Electronic Supplementary Material (ESI) for Environmental Science: Water Research & Technology.

Guide for identifying power plants using Satellite photographs.

Introduction:

During the inventory of power plants to estimate the water footprint, there is usually the need to identify power plants using satellite images or photographs. Depending on the detail of the required analysis, the simple categorization of power plants (thermal, hydro, biomass, solar, etc.) is not enough, and individual power plants need to be categorized into more specific groups. This guide provides examples of how the different structural buildings and auxiliary items look from above.

Thermal Power Plants

Thermal power plants include any infrastructure that uses the heat delivered by a source of energy to move a fluid so that it can move a turbine. Thermal power plants include fossil-fueled (coal, gas, oil), biomass-fueled and nuclear power plants.

These power plants can be classified based on the different implications of water usage. In the scientific literature, it is common to cluster thermal power plants based on the fuel they use (coal, gas, oil, nuclear, etc.). However, regarding water usage, it is more insightful to make a classification based on the thermodynamic cycle of the thermal power plant (Rankine, Gas, Internal Combustion Engines). Furthermore, it is crucial to make an additional distinction between power plants based on their cooling system and fuels.

This guide will first describe the difference in the visible structures between the types of thermal power plants. This section will give guidelines to differentiate between the main building (machine room) and auxiliary infrastructure of the three thermodynamic cycles used for power generation. Then, this guide will provide examples of how to differentiate the types of cooling systems used for each thermodynamic cycle. Finally, additional examples will be provided to show the changes in the infrastructure that is caused due to the different fuels each thermodynamic cycle can use.

Rankine Power Plants

The Rankine is a closed-loop thermodynamic cycle in which a working fluid is heated above the boiling point to produce overheated vapour. This vapour will move a turbine coupled to a generator to produce electricity. Figure 1 shows the scheme of the cycle.

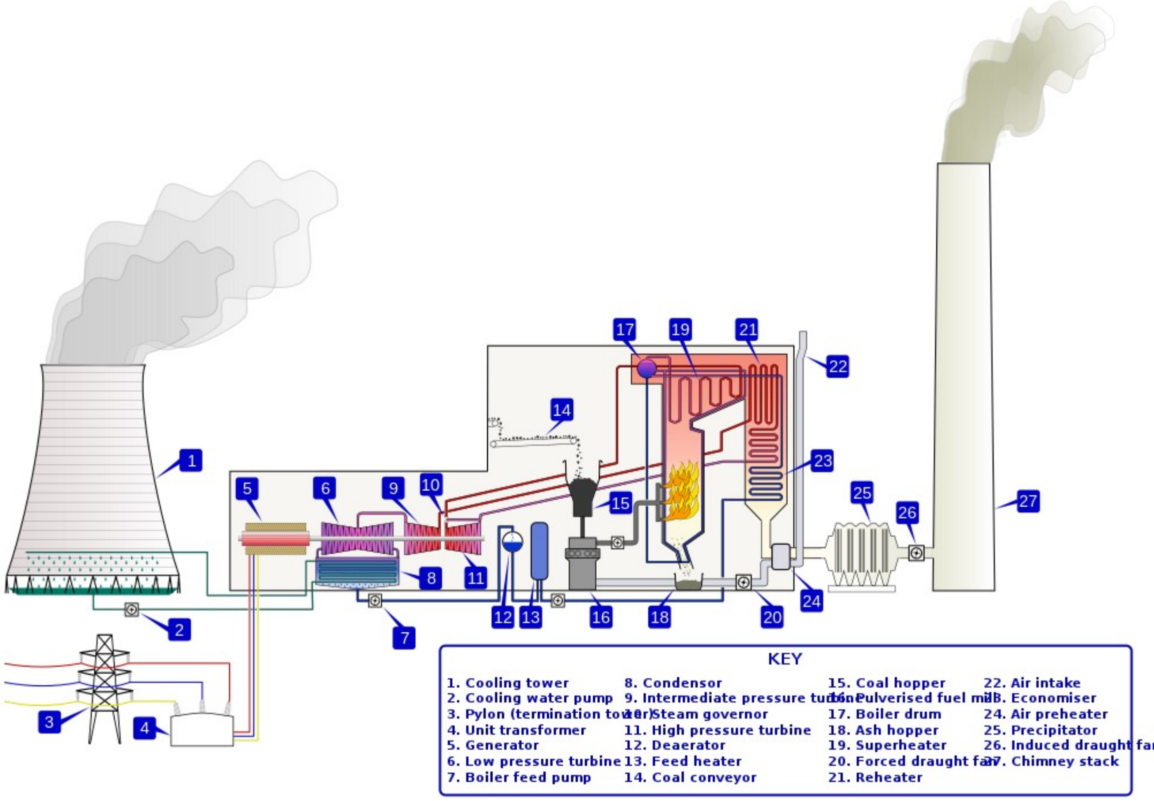


Figure 1. Schematics of the Rankine Thermodynamic Cycle for power generation (Attribution and license *<u>here</u>*)

Visible infrastructure that differentiates the Rankine thermodynamic cycle of thermal power plants

Regarding infrastructure, these types of power plants will differ from their counterparts in the boiler. For the power plant to transfer enough heat from the fuel to the working fluid, the boiler must be massive compared to the main building (machine room). Figure 2 shows a) the schematics and b) a picture of a typical boiler for these power plants (water tube boiler).

