Waste Heat Recovery in Turkish Cement Industry

Review of Existing Installations and Assessment of Remaining Potential

International Finance Corporation
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Creating Markets, Creating Opportunities

IFC International Finance Corporation WORLD BANK GROUP

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Contents

List of Acronyms and Abbreviation

BAT	Best available technology
CSI	Cement Sustainability Initiative
EBITDA	Earnings before interest, taxes, depreciation, and amortization
IFC	International Finance Corporation
IRR	Internal rate of return
OIZ	Organized industrial zone
ORC	Organic Rankine Cycle
O&M	Operating and maintenance
SRC	Steam Rankine Cycle
TCMA	Turkish Cement Manufacturers Association
TL	Turkish lira
TOE	Tons of oil equivalent
VAT	Value-added tax
WHR	Waste heat recovery

Acknowledgements

This report is prepared by IFC team consisting of Alişan Doğan, Barbora Bodnarova, Bruce Hedman, Fatih Avcı, Viera Feckova, Viktoryia Menkova and Yana Gorbatenko.

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Executive Summary

Turkey is the fourth-largest producer of cement in the world and the largest one in Europe. The industry is the second-biggest consumer of industrial energy in Turkey, with a total consumption of 6426 thousand TOE equivalent in 2016, representing about 6 percent of Turkey's total energy use.

Cement manufacturing is an extremely energy-intensive process, with clinker production alone accounting for more than 90 percent of the total energy used by the industry. However, during the clinker manufacturing process, surplus thermal energy is produced, which can be harvested and converted into power. For example, waste heat from the preheater and clinker-cooler exhausts can be recovered and used to provide low-temperature heating needs in the plant, or used to generate power. Waste heat recovery (WHR) can provide up to 30 percent of a cement plant's overall electricity needs. Besides, it offers several other benefits, including reduced greenhouse gas emissions and less dependency on external power suppliers. Levelized cost of electricity (LCOE) is a convenient measure of the overall competitiveness of a generation investment compared to other electricity supply options[1]. Existing WHR projects within Turkey showed that LCOE can even go above grid price caused by higher than projected investment costs or lower than anticipated capacity utilization, underscoring the need for adequate upfront preparation and realistic projections of key project performance and cost parameters in project planning.

The Turkish cement industry has been an early adopter of WHR technology. The first WHR installation was commissioned in 2011. By the end of 2016, there were 10 clinker plants operating WHR systems with a total design capacity of 100.7 MW. An additional 34 MW of WHR capacity is in development at four other plants.

IFC's Energy and Water Advisory Team launched a review of WHR investments in the cement sector in Turkey in order to:

- Analyze how existing WHR installations performed compared with designed capacity and other installations
- Identify lessons learned in implementing and operating WHR systems across the sector
- Evaluate potential improvements for enhancing performance
- Assess additional investments needed to fully utilize the potential for WHR projects in Turkey's cement industry

[1] Levelized Cost of Electricity (LCOE) represents the per-kWh cost (in discounted real dollars and discounted kWhs) of installing and operating a generating asset over an assumed financial life and duty cycle. Key inputs to calculating LCOE for a project include capital costs, operating and maintenance (O&M) costs, financing costs, and an assumed utilization rate.

Cement is the key component of concrete, the world's most widely used construction material. The industry itself is resource-intensive, involving large amounts of raw materials, energy, labor, and capital. The production process typically involves grinding and blending raw material such as limestone, chalk, shale, clay, and sand with additives such as iron ore. The fine mixture is then fed into a large rotary kiln (cylindrical furnace) where it is heated to about 1,450°C. The high temperature causes the raw materials to react and form a hard granular material called "clinker." Clinker is cooled and ground with gypsum and other additives to produce cement.

The team gathered raw data from a representative group of 12 integrated cement plants in Turkey, of which six had installed WHR systems and six had yet to decide on implementing WHR. Data was gathered on the basis of survey questions sent out to cement manufacturing plants.

Actual WHR Performance Was Lower than Design Projections, yet Boosted Bottom Lines

IFC's team reviewing the survey responses found that the design capacities of the WHR systems were well within international practice standards of generating between 25 and 45 kWh/ton of clinker. The actual WHR generated was lower than design estimates for five plants, but still within the range of international practice expectations. The performance of a WHR system can fall below its designed performance for a variety of reasons, including seasonal variations in moisture content of raw materials or coal, and the specifics of drying practices adopted at the plant, which reduce available heat to the WHR system. Other factors that contribute to sub-optimal performance include changes in kiln operations that reduce the number of WHR operating hours, extended downtime of the WHR system itself due to operational issues, and oversizing of the WHR system in the initial design.

