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DECARBONIZING HEAVY INDUSTRY AND INCREASING GRID STABILITY THROUGH WASTE HEAT TO POWER SOLUTIONS

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1. Introduction

Heavy industry in North America plays a critical role in driving economic growth and meeting the demands of modern society. Natural gas fired turbine compressor stations form a crucial part of the energy infrastructure, supporting the transportation of natural gas across vast distances in North America. These stations efficiently and reliably maintain the pressure required for efficient gas transmission through pipelines, facilitating the delivery of the fuel to consumers and various industrial facilities and end-users, supporting the nation's energy infrastructure.

However, the sector's significant energy consumption and greenhouse gas (GHG) emissions have raised environmental concerns and prompted a pressing need for sustainable solutions. Waste Heat to Power (WHP) systems, specifically designed for natural gas fired turbine compressor stations, present an innovative and viable approach to decarbonizing the heavy industry. North America boasts an extensive network of pipeline infrastructure, and the implementation of WHP systems holds immense potential for decarbonizing this critical part of the energy supply chain. Recent studies have identified that the potential for WHP solutions in Canada is roughly 7 GW, and in the United States is roughly 15 GW.

WHP systems offer a potentially transformative solution for addressing the environmental challenges faced by natural gas compressor stations in North America. These systems capitalize on the excess heat produced during turbine operation, which is traditionally vented into the atmosphere, and convert it into usable electricity. This is done using waste heat recovery technology such as an Organic Rankine Cycle (ORC) which turns a turbine to generate clean baseload power. While waste heat can be found in a large number of locations, waste heat from industrial processes provides the best use for WHP because of the regularity of the heat source and relatively high temperatures of exhaust help to make projects viable.

Several critical factors influence the successful implementation and operation of WHP systems in natural gas-fired turbine compressor stations. Operators must consider these factors to optimize the performance, reliability, and overall efficiency of the WHP system.

2. WHP System Factors

I. Site Elevation

The elevation of the compressor station's site impacts the density of air and, consequently, the turbine's performance. As the elevation increases, the turbine's power output tends to decrease due to reduced air density. This reduction in power output affects the waste heat available for conversion to electricity in the WHP system.

II. Ambient Temperature

The ambient temperature of the compressor station's location plays a pivotal role in determining the waste heat available for conversion to electricity. It plays a dual role on the potential power generation from the waste heat of the turbine: (A) The ambient temperature will affect the operating performance of the gas turbines (GT) as with a colder temperature the efficiency of the gas turbine will increase, but (B) the exhaust temperature will decrease. Waste heat to power systems rely on the temperature difference between the exhaust gas from the turbine and the surrounding environment. Lower ambient temperatures generally lead to more substantial temperature gradients, which can increase electricity generation and overall system efficiency. Similarly, higher exhaust temperatures generally lead to more thermal energy available and a higher WHP conversion efficiency.

Operators should consider seasonal variations and climatic conditions at the site when assessing the potential for WHP implementation. Additionally, strategies for managing system performance during extreme temperature conditions, such as insulation and heat recovery optimization, should be evaluated.

III. Turbine Load

The turbine's load, which represents the amount of power demanded by the compressor station, directly affects the waste heat generated during operation. Turbine load variations can result from changes in the facility's gas demand or operational requirements. Higher loads represent a higher natural gas consumption, and therefore a higher exhaust flow rate which will be translated into more thermal energy available for the WHP system.

To ensure the efficient operation of the WHP system, operators need to optimize its capacity to match the fluctuating turbine load. Implementing load-following strategies and advanced control systems can help adapt the waste heat to power system to varying demands, maintaining stable electricity generation and maximizing energy utilization.