a) Schematics of the boiler b) Picture of the boiler

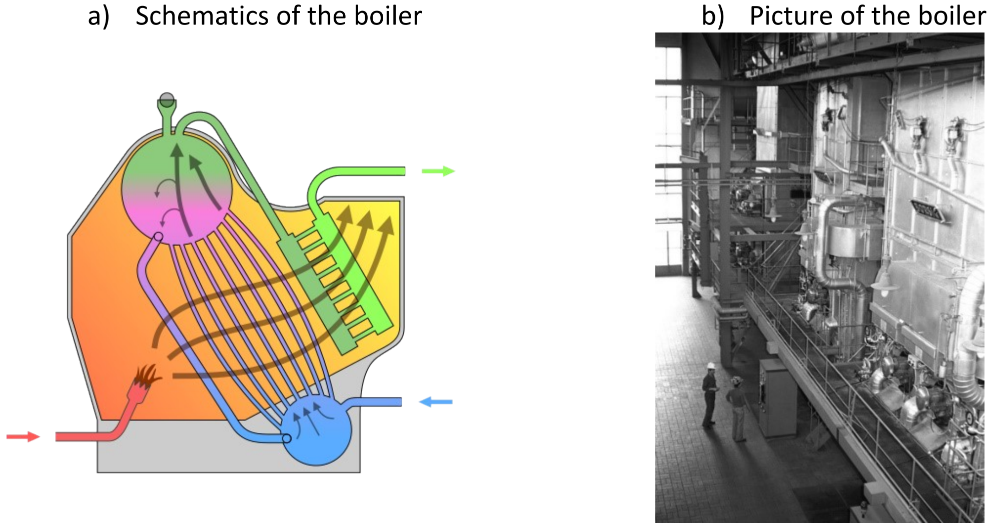
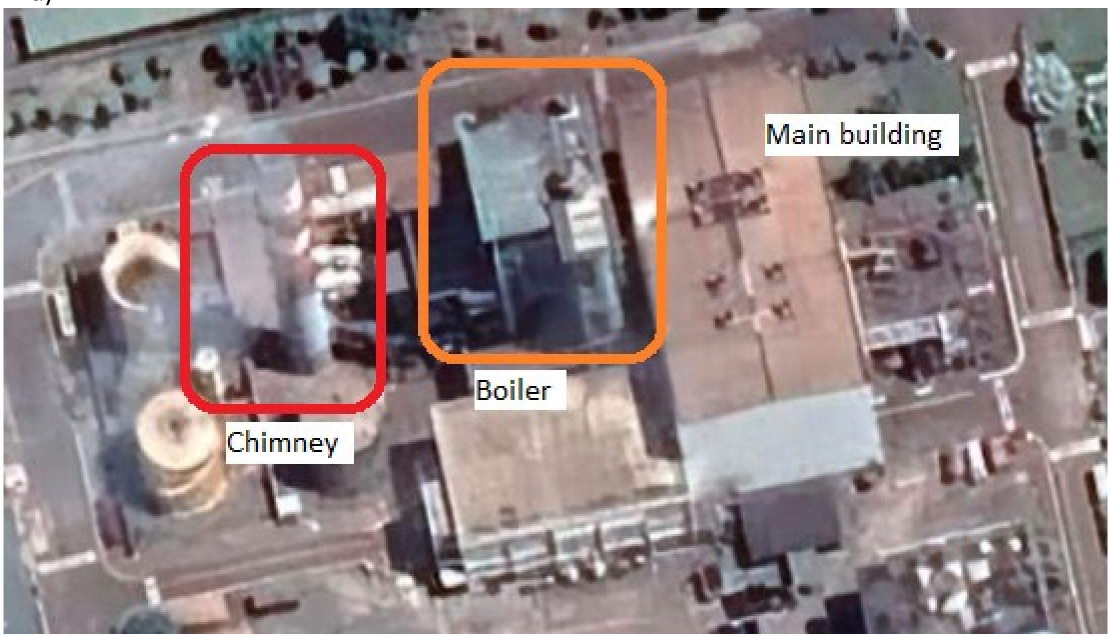


Figure 2a-b. Schematics and the picture of a high-pressure boiler (water tube boiler).

Moreover, from above, the satellite picture of these power plants should show an extensive infrastructure, with chimney(s) next to the main building, as shown in Figure 3a-b. It is worth mentioning that the boiler should be outside the main building, and probably a few stories bigger than the other buildings.

a)



b)

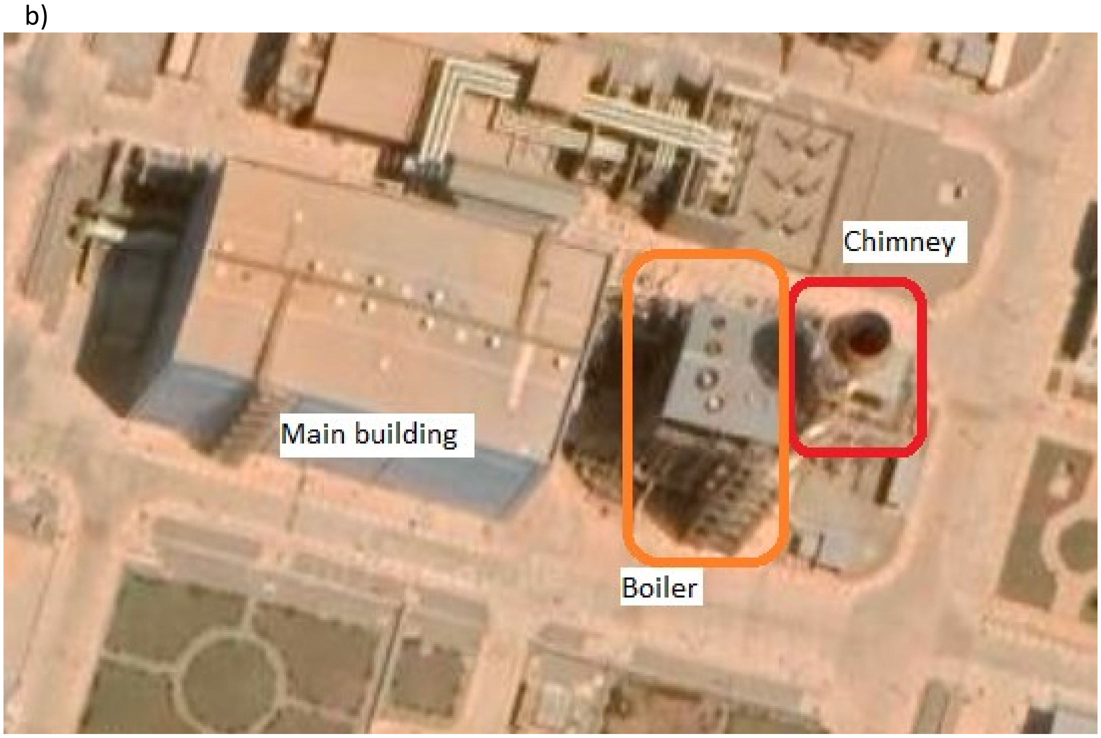


Figure 3a-b. Examples of the infrastructure seen in Satellite Images of Rankine power plants.

The visible infrastructure of the cooling systems that can be used in Rankine power plants

Rankine power plants need active cooling as the working fluid is in a closed loop. The condenser introduces the cooling fluid, which cools the vapour into liquid. Three cooling systems can be used for this purpose: once-through cooling (open loop), cooling towers (close loop), and dry cooling (close loop).

