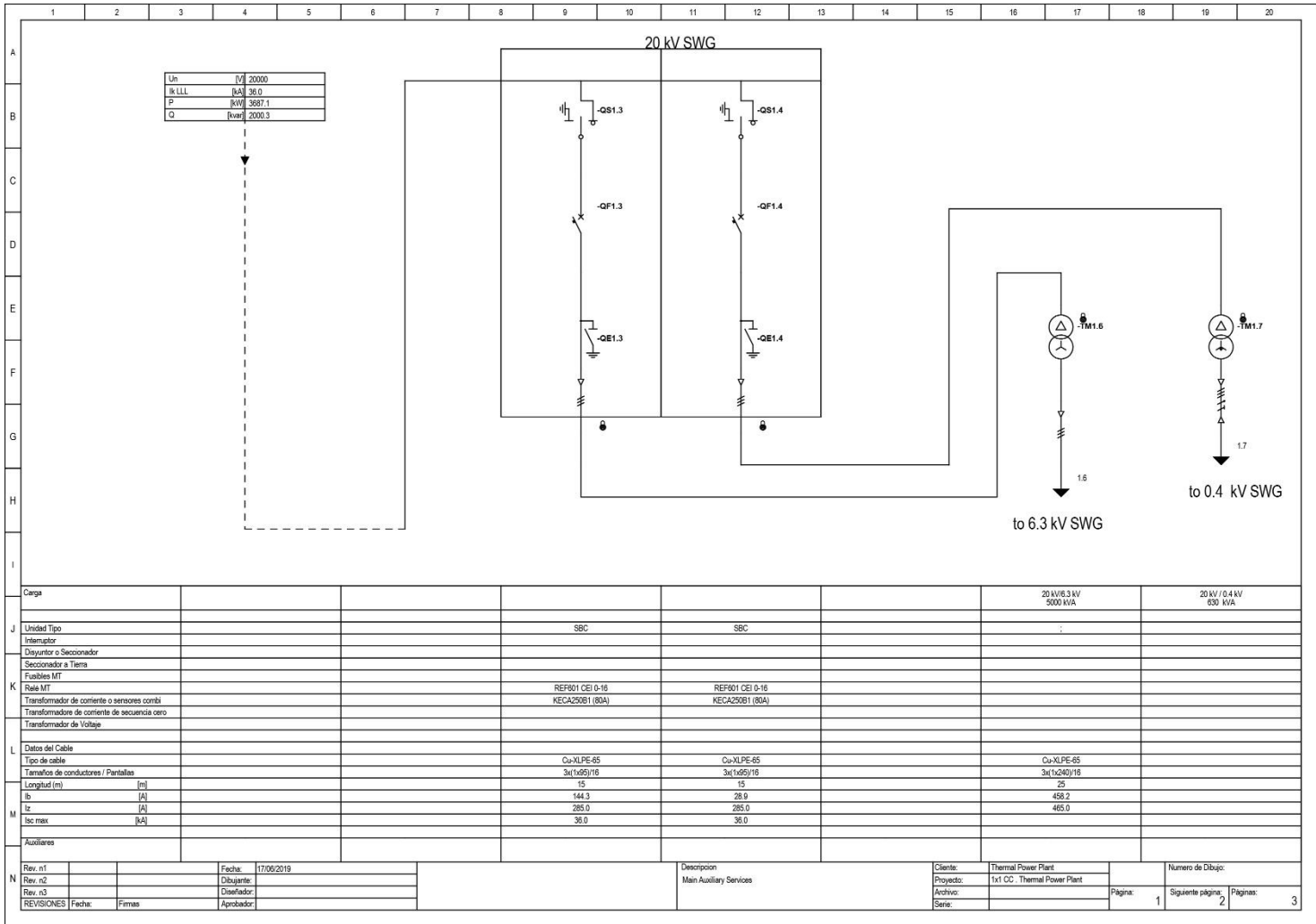
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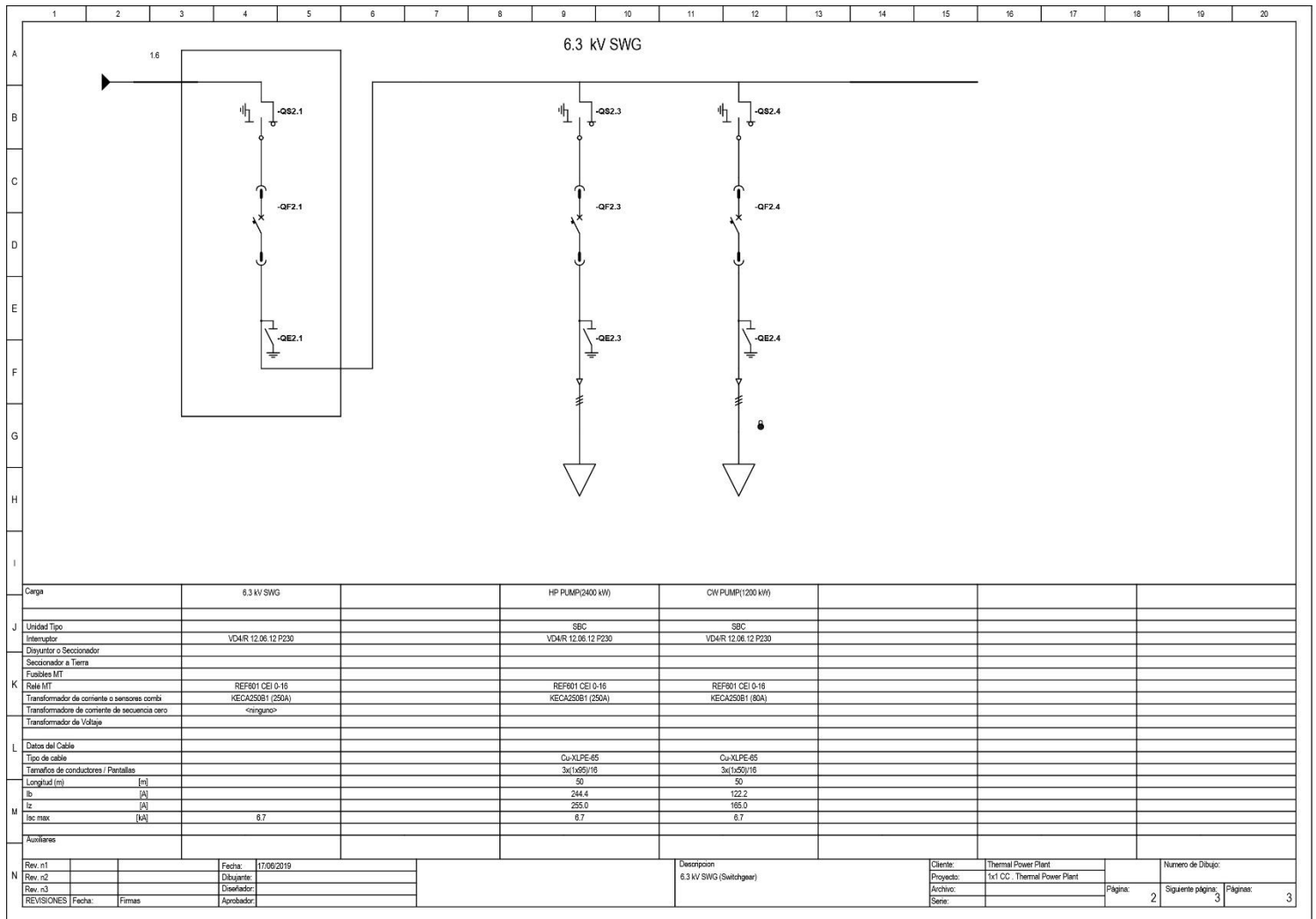
- Unión Fenosa Generación: “Curso de introducción práctica a las centrales de ciclo combinado”
- “Cuaderno de transmisión de calor de la sección de publicaciones de la ETS Ingenieros Industriales Universidad Politécnica de Madrid”
- General Electric 9HA fact sheet: <https://www.ge.com/power/gas/gas-turbines/9ha>
- Ares Asia heat value of coal: <http://www.aresasialtd.com/en/our-business/coal-trading/coal-specifications.html>
- CO2 emission nuclear power stations: <https://timeforchange.org/co2-emission-nuclear-power-stations-electricity>
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- FERC efficiency value for CHP applications: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies_appendix_a_expressing_chp_efficiency.pdf
- State Registry of Emissions: <http://laotraandalucia.org/?p=32533> and http://www.prtr-es.es/informes/fichacomplejo.aspx?Id_Complejo=3191