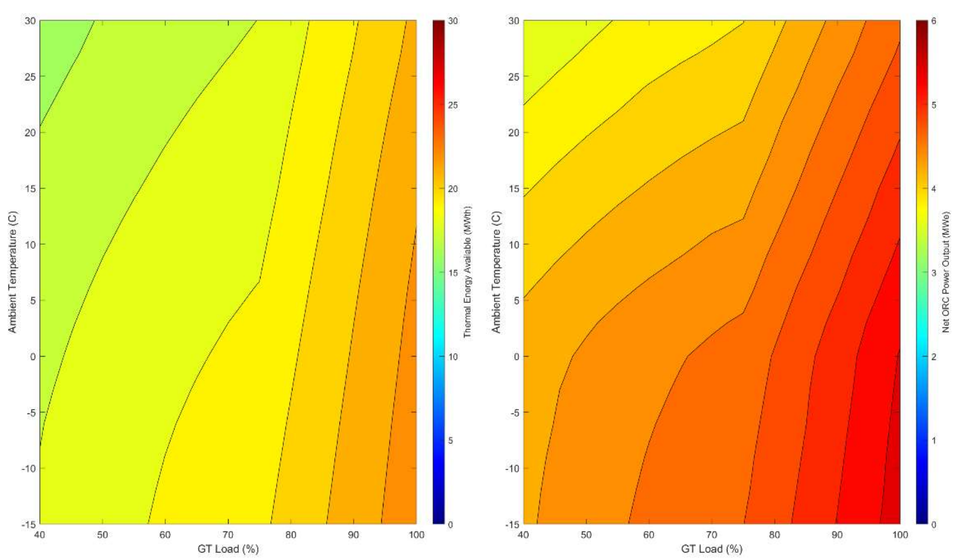

Figure 1: (A) Plot of thermal energy available and (B) ORC Power Output vs Load and ambient temperature from a typical 30,000HP gas turbine and a 5MWe net ORC system at sea level.

IV. Facility Uptime

The reliable and continuous operation of the compressor station is critical for successful WHP implementation. The thermal energy available for the WHP system, and therefore the electricity produced from it, will depend on the runtime of the GTs, which will affect the revenue generated from the electricity produced and the viability of the WHP project.

Unplanned downtime or maintenance activities may disrupt waste heat availability and impact the electricity generation process. However, the waste heat recovery unit (WHRU) ducting features a fail-closed guillotine isolation damper to completely isolate the WHRU from the heat source. In addition, the WHRU ducting contains a 3-way exhaust diverter valve that controls the flow of exhaust from the gas turbine to the WHRU, providing another layer of isolation. In a shut-down scenario with the heat source removed, the vaporisation of pentane will quickly stop and all vapor in the system is diverted to the ACCs via the WHP turbine bypass, preventing any repercussions in the operations of the gas turbines.

Operators should carefully plan maintenance schedules and consider system redundancies to minimize the impact of downtime on power generation. Implementing predictive maintenance practices and monitoring equipment health can further enhance the system's uptime and overall reliability.

V. Pressure Loss Limitations

The heat exchanger plays a pivotal role in transferring heat from the heat source to the working fluid. However, during this heat exchange process, it is common to encounter challenges related to back pressure. This back pressure can arise due to the resistance offered by the heat exchanger's internal tubing, fins, or other structural elements, which may hinder the smooth flow of the working fluid and reduce the overall performance of the gas turbine. To mitigate this challenge and ensure optimal system performance, induced draft fans can be strategically employed. By strategically positioning induced draft fans, the airflow within the heat exchanger can be optimized, helping to reduce back pressure and enhance heat transfer efficiency. These fans create a negative pressure environment that assists in expelling exhaust gases or vaporized working fluid, thereby maintaining the desired pressure differentials within the system. Moreover, a well-designed heat exchanger can be engineered to meet the maximum pressure drop allowable, ensuring that the back pressure remains within acceptable limits while efficiently transferring heat, ultimately maximizing energy conversion and system performance.

3. Technologies

There are several different types of technologies that can be used for waste heat recovery, each with distinct advantages and disadvantages. Which technology is best suited from a techno-economic perspective is dependent on the above factors such as ambient temperature, evaluation of site, and availability of waste heat.

ORCs are a technology used to convert waste heat to power. Waste heat from exhaust is diverted to pass over a heat exchanger, connected to an ORC acting as an evaporator. The ORC is a closed-loop system that pipes an organic fluid with a low boiling point through the heat exchanger to convert the fluid into a gas. The gas then passes through a turbine to create electricity. Then the low-pressure gas passes through a condenser, usually an air-cooled condenser, to return to a liquid form to later be compressed with a pump and repeat the process.

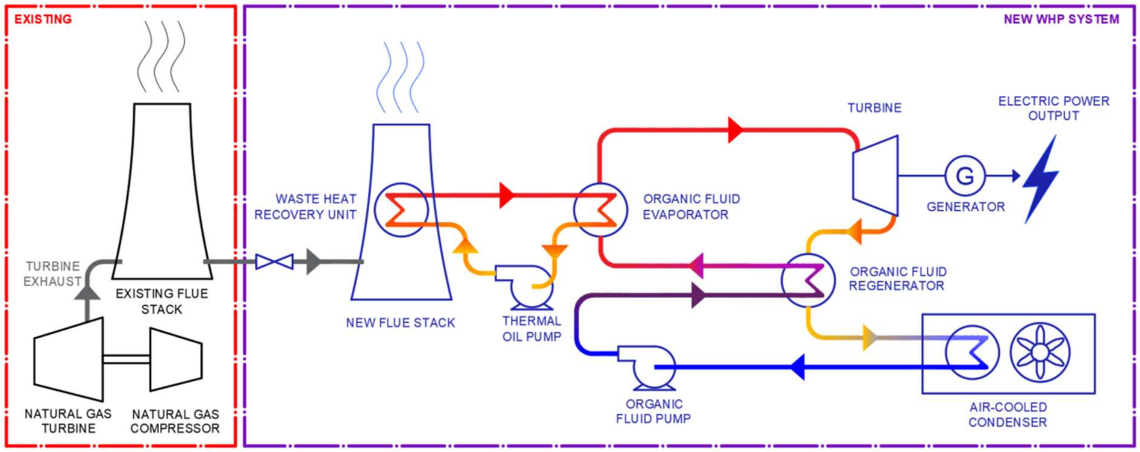

Figure 2: Illustration of WHP System Integration with Gas Turbine

Other technologies for power generation through heat recovery exist as well. Steam Rankine Cycle (SRC) technology uses the same principles and process as an ORC system but replaces the working fluid with water to create steam and drive a turbine. Steam turbines have been in use for over 100 years and represent the most common source of electricity generation in the world, where coal, natural gas, and nuclear fission are all used as fuel sources for generation.

The Kalina cycle is a variation of the ORC which uses two working fluids in its cycle, typically water and ammonia. Kalina systems are well-suited to low temperature heat sources compared with the ambient temperature. A key difference between Kalina cycles and ORC/SRCs is the temperature profile of the fluid during boiling and condensation. The binary fluids in a Kalina cycle have different boiling points and will increase in temperature during evaporation, whereas in single fluid cycles the temperature remains constant.

Consequently, the Kalina cycle provides better thermal matching to a heat source and with cooling in the condensing phase. The result is relatively improved energy efficiency compared with the other ORC thermodynamic cycles.

Supercritical CO2 Rankine Cycle is another variation of Rankine cycle, which uses carbon dioxide in place of water or steam. In this heat engine, CO_2 in a liquid or dense supercritical form is compressed. It is then heated from a waste heat stream and is expanded through a turbine to drive an electrical generator. Because the pressure ratio of supercritical CO_2 is relatively low, the fluid retains some heat so is passed through a heat recuperator before returning to the pump for pressurization. There are several advantages to a supercritical CO_2 system. Carbon dioxide is low-cost, non-toxic, and non-flammable. Its density also allows for compact turbomachinery design which translates to an overall system footprint reduction. Finally, the stability of the fluid allows it to come in contact directly with high temperature heat sources, eliminating any requirement for a heat transfer loop.

The key differentiation between these various types of heat engines is their viability to extract energy efficiency from a different heat ranges and convert it into electricity. The table below details the heat ranges of these activities and the associated efficiency of the engines to best capture and convert heat to produce electricity.

Table 1: WHP Technology Summary

Technology	Organic Rankine	Steam Rankine	Kalina Cycle	Super Critical CO_2
Heat Range	85 to 400 ∘C	250 to +1000 ∘C	100 to 300 ∘C	250 to700 ∘C
Efficiency	5 to 30%	30 to 45%	10 to 27%	25 to 50%
TRL	9	9	6 to 9	3 to 6

Several emerging technologies exist for WHP; however, most are at various stages of R&D and not yet commercially available. These technologies include Stirling engines, thermoelectric generators, piezoelectric generators, thermionic devices, thermo-photovoltaic generators, and innovations to improve performance for existing heat engine systems.

The selection of the WHP systems depends on multiple factors, which is mainly driven by the temperature of the heat source. Natural gas turbines typically exhaust hot gases at temperatures that are often too low for efficient steam cycles but suitable for ORCs. ORCs can effectively recover energy from lower-temperature exhaust gases, thereby increasing the overall efficiency of the system. Also, ORC systems can start up quickly and respond rapidly to changes in load demand. This flexibility is advantageous in natural gas turbine applications, where load fluctuations are common.

4. WHP as a Carbon-Free Solution

WHP is carbon-free because there are no incremental emissions in its production of electricity. In using exhaust heat from existing thermal processes, a WHP system does not generate emissions and instead offsets the need to generate additional electricity, which in many cases has a carbon fuel source.

In order to assess the emissions benefits of WHP compared to other technologies, ICF analyzed the emissions reduction potential of WHP, PV, wind, and gas-fired combined heat and power (CHP) systems in three U.S. locations.

- Los Angeles, California
- Columbus, Ohio
- Baton Rouge, Louisiana

ICF determined the average carbon emissions impact of WHP systems *per MWh* of generation and reached the following conclusions:

- WHP, PV, and wind all produce *zero on-site carbon emissions*.
- WHP and solar PV systems have similar avoided grid emission rates *per MWh* of generation.
- WHP systems offer higher avoided grid emissions compared to wind systems across all three analysis locations.

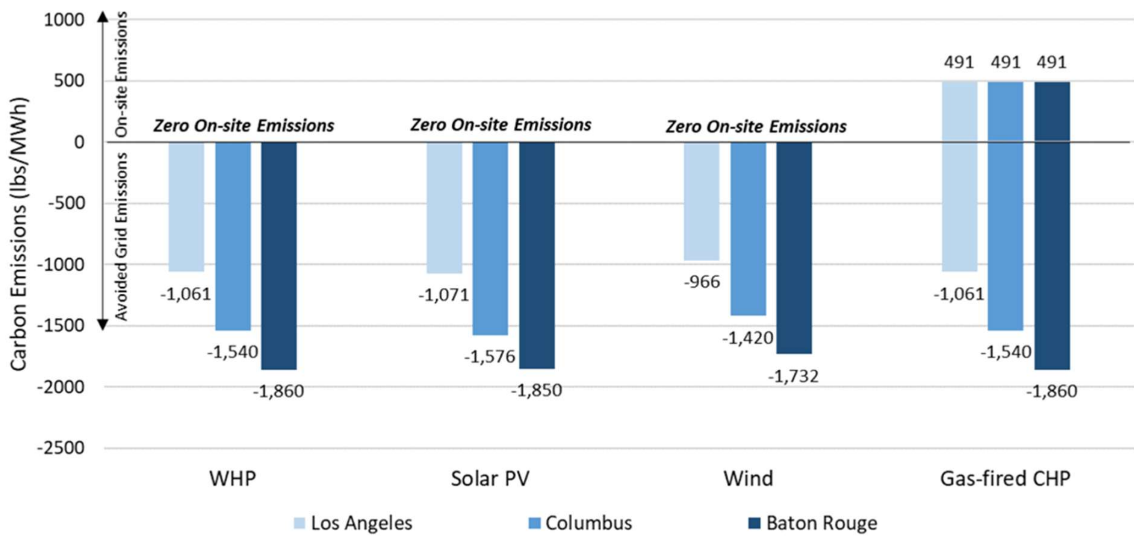

Figure 3: Carbon Emissions Impact by Technology per MWh of Energy Generation

Above figure shows the carbon emissions impact per MWh of energy generation by technology in all three analysis locations. In the chart, the negative Y-axis shows avoided grid emissions while the positive Y-axis shows on-site emissions.

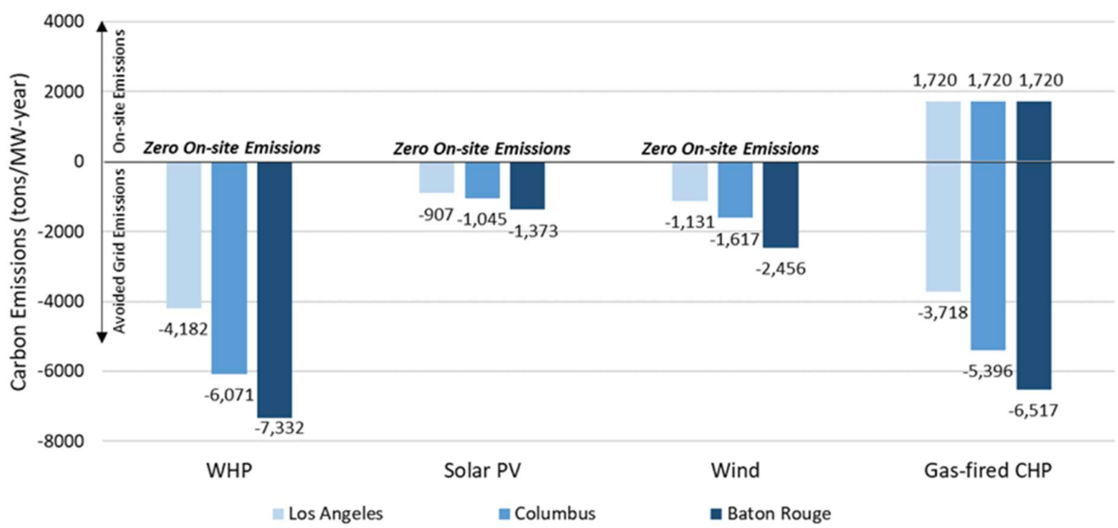

Figure 4: Annual Carbon Emissions Impact by Technology for 1 MW of Capacity

ICF also analyzed the *annual* carbon emissions impact of 1 MW of WHP compared to solar PV, wind, and CHP systems of equivalent generation capacity. The key takeaways of this analysis include:

- WHP systems have the highest avoided grid emissions on a tons/MW-year basis. This is due to the high annual capacity factor of WHP systems.
- For an equivalent capacity, WHP systems displace substantially higher amounts of grid electricity and associated grid emissions compared to other generation technologies.

Above figure shows the *annual* carbon emissions impact (in tons/MW-year) of 1 MW of generation capacity by technology in all three analysis locations.

5. WHP Role in the Energy Transition

In the energy transition, WHP is a readily available solution that allows heavy industry to decarbonize, while also providing additional benefits to electricity grids. The viability of WHP is established, but its adoption at scale has yet to be realized because policy, economic, and environmental conditions have not yet been aligned.

Heavy industry, specifically natural gas industry, is a good candidate for WHP solutions given the typical base-load operating profile of compressor stations and the significant temperatures and flow rates available in turbine exhaust streams. The gas turbine's responsiveness and load-following capabilities primarily depend on its own combustion and turbine controls, which are designed to swiftly adjust to changes in electrical load/gas demand. The addition of a WHP system, focused on harnessing waste heat from the exhaust gases, does not interfere with the gas turbine's core operation. In fact, the WHP system operates independently alongside the gas turbine, capturing heat that would otherwise be wasted and converting it into additional electricity or useful thermal energy. This synergistic setup allows for improved overall system efficiency without compromising the gas turbine's ability to quickly respond to variations in load, making it a harmonious and energy-efficient combination for various applications.

Traditional natural gas compressor stations, while vital for maintaining gas pressure and facilitating gas transmission through pipelines, are often significant emitters of greenhouse gases. These emissions predominantly comprise carbon dioxide (CO_2) resulting from the combustion of natural gas in the turbines to generate mechanical energy for compression.

Both Scope 1 and Scope 2 emissions can be offset by the installation of a WHP system depending on the use of the generated power. Scope 1 emissions are from sources that an organisation owns or controls directly, e.g. the emissions from an on-site turbine, boiler or heater. Scope 2 emissions are caused indirectly, not produced directly by an organisation but associated with their operations, e.g. grid electricity consumed on-site.

While grid interconnection is the typical pathway from electron generation to sales, the electricity produced from the waste heat could also be utilized ‘behind the meter’ to power an electric motor drive (EMD) and either increase the compression capacity of the plant or offset one of the existing compressors in the station. Electric motor drives produce zero direct emissions at the point of operation. By replacing conventional drive systems, such as gas turbines or internal combustion engines, with electric motor drives, the compression plant can reduce on-site emissions associated with burning fossil fuels for power generation or compressing natural gas. This switch to emission-free operation directly reduces the plant's carbon footprint and contributes to lowering Scope 1 emissions.

In the case of grid interconnection, the introduction of WHP systems in compressor stations represents an approach to reducing Scope 2 emissions by capitalizing on the untapped potential of waste heat generated during turbine operation. Power generated by a WHP system and provided to the grid will offset power generated by existing CO_2 emitting facilities already on the grid. Every MW generated by WHP can offset a MW of coal or gas power from the grid mix and reduce scope 2 emissions accordingly.

Generally, WHP delivers improved efficiency to industrial operations and offset GHGs from electricity generated from fossil fuels. These are significant benefits for heavy industrial sites that incur high capital costs and benefit from efficiency measures. WHP is one of the main strategies for increasing energy efficiency at a large scale with minimal impact to an industrial hosts' operations.

WHP technologies capture the waste heat generated by gas turbines and use it to produce additional electricity or provide heating and cooling services. This can lead to significant reductions in greenhouse gas emissions and operating costs while increasing the overall efficiency and reliability of the power generation system.

WHP addresses this problem by capturing waste heat and converting it into valuable baseload electricity. Electricity can be used on site for operations or sold back to an electricity grid, providing a 24/7 complement to intermittent renewable generation such as wind and solar.

Baseload electricity is readily available power that can meet the requirements of an electricity grid at any time of day. In contrast, intermittent electricity is power that is not continuously available. Wind and solar energy are examples of intermittent electricity generation because while they complement each other, on their own they are only able to generate when there are sun and wind available. WHP from industrial processes generates baseload electricity because the processes it connects to are in operation continuously. In electricity markets, clean baseload power is a valuable component of the power mix for utilities decarbonizing their grids.

One of the primary footprint advantages of waste heat to power systems is their space efficiency and minimal land use requirements when compared to similar wind or solar plants. The relatively compact footprint of these systems allows for the efficient use of limited space, making them particularly suitable for retrofitting and optimizing the energy output of industrial processes without significant additional land requirements.

On the other hand, solar farms demand vast land areas to deploy solar panels. Large solar farms may compete with agricultural land or natural habitats, leading to potential land use conflicts and environmental concerns. In contrast, waste heat to power systems can be seamlessly incorporated within existing infrastructures, minimizing land use impacts.

The footprint required for the solar farms will vary depending on the peak sun hours of the location of the project. Also, as the solar and wind power generation are intermittent power generations, for the equivalent nameplate of a WHP system, to generate the same annual electricity, is much smaller.

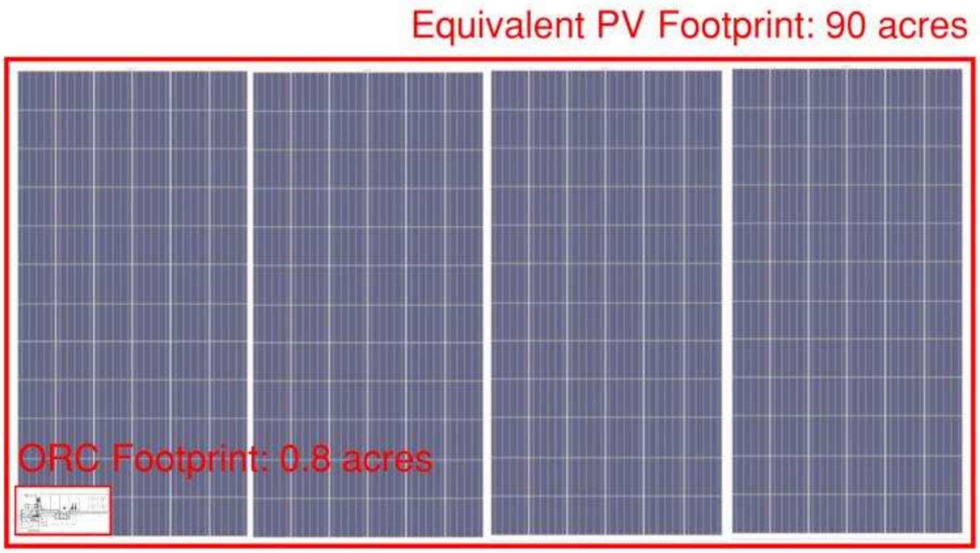

Figure 5: Footprint Comparison for PV and ORC

Comparison between the footprint requirements for a 12 MWe net system in Alabama where the PV footprint is approximately 100 times the size of an ORC system using the waste heat from gas turbines.