Once-through cooling is a system that withdraws large amounts of water to pass it through the power plant's condenser. In the satellite images, the most visible infrastructure is the inlet and outlet of the system, as shown in Figure 4a-b. At least one of them should be visible from above. The outlet should be easiest to spot as power plants make the water pass certain obstructions to help decrease its temperature before reaching the body of water.

a) Inlet and outlet observed

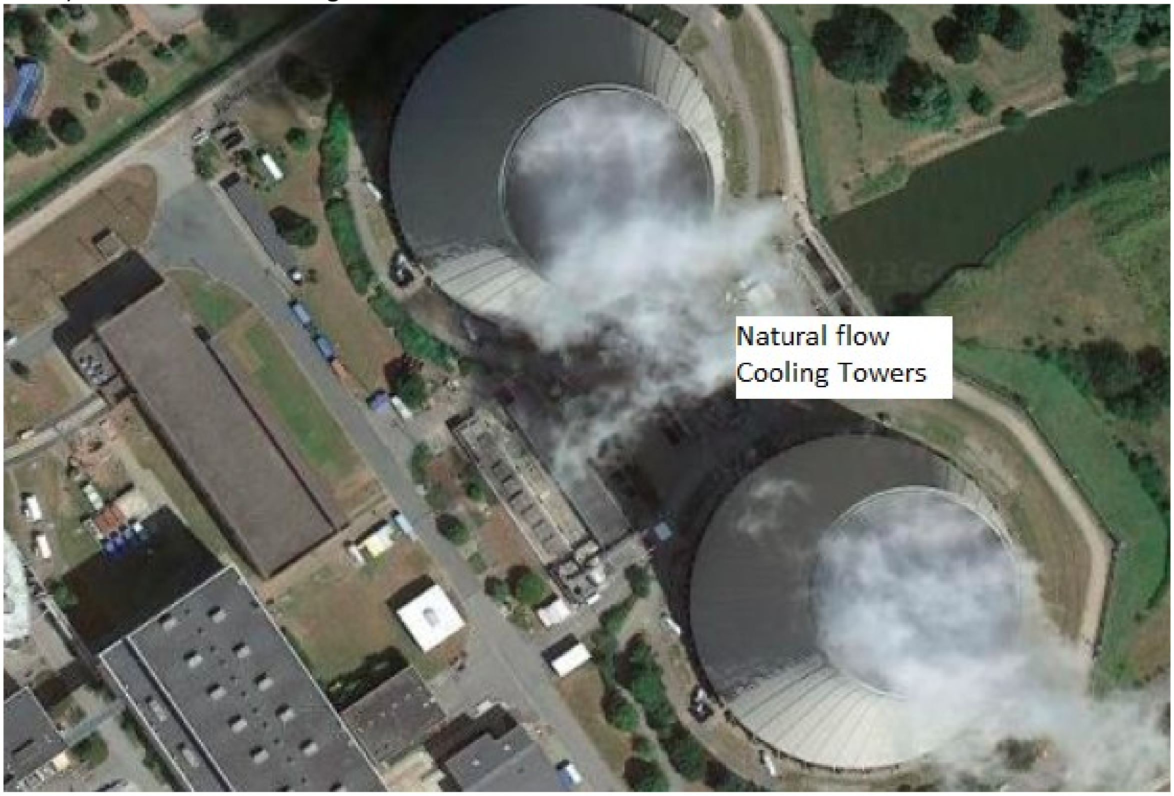
b) Only outlet observed

Figure 4a-b. Examples of the infrastructure seen in Satellite Images of Once-through Cooling Systems.

Most of the cases, these systems are near a large body of water (namely sea, lake, river, etc.) because the water required for the cooling is ample.

The cooling tower is a system that aims to be water-efficient, so it recirculates the cooling water through an additional cooling system (wet tower) to decrease the cooling water temperature near its original value. By doing this, the system does not require to withdraw large volumes of water. In the satellite images, the most visible infrastructure is these wet towers. Two types of cooling towers can be observed: natural and forced flow. Natural flow cooling towers are larger than forced flow as they do not require fans to move air through the towers. Figure 5a) natural and b) forced flow cooling towers.

a) Natural flow cooling towers



b) Forced flow cooling towers

Figure 5a-b. Examples of the infrastructure seen in Satellite Images of Natural and Forced Flow Cooling Towers.

The system requires make-up water because the cooling tower evaporates large volumes of water. In this sense, the power plants should be close to a water source (a body of water like rivers, lakes, or canals). Nonetheless, there are cases in which smaller power plants use groundwater for the cooling system. In these cases, the infrastructure that can be seen from above is the inlet of groundwater, as shown in Figure 6.

Figure 6. Example of the infrastructure seen in Satellite Images of groundwater-fed cooling towers.

Dry cooling is a system that aims to use air, instead of water, as the cooling fluid. With this change, the system does not require to withdraw or consume large volumes of water but only depends on a closed-loop system of coolant (usually water-based) that removes heat from the power plant, just like a car's cooling system. In the satellite images, their most visible infrastructure is the rack of ventilators. Figure a-b shows examples of dry cooling systems.

a)

b)

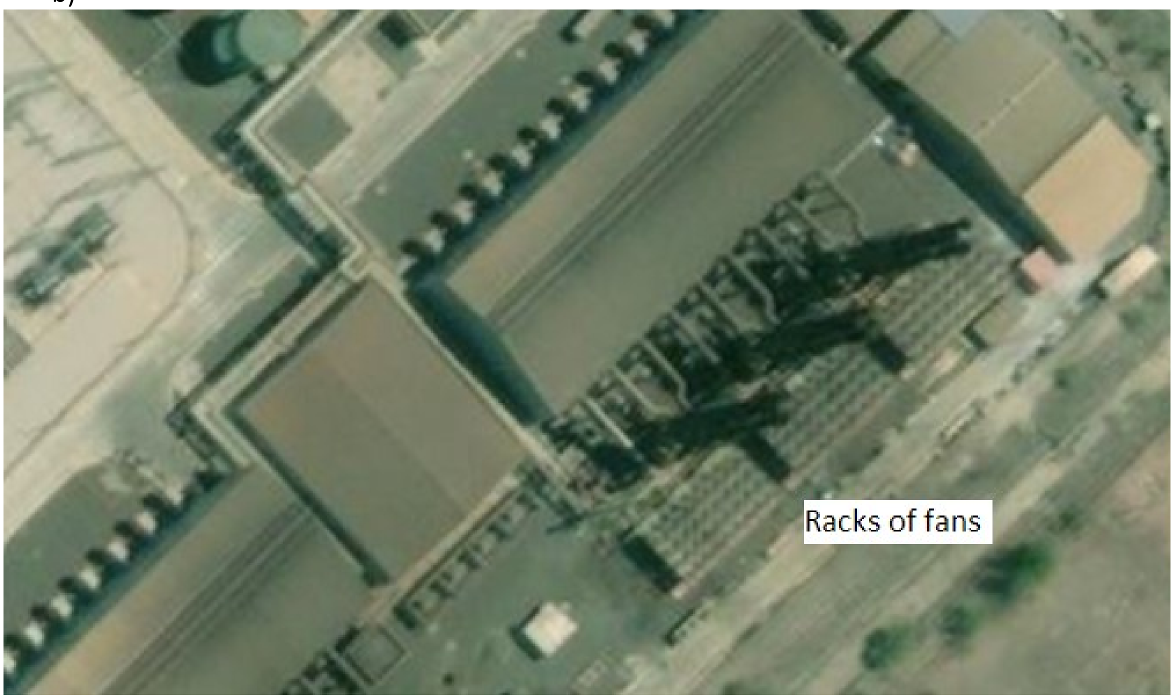


Figure 7a-b. Examples of the infrastructure seen in Satellite Images of Dry Cooling systems.

