Bakary Coulibaly
ECE 6699
Course Project Assignment

Conventional Electric Power Generation

Introduction

In the realm of energy production, conventional electric power generation technologies stand as the bedrock of modern industrialization and societal development. This paper delves into an extensive examination of various conventional power generation methods, each pivotal in meeting the world's growing energy demands. We consider a diverse range of technologies, including pulverized coal (dual unit), Integrated Coal Gasification Combined Cycle (IGCC, dual unit), conventional and advanced natural gas combustion turbines (CT), conventional and advanced natural gas combined cycle (CC), diesel generation on a megawatt scale, and nuclear reactors, specifically pressurized water (PWR) and boiling water (BWR) dual unit reactors. Each technology is evaluated through a detailed exploration of its power cycle, encompassing the Rankine cycle, Brayton cycle, Diesel cycle (including both 2 and 4-stroke cycles), and Combined cycles. The paper aims to dissect the intricacies of these cycles, focusing on the operational temperatures achieved - both the higher operational temperature and the condenser temperature. Furthermore, the power capacities of these technologies, ranging in megawatts (MW), are scrutinized, highlighting their capacity factors for base load and peaking load, where applicable. This analysis offers insights into their operational flexibility and efficiency in different demand scenarios. The efficiency of these technologies is dissected in terms of their cycle efficiency, specifically from heat to electric power conversion, including separate and combined efficiencies in the case of combined cycles.

A critical component of these technologies is their cooling systems, particularly the rate of water condensers, which plays a significant role in overall efficiency and environmental impact. Additionally, the paper provides an in-depth examination of the fuel types utilized in these technologies, including their heat values (expressed in kJ/kg, Btu/lb, or Btu/scf for natural gas), sources, and compositions. This analysis extends to the assessment of the heat rate (Btu/kWh) for fossil fuel-based energy generation.

Environmental implications are at the forefront of energy generation discussions. Thus, this paper includes a comprehensive study of emission rates, focusing on NOx, CO_2, and particulate emissions from coal generation, and explores the methods and technologies involved in emission treatment, including the emerging Carbon Capture and Storage (CCS) technologies. Additionally, the waste treatment processes for coal ash and nuclear fuel storage and reprocessing are critically evaluated.

Lastly, the economic aspects of these technologies are examined, considering the capital cost ($/kW installed), fixed and variable Operation & Maintenance (O&M) costs ($/kW-year and $/MWh, respectively). The variable costs include the price of the fuel, providing a holistic view of the financial implications of each technology.

This paper aims to present a comprehensive understanding of conventional electric power generation technologies, addressing their operational dynamics, environmental impacts, and economic considerations, thus providing a foundational understanding essential for informed decision-making in the energy sector.

<u>Part 1</u>

Pulverized coal, dual unit:

1. Power Cycle Description
    - Cycle Type: Pulverized coal plants predominantly use the Rankine cycle. This involves boiling water to produce steam in high-pressure boilers. The high-pressure steam drives a turbine, which generates electricity.
    - Cycle Phases: The process includes water heating, steam generation, turbine movement, and steam condensation.

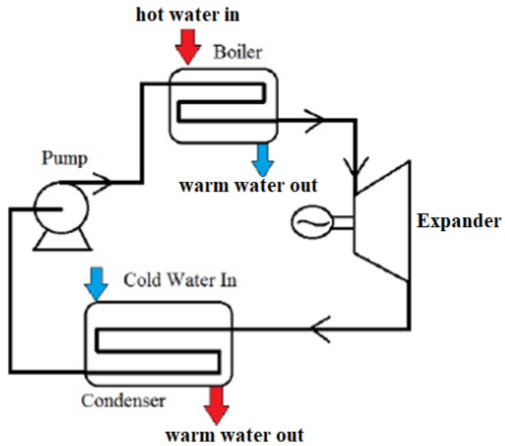

Fig.1 Rankine cycle process(*Lecture 7 October 6 2023.Pptx*)

2. Temperatures in the Power Cycle
    - Boiler Outlet Steam Temperature: Typically ranges from 540°C to 600°C, crucial for achieving high thermal efficiency.
    - Condenser Temperature: Varies from 30°C to 50°C, dependent on ambient conditions and cooling technology.
3. Power Capacities of Commercial Plants
    - Capacity Range: Modern pulverized coal plants range from 300 MW to over 1000 MW, catering to large-scale power demands.
4. Capacity Factors
    - Base Load Operation: These plants are generally base load with capacity factors often exceeding 70%, indicating high reliability and continuous operation.
    - Peaking Load: Not suitable due to longer start-up times and less operational flexibility.
5. Cycle Efficiency
    - Efficiency Range: Average efficiency varies between 33% to 40%. This is influenced by the technology used, plant age, and operational practices.
6. Cooling Rate in Water Condensers
    - Rate Details: The cooling rate depends on the plant’s condenser design, ambient temperature, and water availability. The rate is critical for maintaining the condenser's vacuum and overall cycle efficiency.
7. Fuel Heat Value
    - Coal: Typically, around 24 MJ/kg (10,000 Btu/lb). This value is influenced by the coal's grade, with bituminous coal having higher heat values.
8. Coal Fuel Sources and Composition
    - Major Sources: USA's Appalachian region, Illinois Basin, Western coal region; globally from Australia, China, India.

- Composition: Predominantly carbon, with impurities including sulfur, ash, and varying moisture content.

9. Heat Rate for Fossil Energy Generation
   - Range: Generally, between 9,000 to 10,500 Btu/kWh, where lower values indicate higher efficiency.
10. Emission Rates of Fossil Energy Generation
    - Emission Details: Significant emissions of CO_2, NOx, and particulates. The specific rates vary based on the coal type, plant technology, and emission control systems used.
11. Emission Treatment
    - Carbon Capture and Storage (CCS): An emerging technology aimed at capturing and storing CO_2 emissions underground. Its implementation is still limited by technological and economic challenges.
    - Other Treatments: Use of scrubbers, electrostatic precipitators, and baghouses for controlling SOx, NOx, and particulate matter.
12. Waste Treatment
    - Coal Ash Management: Coal ash is managed through ash ponds or landfills, with environmental safeguards to prevent leaching and contamination.
    - Nuclear Aspects: Not applicable to coal-fired plants.
13. Capital Costs
    - Approximate Costs: Around $2,500 to $4,000 per kW. Costs can vary based on environmental control systems and site-specific factors.
14. Fixed O&M Costs
    - Annual Costs: Typically, in the range of $30 to $60 per kW-year. This includes costs for maintenance, labor, and routine plant operations.
15. Variable O&M Costs
    - Costs Including Fuel: Ranges from $20 to $40 per MWh, heavily influenced by coal prices and the plant's operational efficiency.
16. References

Lecture 7 October 6 2023.Pptx.
Speight, James G. *Coal-Fired Power Generation Handbook 2nd Edition*.

Dual unit Integrated Coal Gasification Combined Cycle IGCC:

1. Power Cycle Description
   - **Cycle Type**: The IGCC power generation utilizes a combination of the Brayton and Rankine cycles. It starts with coal gasification, where coal is converted into syngas (a mixture of hydrogen and carbon monoxide).
   - **Process Flow**: Syngas is cleaned of impurities and combusted in a gas turbine (Brayton cycle). The hot exhaust gases from the gas turbine are then used to produce steam, which drives a steam turbine (Rankine cycle), enhancing the overall efficiency.

