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Pilot-Scale Thermoelectric Generation System at a Cement Plant

Introduction

The U.S. Department of Energy's Industrial Technologies Office Industrial Technology Validation (ITV) program rigorously assesses the performance of emerging technologies in industrial environments to explore their viability in real-world conditions. These efforts accelerate the development and adoption of transformational technologies that optimize industrial processes, reduce operating costs, and enhance the competitiveness of U.S. industry. By sharing field validation results through publicly available reports, the ITV program helps move innovative technologies out of the laboratory and into the market.

The energy-intensive nature of the cement industry, driven by high-temperature clinker production, presents an opportunity to integrate optimized waste-heat-to-power solutions as a way to reclaim part of the energy lost during kiln operations and convert it to electricity to offset a portion of the energy use and related costs. Kiln operation, the dominant source of energy consumption, generates substantial waste heat. Implementing waste heat recovery technologies offers a key strategy for lowering operational costs, enhancing energy efficiency, and mitigating associated emissions within the sector.

Thermoelectric generators (TEGs) offer a solid-state solution to recover waste heat from kiln operations and convert it to electricity. This study evaluated a pilot-scale TEG system to determine its effectiveness in capturing a cement plant's waste heat and converting it to electricity. This technology was determined to have the potential to be replicated across 96 cement plants in 34 states, with additional opportunities identified in other low- and medium-temperature processes across other industries including glass, cement, steel, aluminum, and metal casting.[1]

Header image credit: Holcim Cement Plant in Alpena, MI.

1 U.S. Geological Survey. 2023. Mineral Commodity Summaries. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf.

Impacts

Energy generation

- 3.1 gross kWh/ton clinker
- 2.0 net kWh/ton clinker

Net cost savings

- **$241,000 annually for a typical plant producing 3,300 tons clinker/day**
  $0.2/ton clinker at $0.10/kWh

Thermal efficiency

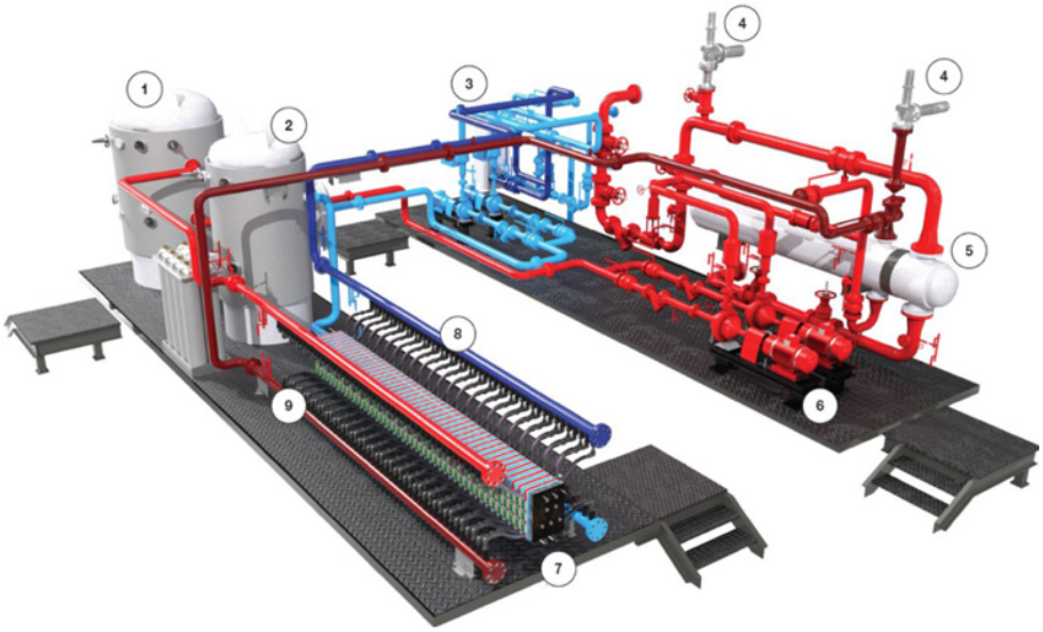
- **5.0% system peak, 4.3% average**
  For hot plate temperatures range of 130–212°C
- **10% cartridge peak, 5.2% average**
  For hot plate temperatures range of 207–212°C

Emissions avoided

- **1.64 lbs $Co2_{2}$/ton clinker**

The U.S. Department of Energy's Industrial Technology Office Industrial Technology Validation program is open to all industrial host sites and technology developers that seek to evaluate emerging manufacturing technologies in their plants, enhance competitiveness, reduce costs, and achieve energy goals.