It is possible to confuse the racks of fans of dry cooling systems with a forced flow wet tower. However, the fans' racks are usually smaller than cooling towers, with more fans per cooling area, and if you see it from a side, you can see that the fans' racks do not have the same height (or depth) as cooling towers.

Visible infrastructure of the Fuel types

Figure 8a-e shows the visible infrastructure of Rankine power plants that indicates the primary fuel type of these power plants. It is worth noting that there are critical differences between the fuel sources. For coal, the power plant requires a large space where the coal that will be burnt is stored, as shown in Figure 8a; for gas, the power plant requires a distinctive set of spherical-shaped tanks, as shown in Figure 8b; for oil, the power plants require standard cylindrical-shaped storage tanks, as shown in Figure 8c; and for biomass, most of the power plants also require a large physical space to store the biomass source (woody biomass or residues), as shown in Figure 8d. Nuclear power plants are different from other thermal power plants as the fuel source requires almost insignificant space. However, the way to differentiate these types of power plants is by the infrastructure of the nuclear reactor, which should be in the same place where the boiler must be in the other thermal power plants. This reactor usually has a circular or spherical, shaped dome, and a small chimney, as shown in Figure 8e.

a) Coal-fueled power plants

b) Natural gas-fueled power plants

c) Oil-fueled power plants

d) Biomass power plants

e) Nuclear power plants

Figure 8a-e. Examples of the infrastructure seen in Satellite Images of different fuels used in Rankine power plants.

It is worth mentioning that natural gas, or biogas, is not commonly used for Rankine power plants because these fuels are more efficiently used in Brayton Internal Combustion Engines power plants.

Brayton Power Plants

The Brayton is an open loop thermodynamic cycle in which a working fluid is heated, due to combustion, to produce a mix of gases. This mix will move a turbine coupled to a generator to produce electricity. Figure 9 shows the scheme of the cycle.

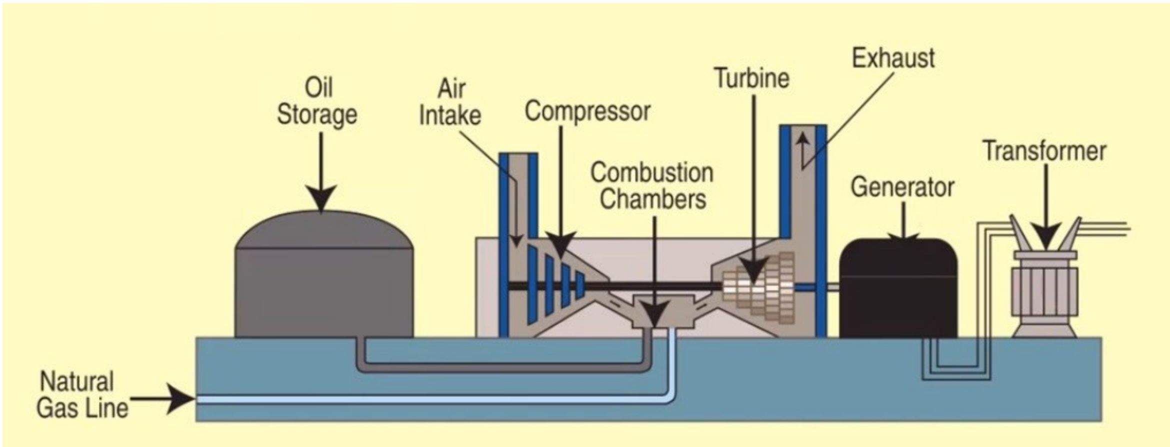


Figure 9. Schematics of the Brayton Thermodynamic Cycle for power generation

It is essential to clarify that even when the Brayton thermodynamic cycle works with a gas turbine, it does not mean that the fuel needs to be initially in gaseous form (namely, natural gas). Some cases of Brayton power plants use diesel, gasoline, oil, or other fuels. In those cases, the compressed gas is air, and the gas used to move the turbine is air plus combustion gases.

Visible infrastructure that differentiates the Rankine thermodynamic cycle of thermal power plants

Considering that the most crucial part of the thermodynamic cycle is the combustion chamber, in terms of infrastructure, these types of power plants will differ from their counterparts, mainly in the air intake. For the working fluid to have enough energy, the fuel must combust with enough air, so the air intake must be larger than other sections of the infrastructure of the main building (machine room). Figure 10 shows the schematics of the Brayton cycle, in which the air intake's size is shown compared to the rest of the components of the system.