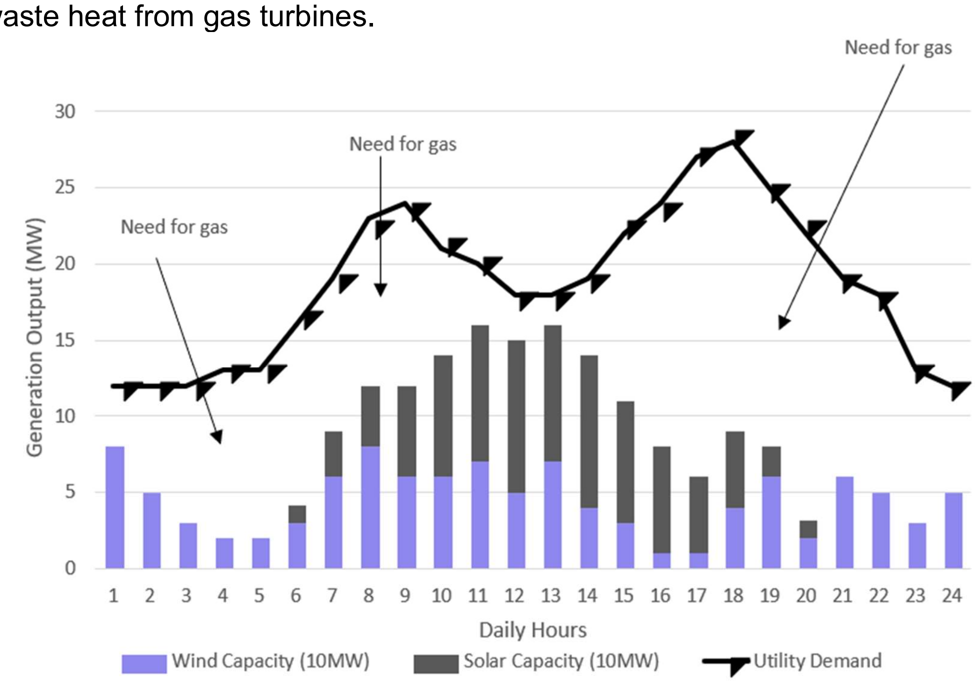

Figure 6: Meeting Utility Demand Without WHP

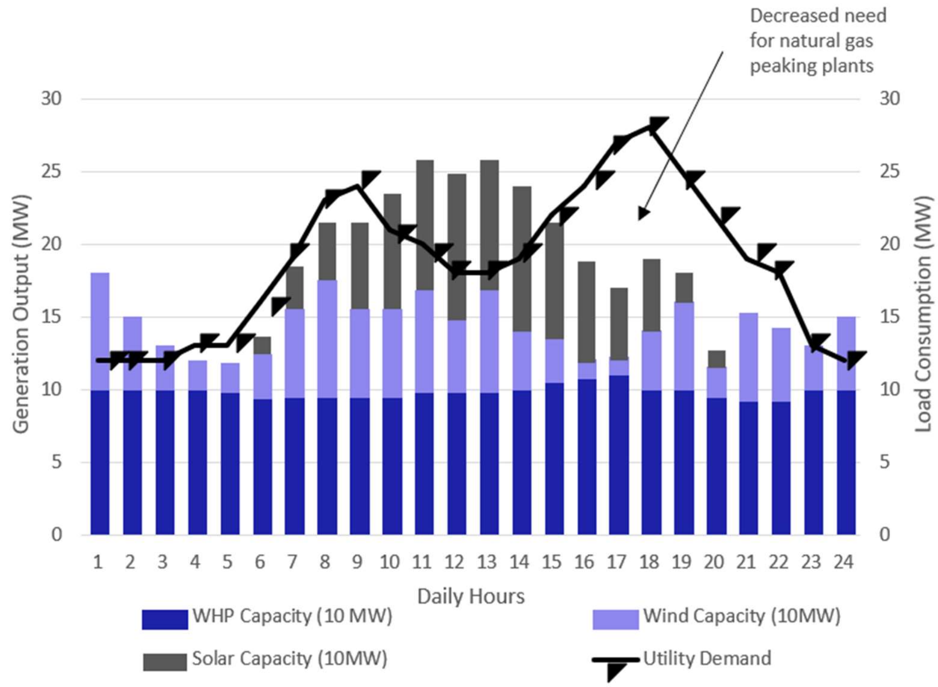

Figure 7: Meeting Utility Demand with WHP

6. Gas Turbines Role in the Energy Transition

WHP systems do not generate emissions and instead offset the need to generate additional electricity, therefore, displacing energy commonly procured from fossil fuels. An important benefit of WHP to the compressor stations is providing emission-free baseload electricity. Depending on the uptime of the gas turbine, WHP has the potential of producing and serving consumer loads 24 hours a day. Which is different from other clean energy sources, such as wind and solar.

WHP is an onsite, distributed energy resource (DER), this provides an onsite access to clean electricity, but also provides the client with the option to sell the unused WHP generated electricity back into the grid during minimum consumption hours, therefore, utilizing 100% of the WHP generation.

When analysing gas turbines in comparison to other waste heat sources, gas turbines provide a cleaner exhaust gas that provides more efficient and simpler waste heat recovery. Each gas turbine used at compressor stations have predictable exhaust parameters which can be estimated from the performance datasheets provided by the gas turbine's manufacturer, resulting in a more reliable calculation of the thermal energy available for the WHP system. While WHP projects are possible (and exist) on other industrial processes, exhaust streams with particulates or other contaminants lead to significantly more complex heat recovery and therefore more challenging economics.

WHP is a cycle improvement that can help with the energy transition by providing 24/7 carbon-free energy. Helping gas turbines take a more prominent role in the transition toward cleaner industry, green grid stability and overall grid decarbonization.

7. Working with a Developer to Install WHP Solutions

There are several hurdles to why WHP projects have not have not been more widely deployed to date. These reasons have included the need for a cross-functional development team with hyper-specific skills in technical and commercial realms, in addition to finding the right alignment of project capital to unlock these opportunities.

While technically complex, WHP project development also requires extensive experience with interconnection processes, electricity and environmental markets, specific regulatory and tax filing considerations. Many of these skill sets will not be core competencies to an industrial operator.

Industrial decarbonization developers, such as Kanin Energy exist to increase accessibility of these critically important projects. Through a turnkey development approach, WHP technology and projects have been successfully de-risked for industrial operators to be comfortable with site integration and for capital providers to ensure the appropriate commercial structuring is in place.

By leveraging third-party capital financing structures, aligning the right capital providers to energy infrastructure projects such as WHP, this will enable more projects to be deployed. This approach emulates how wind and solar were able to scale successfully in the United States.