Figure 1: Rendering of TEG system pilot scale unit.



Key

1 – Hot-Side Expansion Tank
2 – Cold-Side Expansion Tank
3 – Cold-Side Exchanger
4 – Pressure Safety Valve
5 – Hot-Side Exchanger
6 – Redundant Pumping
7 – Cartridge Exchanger Array
8 – Cold-Side Headers
9 – Hot-Side Headers

The Process

Cement manufacturing encompasses several key steps, including raw material preparation, clinker production, and cement grinding. The process begins with the extraction and preparation of raw materials such as limestone, clay, shale, iron ore, and sand. These materials are quarried, crushed, and ground into a fine powder known as raw meal or raw mix. The raw meal is then fed into rotary kilns where it is heated to high temperatures to produce clinker, the primary component of cement. The clinker is subsequently cooled and ground with gypsum and other additives to produce the final cement product. The considerable thermal energy wasted during clinker production represents a potential resource; its capture and utilization can contribute to reduced operational costs through energy efficiency within cement manufacturing.

The Technology

The TEG system, developed by Advanced Thermovoltaic Systems (ATS), works by leveraging the Seebeck effect to convert the potential from temperature differences on two sides of semiconductor cartridges into electrical power. This system operates with minimal moving parts compared to existing solutions and supports the harnessing of lower-temperature heat compared to the common steam Rankine cycle systems. The project validated a scalable solution for capturing waste heat ideally suited for low- to medium-temperature applications. By recovering this otherwise wasted heat, this technology aims to reduce energy costs and consumption, along with an associated reduction in emissions.

The demonstration unit consists of several key components, including heat exchangers, thermal oil pumps, hot and cold plates, and a programmable logic controller (Figure 1). Wasted heat captured by the system is transferred to thermal oil, which circulates through the TEG hot plates. This heat, in conjunction with the cooler temperature provided by nearby surface water circulating through the cold plates (though auxiliary cooling systems may be necessary in other installations), establishes a temperature differential that drives the generation of electricity.

Figure 2: Cartridges of the TEG demonstration unit used for evaluation.

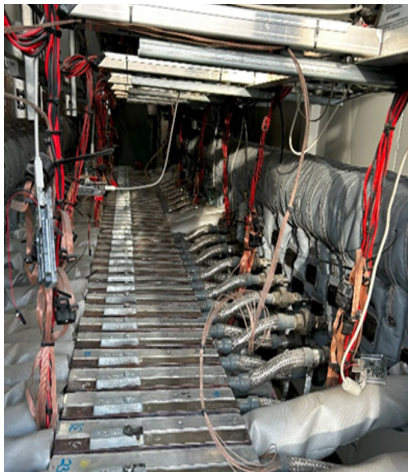


Figure 3: Rotary kilns at the Holcim Alpena plant.

A pilot system of 573 active modules was installed—with a rated gross power of 20 watts (W)/cartridge or 11.5 kilowatts (kW) total—to integrate with the plant's existing infrastructure and assess energy performance under various operating conditions (Figure 2). The TEG system's output is connected to the main distribution panel via micro-inverters, thereby supplementing the plant's power supply with low-cost, emissions-free energy.

The Demonstration Site

The Holcim cement plant, located in Alpena, Michigan, was selected as the demonstration site for the TEG system. Established in 1907, the company's Alpena Plant is a fully operational cement manufacturing facility. It operates continuously 24 hours a day, 7 days a week, and 365 days a year, with a production capacity of 7,852 tons per day. The plant employs approximately 250 people and serves customers throughout the Midwest and Ontario. Driven by a science-based approach, Holcim has set a commitment to reach net-zero greenhouse gas emissions across its value chain by 2050. The assessment of waste heat recovery technologies can support the company's goal to reduce greenhouse gas impacts across its operations.

The Alpena Plant was selected for the demonstration due to its significant waste heat output from its rotary kilns (Figure 3) and its existing infrastructure, which includes a steam turbine generation system and a nearby cooling water source from Lake Huron. The plant captures waste heat from five rotary kilns to produce superheated steam, which powers turbine generators to produce electricity. The TEG system demonstration used some of this steam at various conditions to assess its performance in capturing and converting waste heat into electricity (Figure 4).