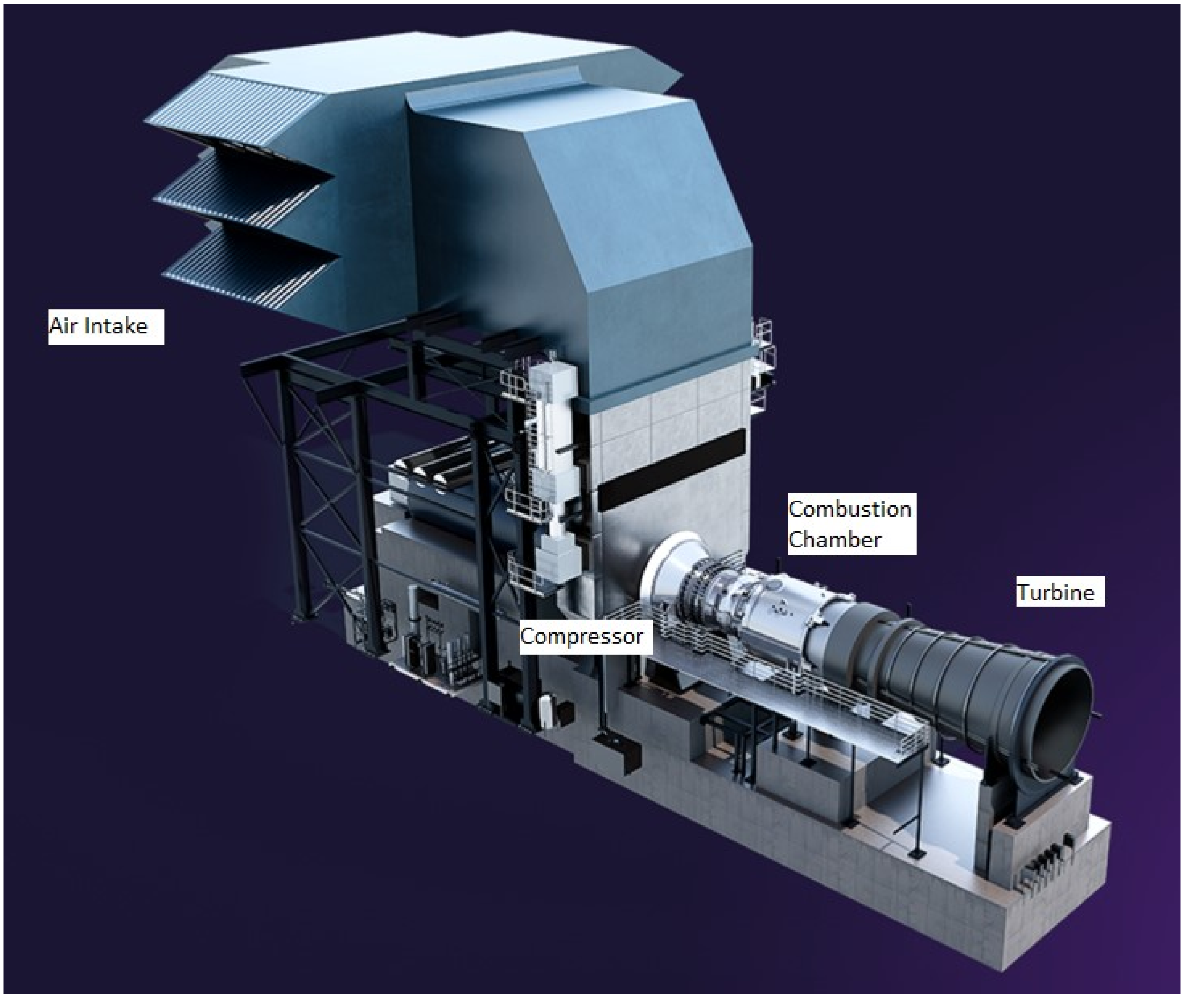
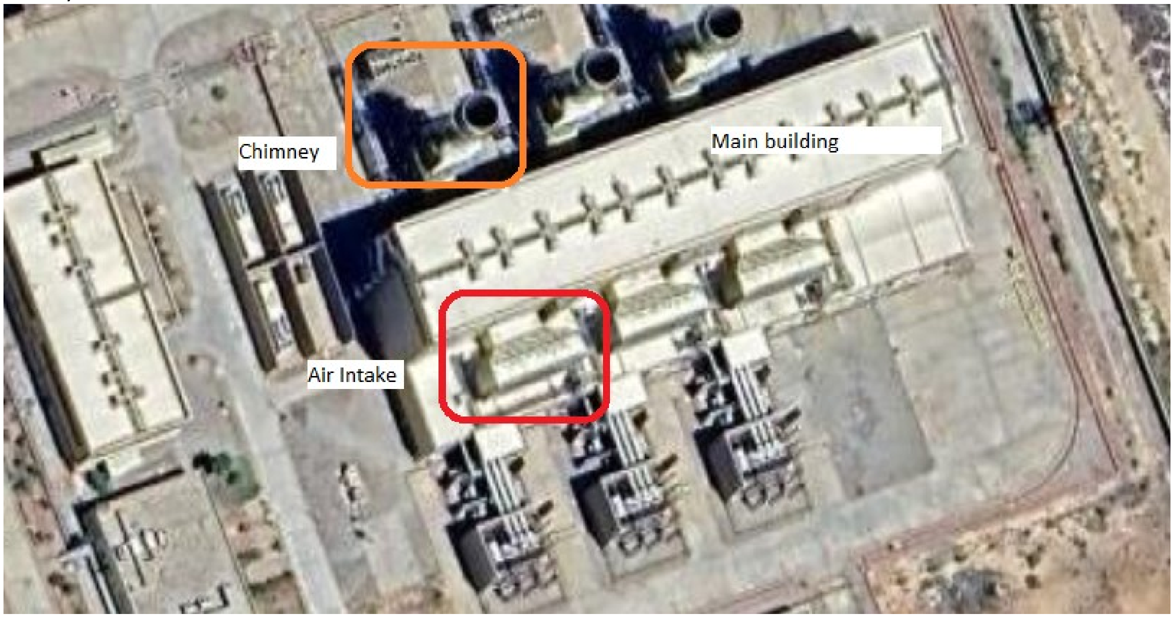


Figure 10. Schematics of a Brayton cycle Power Plant, in which the air intake is shown.

In practice, these air intakes are significantly larger than the rest of the infrastructure surrounding the power plant, as seen in Figure 11a.b.

a)



b)