- Agencia del Boletín Oficial del Estado: <https://www.boe.es/>
- European Legislation on environmental impact: <https://www.miteco.gob.es/en/calidad-y-evaluacion-ambiental/temas/evaluacion-ambiental/legislacion/default.aspx>

7- ANNEX

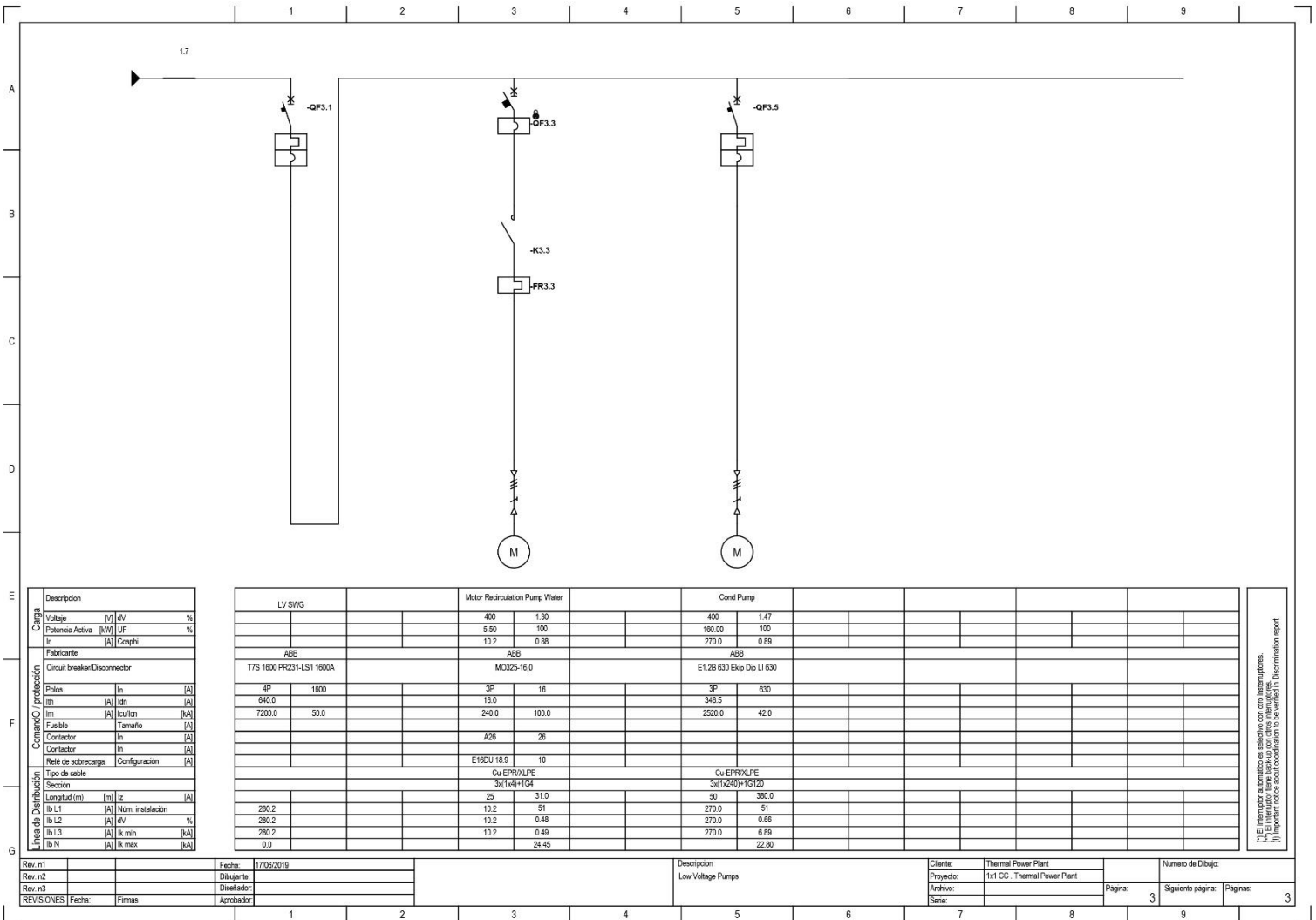






Carga	6.3 kV SWG	HP PUMP(2400 kW)	CW PUMP(1200 kW)		
Unidad Tipo		SBC	SBC		
Interruptor	VD4R 12.06.12 P230	VD4R 12.06.12 P230	VD4R 12.06.12 P230		
Disyuntor o Seccionador					
Seccionador a Tierra					
Fusibles MT					
Relé MT	REF001 CEI 0-16	REF001 CEI 0-16	REF001 CEI 0-16		
Transformador de corriente o sensores combi	KECA250B1 (250A)	KECA250B1 (250A)	KECA250B1 (80A)		
Transformador de corriente de secuencia cero	<ninguno>				
Transformador de Voltaje					
Datos del Cable					
Tipo de cable		Cu-XLPE-65	Cu-XLPE-65		
Tamaño de conductores / Pantallas		3x(1x50)/16	3x(1x50)/16		
Longitud (m)	[m]	50	50		
Ib	[A]	244.4	122.2		
Iz	[A]	255.0	165.0		
Isc max	[kA]	6.7	6.7		
Auxiliares					

Rev. n1		Fecha:	17/06/2019	Descripción	6.3 kV SWG (Switchgear)	Cliente:	Thermal Power Plant	Numero de Dibujo:	
Rev. n2		Dibujante:				Proyecto:	1x1 CC. Thermal Power Plant		
Rev. n3		Diseñador:				Dossier:		Página:	2
REVISIONES	Fecha:	Firmas	Aprobador			Serie:		Siguiente página:	3
								Página:	3



Description	
Carga	
Voltaje [V] dV	%
