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NOVACAB Energy Solutions

Conversion of Waste Heat into Electricity Using Combined TESS-ORC Technology

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Abstract

The integration of the Novacab Thermal Energy Storage System (TESS) with an Organic Rankine Cycle (ORC) represents a transformative approach to converting low- to medium-temperature waste heat into electricity. This white paper explores the operational principles and advantages of the TESS-ORC system, which enables the effective capture and storage of waste heat from diverse sources such as industrial processes, geothermal energy, and solar thermal applications. The TESS facilitates a decoupling between heat supply and electricity generation, enhancing overall system efficiency by enabling energy production to occur during high-demand periods, even when heat sources are intermittent.

Through detailed analysis, the report highlights the efficiency gains associated with varying waste heat temperatures and the critical components of the ORC system, including heat exchangers, turbo-expanders, and condensers. Comparisons with traditional Rankine cycles further illustrate the advantages of the TESS-ORC system in optimizing performance for lower temperature applications. Additionally, the integration of power electronics ensures generation compatibility with grid requirements, thereby enhancing operational reliability and economic viability.

The TESS-ORC system not only improves energy efficiency and reduces emissions but also presents significant opportunities for revenue optimization through effective load balancing and peak shaving. Overall, this technology plays a crucial role in advancing sustainable energy solutions, maximizing the utilization of available waste heat, and integrating renewable energy sources into modern power generation strategies.

Executive Summary

The **TESS-ORC White Paper** outlines integrating the Novacab Thermal Energy Storage System (TESS) with an Organic Rankine Cycle (ORC) to convert waste heat into electricity.

Key Highlights:

1. **Introduction**:

The TESS-ORC technology addresses energy efficiency and emission reduction by converting low-temperature waste heat from various sources (e.g., industrial processes, geothermal energy) into electricity.

2. **System Operation**:

The TESS captures and stores waste heat, which can later be converted into mechanical energy by the ORC. The ORC operates effectively at lower temperatures (70°C to 300°C) using organic fluids, featuring components like heat exchangers, turbo-expanders, condensers, and pumps.

3. **Benefits of TESS**:

Decoupling Heat Supply: Allows for electricity generation to continue during periods when heat is unavailable.

Increased Efficiency: Minimizes heat loss and maximizes the utilization of waste heat.

Reliability and Resilience: Provides a thermal buffer to stabilize operations amidst fluctuating heat supply.

Grid Flexibility: Enhances integration with renewable energy by storing excess heat during peak availability for later use.

4. **Performance Factors**:

Higher waste heat temperatures lead to increased efficiency and power output from the ORC system due to greater enthalpy changes. Comparisons highlight how waste heat at 225°C generates significantly more electricity than at lower temperatures (e.g., 125°C).

5. **Comparison to Traditional Rankine Cycles**:

TESS-ORC systems are more suitable for low to medium-temperature applications compared to traditional Rankine cycles, which thrive at higher temperatures.

6. **Power Conversion**:

The power generated is transformed from mechanical to electrical energy via a generator, supplemented by inverters and transformers as needed for grid compatibility.

7. **Operational and Economic Advantages**:

TESS reduces operational costs, increases reliability, and improves return on investment by better utilizing available waste heat and allowing for efficient electricity production when needed.

8. **Environmental Impact**:

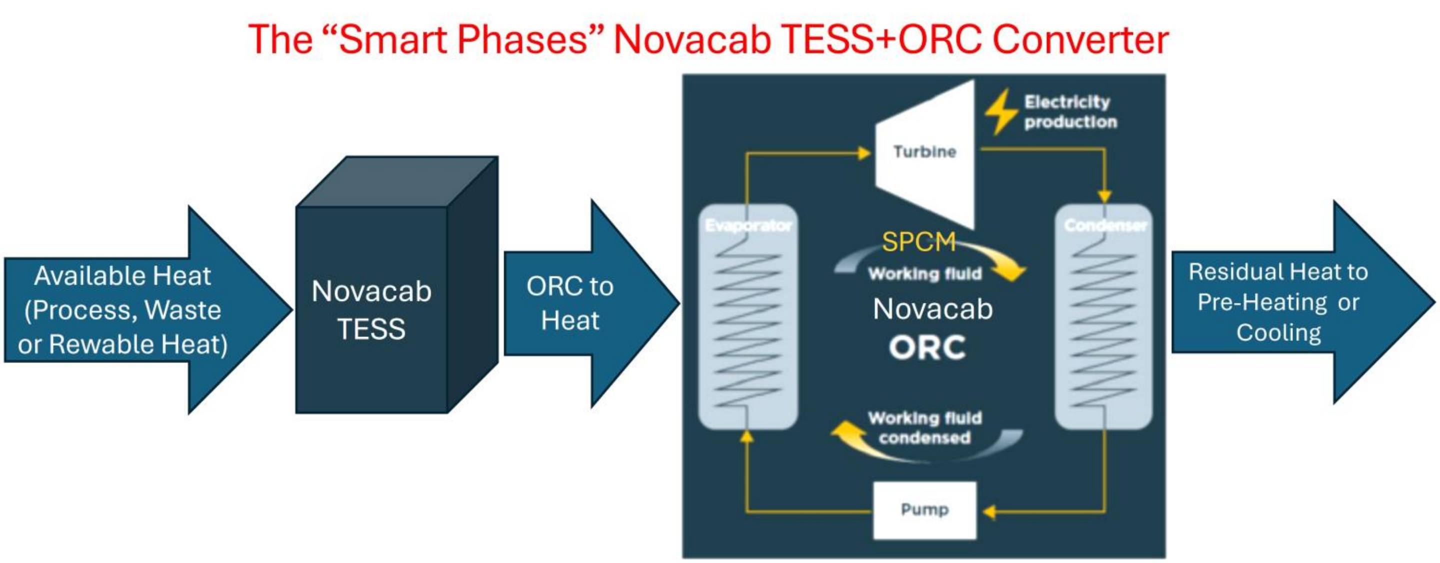
Enhances sustainability by reducing fuel consumption and greenhouse gas emissions while effectively using low-grade waste heat.

Conclusion: The TESS-ORC system is an innovative solution for efficiently converting waste heat into electricity, offering significant advantages in energy recovery, operational flexibility, and economic returns. This technology plays a crucial role in advancing sustainable energy practices by enabling the effective integration of renewable sources and optimizing waste heat recovery in various industrial applications.

1. Introduction

The quest for improving energy efficiency and reducing emissions has led to the development of technologies that recover and convert waste heat into usable energy. The Novacab Thermal Energy Storage System (TESS) integrated with an Organic Rankine Cycle (ORC) represents a significant advancement in this area, offering the ability to store waste heat and convert it into electricity.

The increasing focus on energy efficiency and sustainability has led to the development of innovative technologies that convert waste heat into usable energy. The Novacab Thermal Energy Storage System (TESS) combined with an Organic Rankine Cycle (ORC) represents a state-of-the-art solution for capturing and converting waste heat into electricity. This white paper explains how the TESS-ORC system works, compares it to traditional Rankine cycles, and explores its potential applications in various industries. It explores how the TESS-ORC system operates, its key components, and how it can be utilized in a variety of heat recovery applications, such as Combined Heat and Power (CHP), industrial processes, geothermal, and solar thermal systems. We will further illustrate the system's efficiency by examining two cases: waste heat at 125°C and 225°C. It also provides specific examples of waste heat conversion at different temperature levels and discusses how the system integrates power electronics to ensure the generated electricity is suitable for various needs.



2. How the TESS-ORC System Generates Electricity

The TESS-ORC system operates through two interrelated processes: storing heat from waste sources and converting that stored heat into mechanical energy, which is subsequently transformed into electricity.

2.1 Thermal Energy Storage (TESS)

TESS captures the waste heat from the heat source and stores it in a thermal medium (such as a synthetic phase change material, SPCM). This waste heat might come from various sources such as Combined Heat and Power (CHP) units, geothermal heat, or solar thermal energy. The stored heat can be accessed as needed, allowing flexibility in operation and aligning energy production with electricity demand. This stored heat can be dispatched on demand to feed the ORC system, which converts the stored thermal energy into electricity when needed.