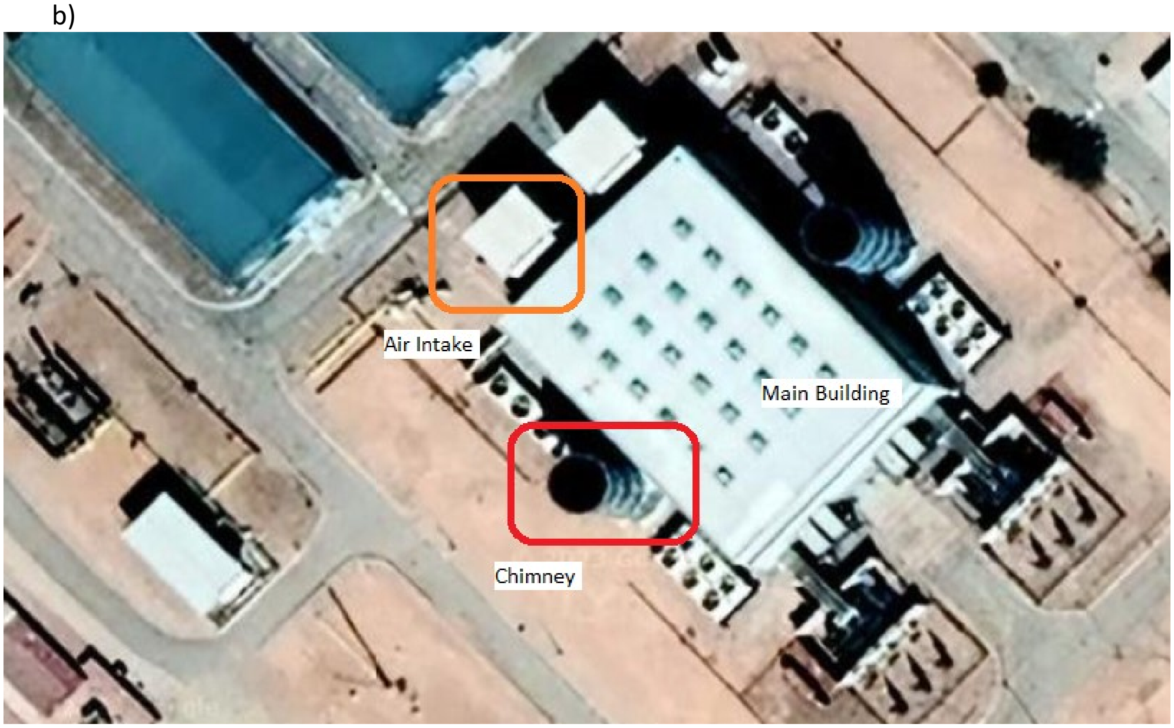


Figure 11a-b. Examples of the infrastructure seen in Satellite Images of Brayton power plants.

Additionally, the lack of the boiler infrastructure in a thermal power plant is also a giveaway that the system may be a Brayton system.

Visible infrastructure of the cooling systems that can be used in Brayton power plants

Considering the open loop cycle of the Brayton systems, these power plants are usually self-cooling systems. The air that enters the cycle is in charge of cooling the system.

Visible infrastructure of the Fuel types

The fuels most used for the Brayton systems are natural gas and diesel. In both cases, the infrastructure seen in the Satellite images is the same as discussed for Rankine Systems.

Combined Cycles

When Brayton power plants are combined with Rankine power plants, they create Combined Cycle Power Plants. The idea for this combination is to take advantage of most of the energy (heat) of the combustion gases, so after the gases are passed through the gas turbine, they are used inside a boiler to produce steam that will be used to generate electricity using a steam turbine. Figure 12 shows the schematics of these power plants.

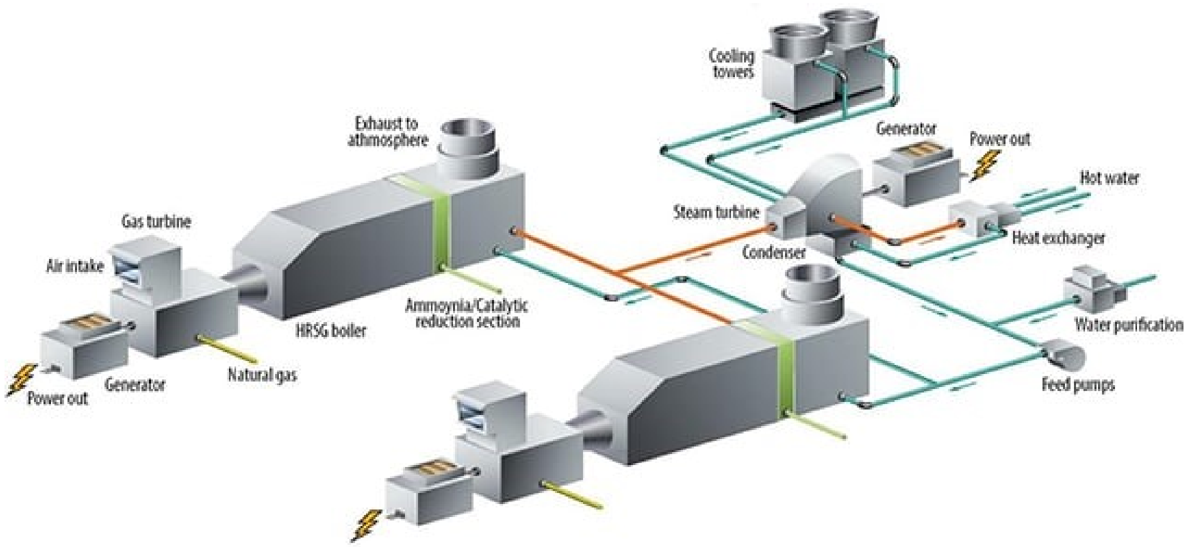


Figure 12. Schematics of the Combined Cycles (Brayton – Rankine) for power generation.

Visible infrastructure that differentiates the Combined Cycles thermal power plants

Because these power plants have two cycles in one power plant, it is possible to find infrastructure that was used as guidelines to differentiate both using Satellite images (the boiler in the case of the Rankine and the air intake in the case of the Brayton). In order to differentiate between these two types of power plants and the combined cycle, there is a need to look for the HRSG boiler connected with the gas turbine's exhaust. Figure 13 shows a picture of the combined cycle in which these components are identified.