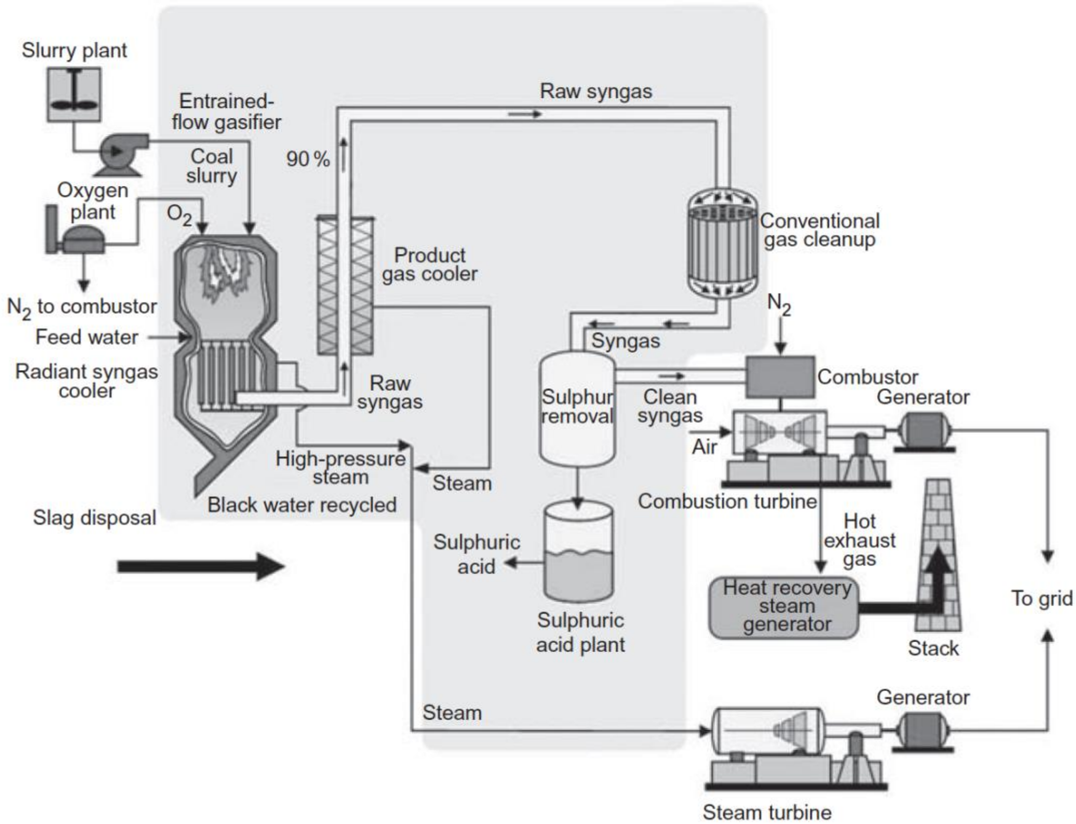

fig 2. Flow diagram of an IGCC plant(Breeze)

2. Temperatures in the Power Cycle
   - **Gas Turbine Inlet Temperature**: The gas turbine component operates at high temperatures, often reaching up to 1,400°C to maximize efficiency.
   - **Steam Cycle Temperature**: The steam turbine component operates at temperatures similar to conventional coal-fired power plants, generally around 540°C to 600°C.
3. Power Capacities of Commercial Plants
   - **Capacity Range**: IGCC plants have a wide capacity range, typically from 250 MW up to 600 MW or more. This range caters to diverse utility-scale power requirements.
4. Capacity Factors
   - **Base Load Operation**: IGCC plants are designed for high capacity factors, often in the range of 70-80%, similar to conventional coal-fired plants.
   - **Operational Flexibility**: IGCC plants offer greater operational flexibility and faster start-up times than conventional coal-fired power plants, though not as flexible as natural gas-fired plants.
5. Cycle Efficiency
   - **IGCC Efficiency**: The efficiency of IGCC plants is typically between 40-45%. Advanced IGCC technologies with enhanced gasification and turbine technology have the potential to achieve efficiencies up to 50%.
6. Cooling Rate in Water Condensers
   - **Specifics**: The cooling rate in IGCC plants depends on the condenser design and ambient temperature. Water-cooled systems are common, but air-cooled condensers are also used in water-scarce areas, albeit with a slight efficiency penalty.

7. Fuel Heat Value
   - **Coal Heat Value**: The heat value of coal used in IGCC plants varies but is typically around 24 MJ/kg (10,000 Btu/lb), depending on the coal type and quality.
8. Coal Fuel Sources and Composition
   - **Sources**: Major coal sources for IGCC include bituminous, sub-bituminous, and lignite coals.
   - **Composition Variability**: The composition of coal affects the gasification process and syngas quality, impacting plant performance.
9. Heat Rate for IGCC Generation
   - **Specific Range**: The heat rate for IGCC plants is generally lower than conventional coal plants, with values typically ranging from 8,500 to 9,500 Btu/kWh.
10. Emission Rates of IGCC Generation
   - **Emission Levels**: IGCC plants demonstrate lower emissions of CO2, NOx, SOx, and particulates compared to conventional coal plants due to efficient gasification and syngas cleaning processes.
11. Emission Treatment
   - **Syngas Cleaning Technologies**: Advanced cleaning technologies are integrated into IGCC plants to remove contaminants like sulfur and mercury from syngas before combustion, leading to significantly cleaner emissions.
12. Waste Treatment
   - **By-products Management**: The gasification process in IGCC produces by-products such as slag, which can be used in construction materials. Proper disposal and management are crucial for other residuals.
13. Capital Costs
   - **Precise Costs**: The capital cost for IGCC plants is typically in the range of $4,000 to $6,000 per kW, influenced by the complexity of gasification and gas clean-up systems.
14. Fixed O&M Costs
   - **Exact Costs**: Fixed operation and maintenance (O&M) costs for IGCC plants are in the range of $40 to $80 per kW-year, factoring in the advanced technology and maintenance of gasification components.
15. Variable O&M Costs
   - **Detailed Costs**: The variable O&M costs for IGCC, including fuel, are in the range of $25 to $45 per MWh, influenced by the coal price, plant design, and operational efficiency.
16. References

Breeze, Paul A. *Power Generation Technologies*. Third edition, Newnes, an imprint of Elsevier, 2019.

Speight, James G. *Coal-Fired Power Generation Handbook 2nd Edition*.

Conventional natural gas combustion turbine CT:

1. Power Cycle Description
   - **Cycle Type**: Conventional natural gas combustion turbines (CTs) operate on the Brayton cycle. This cycle involves compressing air, mixing it with natural gas, igniting the mixture for high-temperature combustion, and using the expanding gases to drive the turbine.

- **Process Flow**: Air is drawn into the compressor, where its pressure is significantly increased. This compressed air is then mixed with natural gas in the combustion chamber. The resulting high-pressure, high-temperature gas drives the turbine, which is connected to a generator for electricity production.

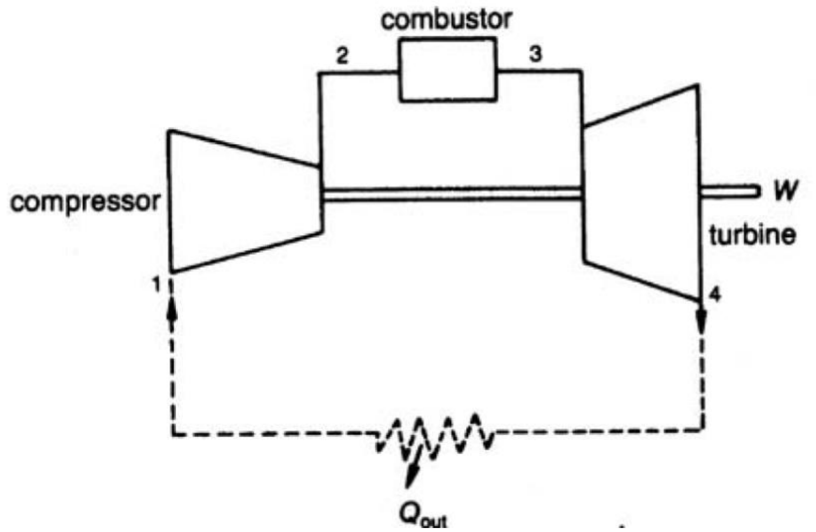

Fig.3 The air-standard Brayton cycle (Boyce)

2. Temperatures in the Power Cycle
   - **Combustion Temperature**: The combustion temperature in a CT can exceed 1,400°C. This high temperature is essential for achieving the desired energy conversion efficiency.
   - **Exhaust Gas Temperature**: The temperature of the exhaust gas leaving the turbine can range from 450°C to 650°C, depending on the specific design and operational settings of the turbine.
3. Power Capacities of Commercial Plants
   - **Capacity Range**: Conventional CTs typically range from 40 MW to over 300 MW. This makes them suitable for both mid-scale and large-scale power generation needs.
4. Capacity Factors
   - **Base Load and Peaking Load**: While CTs can be used for base load operation, they are particularly valued for their ability to quickly ramp up and meet peaking load demands due to their fast start-up capabilities.
5. Cycle Efficiency
   - **Stand-alone Efficiency**: The thermal efficiency of standalone CTs generally ranges from 35% to 40%. This efficiency can be significantly increased (up to 60% or more) when used in combined cycle configurations.
6. Cooling Rate in CTs
   - **Cooling Technology**: Most CTs use air cooling for the turbine components. The cooling rate is optimized to manage the thermal stresses and maintain turbine material integrity.
7. Fuel Heat Value
   - **Natural Gas Heat Value**: The calorific value of natural gas used in CTs typically ranges from 35 MJ/m³ to 55 MJ/m³ (950 to 1,500 Btu/ft³).
8. Natural Gas Sources and Composition
   - **Major Sources**: Key sources include North America, Russia, the Middle East, and increasingly, LNG (liquefied natural gas) from various global locations.

- **Composition**: Predominantly methane (CH4), with minor amounts of other hydrocarbons, carbon dioxide, nitrogen, and sulfur compounds.

9. Heat Rate
    - **Heat Rate**: Advanced natural gas combustion turbines typically have a heat rate in the range of 7,500 to 10,000 Btu/kWh. This range reflects the improved efficiency of advanced turbines compared to older or conventional models.
10. Emission Rates of CT Generation
    - **Emission Levels**: Natural gas CTs produce lower levels of NOx, SOx, and particulate matter compared to coal-based systems. CO2 emissions are also lower due to higher hydrogen content in natural gas.
11. Emission Treatment
    - **NOx Control Technologies**: Technologies such as selective catalytic reduction (SCR) and dry low NOx (DLN) burners are used to minimize NOx emissions.
12. Waste Treatment
    - **Waste Treatment in CTs**: Advanced natural gas combustion turbines, due to their fuel type and combustion process, produce significantly less solid waste compared to coal-based power plants. The primary by-products of natural gas combustion are CO2 and water vapor. However, there are still considerations in waste treatment:
        - **NOx Emissions**: While lower than coal plants, NOx is a notable emission from natural gas CTs and requires management through technologies like Selective Catalytic Reduction (SCR).
        - **CO2 Management**: Although CO2 emissions are lower per unit of energy produced compared to coal, they are still significant and contribute to greenhouse gas emissions. While direct waste treatment like CCS (Carbon Capture and Storage) is less common in CT plants, ongoing research and development in this area aim to reduce the carbon footprint.
        - **Water Management**: For plants using water cooling, the treatment of cooling water to prevent thermal pollution and protect aquatic life is essential. Water used in the cooling process needs to be carefully managed to minimize environmental impacts.
13. Capital Costs
    - **Specific Costs**: The capital cost for conventional CTs ranges from $500 to $1,000 per kW, influenced by the turbine size, technology, and local factors.
14. Fixed O&M Costs
    - **Detailed Costs**: Fixed O&M costs for CTs are approximately $15 to $30 per kW-year, considering the simpler operational requirements compared to more complex systems like coal plants.
15. Variable O&M Costs
    - **Detailed Costs**: Variable O&M costs, including fuel, typically range from $15 to $35 per MWh, depending on the price of natural gas and operational efficiency.
16. References

Boyce, Meherwan P. *Gas Turbine Engineering Handbook*. 2nd ed, Gulf Professional Pub, 2002.

Guo, Boyan, and Ali Ghalambor. *Natural Gas Engineering Handbook*.

Advanced natural gas combustion turbine CT:

1. Power Cycle Description
    - **Cycle Type**: Advanced natural gas combustion turbines function on the Brayton cycle, which includes air compression, natural gas combustion, and turbine generation.
    - **Detailed Process Flow**: Air is compressed to a high pressure in a multi-stage compressor, then mixed with natural gas in the combustion chamber. The mixture is ignited, generating high-temperature, high-pressure gases that expand through the turbine, producing mechanical power that drives an electric generator.
2. Temperatures in the Power Cycle
    - **Combustion Temperature**: Typically exceeds 1,500°C, which is critical for high thermal efficiency.
    - **Exhaust Gas Temperature**: Ranges from 550°C to 600°C, varying with the operational load and turbine design.
3. Power Capacities of Commercial Plants
    - **Capacity Range**: Specifically designed within the 100 MW to 500 MW range, catering to both medium and large-scale power generation needs.
4. Capacity Factors
    - **Base Load Operation**: Optimized for high capacity factors similar to base load power plants, enabling continuous and reliable operation.
    - **Peaking Load**: Exhibits fast ramp-up capabilities, making it highly suitable for peaking power generation.
5. Cycle Efficiency
    - **Efficiency Range**: Achieves thermal efficiencies ranging from 40% to over 50% in standalone mode. In combined cycle configurations, efficiencies can exceed 60%.
6. Cooling Technologies
    - **Cooling Method**: Employs advanced technologies such as film cooling in turbine blades and vanes to manage the high temperatures of combustion gases.
7. Fuel Heat Value
    - **Calorific Value**: Natural gas used in CTs typically has a calorific value ranging from 35 MJ/m^3 to 55 MJ/m^3, which is a critical factor in determining the turbine's fuel efficiency.
8. Natural Gas Sources and Composition
    - **Sources**: Includes diverse global sources such as North American shale formations, Russian fields, and Middle Eastern reserves.
    - **Composition**: Primarily methane (CH_4), with minor constituents like ethane, propane, butane, and trace amounts of nitrogen and sulfur compounds.
9. Heat Rate for Fossil Energy Generation
    - **Specific Range**: The heat rate for advanced CTs is in the range of 7,500 to 10,000 Btu/kWh, indicating high fuel efficiency.
10. Emission Rates of Fossil Energy Generation
    - **NOx, CO2, Particulates**: Advanced CTs have significantly lower emissions of NOx and CO_2 compared to older CT designs and other fossil fuel-based technologies.
11. Emission Treatment
    - **NOx Control**: Employs technologies like Selective Catalytic Reduction (SCR) and Dry Low NOx (DLN) burners.
    - **CO2 Emissions**: CO_2 management is an area of active research, with Carbon Capture and Storage (CCS) technologies being explored for future integration.
12. Waste Treatment

- **Primary Focus**: Addresses NOx emissions and cooling water treatment. Solid waste production is minimal.

13. Capital Cost
    - **Investment Cost**: Ranges from $800 to $1,200 per kW, depending on technology, plant size, and location.
14. Fixed O&M Costs
    - **Annual Expenditure**: Estimated at $20 to $40 per kW-year, incorporating maintenance of advanced turbine components and control systems.
15. Variable O&M Costs
    - **Operational Costs**: Defined within the range of $10 to $30 per MWh. These costs are heavily influenced by natural gas market prices and the plant's operational efficiency.
16. References

Boyce, Meherwan P. *Gas Turbine Engineering Handbook*. 2nd ed, Gulf Professional Pub, 2002.

Guo, Boyan, and Ali Ghalambor. *Natural Gas Engineering Handbook*.

Conventional natural gas combined cycle CC:

1. Power Cycle Description
    - **Cycle Type:** Utilizes a combined Brayton and Rankine cycle. The process begins with a natural gas combustion turbine (Brayton cycle) followed by a Heat Recovery Steam Generator (HRSG) that captures exhaust heat to produce steam, which drives a steam turbine (Rankine cycle).
    - **Detailed Process Flow**: Air is compressed in the combustion turbine, mixed with natural gas, and combusted. The hot gases drive the turbine to generate electricity. Exhaust gases are then routed to the HRSG, where they generate steam for additional electricity production in the steam turbine.

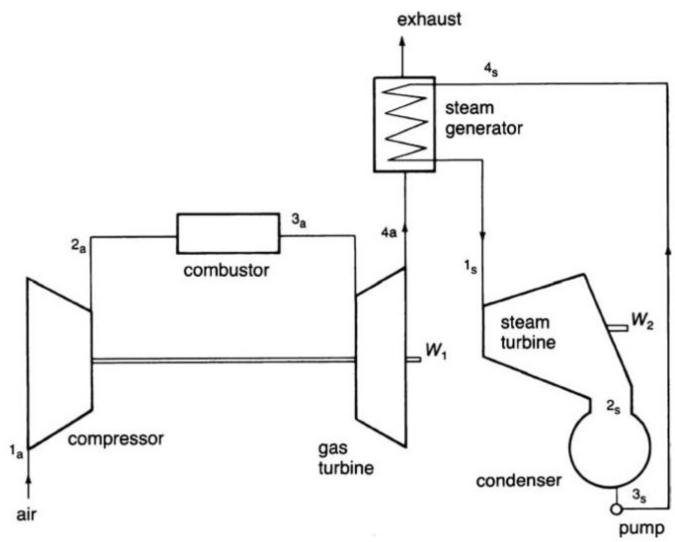

Fig.4 The Brayton-Rankine combined cycle

2. Temperatures in the Power Cycle
    - **Combustion Temperature**: In the combustion turbine, temperatures can reach up to 1,400°C, optimizing gas turbine efficiency.
    - **HRSG Temperature**: The steam cycle operates at approximately 540°C, similar to conventional steam power plants.

3. Power Capacities of Commercial Plants
    - **Capacity Range**: Designed for a broad range of capacities, typically from 200 MW to over 1,000 MW, suitable for large-scale utility applications.
4. Capacity Factors
    - **Base Load Operation**: High capacity factors, often above 80%, signifying its role as a reliable base load power source.
    - **Peaking Load**: While not as rapid as peaking plants, CC plants can adjust output to meet varying demand.
5. Cycle Efficiency
    - **Efficiency Range**: Achieves between 50% to 60% efficiency, making it one of the most efficient fossil fuel-based power generation technologies.
6. Cooling Technologies
    - **Cooling System**: Predominantly uses water-based cooling for the steam cycle and air cooling for the gas turbines. The choice of cooling technology affects the overall plant efficiency and water usage.
7. Fuel Heat Value
    - **Natural Gas Calorific Value**: Typically ranges from 35 MJ/m^3 to 55 MJ/m^3, a critical parameter in determining the plant's overall fuel efficiency.
8. Natural Gas Sources and Composition
    - **Sources**: Includes a variety of global sources like North American shale gas, Middle Eastern, and Russian natural gas fields.
    - **Composition**: Primarily consists of methane, with minor components like ethane, propane, and traces of nitrogen and sulfur compounds.
9. Heat Rate for Fossil Energy Generation
    - **Specific Range**: Ranges from 6,000 to 7,500 Btu/kWh, reflecting the high efficiency of combined cycle plants.
10. Emission Rates of Fossil Energy Generation
    - **Emissions**: Produces lower levels of CO2, NOx, and SOx per unit of electricity compared to conventional steam turbines and older gas turbines.
11. Emission Treatment
    - **NOx Control**: Includes the use of Selective Catalytic Reduction (SCR) and other advanced technologies to minimize NOx emissions.
    - **CO2 Management**: Ongoing research and potential future implementation of Carbon Capture and Storage (CCS) technologies.
12. Waste Treatment
    - **Focus Areas**: Primarily addresses the management of NOx emissions and cooling water. Solid waste generation is minimal.
13. Capital Cost
    - **Investment Cost**: Typically falls between $600 to $1,000 per kW, varying with plant size, technology, and location factors.
14. Fixed O&M Costs
    - **Annual Expenditure**: Estimated at $15 to $35 per kW-year, which includes routine maintenance, labor, and plant operation costs.
15. Variable O&M Costs
    - **Operational Costs**: Ranges from $20 to $40 per MWh, largely influenced by the price of natural gas and operational efficiency of the plant.

16. References

Boyce, Meherwan P. *Gas Turbine Engineering Handbook*. 2nd ed, Gulf Professional Pub, 2002.

Guo, Boyan, and Ali Ghalambor. *Natural Gas Engineering Handbook*.

Advanced natural gas combined cycle CC:

1. Power Cycle Description
   - **Cycle Type**: Employs an integrated Brayton (gas turbine) and Rankine (steam turbine) cycle, with advanced technological enhancements for efficiency.
   - **Detailed Process Flow**: Involves air compression, natural gas combustion in an advanced gas turbine, and using exhaust heat in a Heat Recovery Steam Generator (HRSG) to produce steam for driving a steam turbine.

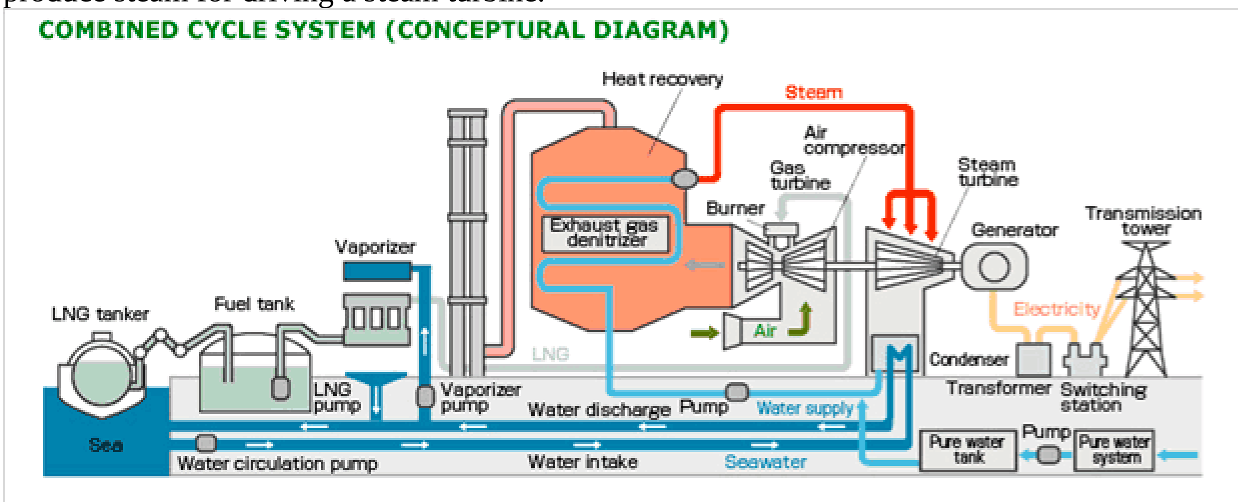

Fig. 5 Combined cycle power plant diagram (Araner)

2. Temperatures in the Power Cycle
   - **Gas Turbine Combustion Temperature**: Can exceed 1,500°C due to advanced combustion technologies.
   - **Steam Cycle Temperature**: Typically, around 600°C in the HRSG, enhanced for optimal steam cycle efficiency.
3. Power Capacities of Commercial Plants
   - **Capacity Range**: Specifically designed for capacities ranging from 250 MW to over 1,000 MW, accommodating large-scale utility demands.
4. Capacity Factors
   - **Base Load Operation**: Engineered for high capacity factors, often above 85%, demonstrating its role as a primary power source.
   - **Peaking Load**: While more efficient in base load, they can be modulated for peak demand, though not as rapidly as peaking plants.
5. Cycle Efficiency
   - **Efficiency Range**: Achieves efficiencies from 55% to over 60%, making it one of the most efficient power generation technologies available.
6. Cooling Technologies
   - **Cooling Method**: Utilizes advanced cooling systems, including air or water-based cooling for the gas turbine and steam cycle, with a focus on minimizing water usage and maximizing efficiency.

7. Fuel Heat Value
    - **Natural Gas Calorific Value**: Ranges from 35 MJ/m³ to 55 MJ/m³, critical for determining the power plant's fuel efficiency.
8. Natural Gas Sources and Composition
    - **Sources**: Sourced globally, including North American shale gas, and traditional reserves in the Middle East and Russia.
    - **Composition**: Mainly methane, with minor amounts of other hydrocarbons and trace impurities.
9. Heat Rate for Fossil Energy Generation
    - **Specific Range**: Typically, between 5,500 to 6,500 Btu/kWh, indicating higher fuel efficiency compared to conventional CC plants.
10. Emission Rates of Fossil Energy Generation
    - **Emissions**: Characterized by lower CO2, NOx, and SOx emissions per unit of electricity, benefiting from advanced combustion and emissions control technologies.
11. Emission Treatment
    - **NOx Control**: Advanced SCR systems and low-NOx burner technologies.
    - **CO2 Management**: Potential integration with Carbon Capture and Storage (CCS) technologies for further emission reduction.
12. Waste Treatment
    - **Primary Focus**: Addresses NOx and CO2 emissions, with an emphasis on advanced treatment technologies. Solid waste is minimal.
13. Capital Cost
    - **Investment Cost**: Ranges from $700 to $1,200 per kW, influenced by the advanced technology, scale, and location.
14. Fixed O&M Costs
    - **Annual Expenditure**: Approximately $20 to $50 per kW-year, accounting for the advanced systems' maintenance and operational requirements.
15. Variable O&M Costs
    - **Operational Costs**: Typically, $15 to $35 per MWh, largely determined by natural gas prices and plant efficiency.
16. References

Araner. *What Makes Combined Cycle Power Plants so Efficient?* https://www.araner.com/blog/combined-cycle-power-plants.

Boyce, Meherwan P. *Gas Turbine Engineering Handbook*. 2nd ed, Gulf Professional Pub, 2002.

Guo, Boyan, and Ali Ghalambor. *Natural Gas Engineering Handbook*.

Diesel generation, MW scale:

1. Power Cycle Description
    - **Cycle Type**: Diesel generators operate on the Diesel cycle, involving distinct phases of air compression, fuel injection, combustion, and exhaust.
    - **Process Flow**: Air is compressed to high pressures in the cylinder, diesel fuel is injected, ignites due to the high temperature from compression, drives a piston, and rotates a generator for electricity production.

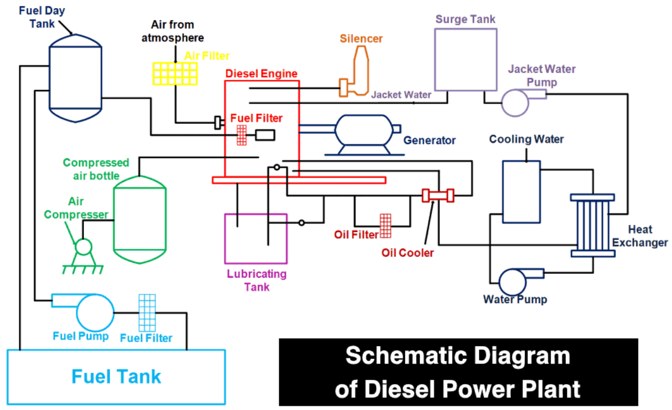

Fig. 6 Diagram of a diesel power plant(Technology)

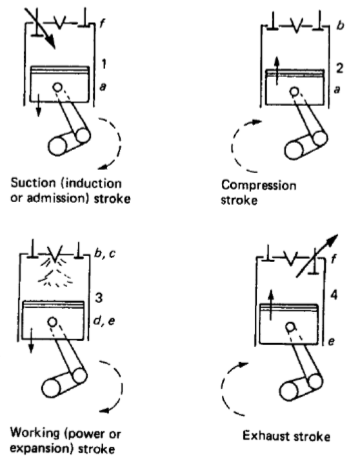

Fig. 7 Four Strokes Diesel Engine Working Cycles (Mahon)

2. Temperatures in the Power Cycle
    - **Combustion Temperature**: Precisely within 1,000°C - 1,200°C.
    - **Exhaust Gas Temperature**: Maintained at 450°C - 500°C.
3. Power Capacities of Commercial Plants
    - **Capacity Range**: Specifically engineered for 1 MW - 10 MW.
4. Capacity Factors
    - **Usage**: Mainly for peaking, backup, or remote areas, not typically used as base load.
5. Cycle Efficiency
    - **Efficiency**: Diesel engines operate at an exact efficiency of 35% - 45%.
6. Cooling Rate of Water Condensers
    - **Cooling Method**: Employ specific water or air-cooled systems.
7. Fuel Heat Value
    - **Diesel Fuel Calorific Value**: Precisely 45 MJ/kg.
8. Diesel Fuel Sources and Composition
    - **Sources**: Derived exclusively from crude oil.
    - **Composition**: Composed of alkanes, cycloalkanes, and aromatics.
9. Heat Rate for Diesel Generation
    - **Heat Rate**: Defined at 7,500 - 9,500 Btu/kWh.
10. Emission Rates

- **Emissions**: Specific emissions include CO2, NOx, SOx, and particulates.

11. Emission Treatment
    - **Technologies**: Employ particulate filters and SCR for NOx reduction.
12. Waste Treatment
    - **Focus**: Manages exhaust gas emissions; solid waste is minimal.
13. Capital Cost
    - **Cost**: $400 - $800 per kW.
14. Fixed O&M Costs
    - **Costs**: $20 - $40 per kW-year.
15. Variable O&M Costs
    - **Including Fuel**: $30 - $50 per MWh.
16. References

Mahon, L. L. J. *Diesel Generator Handbook*. Butterworth-Heinemann, 1992.

Technology, Electrical. "Diesel Power Plant - Components, Operation and Applications." *ELECTRICAL TECHNOLOGY*, 24 Aug. 2021, https://www.electricaltechnology.org/2021/08/diesel-power-plant.html.

Pressurized water dual unit nuclear reactor PWR:

1. Power Cycle Description
    - **Cycle Type**: PWRs use a pressurized water reactor design, heating water under high pressure without boiling.
    - **Process Flow**: Heated water circulates in the reactor core, transfers heat to a secondary circuit in the heat exchanger, producing steam that drives turbines.

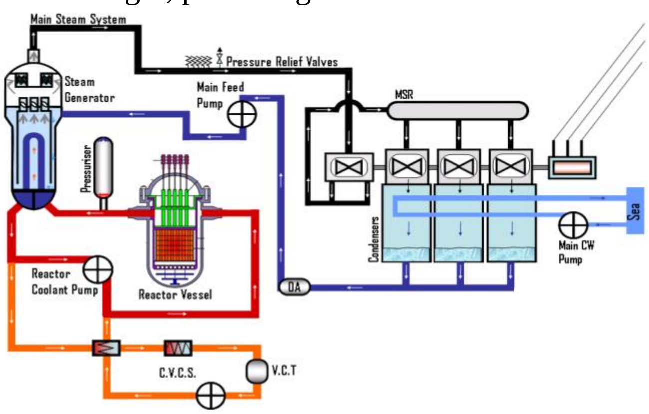

Fig. 8 Diagram of the PWR system layout(Bays et al.)

2. Temperatures in the Power Cycle
    - **Reactor Core Temperature**: 300°C - 325°C.
    - **Steam Temperature**: 280°C - 300°C.
3. Power Capacities of Commercial Plants
    - **Capacity Range**: 600 MW - 1,200 MW per unit.
4. Capacity Factors
    - **Operation**: Typically, above 90%.
5. Cycle Efficiency
    - **Efficiency**: 33% - 37%.
6. Cooling Technologies
    - **System**: Utilizes large-scale water cooling systems.

7. Nuclear Fuel Heat Value
   - **Fuel**: Enriched uranium with high energy density.
8. Nuclear Fuel Sources and Composition
   - **Sources**: Uranium mines.
   - **Composition**: Mainly UO_2 pellets.
9. Heat Rate
   - **Not Applicable**: Nuclear plants use nuclear fission.
10. Emission Rates
    - **Emissions**: No CO_2 emissions in operation.
11. Emission Treatment
    - **Radiation Safety**: Emphasizes radiation containment.
12. Waste Treatment
    - **Management**: Involves spent fuel storage.
13. Capital Cost
    - **Cost**: $6,000 - $9,000 per kW.
14. Fixed O&M Costs
    - **Costs**: $100 - $150 per kW-year.
15. Variable O&M Costs
    - **Low Cost**: Fuel is a small part of total costs.
16. References

Bays, Samuel, et al. *Reactor Fundamentals Handbook*. INL/EXT-19-53301-Rev000, 1615634, 1 Apr. 2019, p. INL/EXT-19-53301-Rev000, 1615634. *DOI.org (Crossref)*, https://doi.org/10.2172/1615634.

"DOE-HDBK-1019/1-93; Doe Fundamentals Handbook Nuclear Physics ... - Energy." *Doe.Gov*, 1996, www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1/@@images/file.

Boiling water dual unit nuclear reactor BWR:

1. Power Cycle Description
   - **Cycle Type**: BWRs boil water directly in the reactor core.
   - **Process Flow**: Water absorbs heat from nuclear fission, boils, and steam directly drives turbines.

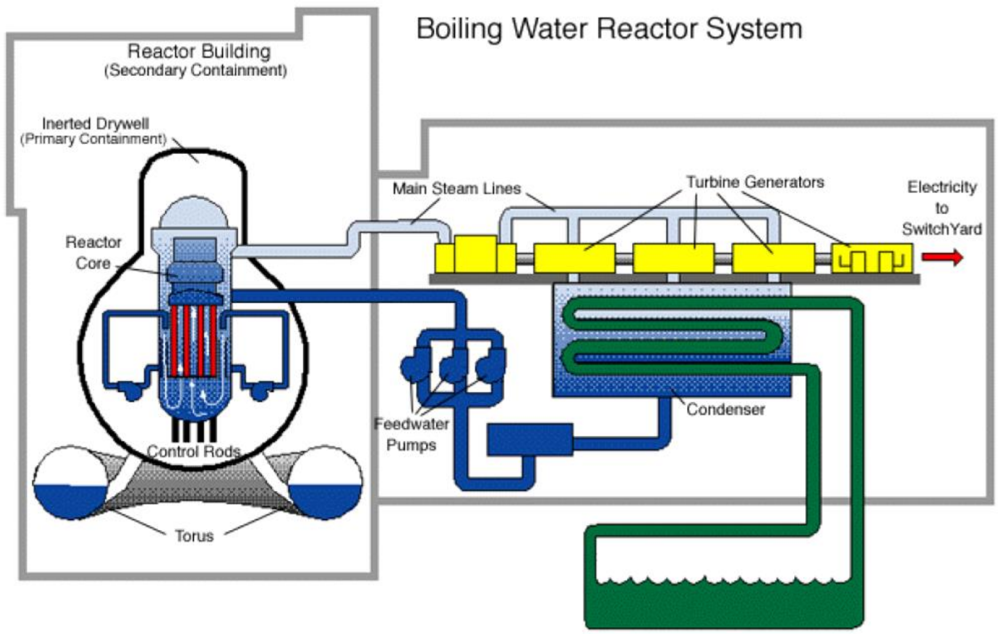

Fig.9 Diagram of the BWR system layout.

2. Temperatures in the Power Cycle
    - **Reactor Core Temperature**: 270°C - 300°C.
    - **Steam Temperature**: Same as reactor core temperature.
3. Power Capacities of Commercial Plants
    - **Capacity Range**: 500 MW - 1,300 MW per unit.
4. Capacity Factors
    - **Operation**: Typically exceeds 85%.
5. Cycle Efficiency
    - **Efficiency**: 33% - 37%.
6. Cooling Technologies
    - **System**: Primarily water cooling; some designs use natural circulation.
7. Nuclear Fuel Heat Value
    - **Fuel**: Uranium, similar to PWRs.
8. Nuclear Fuel Sources and Composition
    - **Sources**: Similar to PWRs.
    - **Composition**: Enriched uranium oxide.
9. Heat Rate
    - **Not Applicable**: Nuclear energy based.
10. Emission Rates
    - **Emissions**: No CO_2 emissions during operation.
11. Emission Treatment
    - **Radiation Safety**: Focuses on containment and safety.
12. Waste Treatment
    - **Management**: Spent fuel storage, similar to PWRs.
13. Capital Cost
    - **Cost**: $6,500 - $8,500 per kW.
14. Fixed O&M Costs
    - **Costs**: $90 - $140 per kW-year.

15. Variable O&M Costs
    - **Low Cost**: Minimal fuel costs.
16. References

Bays, Samuel, et al. *Reactor Fundamentals Handbook*. INL/EXT-19-53301-Rev000, 1615634, 1 Apr. 2019, p. INL/EXT-19-53301-Rev000, 1615634. *DOI.org (Crossref)*, https://doi.org/10.2172/1615634.

"DOE-HDBK-1019/1-93; Doe Fundamentals Handbook Nuclear Physics ... - Energy." *Doe.Gov*, 1996, www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1/@@images/file.

<u>Part 2:</u>

Pulverized Coal, Dual Unit

1. **Location Factors**
    - Proximity to coal supply sources to minimize transportation costs.
    - Access to large water sources for cooling.
    - Location away from densely populated areas due to emissions.

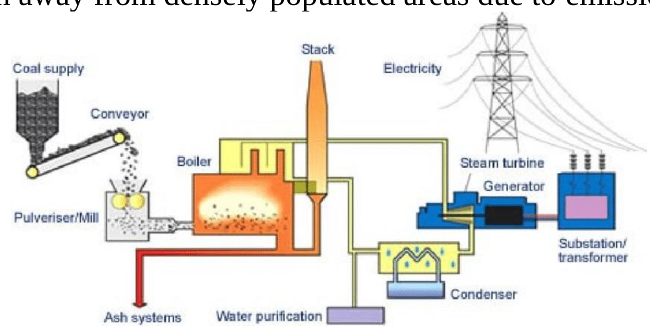

Fig.10 Pulverized coal Power Plant Layout(Sunjay et al.)

2. **Electricity Price Factors**
    - Cost of coal, operational and maintenance costs.
    - Environmental regulation compliance costs.
3. **New/Planned Plants**
    - Significant decline in new coal plants in the USA; growing in countries like China and India.
4. **Future Prospects**
    - Declining due to environmental concerns and competition from renewable energy sources.
5. **Reference**

Sunjay, et al. *CLEAN FUEL TECHNOLOGY FOR WORLD ENERGY SECURITY*. 2019.

Dual Unit Integrated Coal Gasification Combined Cycle (IGCC)

1. **Location Factors**
    - Requires access to coal reserves.
    - Suitable for areas with stringent emission regulations.

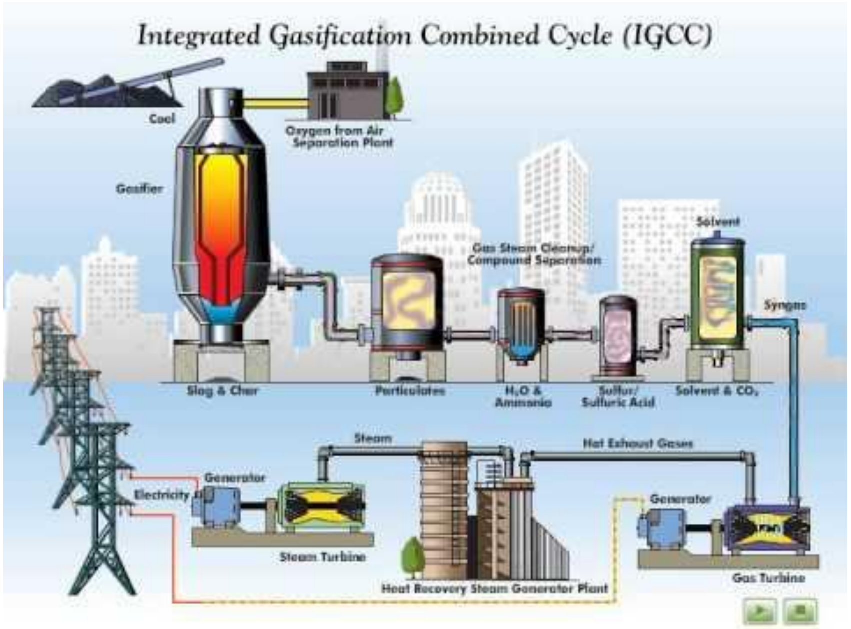

Fig. 11 IGCC Power Plant Layout(*Integrated Gasification Combined Cycle*)

2. **Electricity Price Factors**
   - High capital and operational costs.
   - Fluctuating coal prices.
3. **New/Planned Plants**
   - Limited growth globally due to high costs and shift towards cleaner energy.
4. **Future Prospects**
   - Potential growth in carbon capture and storage technology implementation.
5. **Reference**

Integrated Gasification Combined Cycle. Directed by UK Center for Applied Energy Research, 2015. *YouTube*, https://www.youtube.com/watch?app=desktop&v=V3jfECTjMS8.