This study aimed to validate the performance of the TEG technology in a real-world industrial setting at various operating conditions, focusing on its scalability and potential for broader adoption in the cement and other process industries with low- and medium-temperature waste heat. The project also studied the overall energy impact if this TEG technology were to be implemented across the cement industry.

Findings

Field Demonstration Results

During the demonstration, the TEG technology achieved a peak thermal efficiency of 5%, delivering a maximum net power output of 7.7 kW. This performance was recorded at mean hot plate and cold plate temperatures of 208 °C and 10.5 °C, respectively (Figure 5). Further analysis of individual cartridge performance within the hot-side temperature range of 130-212 °C revealed an average wattage of 15 W, with some cartridges reaching up to 35 W at 10% efficiency. The demonstrated 5% peak thermal efficiency aligns with the stated performance metric claims, confirming the TEG's effectiveness in converting waste heat into usable electrical power.

Figure 4: Typical suspension preheater pre-calciner kiln and TEG tap-in points

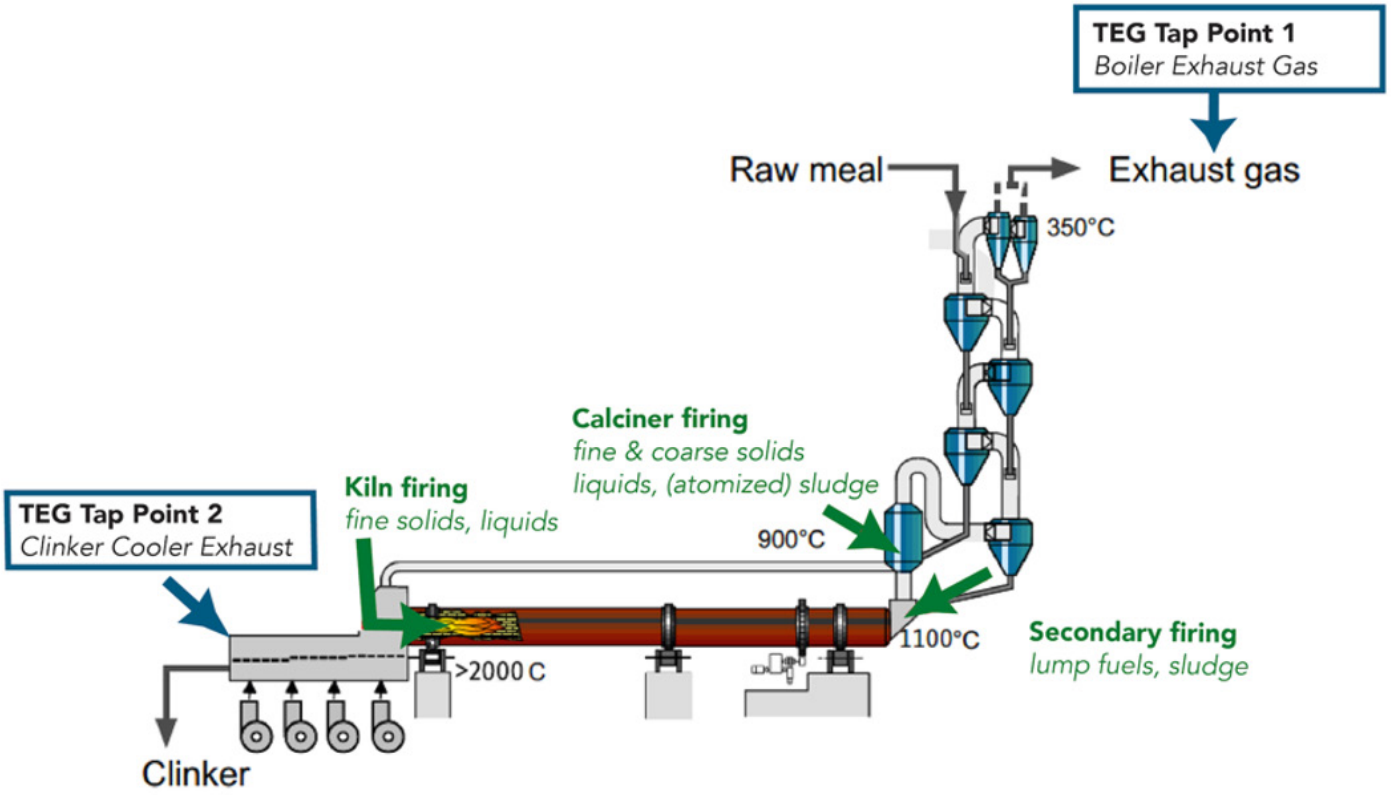
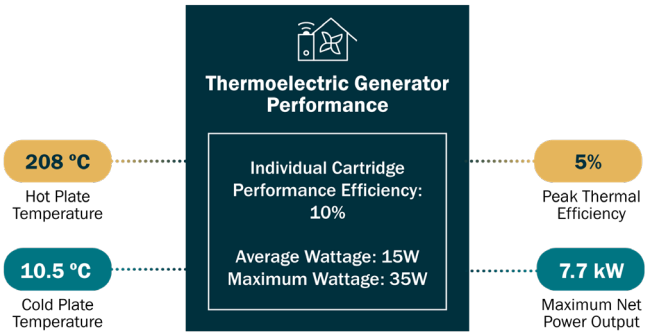