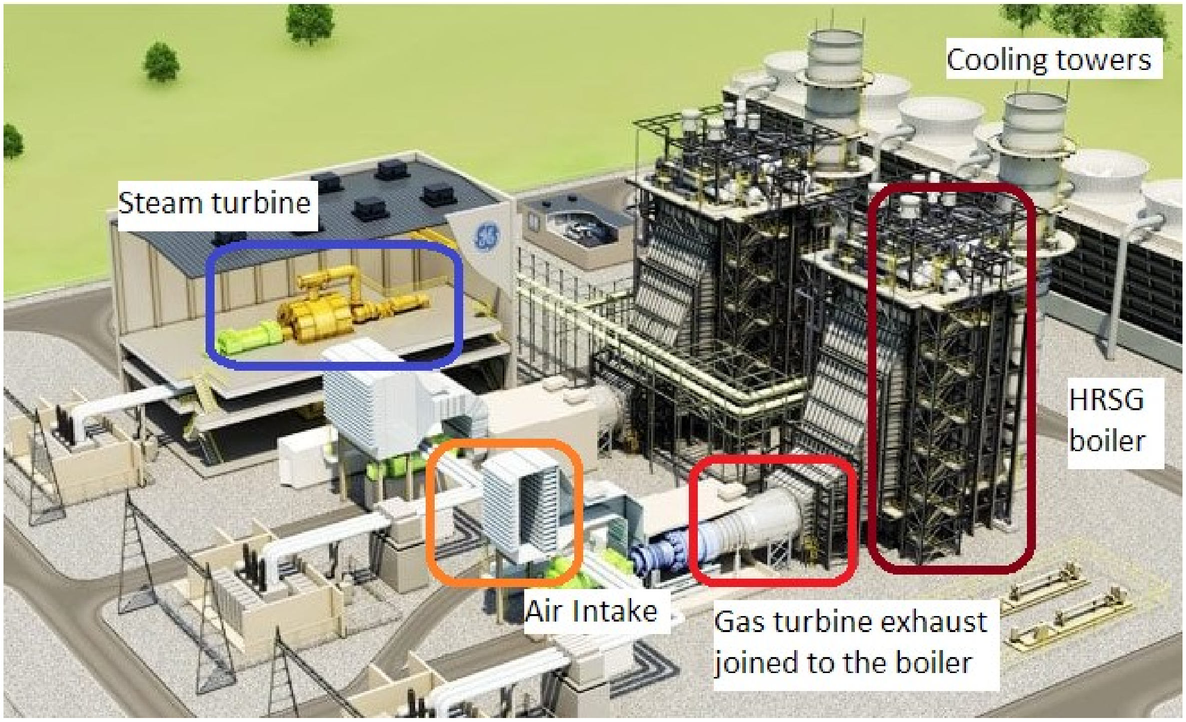
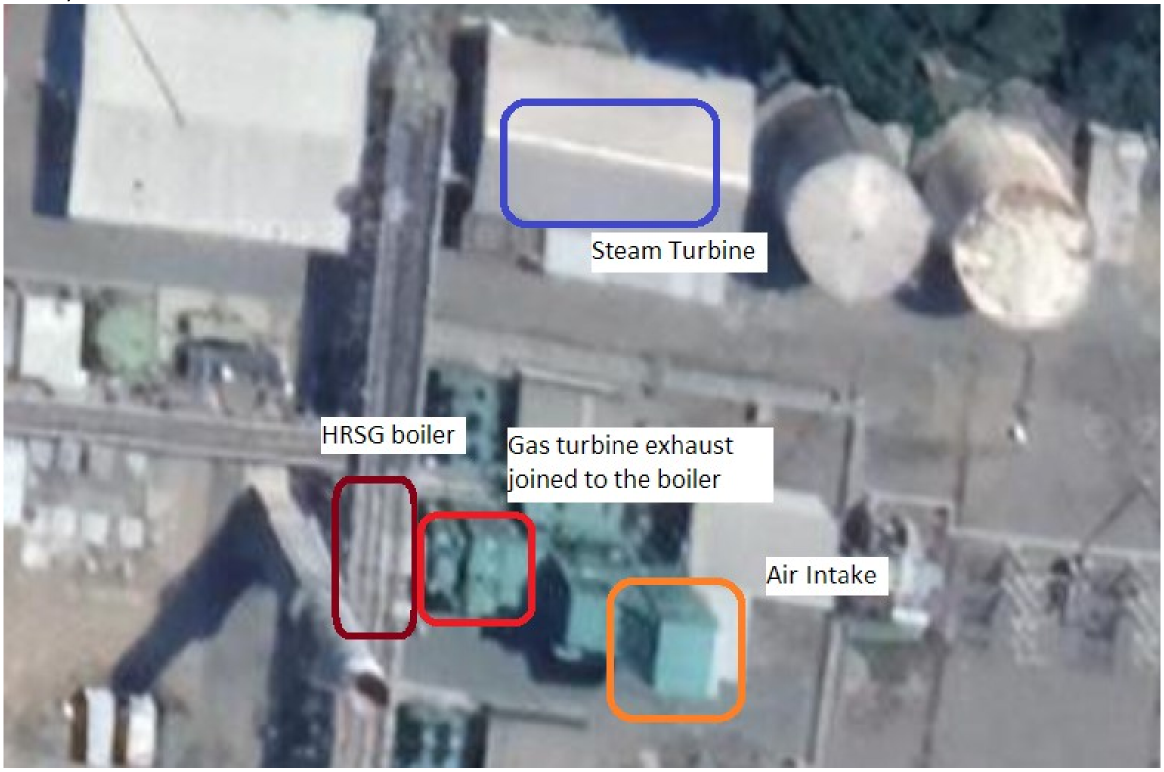


Figure 13. Schematics of a Combine cycles Power Plant, in which the air intake.

From above, the visible infrastructure should be easy to spot, as there is a large building for the steam turbine, and a smaller one for the gas turbine. Additionally, there are air intakes and HRSG boilers. Figure 14a-b shows two examples of Satellite images of these power plants.

a)



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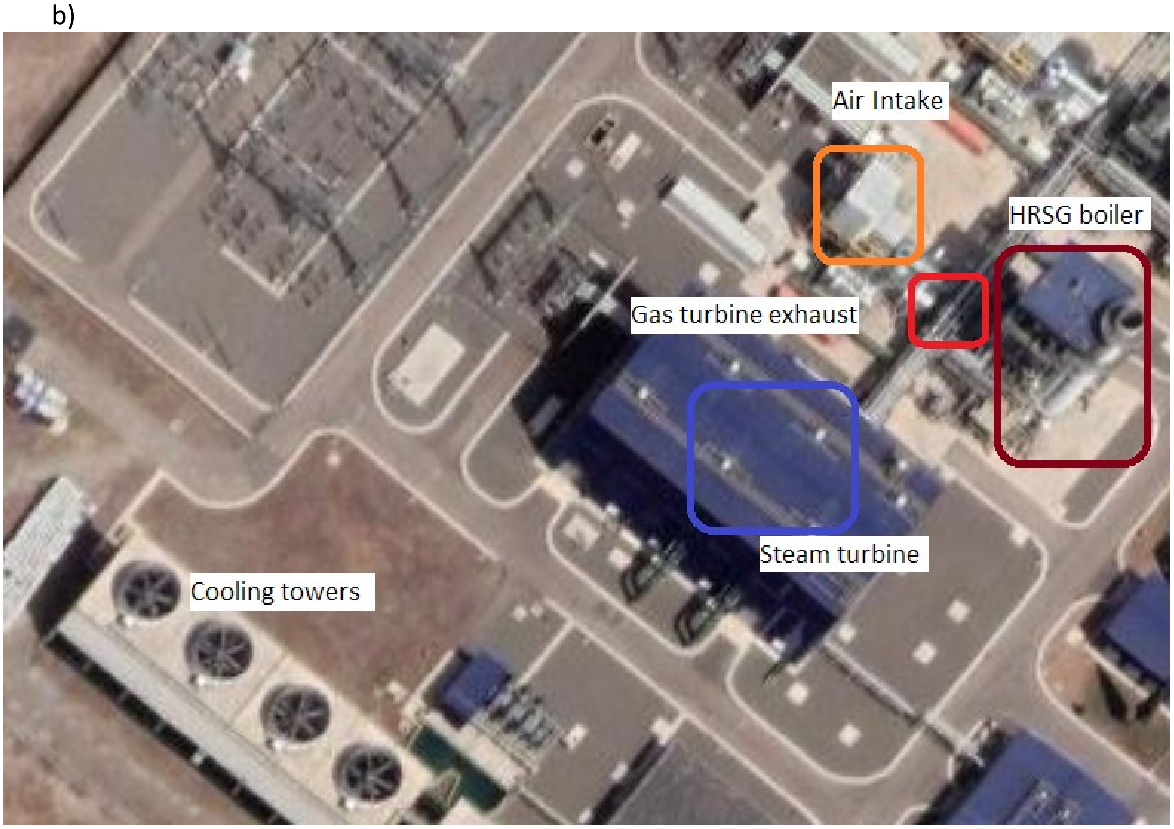

Figure 14. Examples of the infrastructure seen in Satellite Images of Combined Cycles power plants

Internal Combustion Engines

Internal Combustion Engines for power generation use the diesel thermodynamic cycle. This is a closed-loop cycle in which a piston inside the engine's combustion chamber performs the motion to rotate the shaft connected to the generator. Figure 15 shows the schematics of a diesel generation unit.

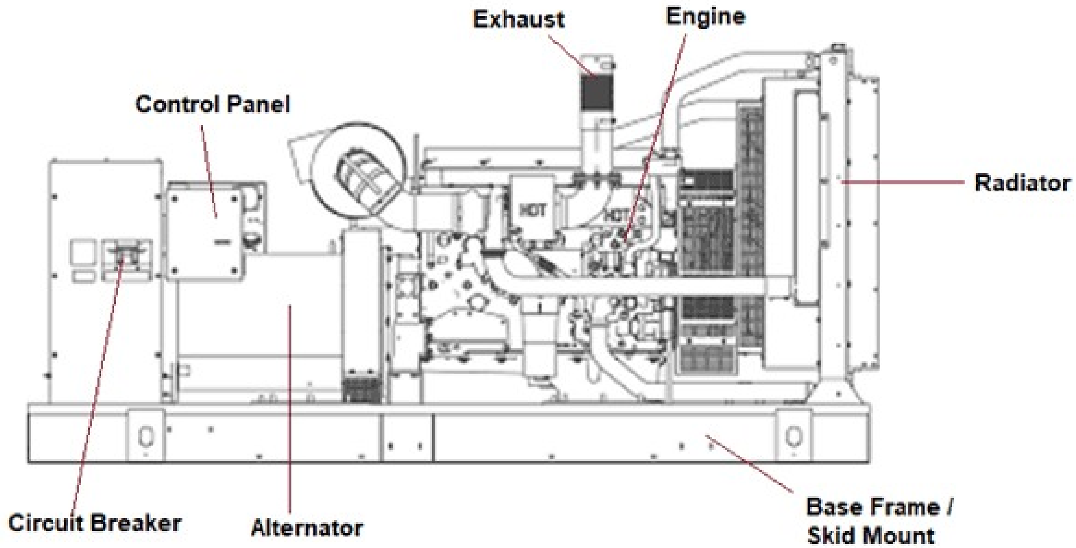

Figure 15. Schematics of the Diesel Cycle for power generation using Internal Combustion Engines

In this type of power plant, it is important to note that even when the thermodynamic cycle refers to diesel, it is not because the only fuel that works in these engines is diesel. These engines can use several liquid fuels, like oil and bunker.

Visible infrastructure that differentiates the Diesel thermodynamic cycle of thermal power plants

The main characteristic of these types of engines is their scalability. Usually, each unit does not generate a large amount of electricity. Thus, one power plant requires more units than Rankine or Brayton power plants to be comparable in size and production. When observed from the Satellite, these power plants will differentiate from their counterparts in the main building (machine room), as the picture will show a building with a few units with their chimneys, as shown in Figure 16a-b.

a)

b)

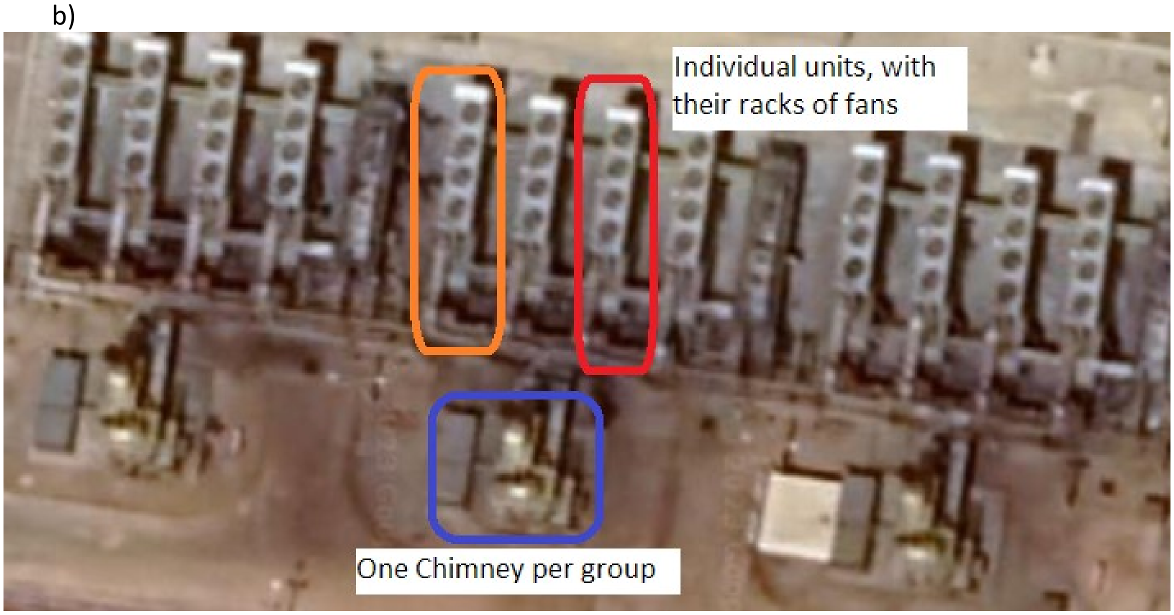

Figure 16a-b. Examples of the infrastructure seen in Satellite Images of Internal Combustion Engines power plants.

Visible infrastructure of the cooling systems that can be used in Brayton power plants

These power plants mostly use the dry cooling system.

Visible infrastructure of the Fuel types

The fuels most used for the Diesel cycle are liquid fuels, mainly oil derivatives such as diesel, bunker, Oil residue, etc. The infrastructure that can be seen in the Satellite images is the same as discussed for Rankine Systems.

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