Potencia Activa [kW] LUF	%
I _r [A] Cough	
Fabricante	
Circuit breaker/Disconnector	
Comando/ Protección	
Polos	In [A]
Ip [A]	Idn [A]
I _m [A]	I _{cu} /I _m [kA]
Fusible	Tamaño [A]
Contactor	In [A]
Contactor	In [A]
Relé de sobrecarga	Configuración [A]
Linea de Distribución	
Tipo de cable	
Seccion	
Longitud (m) [m] Lr	[A]
I _b L1 [A]	Num. instalacion
I _b L2 [A]	dV
I _b L3 [A]	I _k min [kA]
I _b N [A]	I _k max [kA]

LV SWG	Motor Recirculation Pump Water		Cond Pump		
	400	1.30	400	1.47	
	5.50	100	160.00	100	
	10.2	0.68	270.0	0.69	
ABB		ABB		ABB	
T7S 1600 PR231-LS1 1600A		M032S-16.0		E1.2B 630 Ekip Dep LI 630	
4P	1800	3P	16	3P	630
640.0		16.0		348.5	
7200.0	50.0	240.0	100.0	2520.0	42.0
		A26	26		
		E180U 18.9		10	
		Cu-EPR/XLPE		Cu-EPR/XLPE	
		3x(1x40)+1G4		3x(1x240)+1G120	
		25	31.0	50	360.0
280.2		10.2	51	270.0	51
280.2		10.2	0.48	270.0	0.66
280.2		10.2	0.49	270.0	0.69
0.0			24.45		22.80

C: El interruptor automático es adecuado con otros interruptores.
 I: Important notes about coordination to be verified in Discrimination report.

Rev. n1		Fecha:	17/06/2019	Description:	Low Voltage Pumps	Cliente:	Thermal Power Plant	Numero de Dibujo:	
Rev. n2		Dibujante:				Proyector:	1x1 CC - Thermal Power Plant		
Rev. n3		Diseñador:				Arhivo:		Página:	3
REVISIONES	Fecha:	Firmas:	Aprobador:			Señe:		Siguiente página:	Página: