THE PROCESS AND SIGNIFICANCE OF THERMAL POWER GENERATION

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Abstract. *This article explores the fundamental principles of thermal power generation, focusing on core components and functions in thermal power plants. It covers thermodynamics, the Rankine cycle, and heat transmission rules, with detailed examination of Rankine cycles and heat transfer mechanisms in plant components. It also discusses internal combustion engines, particularly diesel engines, and Advanced Exergy-Based Analyses in system analysis. These analyses aim to identify preventable exergy destruction sources and costs within components, with ongoing development addressing issues like validating exergy dissipation divisions. Synthesis methodologies include superstructure-based and superstructure-free approaches. The former uses a steam network to create a steam-cycle superstructure, integrating with a heat exchanger network for comprehensive flowsheets. The latter employs SYNTHSEP and ECH-based methods, with the ECH-based method excelling in comprehensive flowsheet synthesis and offering easy expansion with precise models. Both methods use bi-level decomposition techniques combining evolutionary algorithms and mathematical programming.*

Keywords: *Thermal Power Generation, Rankine Cycle, Internal Combustion Engines.*

Introduction

The term "Thermal Power Plant" is commonly used to describe a type of power station that generates electricity through Rankine/combined cycles that use working fluids and heat from diverse sources, such as fossil fuels, nuclear power, solar energy, and geothermal heat. For Rankine cycles with high-temperature heat sources and large-scale applications, water and steam are the most frequently used working fluids. For small-scale cycles with intermediate or low-grade heat, various organic fluids are utilised. According to the heat source, thermal power plants can be categorised as either coal-fired, nuclear, concentrated solar, geothermal, or any other type of alternative energy. Traditional thermal power plants, however, are those that run on fossil fuels like coal or natural gas. In particular, despite the present situation of rapidly expanding renewable power sources that produce less pollution, coal-fired power will continue to account for 40% of the world's total electricity output in 2020 (1). Furthermore, in order to accommodate the growing influx of intermittent renewable energy sources while ensuring the stability and security of the grid, it is anticipated that thermal power plants will adopt a flexible operation strategy that permits quicker load shifting (2). This transition should occur prior to the widespread availability and affordability of large-scale electrical storage technologies, such as power-to-gas. Consequently, thermal power facilities will continue to make the greatest contribution to the power generation sector for the foreseeable future (3, 4). **Figure 1** shows that these parts include things like turbines, condensers, cooling towers, pumps, chemical treatment, generators, transformers, conveyors, electrostatic precipitators, pulverizers, and boilers and superheaters. The following section provides a more detailed explanation of these parts and how they work (5).

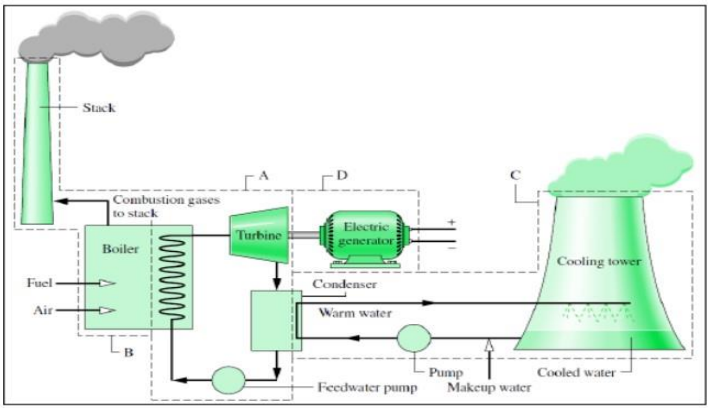

Figure 1. Parts of a power facility (5).

Nearly a century has been devoted to developing coal-fired power facilities, with material improvement milestones driving significant technological advancements (**Figure 2**). Ferritic steel suffices for main steam pressure around 250 bar and steam temperatures below approximately 580°C. Austenitic steel, constituting 20% of high-temperature components, enables steam temperatures of 620°C and steam pressure of 280 bar in superheaters, reheaters, and steam turbines. Combining Ni-based steel (20%) with austenitic steel (25%) allows plant operation with steam temperatures up to 720°C. Recent technological advancements aim to increase steam parameters (heat and pressure) and generating capacity beyond the gigawatt level.

Research and development efforts focus on sophisticated ultra-supercritical power plants, targeting steam temperatures above 700°C and pressures exceeding 350 bar, with a design efficiency expectation of around 50% (6).

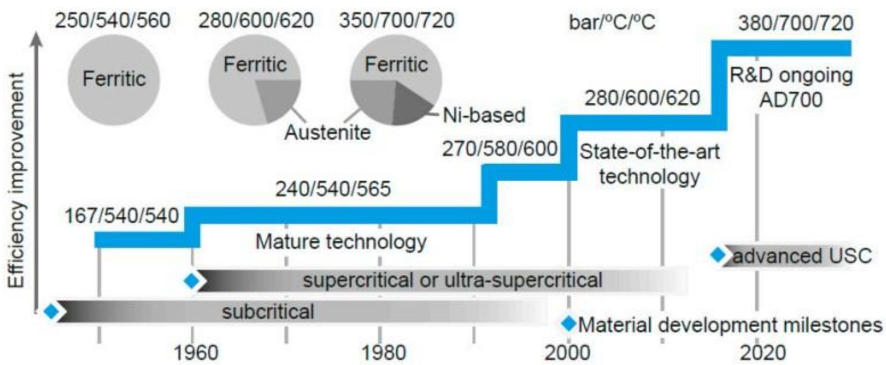

Figure 2. Improvements in pulverised coal power plant technology (7).

Traditional Rankine cycles are the basis of pulverized-coal power plants. The amount of heat that is absorbed ($T_{a,abs}$) and released ($T_{a,rel}$) by the working fluid are the two temperatures that define the ideal Rankine cycle efficiency (η_{ideal}):

$$\eta_{\text{ideal}} = 1 - \frac{T_{a,\text{rel}}}{T_{a,\text{abs}}}, \quad \text{(Equation 1.)}$$

Improved cycle efficiency relies on higher average heat absorption and lower average heat release temperatures. Heat emission temperature from condensing power stations depends on the environment. Increasing average heat absorption temperature is key to enhancing cycle efficiency, achievable through methods like elevating main and reheated stream temperatures, raising final feedwater preheating temperature, adding more feedwater preheaters, or employing multiple reheating.

Real-world Rankine-cycle coal power plants can enhance efficiency by raising main steam pressure and reducing thermodynamic inefficiencies like steam leakage and friction loss in turbines. Future coal-fired power stations consider these efficiency-enhancing design options (8, 9). Overheating of feedwater preheaters, particularly those that remove superheated steam from turbines following reheating, can occur, even though raising the temperature of the main and reheated steams might increase plant efficiency.

Furthermore, the degree of superheat in steam extractions suggests that the steam has not expanded completely, meaning that it has lost some of its work ability. A revised reheating technique, the Master Cycle (10), has been suggested to prevent feedwater preheaters from overheating and to guarantee that the extracted steams are fully expanded.

In order to drastically lower the superheat degrees of steam extractions, the Master Cycle proposes using a secondary turbine (ET) that takes in steam that has not been reheated, powers the boiler feed pump, and provides bled steam to feedwater preheaters. A secondary turbine could improve the overall system's optimal design, but this has received little research (11).

System-level integration poses new challenges. **Figure 3** illustrates the integration of several fluids with different temperature ranges: flue gas (130-1000°C), steam (35-700°C), feedwater (25-350°C), and air (25-400°C). One primary consideration is the necessity to increase heat utilisation to the level of the entire system.

However, this objective has not yet been realised owing to the separate designs of the turbine and boiler subsystems. Conversely, it becomes feasible to include numerous existing technologies or concepts, leading to a notable enhancement in the overall efficiency of the plant.

Potential alternatives encompass topping or bottoming cycles, which include the organic Rankine cycle or the CO_2-based closed Brayton cycle (12); low-rank coal pre-drying (13); and multiple heat sources, with solar thermal energy being particularly noteworthy. Technologies for pollutant removal, especially CO_2 capture, should also be considered.

Thus, the future design paradigm for thermal power plants emphasizes system-level synthesis to incorporate these technologies. The next step involves developing efficient strategies for synthesis and optimization to determine the optimal technology combination.

System synthesis and evaluation are integral to overall plant design, where engineers use synthesis methodologies to generate unique conceptual designs and evaluate them for improvements (1).

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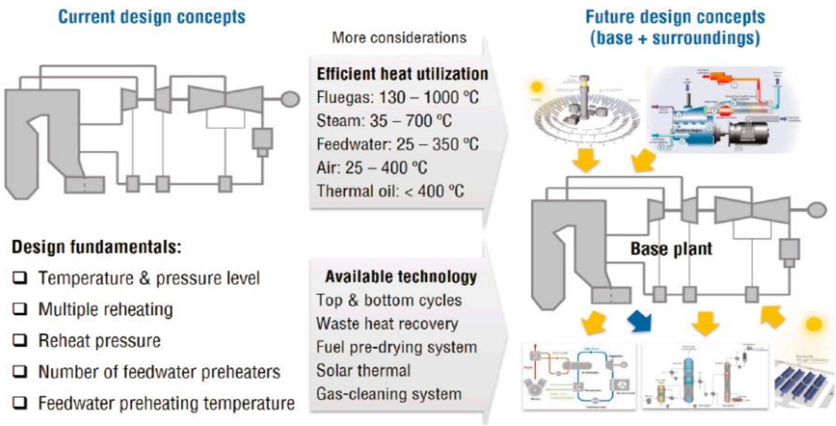

Figure 3. Fundamental principles and emerging obstacles in designing thermal power plants (7).