Conventional Natural Gas Combustion Turbine (CT)

1. **Location Factors**
   - Proximity to natural gas supply lines or LNG terminals.
   - Suitable for regions requiring peaking and fast ramp-up capabilities.

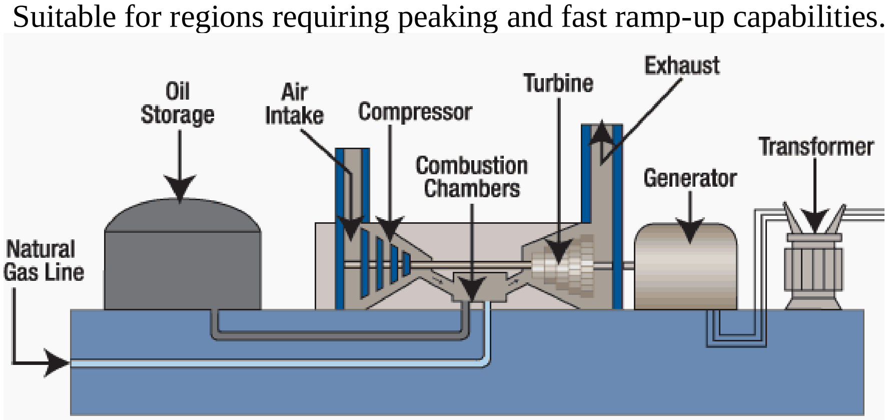

Fig. 12 Conventional Natural Gas Combustion Turbine Power Plant Layout (Portal and Csanyi)

2. **Electricity Price Factors**
    - Natural gas market prices.
    - Lower operation and maintenance costs.
3. **New/Planned Plants**
    - Widespread in the USA for meeting peak demands.
    - Increasing installations in regions with abundant natural gas.
4. **Future Prospects**
    - Continues to be an important peaking power source; may face competition from battery storage.
5. **Reference**

   Portal, EEP-Electrical Engineering, and Edvard Csanyi. "Generating Electricity with Combustion Turbines." *EEP - Electrical Engineering Portal*, 28 May 2014, https://electrical-engineering-portal.com/generating-electricity-with-combustion-turbines.

Advanced Natural Gas Combustion Turbine (CT)

1. **Location Factors**
    - Similar to conventional CT, with added focus on locations benefiting from higher efficiency and lower emissions.
2. **Electricity Price Factors**
    - Higher efficiency reduces fuel costs.
    - Advanced technology leads to higher capital costs.
3. **New/Planned Plants**
    - Gradual replacement of conventional CTs in many regions.
4. **Future Prospects**
    - Increasing demand due to better performance and environmental compliance.

Conventional Natural Gas Combined Cycle (CC)

1. **Location Factors**
    - Access to natural gas pipelines.
    - Preferred in regions needing steady, reliable power supply.

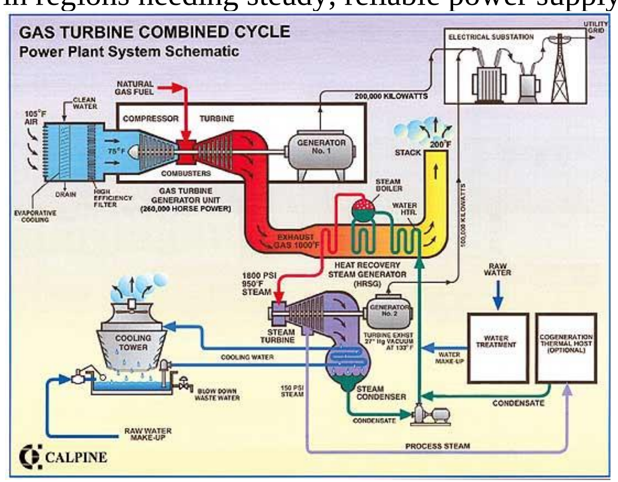

Fig. 13 Conventional Natural Gas Combined Cycle Power Plant Layout (*Energy Zones Mapping Tool*)

2. **Electricity Price Factors**

- Efficiency leads to lower operational costs.
- Influenced by natural gas market prices.

3. **New/Planned Plants**
   - Growing in areas with natural gas availability, like the USA and Middle East.
4. **Future Prospects**
   - Likely to increase due to high efficiency and lower emissions compared to coal.
5. **Reference**
   Energy Zones Mapping Tool. https://ezmt.anl.gov/energy_resources/natural_gas.

Advanced Natural Gas Combined Cycle (CC)

1. **Location Factors**
   - Access to natural gas sources; similar to conventional CC but benefiting more from technological advancements.
2. **Electricity Price Factors**
   - Higher initial investment but lower operational costs due to higher efficiency.
3. **New/Planned Plants**
   - Focus on replacing older CC plants in the USA, Europe, and Asia.
4. **Future Prospects**
   - Continues to grow, especially with advancements in efficiency and emission controls.

Diesel Generation, MW Scale

1. **Location Factors**
   - Ideal for remote locations without grid access.
   - Used as backup power sources in various settings.

Fig. 14 Diesel Generation Power Plant Layout(Technology)

2. **Electricity Price Factors**
   - Diesel fuel costs and maintenance expenses.
3. **New/Planned Plants**
   - Mostly in remote or off-grid areas; declining in developed countries.
4. **Future Prospects**
   - Limited growth potential, mainly used in niche applications.

Pressurized Water Dual Unit Nuclear Reactor (PWR)

1. **Location Factors**
   - Proximity to water bodies for cooling.
   - Remote locations considering safety and regulatory requirements.

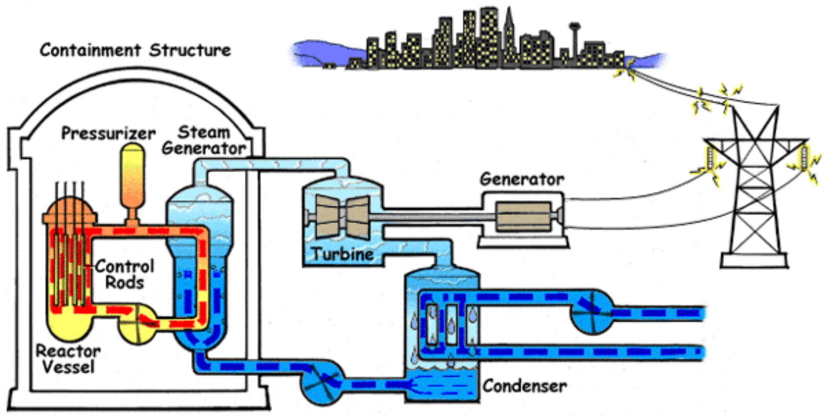

Fig. 15 Nuclear Reactor (PWR) Power Plant Layout (“Animated Images of Plants PWR and BWR”)

2. **Electricity Price Factors**
   - High capital and decommissioning costs.
   - Relatively low fuel costs.
3. **New/Planned Plants**
   - Few new projects in the USA; some growth in China, Russia, and India.
4. **Future Prospects**
   - Challenged by safety concerns and competition from renewables.
5. **Reference**

   “Animated Images of Plants PWR and BWR.” *NRC Web*, https://www.nrc.gov/reading-rm/basic-ref/students/multimedia/animated-images-plants-pwr-bwr.html.

