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Docket Number:	19-ERDD-01
Project Title:	Research Idea Exchange
TN #:	229226
Document Title:	Linde plc Comments - Linde plc response to CEC's Request for Information on Innovative Waste Heat Recovery Technologies
Description:	N/A
Filer:	System
Organization:	Linde plc
Submitter Role:	Public
Submission Date:	8/6/2019 11:30:20 AM
Docketed Date:	8/6/2019

Comment Received From: Linde plc
Submitted On: 8/6/2019
Docket Number: 19-ERDD-01

Linde plc response to CEC's RFI on Innovative Waste Heat Recovery Technologies

Additional submitted attachment is included below.

Introduction

Linde plc is very pleased to respond to the California Energy Commission's "Request for Information" regarding innovative waste heat recovery technologies. Linde is a leading industrial gases and engineering company with 2018 pro forma sales of USD 28 billion (EUR 24 billion). The company employs approximately 80,000 people globally and serves customers in more than 100 countries worldwide. Linde delivers innovative and sustainable solutions to its customers and creates long-term value for all stakeholders. The company is making our world more productive by providing products, technologies and services that help customers improve their economic and environmental performance in a connected world.

Linde plc strongly believes that waste heat recovery is one of the more viable options available for reducing fossil fuel usage and greenhouse gas emissions in the industrial sector. The company has more than sixty years of experience in designing and building fired heaters and waste heat recovery units and has supplied more than 3,000 fired heaters around the world. The company's experience spans the design of waste heat recovery systems for flue and process gases from different furnace applications, such as steam reformers, as well as waste heat recovery from gas turbines and steam superheaters.

Linde plc is pursuing technology and solutions development for heat recovery in high temperature manufacturing industries to address the challenges of improved capital efficiency and economies of scale. Through internal technology developments and external technology partnerships, Linde is participating in several projects at different stages of development to identify promising options for lowering costs and designing for application at scale.

1. **What California industries have large volumes of ultra-low (<250º F) or ultra-high temperature (>1,600º F) waste heat**

Linde plc is interested in recovery of ultra-high temperature waste heat from energy-intensive industries such as iron/steelmaking, refining and glass. In California, refining and glass manufacturing have a strong presence. However, glass manufacturing is an energy-intensive industry mainly fueled by natural gas. It also generates tremendous amounts of waste heat, with approximately 30 - 60% of consumed energy being lost, depending on the segment of the glass industry. According to the Greenhouse Gas Emissions Inventory from the California Air Resources Board, the glass industry recorded 0.4 million tonnes of CO_2 equivalent greenhouse gas emissions in 2016 from combustion of natural gas. Our customers in this sector have expressed concerns about this and are actively pursuing solutions that can improve the energy efficiency of their furnaces, not only to mitigate the fluctuating costs of energy but also to improve their environmental performance. Linde plc submits that the glass industry is one that would greatly benefit from additional research and development in waste heat recovery.

2. **What research is needed on advanced technologies or materials (including coatings) for recovering waste heat cost effectively in ultra-low heat or ultra-high temperatures?**

Linde plc believes that any research program in this space should embrace both continuous improvement of conventional technologies as well as the development of advanced or emerging technologies. An emphasis should also be placed on demonstration and deployment of technologies at scale for field trials at operational sites. By focusing on large projects at scale, a significant impact can be made on realizing reductions in natural gas consumption and greenhouse gas emissions.

Linde is developing an innovative waste heat recovery process for thermo-chemical heat recovery from oxy-fired furnaces employing regenerators such as in the glass, aluminum, steel and cement industries. Thermo-chemical regeneration can be used for heat recovery of medium- and high-temperature waste heat streams above 1200°C. This technology uses waste heat to drive an endothermic natural gas reforming reaction that would result in production of a combustible fuel mixture with a higher energy content than natural gas, thereby reducing the amount of fuel required. This technology has the potential for an overall energy reduction of 20 - 30%–when compared to widely adopted combustion technologies in the glass industry. For California, this may mean a reduction in CO_2 emissions anywhere between 80,000 to 120,000 tonnes annually.

The equipment performance of waste heat recovery technologies is the most important issue preventing use of heat recovery systems in high-temperature processes, and this is true also for thermo-chemical regeneration. This area would also benefit from research that focuses on heat recovery of waste streams that have high concentrations of contaminants. In the glass industry, sulfates in the flue gas may be a challenge that limits the waste heat recovery potential of combustion flue gases.

To support the development and deployment of these new systems, the cost basis of the equipment would need to be reduced through improved design and manufacturing. This may include:

- the use of different materials or material coatings that can withstand high temperatures and corrosive contaminants within these streams;
- design and engineering of more compact systems with smaller footprint and greater capital efficiency;
- low cost manufacturing processes and techniques for waste heat recovery technologies and materials;
- low-cost flue gas cleanup that can operate at high temperatures or advanced cleaning systems that can address scaling and fouling while heat recovery systems are online; and
- improved automation for control of heat recovery and heat flux optimization using more compact designs, e.g. machine learning.

3. Should research focus primarily on the ultra-low or ultra-high temperature waste heat or, if not, what other temperature ranges?

Linde plc is interested in research that focuses primarily on recovery of ultra-high temperature waste heat. The justification for any heat recovery system is mainly an economic consideration. Industrial manufacturing facilities will only invest in waste heat recovery if it results in savings with a quick payback period and negligible risk. Ultra-high temperature waste streams have the most thermal value and is therefore more likely to result in a viable economic solution that would lead to commercialization. This is especially applicable to California, when you consider the type of manufacturing industries that are prevalent within the state and the quality of waste heat that would be encountered within these industries.

4. What advanced heat recovery technology improvements are needed to increase wide spread deployment by industry?

Linde has identified the following as specific improvements that are needed to increase the widespread deployment of waste heat recovery technologies by industry:

- Improved efficiency of heat recovery,
- Improved cost and performance of materials used for heat recovery,

- Reduced size and optimized geometry of heat recovery equipment,
- Improved rate of return on investment in heat recovery equipment and demonstrated economic viability,
- Low maintenance and operating costs,
- Reduced greenhouse gas and air pollutant emissions, such as nitrous oxides,
- Reduced complexity of integration with process units, and
- Reliable process control to ensure consistent and quality of product.

5. What are the cost and technical targets that must to be met to drive customer adoption (such as minimum rate of return or minimum percent heat recovery)?

To support the economic viability of these technologies and drive customer adoption, Linde puts forth that the following cost and technical targets would help drive customer adoption:

- >20% reduction in energy consumption
- >20% reduction in CO_2 emissions
- Equipment payback period <3 years

6. What complementary technologies and approaches can be combined to increase the value proposition of waste heat recovery systems?

There are several waste heat recovery technologies and options that are currently deployed in the market and under development for improved performance. One of the benefits of heat recovery from ultra-high temperature waste streams is that these technologies can be combined with other heat recovery systems, either in parallel or in series, thereby maximizing the amount of waste heat that can be captured. For example, a waste heat boiler can be installed downstream of a primary heat recovery system to generate steam, to produce either heat or power. However, as the temperature of the waste stream goes down, the ease with which energy can be recovered also decreases. The tradeoff between increased capital costs, reduced efficiency and longer payback periods will have to be considered for each specific case.