Parts of a power facility

A shell-and-tube condenser cools steam from turbines using water from a cooling tower, usually located near turbine discharge ports. Condensation transforms steam from gas to liquid at constant pressure. A smoke stack expels exhaust gas and circulates air within the boiler chamber.

The coal conveyor moves coal and fuel tanks to the boiler. Coal fuel is pulverized before entering the boiler. Boilers heat water to a specific temperature before sending it to the superheater. Regenerative power plants have multiple boiler units. Electrostatic precipitators remove dust from exhaust using an electric field. Electricity is mainly generated by generators using turbine blade kinetic energy. Economizers recirculate heat from exhaust gases. Cooling towers draw hot steam from the condenser and return cold water. Their components include a water basin, pipes, filler, fans, and fins. They can be mechanical draft or natural draft types, affected by factors like ambient wet bulb temperature, air pressure, and water quality. **Figure 4** illustrates cooling tower function, with splash bars and spray nozzles for water, and fans or wind currents for air circulation (5).

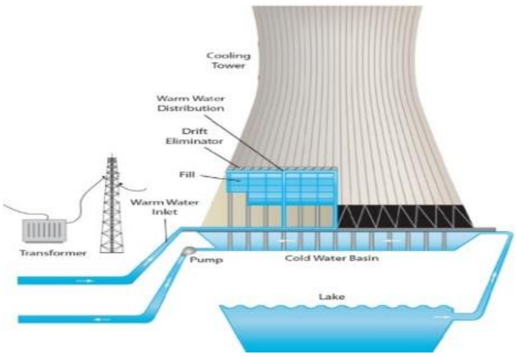

Figure 4. Cooling tower system (5).

Essential Principles of Thermal Power Production

The core concept of a thermal power plant revolves around the ideal Rankine cycle, depicted in Figure 5. In this cycle, the working fluid undergoes irreversible flow through all components, such as the boiler and condenser, without pressure drops due to friction. Ideally, turbine and pump processes are isentropic when there's no irreversibility or heat exchange with the environment.

The Rankine cycle comprises several internally reversible processes: Compression (isentropic) within a pump (Stages 1-2); isothermal heat addition at constant pressure in a boiler (Stages 2-3); expansion (isentropic) within a turbine (Stages 3-4); and isothermal heat rejection at constant pressure in a condenser (Stages 4-1).

Water, entering the pump saturated at state 1, undergoes isentropic compression to boiler pressure, raising its temperature by reducing specific volume. The T-s diagram exaggerates the vertical distance between states 1 and 2 for clarity. At stage 2, compressed water enters the boiler and emerges as superheated vapor at state 3. Essentially, the boiler acts as a large heat exchanger transferring heat to water at constant pressure from various sources like combustion gases or nuclear reactors.

Steam generators include both the boiler and superheater. In state 3, superheated vapor expands isentropically in the turbine, driving an electric generator shaft. Steam pressure and temperature decrease to state 4, entering the condenser. Here, steam typically becomes a high-quality saturated liquid-vapor mixture.

The condenser, acting as a large heat exchanger, condenses steam at constant pressure by transferring heat to a cooling medium like the atmosphere, a lake, or a river. The cycle completes as saturated liquid steam exits the condenser and enters the pump.

In water-constrained areas, power plants employ dry cooling, a water-saving technique also used in automobile engines. Several power plants globally, including some in the US, utilize dry cooling (5).

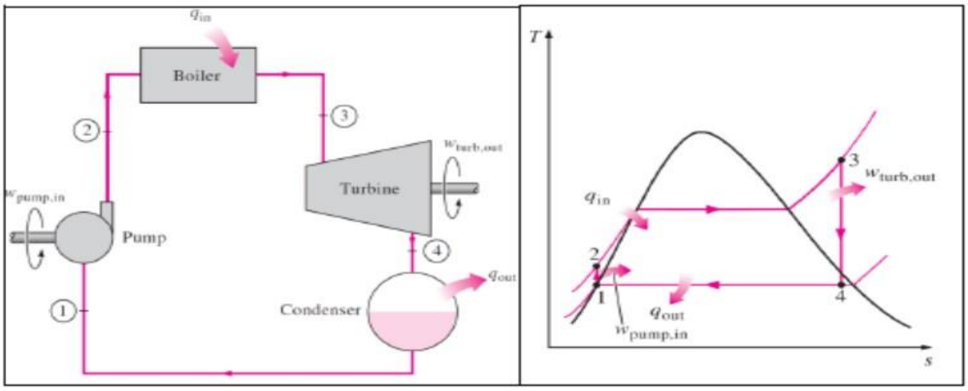

Figure 5. Diagram of an optimal rankine cycle (5).

Power plants using diesel

Due to its industrial suitability, many larger enterprises prefer the diesel generator (**Figure 6**) (14). Since the original diesel generators were noisy, its usage in retail has been discouraged. Now, it's practically as quiet as petrol generators.

One reason these generators are so popular in industrial settings is because of the additional benefits they provide, such as better fuel economy and less maintenance costs (5).

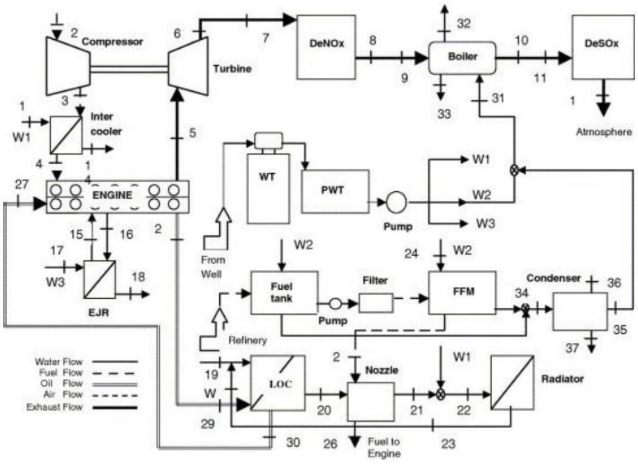

Figure 6. visual representation of the diesel power plant (5).

Piston engines are widely used in power generation. Small units can power sixty homes or provide combined heat and electricity. Larger backup units are needed for critical facilities like hospitals and air traffic control centers. Medium-sized piston engines are common in combined heat and power systems for commercial and industrial buildings. Large engines are suitable for grid-connected base-load power generation, while smaller units are ideal for remote areas. Most electricity-generating piston engines are adapted from automotive engines, with cars or trucks serving as the basis for smaller units, and locomotives or ships for larger ones. Smaller engines, although cheaper due to mass production, tend to have lower efficiency and shorter lifespans. Engines with higher displacement and cylinders are more expensive but last longer (5, 15). A generating set, or gen set, is a pre-assembled diesel engine and generator with all necessary accessories like a base, sound attenuation, canopy, control systems, jacket water heaters, circuit breakers, and starting systems. Large industrial generators range from 2,000 kVA for massive buildings to 8-30 kVA for smaller setups. A 2,000 kVA unit can fit inside a 40ft ISO container. Small power plants typically use sizes up to 5 MW, with one to twenty units. Larger sizes require additional equipment transported separately and assembled on-site (5). Diesel generators, as small as 250 kVA, provide emergency power and supplement utility systems during peak demand. They can power lighting, fans, winches, and even serve as primary propulsion on ships (16). Electric propulsion (Figure 7) allows generators to be placed conveniently for additional freight. During World War II, many ships were equipped with electric drives due to gear shortages and surplus electrical equipment. Large land vehicles also employ diesel-electric configurations (5).

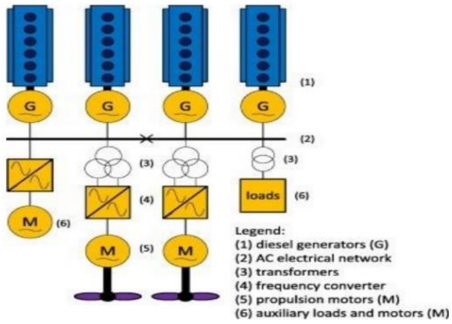

Figure 7. Systems of propulsion and generators (16).

When selecting generating sets, it's crucial to consider the type of load they'll be powering—whether it's for emergency or continuous power, the load size, and the size of motors needing startup, which is often the most critical specification. Stationary power generation across multiple sectors relies on various internal combustion engine types. These engines are utilized in oil fields, pipelines, sewage disposal, central stations, commercial, institutional, and military bases. **Figure 8** illustrates the use of compression ignition engines in steam stations for auxiliary power and as emergency standby sources in various industries and institutions. Smaller systems combine IC engines with steam units to meet peak load demands (17).

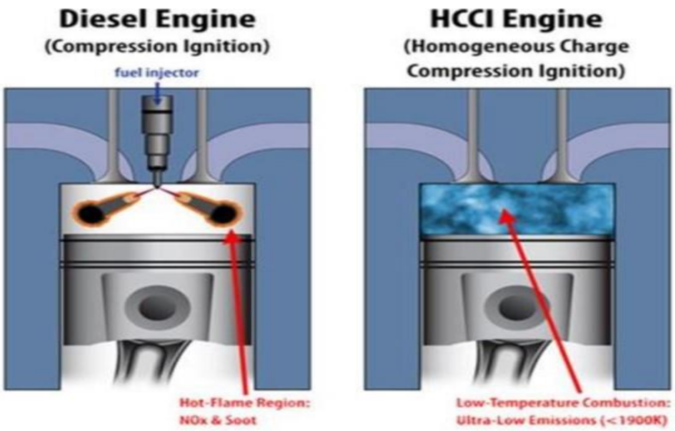

Figure 8. Two Types of Engines: Diesel and Compression (17).

Thermal Power Plant Applications

Nonlinearity and Integrity

Heat energy system optimization problems typically fit into the nonlinear and highly constrained categories of NLP or MINLP. Various factors, such as thermodynamic properties of working fluids, design and operational characteristics of components, investment cost functions, and energy balance equations, contribute to this nonlinearity and complexity. Resolving these issues is essential to potentially transform them into Linear Programming (LP) or Mixed-Integer Linear Programming (MILP) problems for deterministic optimization. Detailed nonlinear mathematical formulations are often unnecessary, particularly when describing the characteristics of working fluids like steam and water (IAPWS-IF97) (18). A direct method that sacrifices accuracy for low-degree nonlinearity polynomial approximations is one option. Inaccurate regressions often lead to impractical "optimal" solutions. The value of the property and its derivatives can also be accurately assessed using reprocessed steam tables or reformulated precise formulas, as shown in libraries like freesteam and TILMedia Suite (1). These libraries address thermodynamic property discontinuities and encapsulate state zone integer variables. They enable correction of components' nonlinear or discrete thermodynamic behavior. Alternate turbine models include the Stodola ellipse, Turbine Hardware Model, Willan's Line, and constant entropy efficiency (1, 19). Off-design behavior predictions vary inaccurately across models due to changes in the list of variables determining isentropic efficiency. An alternative method for heat exchangers to the logarithmic mean temperature difference is iteration of the arithmetic mean (20).

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The discrete equality nonlinear relationship of flow pressures between inlets and outlets can be relaxed as an inequality nonlinear restriction or linearized by adding integer variables for mixers (1). When optimizing for an economic goal, investment cost functions are necessary.

These functions can be highly nonlinear, linking the equipment cost of a component to its key characteristic variables and related flow parameters. To manage this, cost functions are often rewritten with independent variables and then piecewise linearized using integer SOS2 variables (21). Nonlinearity can also be caused by continuous nonconvex bilinear terms ($v_1.v_2$), such as the term m·h in energy balance equations. Common methods for dealing with nonconvex nonlinearity include quadratic reformulation or convex/concave McCormick relaxation. In order to substitute the bilinear term with $z_{2}^{1} - z_{2}^{2}$ in the second method, two additional variables $z_1 = (v_1 + v_2)/2$ and $z_1 = (v_1 - v_2)/2$ are constructed. Additional linearization of the quadratic term is also possible using SOS2 variables (1). Due to the rarity of integer variables in any particular energy system design, optimising such a system becomes a simple task once its structure is known. The initial implementations of mathematical optimisation in the context of thermal power plants or steam cycles occurred fifty years ago (22). These applications utilised analytical deduction to determine the most efficient way to distribute heat loads among feedwater preheaters. In doing so, they derived the two widely recognised methods of equal increase in feed water enthalpy or temperature. In modern times, optimisation techniques are typically employed in conjunction with the optimisation of non-continuous or integer variables, which will be covered in the reference (1), in order to achieve more substantial gains in performance. It is possible to optimise steam cycles parametrically using mathematical methods while aiming for thermodynamic, economic, or environmental goals, or by combining these with thermoeconomic techniques to achieve an economic optimisation. In (23), the authors used SQP and appropriate decomposition methods to study the most cost-effective design of a power plant's dry-cooling system. Their findings demonstrated that direct optimisation of complex problems does not have to be laborious or time-consuming as long as the problem and solving strategy are well-structured. By taking a more holistic view of the off-design performance of the entire plant calibrated with historical operating data, the optimisation problem for modern coal-fired power plants is solved in (24). This approach has the potential to produce operational strategies that are practical and can handle different operating scenarios with ease. By optimising the steam cycles in relation to the boiler cold-end, which used the steam-extraction pressures as independent variables to maximise plant efficiency, the SQP algorithms were also used in (25). A 0.7 percentage point improvement in efficiency was accomplished. The optimisation was implemented by simulating the plant's performance using Aspen Plus and the provided choice variables. By integrating thermoeconomic optimisation methods, Uche et al. were able to optimise a power and desalination facility that served dual purposes, resulting in an 11% reduction in overall cost under nominal operating conditions (26). Xiong et al. have used structural theory of thermoeconomics to optimise a 300 MW coal-fired power plant's operation, resulting in a 2.5% reduction in total annual cost (27). Thermal power plant optimization using heuristic methods like genetic algorithms (GA) and artificial neural networks (ANN) emerged after 2010. In the referenced study (28), these methods optimized plant efficiency by considering nine design characteristics such as main and reheated steam pressures.

The optimizer utilized a professional process simulator for efficiency assessment and GA-ANN to fine-tune decision factors. Expert simulators handle nonlinearity effectively. Results indicate that the GA-ANN technique significantly enhances computing performance while maintaining accuracy, suitable for web-based applications. Heuristic approaches may achieve global optimum, as GA-ANN algorithm's optimal plant efficiency surpasses mathematical programming. Another reference (29), considered 10 additional choice variables to maximize plant efficiency and minimize total cost rate. Wang et al. proposed addressing this issue through optimal synthesis of energy systems (1).

The Creation of Energy Systems

At the system as a whole, process synthesis, specifically comprehensive flowsheet synthesis, addresses the determination of process structure (topology), which refers to the collection of technical components utilised and their interrelationships. In most cases, the best synthesis phase is a key component in reaching the target or discovering the best design choice on a worldwide scale (30). On the other hand, optimising synthesis is typically more challenging than optimising a basic design or operation: Typically, the optimisation of design and/or operations is considered concurrently or sequentially; furthermore, the design space of structural alternatives for complex systems is not essentially known in advance; therefore, it appears that a comprehensive, exact mathematical formulation of the synthesis problem is not feasible.

Numerous academics have evaluated the methodology of previous studies that attempt to comprehensively address energy and process system synthesis. The three main categories of synthesis procedures are heuristic methods, targeted or task-oriented methods, and mathematical optimization-based methods. These groupings are complementary to each other (1).

The Heuristic and The Targeted Approaches

Both approaches utilize prior knowledge. Heuristic approaches employ rules based on longstanding technical knowledge and experience to generate initial starting points and iteratively improve them. An example of this category is the hierarchical decision procedure for process synthesis, which forms the basis for subsequent systematic synthesis methods. This approach decomposes and assembles processes sequentially, and has been further refined to synthesize complete separation system flowsheets (1). Targeting approaches employ physical concepts to achieve, approach, and attain optimal process synthesis targets. The pinch methodology is the most common targeting method, initially designed for systematic Heat Exchanger Networks (HEN) synthesis and later expanded to encompass total site utility systems (31). Knowledge-based expert systems have been developed for various processes and systems, such as chemical, thermal, and renewable energy supply, enabling automatic and computer-aided synthesis based on specific criteria. These systems employ logical inference methods like means-end analysis and case-based reasoning to replicate engineers' design strategies and recommend suitable processes. While heuristic and targeted approaches can quickly identify suboptimal structural options, they lack mathematical rigor and sequential nature, thus unable to ensure optimality. This limitation led to the development of mathematical optimization-based methods, which rigorously account for objective functions while considering structural alternatives, design conditions, and operational circumstances.

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These techniques transform synthesis tasks into mathematical optimization problems, incorporating either explicit (based on a superstructure) or implicit (without a superstructure) representations of all possible structures (1).

Synthesis based on superstructure

To mathematically define synthesis issues, a superstructure delineates the a priori structural space. Duran and Grossmann introduced the concept of the superstructure to elucidate the outer approximation method for solving MINLP, initially applied to process synthesis problems in HEN (32). A systematic superstructure-based synthesis method evolved from the original concept, finding extensive use in various process syntheses, including HEN, water networks, polygeneration processes, steam utility systems, thermal power plants, and water networks. The objective of superstructure-based synthesis is to identify the optimal solution among all possibilities, with the superstructure representing all components and potential links under evaluation. The synthesis based on superstructures relies on three key components: mathematical optimization, superstructure representation and creation, and superstructure modeling (1).

Superstructure-Free Synthesis

Optimization based on superstructures still faces core issues. To overcome these, methods independent of superstructures employ metaheuristic algorithms to explore solution spaces without preconceived models. Two such approaches for superstructure-free synthesis of steam cycles are the SYNTHSEP method (33, 34) and the ECH-based method (35). **Figure 9** illustrates SYNTHSEP's derivation from the HEATSEP method, which decomposes energy system configurations into fundamental thermodynamic cycles to optimize design by identifying variable temperatures (decision variables). SYNTHSEP, a bottom-up technique, optimizes system configurations by aggregating primitive thermodynamic cycles, reversing HEATSEP.

Elementary cycles include compression, heating, expansion, and cooling processes. **Figure 10** demonstrates merging two elementary cycles sharing a single thermodynamic process to form a fundamental system configuration. Heat integration follows basic design construction using mixers, splitters, and thermal cut placement as shown in Figure 9 (right) (1).

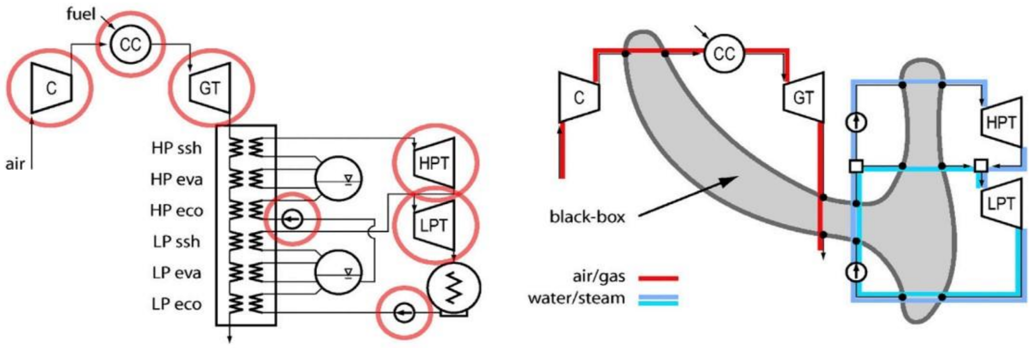

Figure 9. Breakdown of a combined cycle with two pressure levels: the initial setup (on the left) and the final state (on the right) (36).

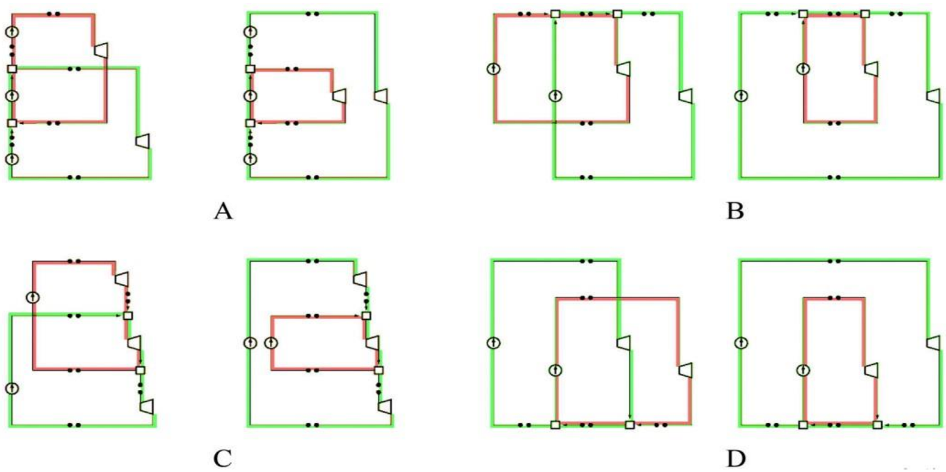

Figure 10. Each possible configuration that results from two basic cycles sharing a single thermodynamic process ((A-D)): compression, heating, expansion, and cooling (34).

In order to optimise (organic) Rankine and steam cycles, the SYNTHSEP technique has been used on multiple occasions**. Figure 11** for steam cycles is only one example of how various configurations can be efficiently developed and optimised.