Boiling Water Dual Unit Nuclear Reactor (BWR)

1. **Location Factors**
   - Similar to PWR, with added emphasis on advanced safety measures.

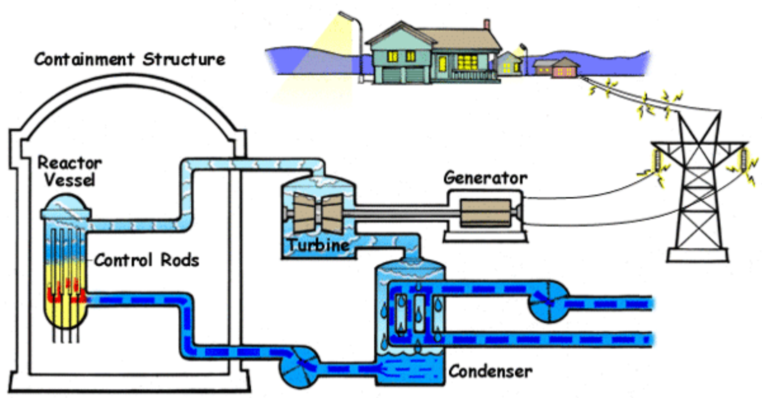

Fig. 16 Nuclear Reactor (BWR) Power Plant Layout (“Animated Images of Plants PWR and BWR”)

2. **Electricity Price Factors**
    - Comparable to PWR in terms of capital and operational costs.
3. **New/Planned Plants**
    - Limited new installations globally.
4. **Future Prospects**
    - Faces similar challenges as PWR, including public perception and regulatory hurdles.
5. **Reference**

"Animated Images of Plants PWR and BWR." *NRC Web*, https://www.nrc.gov/reading-rm/basic-ref/students/multimedia/animated-images-plants-pwr-bwr.html.

Conclusion

Technology Specifics: Each technology exhibits distinct characteristics in terms of its power cycle, operational temperatures, power capacities, and efficiency, which necessitates a comprehensive understanding of these particularities in order to optimize performance and effectively address environmental concerns. It is imperative to grasp the idiosyncrasies of each technology to ensure that its potential is fully harnessed and any potential drawbacks are mitigated.

Environmental Impact: As fossil fuel-based technologies currently dominate global energy production, it is crucial to acknowledge and grapple with the significant environmental challenges they pose. These challenges primarily arise due to their alarming emission rates of CO_2, NO_x, and particulate matter. In order to combat these adverse environmental effects, it is imperative to adopt advanced technologies and employ emission treatment methods such as Carbon Capture and Storage (CCS). The implementation of such measures is paramount to effectively mitigate the environmental impact of fossil fuel-based technologies.

Nuclear Energy: Nuclear reactors, specifically Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), offer a highly viable alternative to fossil fuels in terms of their greater power capacity and lower greenhouse gas emissions. However, it is crucial to address the inherent challenges associated with nuclear energy, such as the management of nuclear waste and the significant initial capital costs involved. By effectively addressing these challenges, the full potential of nuclear energy can be harnessed, thereby contributing to a more sustainable and low-emission energy landscape.

Economic Aspects: The comprehensive report highlights the intricate interplay of varying capital, operational, and maintenance costs that are associated with each technology. These economic factors play a pivotal role in decision-making processes related to the establishment of new power plants or the upgrading of existing ones. A thorough understanding of the economic aspects of electricity generation technologies is essential to make informed choices and ensure the long-term viability and financial sustainability of power generation projects.

Location and Electricity Pricing: The location of power plants and the pricing of electricity generated are influenced by a multitude of factors that were meticulously explored in the report. These factors include the availability of resources, environmental regulations, and infrastructural considerations. By taking these influential factors into account, stakeholders can make well-informed decisions regarding the placement of power plants and the pricing of electricity generated, thereby optimizing the utilization of resources, and ensuring a sustainable and economically viable energy landscape.

Future Prospects: The report underscores the pivotal role that innovation and regulatory support play in shaping the future trajectory of conventional power sources. The ongoing transition to more sustainable forms of energy, coupled with advancements in technology, will significantly influence the trajectory of conventional power sources. It is imperative to recognize the potential of innovation and regulatory support to pave the way for a more sustainable and environmentally friendly energy landscape that aligns with the global goals of mitigating climate change and achieving sustainable development.

Global Perspective: The study presented in the report provides valuable insights into significant existing and planned power plants around the world, offering a comprehensive understanding of the diverse energy landscape that varies significantly across regions. This global perspective is instrumental in fostering a nuanced understanding of the unique energy challenges and opportunities that different regions face. By considering this global perspective, policymakers and stakeholders can make well-informed decisions that consider the regional nuances and the potential for collaboration and knowledge sharing.

Challenges and Opportunities: Each technology faces distinct challenges that range from environmental concerns for fossil fuel-based power plants to technological and safety concerns for nuclear reactors. However, it is essential to recognize that these challenges also present opportunities for improvement and innovation. Advancements in technology and an increasing awareness of environmental issues provide a fertile ground for addressing these challenges and capitalizing on the opportunities that arise. By embracing these challenges and seizing the opportunities, stakeholders can drive progress and foster a more sustainable and efficient electrification of the global energy landscape.

Comprehensive Understanding: The overarching aim of the report is to provide a comprehensive understanding of conventional electric power generation, encompassing its operations, associated costs, and the myriad of issues that arise. By offering a holistic view of power generation technologies, the report serves as an invaluable resource for individuals involved in energy production and policymaking. It equips them with the necessary knowledge and insights to make informed decisions and shape policies that are aligned with the overarching goals of sustainability and energy security.

Relevant References

"Animated Images of Plants PWR and BWR." *NRC Web*, https://www.nrc.gov/reading-rm/basic-ref/students/multimedia/animated-images-plants-pwr-bwr.html. Accessed 22 Dec. 2023.

Araner. *What Makes Combined Cycle Power Plants so Efficient?* https://www.araner.com/blog/combined-cycle-power-plants. Accessed 22 Dec. 2023.

Bays, Samuel, et al. *Reactor Fundamentals Handbook*. INL/EXT-19-53301-Rev000, 1615634, 1 Apr. 2019, p. INL/EXT-19-53301-Rev000, 1615634. *DOI.org (Crossref)*, https://doi.org/10.2172/1615634.

Boyce, Meherwan P. *Gas Turbine Engineering Handbook*. 2nd ed, Gulf Professional Pub, 2002.

Breeze, Paul A. *Power Generation Technologies*. Third edition, Newnes, an imprint of Elsevier, 2019.

Energy Zones Mapping Tool. https://ezmt.anl.gov/energy_resources/natural_gas. Accessed 22 Dec. 2023.

Integrated Gasification Combined Cycle. Directed by UK Center for Applied Energy Research, 2015. *YouTube*, https://www.youtube.com/watch?app=desktop&v=V3jfECTjMS8.

Lecture 7 October 6 2023.Pptx.

Mahon, L. L. J. *Diesel Generator Handbook*. Butterworth-Heinemann, 1992.

Portal, EEP-Electrical Engineering, and Edvard Csanyi. "Generating Electricity with Combustion Turbines." *EEP - Electrical Engineering Portal*, 28 May 2014, https://electrical-engineering-portal.com/generating-electricity-with-combustion-turbines.

Sunjay, et al. *CLEAN FUEL TECHNOLOGY FOR WORLD ENERGY SECURITY*. 2019.

Technology, Electrical. “Diesel Power Plant - Components, Operation and Applications.” *ELECTRICAL TECHNOLOGY*, 24 Aug. 2021, https://www.electricaltechnology.org/2021/08/diesel-power-plant.html.

Speight, James G. *Coal-Fired Power Generation Handbook 2nd Edition*.