2.2 Organic Rankine Cycle (ORC)

The ORC works similarly to a traditional Rankine cycle but uses organic fluids with lower boiling points, allowing it to efficiently convert low-temperature heat sources (from 70°C to 300°C) into electricity. The ORC converts the heat from the TESS into electricity via the following components:
- Heat Exchanger/Boiler: Transfers the stored heat to an organic working fluid.
- Turbo Expander: The organic fluid expands, driving a turbine to generate electricity.
- Condenser: The organic fluid is cooled and condensed back into a liquid.
- Pump: Pressurizes the fluid before re-entering the heat exchanger.

Organic Rankine Cycle (ORC) turbines, like all turbines, are designed to operate at a specific set of conditions, known as the **design point**. This design point optimizes parameters such as flow rate, temperature, pressure, and rotational speed to achieve the highest efficiency. However, in regular applications, ORC systems frequently encounter **off-design conditions** due to fluctuations in heat source availability (e.g., waste heat, geothermal, solar thermal) or varying power demands.

Handling off-design conditions efficiently is crucial for maintaining performance and extending the operational life of the turbine. That is one of the crucial purposes of the TESS module in the system. It makes sure the conditions stay at the design point. The use of **Thermal Energy Storage (TESS)** can help smooth out fluctuations in the heat source, reducing the occurrence of off-design operation.

- **Working Principle**: Thermal energy from the heat source is stored in a medium (e.g., molten salts, phase-change materials) and released as needed to maintain a stable temperature and pressure entering the turbine.

- **Benefits**: By buffering the variability in heat input, TESS allows the turbine to operate closer to its design point, maintaining high efficiency and reducing wear on turbine components.

3. ORC Components and Enthalpy Changes

3.1 Waste Heat Fed Boiler (Heat Exchanger)

The boiler transfers heat from the TESS to the organic working fluid, increasing its enthalpy and vaporizing the fluid. The enthalpy increase is proportional to the temperature of the heat source. TESS-ORC systems are versatile and can utilize waste heat from a variety of sources:
- Combined Heat and Power (CHP): CHP systems generate both electricity and heat. The TESS-ORC system can effectively capture the waste heat rejected from CHP systems to produce additional electricity.
- Geothermal Energy: Geothermal heat from underground reservoirs often exists at relatively low temperatures, making it a suitable heat source for ORC systems.
- Solar Thermal: Concentrated solar power (CSP) plants generate heat using mirrors or lenses to focus sunlight. This heat can be stored in the TESS system and used in the ORC.
- Industrial Waste Heat: Many industrial processes, such as steelmaking or chemical manufacturing, produce large amounts of waste heat. Capturing this heat for power generation can improve overall plant efficiency.

Enthalpy Change: The enthalpy of the working fluid increases as heat is added, transforming the liquid into a vapor. The amount of heat absorbed and the resulting enthalpy change depends on the source temperature (higher temperatures lead to larger enthalpy increases).

3.2 Turbo Expander

In the turbo expander, the high-pressure vapor expands, driving a turbine to produce mechanical work. The expansion process results in a drop in pressure and temperature, decreasing the enthalpy of the fluid.

Enthalpy Change: The expansion process reduces the fluid’s enthalpy as mechanical work is extracted. The efficiency of this process depends on both the pressure differential and the characteristics of the organic fluid.

3.3 Condenser

The vapor exiting the turbine is cooled in the condenser, which lowers its temperature and condenses it back into a liquid. The cooling process further reduces the fluid's enthalpy as it releases heat to the surroundings or to a cooling medium.

Enthalpy Change: The fluid’s enthalpy decreases as it condenses, releasing latent heat. The condenser operates at a lower temperature than the vapor to facilitate condensation, typically using air or water as the cooling medium.

3.4 Pump

The pump increases the pressure of the condensed liquid, preparing it to re-enter the heat exchanger. The enthalpy increases slightly due to compression, but the overall energy increase is minimal compared to the heat exchange process.

Enthalpy Change: The pump increases the pressure of the fluid with a small increase in enthalpy, as it does not add significant thermal energy to the system.

4. Waste Heat Sources

Waste heat significantly impacts the turbine's performance in an Organic Rankine Cycle (ORC) system because it influences the thermodynamic properties of the working fluid, such as enthalpy, pressure, and temperature. These properties directly affect the turbine's ability to convert thermal energy into mechanical (and subsequently electrical) energy. Below are the key ways in which waste heat impacts turbine performance:

4.1. Higher Waste Heat Temperature Increases Turbine Efficiency

When the temperature of the waste heat increases, more energy is available to transfer into the working fluid in the TESS-ORC system. This energy increase results in the following:

- **Higher Enthalpy of the Working Fluid**: The working fluid entering the turbine has a higher enthalpy (more internal energy), which means it carries more thermal energy that can be converted into mechanical work.
- **Higher Expansion Ratio**: A higher initial temperature leads to a higher pressure in the working fluid before entering the turbine. As the fluid expands through the turbine, the pressure drop is more significant, which means more mechanical work can be extracted.
- **More Power Output**: The greater energy content (enthalpy) in the fluid results in the turbine generating more mechanical power, which is then converted into electricity.

For example, in an ORC system using waste heat at **225°C**, the working fluid entering the turbine has a much higher energy content than one using waste heat at **125°C**. The turbine will extract more energy from the fluid due to the larger pressure and temperature differential, resulting in a higher power output and improved overall system efficiency.

4.2. Lower Waste Heat Temperature Reduces Turbine Efficiency

When waste heat is available at lower temperatures, the working fluid's enthalpy increases less significantly, leading to reduced turbine performance:

- **Lower Pressure and Temperature**: The working fluid does not reach as high pressure or temperature when waste heat is at a lower temperature. This results in a smaller pressure differential across the turbine, leading to less energy being extracted.

- **Lower Expansion Ratio**: With a lower temperature differential, the working fluid's expansion ratio in the turbine is smaller, and the turbine's mechanical efficiency drops.
- **Less Mechanical Work**: The reduced enthalpy and lower expansion ratio mean that the turbine generates less mechanical power, translating to lower electricity output.

In a TESS-ORC system with waste heat at **95°C**, the fluid entering the turbine will have a much lower enthalpy than one using waste heat at 225°C. Consequently, the turbine will produce significantly less power due to the smaller temperature and pressure differences.

4.3. Impact on Turbine Sizing and Design

The characteristics of the waste heat also influence the design and size of the turbine:

- **High-Temperature Systems**: Turbines operating with high-temperature waste heat sources are typically designed to handle higher pressure ratios and larger temperature drops, which can improve overall efficiency.
- **Low-Temperature Systems**: Turbines in low-temperature ORC systems are designed to optimize performance for smaller temperature and pressure differentials. These turbines may need to operate at lower speeds and may require larger volumetric flow rates to compensate for the reduced energy input.

4.4. Increased Efficiency with Optimal Turbine Operation

As the waste heat temperature increases, the ORC system's efficiency improves, and the turbine operates closer to its optimal design point. Optimal turbine operation leads to:

- **Improved Isentropic Efficiency**: The turbine's isentropic efficiency, which is the ratio of the actual mechanical work to the theoretical work (based on ideal expansion), improves with higher temperature waste heat.
- **Higher Power-to-Heat Ratio**: With more waste heat, the ratio of power produced to the heat supplied increases. This ratio is critical in systems where maximizing electricity production is the goal.

4.5. Operational Stability

Higher temperatures often lead to more stable turbine operation due to a greater pressure differential. This stability improves reliability and decreases maintenance needs over time.

Summary of the Impact of Waste Heat on Turbine Performance:

Waste Heat Condition	Effect on Turbine	Key Impact
High-Temperature **Waste Heat (e.g., 225°C)**	Higher enthalpy, pressure, and temperature in the working fluid	Increased power output and efficiency
Low-Temperature **Waste Heat (e.g., 95°C)**	Lower enthalpy, pressure, and temperature in the working fluid	Reduced power output and efficiency
Large Expansion Ratio	High pressure differential across the turbine	More mechanical work and higher efficiency
Small Expansion Ratio	Low pressure differential across the turbine	Less mechanical work and lower efficiency

The temperature and quantity of waste heat are crucial factors that affect turbine performance in an ORC system. Higher-temperature waste heat increases the working fluid's enthalpy, pressure, and temperature, allowing the turbine to generate more power and operate more efficiently. Conversely, lower-temperature waste heat results in reduced turbine performance. Properly matching the waste heat source to the turbine design is key to maximizing the efficiency and electricity output of the ORC system.