Figure 5: Graphic demonstrating TEG performance findings for a 573-cartridge system



Modeled Analysis of Commercial-Scale TEG

The study modeled the performance of the installation of a conceptual commercial-scale TEG to provide estimates of annual generation impacts at cement plants. This included an evaluation for theoretical cement plant production and waste heat profiles with a sensitivity analysis to account for ranges of typical plant operating parameters (preheater exhaust temperature, clinker cooler exhaust temperature, and production rate). Typical commercial TEG systems, as modeled in this analysis, use a modular design of 12-kW units stacked together — suitable for installations at cement plants.

Based on a range of clinker production from 800–12,000 tons/day, this technology can achieve lower operating costs by up to $910,000 by generating between 56 and 1,040 kW of net power, or 0.5 to 9.1 gigawatt-hour (GWh) of net energy annually, assuming preheater exhaust temperature of 340 °C and clinker cooler exhaust temperature of 300 °C, and average cold entering temperature of 7.8 °C. The output depends on factors such as preheater exhaust temperature, clinker cooler exhaust temperature, and plant production rate. Parasitic loads are significant but vary by application. In this study, the parasitic loads were reduced due to the site's available natural water pressure from Lake Huron, which eliminated the need for cooling loop pumps. However, other applications may require additional equipment, such as cooling towers. The results are valid under similar parasitic load conditions (29–35%) or where a high-pressure cold sink is available. Applicability to other locations may be limited if additional systems are needed, potentially impacting overall performance. As discussed, commercial-scale installations at Holcim plants also provide non-energy benefits like reduced emissions up to 3,400 metric tons of CO_2 annually per site, based on the national average emission rate.

Potential Impacts

Based on the design and performance of the assessed pilot unit, suitable applications for the ATS TEG system are industrial applications with waste heat temperatures exceeding 150 °C. Ideally, these systems are consistently maintained above the optimal operating temperature of 240 °C. According to the 2015 Oak Ridge National Laboratory study "Waste Heat to Power Market Assessment," there is approximately 2,245 trillion Btu of annual waste heat available across 21 manufacturing sectors at a reference temperature of 120 °C in the United States. Implementation of TEG systems at a 10% adoption rate within the top five manufacturing subsectors (glass, cement, steel, aluminum, and metal casting) is projected to produce a net annual generation of 620 GWh. Based on this analysis, the system could result in 232,000 tons of carbon dioxide (CO_2) emissions reduction annually, assuming an average emissions rate of 823 pounds CO_2 per megawatt hour of generation.[2]

Future evaluations could consider exploring the non-energy benefits associated with the TEG system, which include reduced maintenance requirements and extended equipment lifespan due to fewer moving parts compared to traditional steam Rankine cycle systems. Additionally, further studies could focus on optimizing the system for different industrial applications, considering site-specific factors such as waste heat quality, access, and cooling source availability.

2 Assuming an average generation efficiency of 4.3%, heat exchanger effectiveness of 0.85, and parasitic loads of 35%

These findings are based on the Industrial Technology Validation report: *Field Validation of Thermoelectric Generation System at Holcim Cement Plant in Alpena, MI*

For more information:

Contact the U.S. Department of Energy's Industrial Technology Validation program at ITV-Support@lbl.gov

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