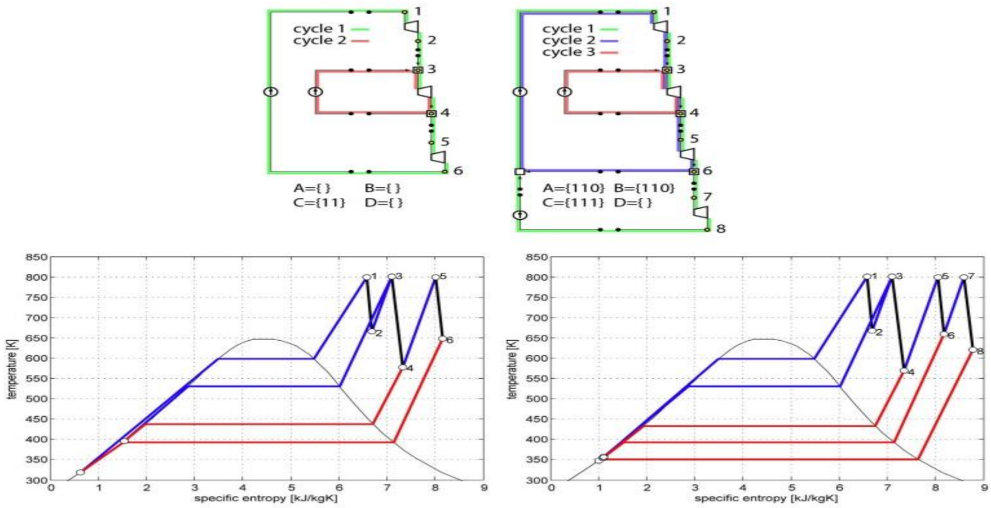

Figure 11. Ideal steam cycles with two or three basic cycles, including topologies and T-S diagrams (36).

SYNTHSEP method excludes heat exchangers from pressure change calculations, unlike the ECH-based approach, which incorporates them. Plant structure modification employs energy conversion hierarchy and six replacement rules to algorithmically generate specific plant structures. **Figure 12** demonstrates ECH application in a thermal power plant, organizing energy conversion technologies and establishing replacement rules. ECH operates on meta, function, and technology levels, with replacement rules depicted as meta-level nodes. Each technical-level node represents a distinct energy conversion method. Functional-level connecting nodes categorize technologies by primary purposes and driving kinds, aiding identification of applicable replacement criteria. ECH approach for thermal power plants includes six finalized rules for replacement and insertion: a) Remove a part and its connections; b) Create a short circuit across connections after removing a component; c) Substitute one part with another; d)

Replace one part with two connected in parallel; e) Combine two components into one by serial connection; and f) Substitute technology-related stream to add a component (1).

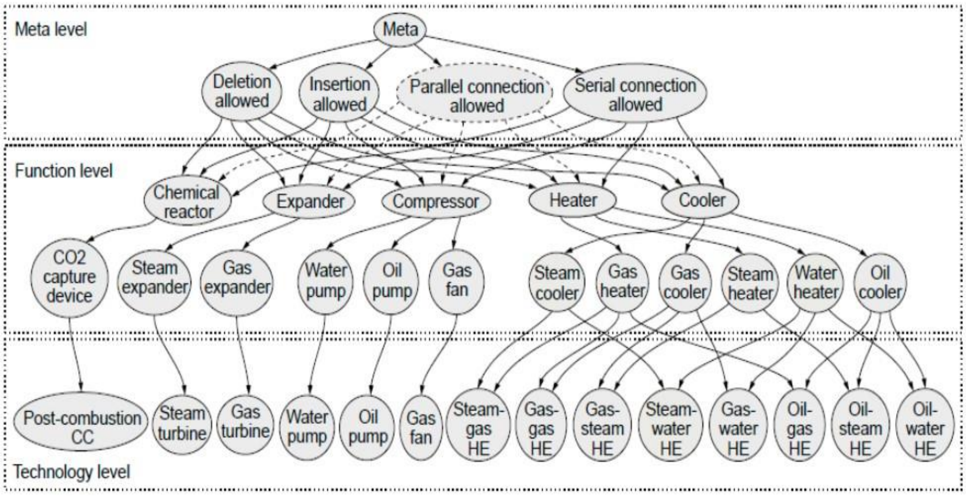

Figure 12. A thermal power plant's energy conversion hierarchy (35).

CONLUSION

This article delves into the fundamental principles of thermal power generation, emphasizing the core components and functions within thermal power plants. Key pillars of this field include thermodynamics, the Rankine cycle, and heat transmission rules, leading to an extensive exploration of Rankine cycles and heat transfer mechanisms within the power plant components. The examination extends to internal combustion engines, particularly diesel engines, and involves an in-depth investigation of Advanced Exergy-Based Analyses in system analysis. These advanced analyses aim to surpass traditional exergy evaluations by pinpointing sources of preventable exergy destruction and associated costs within various components, though ongoing development requires resolution of key issues such as validating exergy dissipation divisions. In synthesis methodologies, the article discusses both superstructure-based and superstructure-free approaches. The former utilizes a steam network to create a steam-cycle superstructure, requiring integration with a superstructure-based heat exchanger network for comprehensive flowsheets. In contrast, superstructure-free synthesis involves SYNTHSEP and ECH-based methods, employing evolutionary structural alterations. While SYNTHSEP, utilizing elementary cycles, is limited in comprehensive flowsheet synthesis and applicability, the ECH-based method excels in conducting comprehensive flowsheet synthesis, offering easy expansion with precise ECH and component models. Both methods employ bi-level decomposition techniques through a combination of evolutionary algorithms and mathematical programming.

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