4.6 Simulation of TESS-ORC System at Different Waste Heat Temperatures

This simulation explores the integration of a Novacab Thermal Energy Storage System (TESS) + Organic Rankine Cycle (ORC) unit with a diesel-powered Combined Heat and Power (CHP) system. The focus is on optimizing waste heat utilization to improve overall energy efficiency. The system's economic and technical performance is evaluated across different waste heat source temperatures and electricity cost scenarios.

The integrated system under study includes:

- **CHP Unit**: A diesel-engine-based CHP unit with a 1 MW output, converting 30% of input energy into electricity and 70% into waste heat.
- **Novacab TESS+ORC**: A system designed to convert waste heat from the CHP unit into additional electricity. It operates with a cooling side at 15°C.

Key System Assumptions:

- **CHP Power Output**: 1 MW
- **CHP Electrical Efficiency**: 30%
- **CHP Waste Heat Efficiency**: 70%
- **Waste heat Source Temperatures**: from 80°C to 225°C

- **TESS-ORC Electrical Efficiency**: 90%
- **Electricity Price Scenarios**: $0.07, $0.10, and $0.14 per kWh
- **Peak Shaving Savings**: $14 per kW/month for reduced demand charges
- **Use Factor**: 92% of the total available hours in a year (8,760 hours)

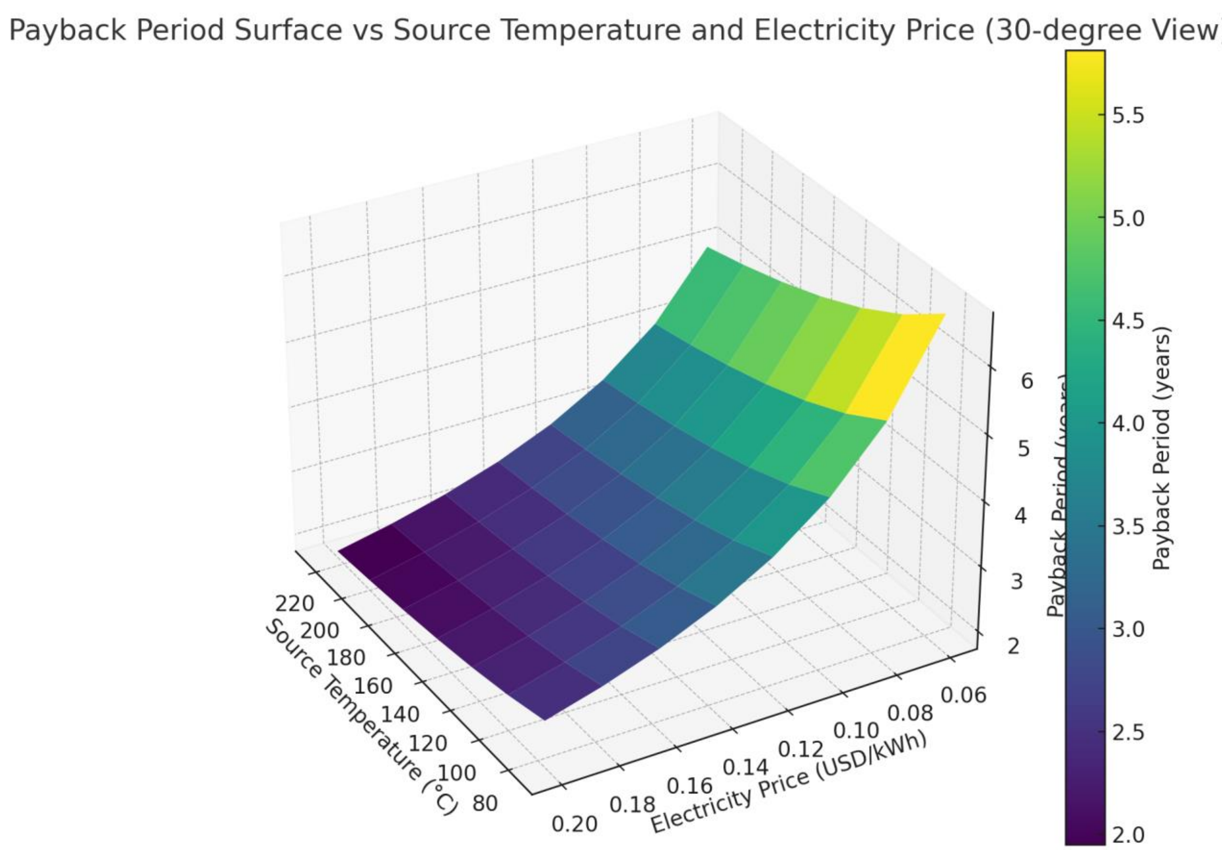
Results and Comparisons

The integration of the Novacab TESS+ORC system with a CHP unit under varying source temperatures and electricity prices shows consistent financial and technical benefits:

- As the source temperature increases, the TESS+ORC unit becomes more efficient, generating more electricity and contributing more to peak shaving savings.
- The payback period decreases as electricity prices rise and waste heat utilization improves, making the system more attractive in regions with higher electricity costs.
- Even under the lowest electricity price scenario demonstrates a payback period of fewer than 2.2 years, which improves significantly with higher electricity costs.

This simulation, for which the results are illustrated in the following graph, highlights the potential for integrating a Novacab TESS+ORC system with a CHP unit to capture waste heat and optimize electricity generation. It could also be using another source of waste heat with comparable or different results. The results demonstrate that such integration enhances energy efficiency and significantly reduces operating costs through peak shaving and increased electricity production.

The following graph is a 3D plot showing the payback period (in years) as a function of electricity price (in USD/kWh) and waste heat source temperature (in °C). The color scale represents the payback period, allowing you to visualize how both variables influence the system's economic performance.



The payback period varies depending on the source temperature and electricity price. Still, in all scenarios, the system proves to be a sound investment, particularly for industrial facilities with high energy demand.

The following sections, 4.6.1 and 4.6.2, go further into some examples extracted from the simulation.

4.6.1 Example 1: Waste Heat at 125°C

At 125°C, the system operates with a thermal efficiency of 24.4%. The ORC generates approximately 153.4 kW of electricity from 700 kW of waste heat. The relatively lower temperature results in a smaller enthalpy change compared to higher temperature systems.

The ORC system generates power using waste heat from a CHP unit, with the following characteristics:

- **TESS-ORC Thermal Efficiency**: 24.4%
- **Power Output**: For 700 kW of waste heat, the ORC generates approximately 153.4 kW of electricity.

Enthalpy Changes: The lower temperature source results in a smaller enthalpy change in the heat exchanger and turbo expander compared to higher temperatures. As a result, the electricity generated is relatively lower than at higher temperatures.

Step 1: Heat Exchanger (Boiler)

In the boiler, the working fluid absorbs heat from the waste heat source and is converted from a liquid to a superheated vapor.

- **Enthalpy at Boiler Inlet (liquid)**: 70 kJ/kg (saturated liquid)
- **Enthalpy at Boiler Outlet (superheated vapor)**: 205 kJ/kg
- **Enthalpy Change (Δh in boiler)**: $\Delta h_{boiler}=205-70=135$ kJ/kg

  This represents the heat input into the working fluid per kilogram, which is **135 kJ/kg**.

Step 2: Turboexpander (Turbine)

The superheated vapor enters the turbine and expands, doing mechanical work to drive the generator. During this process, the working fluid's pressure and enthalpy drop.

- **Enthalpy at Turbine Inlet (superheated vapor)**: 205 kJ/kg
- **Enthalpy at Turbine Outlet (wet vapor)**: 140 kJ/kg
- **Enthalpy Change (Δh in turbine)**: $\Delta h_{turbine}=205-140=65$ kJ/kgΔ

  The mechanical work extracted by the turbine is **65 kJ/kg**.

Step 3: Condenser

In the condenser, the working fluid rejects heat to the environment and condenses back to a liquid.

- **Enthalpy at Condenser Inlet (wet vapor)**: 140 kJ/kg
- **Enthalpy at Condenser Outlet (saturated liquid)**: 70 kJ/kg
- **Enthalpy Change (Δh in condenser)**: $\Delta h_{condenser}=140-70=70$ kJ/kg

  The heat rejected to the environment per kilogram of working fluid is **70 kJ/kg**.

Step 4: Pump

The pump raises the pressure of the working fluid before it re-enters the boiler. The pump work is typically very small, so the enthalpy change is negligible.

- **Enthalpy Change (Δh in pump)**: Small (can be considered negligible for this analysis).

4.6.2 Example 2: Waste Heat at 225°C

At 225°C, the system operates with a higher efficiency of 34.73%. It generates approximately 218.9 kW of electricity from 700 kW of waste heat. The larger temperature differential allows for a more significant enthalpy change, resulting in higher energy conversion.

With 700 kW of waste heat, the system performs more efficiently, generating more electricity:

- **TESS-ORC Thermal Efficiency**: 34.73%
- **Power Output**: For the same amount of waste heat, the ORC generates approximately 218.9 kW of electricity.
- **Enthalpy Changes**: At this higher temperature, the enthalpy change in the heat exchanger is larger, and more energy is extracted in the turbo expander, leading to greater power output. The larger temperature differential also improves the efficiency of the condenser, making it easier to condense the vapor back into a liquid.

Step 1: Heat Exchanger (Boiler)

At 225°C, the working fluid absorbs a greater amount of heat due to the higher source temperature.

- **Enthalpy at Boiler Inlet (liquid)**: 90 kJ/kg (saturated liquid)
- **Enthalpy at Boiler Outlet (superheated vapor)**: 350 kJ/kg
- **Enthalpy Change (Δh in boiler)**: $\Delta h_{boiler}=350-90=260$ kJ/kg

  This represents the heat input into the working fluid, which is **260 kJ/kg**.

Step 2: Turboexpander (Turbine)

With higher enthalpy entering the turbine, more mechanical work is extracted as the fluid expands.

- **Enthalpy at Turbine Inlet (superheated vapor)**: 350 kJ/kg
- **Enthalpy at Turbine Outlet (wet vapor)**: 225 kJ/kg
- **Enthalpy Change (Δh in turbine)**: $\Delta h_{turbin}e=350-225=125$ kJ/kg

  The mechanical work extracted by the turbine is **125 kJ/kg**.

Step 3: Condenser

The fluid condenses back to a liquid, releasing heat to the environment.

- **Enthalpy at Condenser Inlet (wet vapor)**: 225 kJ/kg
- **Enthalpy at Condenser Outlet (saturated liquid)**: 90 kJ/kg
- **Enthalpy Change (Δh in condenser)**: $\Delta h_{condenser} = 225 - 90 = 135$ kJ/kg

  The heat rejected to the environment is **135 kJ/kg**.

Step 4: Pump

Similar to the previous case, the pump's enthalpy change is negligible.

- **Enthalpy Change (Δh in pump)**: Small (can be considered negligible for this analysis).

4.6.3 Comparison of the Two Examples

Comparison of the Two Examples

Parameter	125°C Waste Heat	225°C Waste Heat
Boiler Heat Input	135 kJ/kg	260 kJ/kg
Turbine Work Output	65 kJ/kg	125 kJ/kg
Condenser Heat Rejection	70 kJ/kg	135 kJ/kg
Overall Cycle Efficiency	Moderate (lower temperature)	Higher (due to greater temperature difference)

Power Generation:

- At **125°C** waste heat, the ORC system generates approximately **153.4 kW** of electricity.
- At **225°C** waste heat, the ORC system generates approximately **218.9 kW** of electricity.

The increase in temperature from **125°C to 225°C** results in:

- **Greater enthalpy change** in the boiler and turbine, meaning more energy is converted to mechanical work.
- **Higher power output**, resulting in increased electricity generation.

The **enthalpy change** across each ORC component demonstrates how **waste heat temperature** affects system performance. A higher waste heat temperature results in greater energy conversion, increased power generation, and improved cycle efficiency.

5. Comparison to Traditional Rankine Cycles

The ORC and traditional Rankine cycle differ primarily in the working fluid, temperature range, and efficiency. Traditional Rankine cycles use water as a working fluid and operate at high temperatures (above 300°C) and pressures, making them suitable for large-scale power plants. In contrast, the ORC uses organic fluids with lower boiling points, enabling it to operate efficiently with lower-temperature heat sources. ORC systems are ideal for small- to medium-scale applications, such as waste heat recovery, geothermal, or solar thermal power generation.

5.1 Efficiency Differences

Traditional Rankine cycles are more efficient for high-temperature heat sources, achieving efficiencies of 35-45%. However, their performance drops significantly at lower temperatures. ORC systems achieve efficiencies of 15-25% for low- to medium-temperature heat sources, making them more suitable for waste heat applications.

5.2 Application and Cost Differences

ORC systems are often more cost-effective for distributed energy applications, requiring smaller and less expensive components. Steam Rankine cycles are better suited for large, centralized power generation facilities that can handle high temperatures and pressures.

6. Impact of Waste Heat on Turbine Performance

Waste heat significantly affects the performance of the turbine in an ORC system. Higher temperature waste heat increases the enthalpy of the working fluid, leading to higher turbine efficiency and greater power output. Conversely, lower-temperature waste heat results in smaller enthalpy changes and reduced turbine performance.

6.1 High-Temperature Waste Heat

When the waste heat is at high temperatures (e.g., 225°C), the turbine operates with a large pressure differential, extracting more mechanical energy and producing higher electricity output.

6.2 Low-Temperature Waste Heat

At lower temperatures (e.g., 95°C), the turbine experiences a smaller expansion ratio, reducing mechanical energy extraction and lowering the overall system efficiency.

7. Conversion of Thermo-Mechanical Power to Electricity

The thermo-mechanical power generated by the turboexpander is converted into electrical energy by a generator. The generator is coupled to the turbine shaft, converting the rotational mechanical energy into electrical energy using electromagnetic induction.

The conversion of thermo-mechanical power into electricity in an Organic Rankine Cycle (ORC) system involves the following steps:

- Turboexpander: Converts the thermal energy of the working fluid into mechanical energy.
- Generator: Converts mechanical energy into electrical energy (AC or DC).
- Inverter (if needed): Converts DC to AC if the generator produces DC power, ensuring the correct frequency and voltage.
- Voltage Regulators and Transformers: Ensure stable output voltage and step up/down voltage to match grid or load requirements.
- Frequency Converters (if needed): Adjust the frequency of the AC power to match grid standards.

7.1 Generator Operation

The generator produces alternating current (AC) or direct current (DC) electricity, depending on the design. AC generators are commonly used for grid-tied applications, while DC generators may be used in isolated systems with inverters.

7.2 Power Converters and Voltage Control

To ensure the electricity generated is compatible with the grid or local loads, inverters, voltage regulators, and transformers can be added. Inverters convert DC to AC, while voltage regulators maintain a stable output. Transformers can adjust voltage levels as needed.

8. Conclusion

The Novacab TESS-ORC system offers a versatile and efficient solution for converting waste heat into electricity. It excels in applications where low- to medium-temperature waste heat is available, outperforming traditional steam Rankine cycles in these conditions. The two examples presented illustrate how the performance of the ORC varies with source temperature, with higher temperatures leading to greater electricity generation and improved overall efficiency. With its ability to integrate power electronics such as inverters and voltage regulators, the TESS-ORC system ensures the electricity produced meets grid and application requirements, making it suitable for both grid-tied and off-grid applications.

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APPENDIX A

Comparing the TESS-ORC system to a traditional Rankine cycle

Comparing the **TESS-ORC (Thermal Energy Storage + Organic Rankine Cycle)** system to a **traditional Rankine cycle** helps illustrate the advantages and trade-offs of each technology in terms of efficiency, temperature adaptability, cost, and application suitability. Here's a breakdown of the key differences and similarities:

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1. Working Fluid

- **Traditional Rankine Cycle**:
    - The working fluid in traditional Rankine cycles is usually **water** (steam). Water has a high boiling point and is suitable for systems with high-temperature heat sources, typically above 300°C.
    - It is commonly used in power plants that operate with fossil fuels, nuclear power, or concentrated solar power, where the steam reaches very high pressures and temperatures.
- **TESS-ORC System (Organic Rankine Cycle)**:
    - ORC uses **organic fluids** like **isopentane, R245fa, or toluene**, which have much lower boiling points compared to water. This makes ORC suitable for lower-temperature waste heat sources (as low as 70°C to 300°C).
    - The use of organic fluids allows the ORC system to operate efficiently with heat sources that would not be viable for traditional Rankine cycles, such as industrial waste heat, geothermal sources, or solar thermal energy at moderate temperatures.

Key Difference:

- **Working Temperature Range**: Traditional Rankine cycles operate at much higher temperatures and pressures, making them ideal for large-scale power generation, whereas TESS-ORC systems are optimized for lower-temperature heat sources and can operate in a wider range of conditions.

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2. Efficiency

- **Traditional Rankine Cycle**:
  - The **Carnot efficiency** of traditional Rankine cycles can be higher because they operate with higher-temperature heat sources. Large-scale steam Rankine cycles in power plants can reach thermal efficiencies of **30-40%** or more when combined with modern supercritical or ultra-supercritical technologies.
  - However, efficiency drops significantly when used with low-temperature heat sources (below 200°C), where steam cannot achieve efficient phase changes.
- **TESS-ORC System**:
  - The **Carnot efficiency** of ORC systems is lower than that of traditional Rankine cycles when used with very high-temperature heat sources. However, the ORC system's efficiency at **low to moderate temperature ranges** (70°C to 300°C) is significantly better than that of the Rankine cycle because of the lower boiling points of organic fluids.
  - TESS-ORC systems typically operate at **20-25% efficiency** for medium-temperature sources (125°C-160°C) and can capture waste heat that traditional Rankine cycles would struggle with.

Key Difference:

- **Efficiency at Different Temperatures**: Traditional Rankine cycles are more efficient for high-temperature heat sources, while ORC systems outperform them for low- to medium-temperature waste heat sources.

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3. System Complexity and Flexibility

- **Traditional Rankine Cycle**:
  - Traditional Rankine cycles are generally **more complex** due to the high pressures and temperatures involved. They require high-quality materials to withstand the extreme conditions of superheated steam, making them capital-intensive and generally suited for large-scale power generation facilities.
  - They are **less flexible** in terms of modularity and use in smaller-scale applications or in locations with intermittent or variable heat sources.
- **TESS-ORC System**:

- TESS-ORC systems are **less complex** than steam Rankine cycles at lower temperatures, as the organic fluids used operate at lower pressures and temperatures, reducing the need for heavy-duty materials.
- The TESS system adds an additional layer of flexibility by allowing heat to be stored and dispatched as needed. This makes TESS-ORC particularly useful for **small to medium-sized applications**, **distributed generation**, and settings where waste heat or renewable heat sources (solar, geothermal) may fluctuate over time.

Key Difference:

- **Scalability and Flexibility**: Traditional Rankine cycles are better suited for large, constant heat sources, while TESS-ORC systems offer more flexibility for small to medium-scale applications with variable or lower-temperature heat sources.

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4. Applications and Use Cases

- **Traditional Rankine Cycle**:
  - Traditional Rankine cycles are **dominant in large-scale power plants**, including coal, natural gas, nuclear, and solar thermal power plants (with concentrated solar power systems).
  - They are also used in **combined heat and power (CHP)** plants when the waste heat can be recirculated into the steam cycle.
- **TESS-ORC System**:
  - TESS-ORC systems shine in applications where waste heat is available from industrial processes, **geothermal plants**, **solar thermal plants**, or **CHP systems** at medium to low temperatures.
  - They are ideal for **waste heat recovery** in manufacturing industries (e.g., cement, steel, chemical processes) where waste heat is abundant but at lower temperatures, making traditional Rankine cycles unsuitable.
  - Additionally, the **TESS (thermal energy storage)** component allows for **dispatchable energy generation**, even when the heat source is intermittent (e.g., solar thermal or industrial processes with variable heat output).

Key Difference:

- **Best Use Cases**: Traditional Rankine cycles are well-suited for large, continuous high-temperature heat sources, while TESS-ORC excels in recovering and storing energy from lower-temperature, variable, or intermittent heat sources.

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5. Maintenance and Operation

- **Traditional Rankine Cycle**:
  - Maintenance of steam Rankine systems is generally **costly and complex**, as they operate at high pressures and temperatures. High-quality materials and precise control systems are required to ensure reliability and safety, especially in large power plants.
- **TESS-ORC System**:
  - The ORC system, operating at **lower temperatures and pressures**, is **easier to maintain** and has a **longer operational life** for certain components (such as the turbine and piping).
  - Organic fluids are also **less corrosive** compared to steam, further reducing maintenance costs and operational complexities. This makes ORC systems a preferred choice for distributed or smaller-scale applications.

Key Difference:

- **Maintenance**: Traditional Rankine cycles, especially at high temperatures, require more complex and costly maintenance, whereas TESS-ORC systems, with their lower operating pressures and temperatures, are easier and cheaper to maintain.

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6. Heat Storage Capability

- **Traditional Rankine Cycle**:
  - Traditional Rankine cycles generally do not integrate **thermal energy storage** as a standard feature. Energy is generated from the heat source in real-time, meaning the system must operate continuously when heat is available.
  - In some large-scale applications (e.g., concentrated solar power plants), external molten salt storage systems can be integrated, but this adds significant complexity and cost.
- **TESS-ORC System**:

- The TESS component of TESS-ORC systems allows **thermal energy storage**, meaning heat from sources like industrial waste, solar thermal, or geothermal can be stored for use when needed.
- This **dispatchability** is a major advantage, especially for renewable and intermittent energy sources like solar or fluctuating industrial waste heat. It enables power generation to be decoupled from heat availability, ensuring electricity generation during periods of peak demand or when heat input fluctuates.

Key Difference:

- **Energy Storage**: TESS-ORC integrates thermal energy storage directly into the system, allowing for dispatchable power generation, whereas traditional Rankine cycles are less flexible in this regard and do not typically include storage options.

Comparison Table: TESS-ORC vs. Traditional Rankine Cycle

Feature	TESS-ORC	Traditional Rankine Cycle
Working Fluid	Organic fluids (e.g., isopentane, R245fa)	Water (steam)
Temperature Range	70°C to 300°C	Above 300°C
Efficiency	High efficiency for low/medium temps (20-25%)	High efficiency for high temps (30-40%)
System Complexity	Lower complexity, easier maintenance	Higher complexity, expensive materials needed
Heat Source Applications	Waste heat, geothermal, solar thermal	Power plants (fossil, nuclear, solar CSP)
Scalability	Small to medium scale, distributed energy	Large scale, centralized power generation
Thermal Energy Storage	Integrated TESS, allows dispatchable energy	Rarely integrated, real-time operation
Best for	Low/medium temperature sources, intermittent heat	High temperature, continuous heat sources

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Conclusion

In summary, TESS-ORC systems and traditional Rankine cycles serve different purposes in the energy landscape. Traditional Rankine cycles are well-suited for large-scale, high-temperature applications like fossil fuel power plants and concentrated solar power. In contrast, TESS-ORC systems are ideal for capturing and converting low- to medium-temperature waste heat and other renewable heat sources into electricity. The added flexibility of thermal energy storage in TESS-ORC systems offers significant advantages, especially in distributed energy applications and for intermittent sources like solar thermal or industrial waste heat.

Both technologies have their place in the transition to more efficient, sustainable energy systems, with TESS-ORC playing a crucial role in improving energy efficiency by utilizing heat sources that would otherwise be wasted.

APPENDIX B

Conversion of thermo-mechanical power to electricity

1. Conversion of Thermo-Mechanical Power to Electrical Power

1.1 Turboexpander: Mechanical Power Generation

In an ORC system, the working fluid, heated in the **boiler (heat exchanger)**, vaporizes and becomes a high-pressure gas. This high-energy vapor is expanded in a **turboexpander** (or turbine), where its pressure and temperature drop as it does work on the turbine blades. The energy in the high-pressure vapor is converted into **rotational mechanical energy** as the vapor expands and drives the turbine shaft.

- **Thermo-Mechanical Power**: The power generated in the turboexpander is proportional to the **pressure difference** between the high-pressure vapor entering the turbine and the lower pressure at the turbine's exit, as well as the **enthalpy change** of the working fluid during expansion.
- The rotational speed of the turbine can be very high, typically in the range of several thousand revolutions per minute (RPM), depending on the design of the system and the fluid used.

The mechanical power generated by the turboexpander is transmitted to a **generator**, which converts it into electrical power.

1.2 Generator: Mechanical to Electrical Conversion

The **generator** is coupled to the turbine shaft and converts the rotational mechanical energy into electrical energy using the principles of electromagnetic induction. As the turbine's shaft rotates, it turns a rotor within the generator. The rotor contains magnetic fields that induce a voltage in the stationary coils (stator) of the generator, producing an alternating current (AC).

- **AC Power Output**: In most ORC systems, the generator directly produces **alternating current (AC)**. The output voltage and frequency of the AC power depend on the design of the generator and the speed at which the turbine is driving the rotor.
    - **Voltage**: The output voltage is determined by the generator's design, specifically the number of turns in the stator coils and the strength of the magnetic field.
    - **Frequency**: The frequency of the AC power is determined by the rotational speed of the generator rotor. In many countries, the standard grid frequency

is **50 Hz** (Europe, Asia) or **60 Hz** (North America), so the generator must rotate at a specific speed to match the local grid frequency.

If the generator produces **AC power** at the required voltage and frequency, it can be connected directly to the electrical grid or load. However, additional power conversion equipment is sometimes necessary, especially if the output power characteristics differ from the required specifications.

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2. Voltage and Frequency Regulation: Power Converters

The output from the generator may not always match the desired form of electricity required by the end-use application (grid connection, DC storage, or specific AC voltage/frequency). To address this, **power converters** such as inverters or other converters can be added to the system.

2.1 Inverter: Converting DC to AC

In some ORC systems, particularly those where the generator produces **direct current (DC)** (for example, in smaller or isolated systems), an **inverter** is used to convert the DC power into **alternating current (AC)** for use by standard AC loads or for connection to the grid.

- **DC to AC Conversion**: The inverter takes the DC voltage and generates an AC waveform with the desired frequency (50 Hz or 60 Hz) and voltage level.
- **Voltage Matching**: Inverters can also adjust the output voltage to match the requirements of the grid or connected load.

Inverters are commonly used in renewable energy systems (like solar or wind) where DC power is produced. In the case of ORC systems, an inverter is necessary if a **DC generator** is used or if the output needs to be stabilized before grid connection.

2.2 Voltage Regulators and Transformers

In cases where the generator produces **AC power**, but the voltage level is not suitable for the grid or the application (e.g., high voltage for transmission or low voltage for local use), **voltage regulators** and **transformers** are used.

- **Voltage Regulation**: A voltage regulator ensures that the voltage output remains stable, even as the generator speed or load changes.
- **Transformers**: A transformer can step up or step down the AC voltage. For example, electricity generated at a lower voltage can be stepped up to match grid voltage levels (e.g., from 400V AC to 11kV AC for transmission). Conversely, it can step down voltage for local distribution or usage.

2.3 Frequency Converters

If the generator produces **AC power** but at the wrong frequency (for example, a mismatch between the generator speed and the required 50 Hz or 60 Hz frequency), a **frequency converter** can be used.

- **AC-AC Converters**: These devices convert the AC electricity from one frequency to another. They work by first converting the AC power to DC, then using an inverter to produce AC power at the desired frequency.

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3. Practical Considerations in Power Conversion

3.1 Grid-Connected Systems

In grid-connected ORC systems, the power output must match the grid's specifications in terms of voltage, frequency, and phase synchronization. Therefore, most grid-connected ORC systems include:

- **Inverters or synchronizing controllers** to match the frequency and phase of the grid.
- **Transformers** to step up or down the voltage, ensuring compatibility with the grid.

For large-scale ORC systems, grid synchronization is crucial to avoid issues like phase mismatches, which can cause damage to the grid or equipment.

3.2 Standalone or Off-Grid Systems

For off-grid ORC systems, particularly those used in **remote locations** or in combination with renewable energy sources like solar or geothermal, power conversion flexibility is key. These systems may:

- Use **DC generators** and rely on inverters to provide **AC power** to local loads.
- Include **battery storage**, where excess electricity generated by the ORC system is stored as DC power in batteries. In such cases, inverters are used to convert DC to AC as needed by the load.

3.3 Hybrid Systems

Some ORC systems are part of **hybrid power systems**, where multiple sources of electricity (e.g., solar, wind, ORC) are integrated. In such systems:

- **Power electronics** play a crucial role in balancing the different inputs and ensuring that the electricity generated by various sources can be efficiently managed, stored, and distributed.
- **Inverters and converters** help ensure that the electricity produced by the ORC system is compatible with other sources of power.

Summary of Power Conversion Process in ORC Systems

1. **Turboexpander**: Converts the thermal energy of the working fluid into mechanical energy.
2. **Generator**: Converts mechanical energy into electrical energy (AC or DC).
3. **Inverter (if needed)**: Converts DC to AC if the generator produces DC power, ensuring the correct frequency and voltage.
4. **Voltage Regulators and Transformers**: Ensure stable output voltage and step up/down voltage to match grid or load requirements.
5. **Frequency Converters (if needed)**: Adjust the frequency of the AC power to match grid standards.

Conclusion

In an ORC system, the conversion of thermo-mechanical power to electricity is primarily handled by the turboexpander and the generator. Additional power electronics such as inverters, voltage regulators, and transformers ensure that the electricity produced meets the specific requirements of the grid or the connected load, whether AC or DC. This flexibility in power conversion allows ORC systems to be highly adaptable in various applications, from grid-tied installations to off-grid or hybrid energy systems.

APPENDIX C

Optimizing Turboexpander efficiency

The efficiency of a **turbine** in an Organic Rankine Cycle (ORC) or any thermodynamic cycle is influenced by the **load** (or power demand) placed on the turbine. Turbine efficiency is typically measured as **isentropic efficiency**, which is the ratio of the actual work produced by the turbine to the work that would be produced in an ideal (isentropic) process.

1. Key Factors Influencing Turbine Efficiency with Load:

- **Design Point Efficiency**: Every turbine is designed for a specific operating condition, known as the **design point**. This is the point where the turbine operates at its optimal efficiency. At the design point, the inlet temperature, pressure, flow rate, and load match the intended operating conditions.
- **Off-Design Operation**: When the turbine operates at a load different from the design point (either higher or lower), its efficiency tends to decrease. This is because the turbine is optimized for a specific set of conditions, and deviations from these conditions affect the aerodynamic and mechanical performance of the turbine blades and associated components. **Critical Challenges in Off-Design Conditions:**
    - **Reduced Turbine Efficiency**: Turbines are most efficient at the design point. Operating at off-design conditions typically results in a **drop in isentropic efficiency**, as the flow characteristics, pressure ratios, and temperature differentials deviate from their ideal states.
    - **Aerodynamic Mismatch**: The turbine blades are designed for specific incidence angles and velocities. When flow rates decrease, the working fluid may not hit the blades at the optimal angle, leading to **aerodynamic losses**.
    - **Flow Separation**: In low-flow or low-pressure conditions, the working fluid can experience **flow separation** in the turbine, reducing energy extraction efficiency.
    - **Thermodynamic Mismatch**: At lower temperatures or pressures, the turbine may experience **phase transitions** (from vapor to liquid) in suboptimal regions of the turbine, leading to inefficiencies.

2. Turbine Efficiency vs. Load Behavior:

At Full Load (Near Design Point):

- **High Efficiency**: At or near full load (the design load), the turbine operates with **high efficiency** because the flow of the working fluid through the turbine and the aerodynamic performance of the blades are optimized. The velocity, pressure, and temperature conditions are balanced to ensure maximum energy extraction from the expanding fluid.
- **Minimal Losses**: At full load, energy losses due to friction, turbulence, and pressure drops are minimized, allowing for more effective conversion of thermal energy into mechanical energy.

At Part Load (Below Design Point):

- **Reduced Efficiency**: As the load decreases and the turbine operates below its design point, its efficiency drops. This is due to several factors:
  - **Reduced Fluid Flow**: At part load, the flow rate of the working fluid through the turbine decreases. This can result in **flow separation** or **turbulence** within the turbine, reducing the efficiency of energy conversion.
  - **Blade Incidence Angle Mismatch**: The angle at which the working fluid hits the turbine blades, known as the **incidence angle**, is optimized for a certain flow rate at full load. At part load, the reduced flow causes the working fluid to hit the blades at an angle that is less than optimal, leading to **inefficiencies** in energy transfer.
  - **Increased Leakage**: At lower loads, there may be more leakage of working fluid around the turbine blades, further decreasing efficiency.
- **Throttle Losses**: If the flow of the working fluid is throttled to match the reduced load, there is an additional energy loss due to the reduction in pressure, which lowers turbine efficiency.

At Overload (Above Design Point):

- **Decreased Efficiency**: When the turbine operates above its design load, efficiency also decreases. This happens because:
  - **Overheating and Stress**: The turbine blades and other components may experience higher-than-expected stresses, leading to **aerodynamic losses** and inefficiencies.
  - **Increased Flow Resistance**: The higher flow rate of the working fluid can increase **pressure drops** and frictional losses within the turbine, reducing the amount of useful work extracted from the expanding fluid.

3. Efficiency Curve of a Turbine

Turbine efficiency typically follows a **bell curve** when plotted against load. The peak of the curve represents the design point, where efficiency is highest. Efficiency drops on either side of this peak as the turbine operates at part load or overload conditions.

Load Condition	Efficiency	Explanation
Design Load	**Highest Efficiency**	Optimized fluid flow, ideal blade angle, minimal losses.
Part Load	**Decreased Efficiency**	Mismatch in blade angle, flow separation, increased leakage and throttle losses.
Overload	**Decreased Efficiency**	Excessive fluid flow, increased stress, and aerodynamic inefficiencies.

4. Strategies to Improve Efficiency at Part Load:

To address the reduction in turbine efficiency at part load, some systems employ **adaptive techniques** to optimize performance across a range of loads:

- **Variable Geometry Turbines (VGT)**: These turbines can adjust the position of the **nozzle guide vanes** to optimize the flow angle and velocity at part load. This helps maintain a more optimal incidence angle and reduces flow separation, improving efficiency.
- **Bypass Systems**: Some ORC systems include bypass valves that allow excess working fluid to bypass the turbine at part load conditions. This reduces the flow through the turbine and avoids overloading the system.
- **Multiple Stage Turbines**: Some ORC systems use **multi-stage turbines**, where different stages are optimized for different flow rates. At part load, only certain stages of the turbine may be engaged, allowing the system to operate closer to its optimal efficiency across a range of loads.

5. Impact of Load on ORC System Efficiency:

In an ORC system, the efficiency of the entire cycle, including the turbine, is affected by how well the system matches the load. If the load fluctuates significantly, the overall system efficiency will be lower due to the turbine operating away from its design point. For **distributed energy systems** or **waste heat recovery applications**, the variability of the heat source can further complicate this, as the turbine load may frequently change.

- **Heat Source Variability**: In systems with fluctuating heat sources (like waste heat recovery), the load on the turbine will vary with the availability of heat. This results in the turbine often operating at part load, which can reduce system efficiency.

- **Thermal Energy Storage (TESS)**: Using **thermal energy storage** can help smooth out the fluctuations in heat input, allowing the turbine to operate closer to its design point for longer periods, thus maintaining higher efficiency.

Conclusion

Turbine efficiency is highest when the load matches the design point, but it decreases when the turbine operates at part load or overload conditions. In an ORC system, where waste heat or renewable heat sources may fluctuate, load variability can affect the turbine's performance. Solutions like **variable geometry turbines**, **thermal energy storage**, and **multiple stage turbines** can help mitigate the efficiency loss at part load. By maintaining a more stable load on the turbine, the ORC system can operate more efficiently, extracting more useful work from the heat source.

APPENDIX D

Main Benefits of Using TESS in ORC Systems

Thermal Energy Storage Systems (TESS) in **Organic Rankine Cycle (ORC)** systems provide several key benefits that improve both the efficiency and flexibility of power generation from low- to medium-temperature heat sources. The integration of TESS allows for energy storage, enabling the decoupling of heat supply from power generation, which enhances overall system performance, reliability, and economic viability.

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1. Decoupling Heat Supply from Power Generation

One of the primary benefits of TESS in ORC systems is the ability to **store heat energy** and use it later for electricity generation. This decouples the timing of heat supply from power generation, which is especially useful in applications where heat sources are intermittent or variable.

- **Intermittent Heat Sources**: In systems like solar thermal plants, waste heat recovery, or certain industrial processes, the availability of heat may fluctuate due to changes in operating conditions, weather patterns, or production schedules. By storing heat when it is available and using it to generate electricity when needed, TESS allows the system to continue operating smoothly despite interruptions in the heat supply.
- **Power Generation on Demand**: TESS enables power generation to match **electricity demand**, allowing operators to generate power during peak demand periods even if the heat source is not available at that moment. This provides greater flexibility in managing the power output.

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2. Improved System Efficiency

By storing excess heat for later use, TESS helps improve the overall efficiency of the ORC system. Instead of wasting heat during periods of low electricity demand or heat oversupply, TESS allows that heat to be captured and used when it is most efficient.

- **Minimization of Heat Loss**: Without TESS, excess heat from the heat source might be lost if it cannot be immediately converted to electricity. Storing this heat for later use increases the energy efficiency of the overall system.
- **Optimizing ORC Operation**: The ORC system can be operated at or near its **design point** more frequently, where it is most efficient. TESS allows for more consistent and steady ORC system operation, reducing off-design operation and maximizing turbine efficiency.

- **Increased Waste Heat Utilization**: TESS allows the ORC system to capture and store excess waste heat that would otherwise be lost when the heat source output exceeds the immediate power generation capacity of the ORC. This stored heat can be used later when the heat source is insufficient, maximizing the utilization of the available heat.

- **Heat Availability on Demand**: Instead of discarding heat during times of low electricity demand or system capacity, TESS stores it, enabling continuous or flexible operation of the ORC system. This improves the overall **thermal efficiency** of the system by ensuring that no thermal energy is wasted.

Example:

In an industrial process where waste heat fluctuates, TESS can store excess heat during peak production periods and release it during low production periods, allowing the ORC to generate electricity consistently without downtime.

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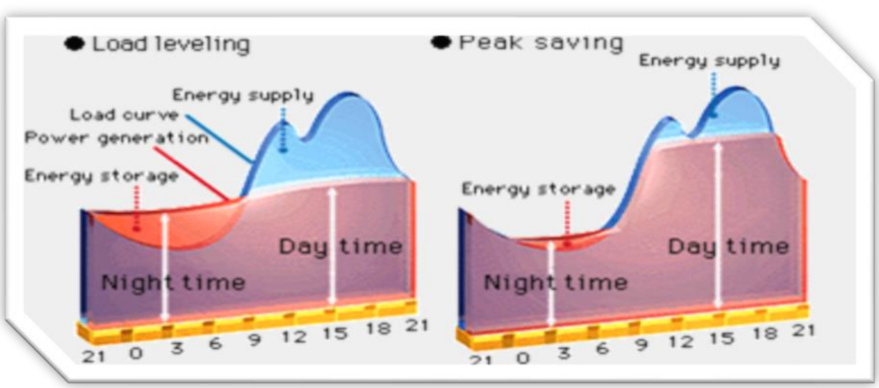
3. Peak Shaving and Load Balancing

TESS provides an opportunity for **peak shaving**, allowing the ORC system to generate electricity during periods of high demand or when electricity prices are higher, without relying on real-time heat availability.

- **Load Balancing**: TESS can store thermal energy during off-peak periods when the heat source is available but electricity demand is low. This stored heat can then be used to generate electricity during peak periods, helping to balance the load on the electricity grid.

- **Revenue Optimization**: By enabling power generation during periods when electricity prices are higher, TESS allows operators to optimize revenues from electricity sales, particularly in markets with dynamic pricing structures.



4. Increased Reliability and Resilience

TESS enhances the **reliability** of ORC systems by providing a thermal buffer that can be used in the event of **heat supply disruptions**. This can help mitigate the effects of fluctuating or unstable heat sources.

- **Backup Thermal Supply**: In the event of heat source interruptions, such as industrial process downtime or reduced solar radiation, TESS can provide a **continuous supply of stored heat**, ensuring that the ORC system continues to generate electricity.
- **Smoother Operation**: The ability to store and release heat as needed reduces the impact of fluctuations in heat supply, leading to more stable and predictable operation of the ORC system.
- **Buffering Against Heat Source Variability**: TESS provides a buffer for heat source variability, particularly in systems where the heat source is intermittent or fluctuating (e.g., solar, industrial waste heat, or biomass). This stabilizes the operation of the ORC, ensuring consistent power generation.
- **Improved Grid Support**: With the ability to generate electricity on demand, ORC systems with TESS can provide better **grid stability** by supplying power during peak hours or when other generators are offline. This makes the system more reliable in supporting local grids or standalone applications.

Example:

In a CHP plant, where waste heat is generated at variable rates, TESS can store excess heat during periods of high production and release it when heat generation drops, ensuring that the ORC system maintains steady power output.

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5. Grid Integration and Flexibility

As energy systems become more decentralized and integrated with renewable energy sources, **flexibility** in power generation is increasingly important. TESS in ORC systems provides the flexibility to better integrate into **modern energy grids**.

- **Demand Response**: With the ability to store heat and dispatch electricity when needed, ORC systems with TESS can participate in **demand response programs**. This flexibility allows operators to ramp up power generation during peak times or reduce output when grid demand is lower.
- **Complementary to Renewable Energy**: TESS is especially valuable in **hybrid systems** that integrate renewable energy sources like solar or wind power. It can

store heat generated during periods of renewable energy surplus and convert it into electricity when other renewable sources (e.g., solar PV or wind) are not producing.

- **Power Generation on Demand**: With TESS, ORC systems can **decouple power generation from heat availability**, meaning electricity can be generated when it is most needed, not just when heat is available. This is especially important for applications with intermittent heat sources, such as **solar thermal energy** or **industrial processes** with variable waste heat.
- **Peak Load Management**: TESS enables ORC systems to generate electricity during periods of peak demand by releasing stored thermal energy. This makes ORC systems more responsive to grid or local load demands, improving their utility as part of **peak shaving** strategies.

Example:

In a solar thermal power plant, TESS stores heat during sunny periods and releases it at night or during cloudy conditions, allowing the ORC to continue generating electricity, making the system dispatchable even when solar energy is not available.

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6. Reduced Maintenance and Increased Lifespan

The presence of TESS in an ORC system can reduce wear and tear on the system's components, especially the turbine, by enabling smoother and more controlled operation.

- **Reduced Turbine Cycling**: In systems without TESS, fluctuations in the heat supply or electricity demand can lead to frequent cycling of the turbine between on and off states, causing mechanical stress and increasing wear. By providing a continuous and stable heat source, TESS reduces the need for turbine cycling, extending its operational lifespan.
- **Less Frequent Start-Stop Cycles**: ORC systems with TESS can continue to generate electricity even when the heat source is temporarily unavailable, reducing the number of start-stop cycles. This improves the longevity and reliability of the system's components, reducing maintenance costs.

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7. Smaller System Footprint in Many Applications

In certain applications, TESS can allow for a **smaller ORC system** by smoothing out peak loads and optimizing heat use. Instead of designing the ORC system to handle the absolute peak load (which might only occur occasionally), the system can be designed for average conditions, with TESS handling peak variations.

- **Lower Capital Costs**: By allowing the ORC system to be sized for average, rather than peak, loads, TESS can reduce the upfront capital costs of the system by avoiding the need for oversizing.

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8. Enhanced System Versatility

TESS increases the **versatility** of ORC systems by enabling them to work with a wider variety of heat sources. Some heat sources are inherently intermittent (e.g., solar thermal), while others may have fluctuating availability (e.g., industrial processes). TESS enables ORC systems to make better use of such sources.

- **Broader Applicability**: With the inclusion of TESS, ORC systems can be effectively used in applications where heat sources are intermittent or unpredictable. This makes TESS particularly valuable for waste heat recovery, geothermal energy, and solar thermal applications.
- **Thermal Buffering**: TESS acts as a **thermal buffer**, allowing the system to smooth out the inconsistencies of heat supply, whether the source is renewable or industrial.

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9. Smoother Operation and Reduced Cycling

- **Minimized Startup and Shutdown Cycles**: ORC systems without TESS may need to shut down when the heat source is insufficient, leading to frequent startups and shutdowns. This can cause mechanical stress and reduce system lifespan. By storing heat during low load periods, TESS enables **smoother operation**, reducing the need for shutdowns and startups.
- **Improved System Longevity**: By reducing the number of operational cycles and smoothing out fluctuations in heat input, TESS helps extend the lifespan of key ORC components, such as the **turboexpander** and **pump**, which would otherwise be subject to wear and tear from frequent cycling.

Example:

In an industrial application where heat production is irregular, TESS allows the ORC system to run continuously by storing heat during peak production and using it during downtime, thus avoiding frequent starts and stops.

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10. Enhanced Integration with Renewable Energy Sources

- **Geothermal**: TESS can be used to store heat in **geothermal power plants** during periods of lower power demand and release it later when electricity demand increases. This allows the plant to operate more flexibly without wasting valuable geothermal heat.
- **Solar Thermal**: In **concentrated solar power (CSP)** systems, TESS stores solar energy in the form of heat during the day when sunlight is abundant, and releases it during the night or during cloudy periods, enabling continuous power generation.
- **Biomass**: TESS can improve the flexibility of **biomass ORC systems** by storing excess heat from combustion processes and using it when fuel supply or combustion rates decrease.

Example:

In a solar thermal application, TESS can store excess heat from the sun during the day and release it at night, allowing the ORC system to generate electricity 24/7, making the solar thermal power plant behave more like a conventional, dispatchable power plant.

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11 Environmental Benefits

By improving the overall energy efficiency of ORC systems and making better use of available heat sources, TESS can reduce both **operational costs** and the **environmental impact** of power generation.

- **Lower Fuel Consumption**: In systems that burn fuel to generate heat, TESS helps reduce the amount of fuel required by capturing excess heat and storing it for later use. This leads to lower fuel consumption and fewer greenhouse gas emissions.
- **Reduced Waste Heat**: TESS makes better use of low-grade waste heat that would otherwise be discarded, reducing thermal pollution and improving the overall sustainability of industrial processes.
- **Combined Heat and Power (CHP) Systems**: In **CHP applications**, TESS allows better integration between heat and power generation, reducing emissions per kWh and improving fuel efficiency. During periods of low electricity demand, heat can be stored in the TESS instead of being wasted, reducing fuel consumption and GHG emissions.

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12. Economic Benefits and Improved ROI

Incorporating TESS in ORC systems can significantly improve the **return on investment (ROI)** by increasing overall system performance and efficiency.

- **Higher Utilization Rate**: TESS allows for better utilization of available heat sources, ensuring that the system operates closer to its full potential over a longer period.
- **Increased Revenue**: By enabling peak shaving and load balancing, TESS can help operators take advantage of higher electricity prices during peak demand, improving revenue potential.
- **Lower Operating Costs**: By storing excess heat and preventing shutdowns or inefficient operation at part-load, TESS can reduce **operating costs**. Running the ORC system closer to its design conditions (due to the availability of stored heat) improves fuel and heat source efficiency.
- **Reduced Need for Backup Power**: In systems without TESS, backup power sources (e.g., batteries or fossil fuel generators) may be required to meet peak demand or ensure continuous operation during heat source downtime. With TESS, these backup systems are less necessary, reducing capital and operational expenditures.

Example:

By using TESS to store waste heat and release it during peak electricity demand periods, an ORC system can reduce the need for expensive backup power systems like diesel generators or grid electricity purchases, thus lowering overall operational costs.

Conclusion

The integration of **Thermal Energy Storage Systems (TESS)** in **ORC systems** offers numerous benefits, including increased efficiency, reliability, flexibility, and economic returns. TESS allows ORC systems to handle intermittent heat sources more effectively, optimize power generation based on electricity demand, and reduce operational and maintenance costs. These advantages make

TESS a valuable addition to ORC systems, especially in applications where heat sources are variable, intermittent, or where peak shaving and load balancing can enhance operational flexibility and economic performance. By enabling heat storage and optimized power generation, TESS helps ORC systems maximize their potential in diverse energy applications, from industrial waste heat recovery to renewable energy integration.

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