Despite a reduced performance compared with design conditions, the WHR systems surveyed provided, on average, 23 percent of a plant's total electricity needs, with individual levels ranging from 18 percent to 31 percent. As a result, all six plants realized sizeable savings on their purchased electricity costs, boosting their economic bottom lines. The estimated cost of electricity from the WHR systems, including operating and capital expenses, ranged from $18 to $45 per megawatt-hour, compared with current purchased electricity prices which ranged from $91 to $106 per megawatt-hour[2]. The estimated savings ranged from $1.4 to $2.7 per ton of clinker.

Correct Estimation of Waste Heat Potential, Capacity Utilization, and Cost of Technology Determine Financial Performance

Existing project paybacks (or IRRs) for the WHR systems surveyed ranged from 6 to 27 percent, while estimated project paybacks varied between 3.2 to 10.1 years. Key design and operational factors which impact a WHR system's project economics include sizing, capital cost and capacity utilization.

This report illustrates that WHR capacity utilization and kiln operating hours have the greatest impact on a WHR project's economics because these factors have a direct bearing on the amount of electricity produced by the WHR system. Cost factors such as WHR capital expenses, displaced electricity prices, and variations in currency exchange rates also have a significant impact on project financials. Reasonable variations in WHR operating and maintenance costs and in WHR auxiliary power requirements have a more modest impact on project performance, as resulted form modelling.

Moisture Content of Raw Materials Is a Critical Factor in WHR Performance

Raw material and fuel moisture content are critical parameters affecting WHR performance, since most plants surveyed use the preheater exhaust to dry raw feed and fuel before they enter the kiln. Using waste heat to dry excessive moisture content in the raw feed or fuel reduces the amount of heat available in the exhaust stream entering the WHR boilers, thus reducing the amount of power produced by the WHR unit. While the average raw material moisture content as reported by the companies is within industry norms, subsequent communication with the survey respondents highlighted that moisture content can vary widely over the course of a year due to variations in weather, changes in raw material sourcing and variations in mining conditions. This can have a significant impact on WHR performance.

[2] Estimated cost of electricity for WHR projects including operating expenses only ranged from 9.1 to 14.4 USD/MWh.

Remaining WHR Potential Represents a Business Opportunity of $450 million to $630 million

Out of the remaining WHR investment potential, $340 to $470 million USD of investments are financially feasible under current circumstances, with generation capacities ranging from 125 to 230 MW. Applying international WHR practice standards to the 39 clinker plants that have not implemented WHR results in an estimate of total WHR potential ranging from 158 MW to 283 MW, with a corresponding range of total investment potential of $450 million to $630 million.

1. Application of Waste Heat Recovery to the Cement Industry

The Cement Production Process Is Energy Intensive

Cement, the binding material that is mixed with an aggregate such as sand or gravel and water to form concrete, is the world's most widely used construction material. Over three tons of concrete are produced each year per person for the entire global population, making it the most widely used manufactured product in the world. Twice as much concrete is used around the globe than the total of all other building materials combined, including wood, steel, plastic, and aluminium – and for most purposes, none of these other materials can replace concrete in terms of effectiveness, price, or performance. The preference for concrete as a building material stems from low manufacturing cost, and its ability to be produced locally from widely available raw materials. Turkey is the fourth largest producer of cement globally, after China, India, and the United States[3].

Cement production is a resource-intensive practice involving large amounts of raw materials, energy, labor, and capital. Cement is produced from raw materials such as limestone, chalk, shale, clay, and sand. These raw materials are quarried, crushed, finely ground, and blended to the correct chemical composition. Small quantities of iron ore, alumina, and other minerals may be added to adjust the raw material composition. Typically, the fine raw material is fed into a large rotary kiln (cylindrical furnace) where it is heated to about 1,450°C. The high temperature causes the raw materials to react and form a hard nodular material called "clinker." Clinker is cooled and ground with gypsum and other additives to produce cement.

Cement manufacturing is an extremely energy-intensive process – the World Business Council for Sustainable Development's Cement Sustainability Initiative (CSI) indicates that in 2014 the average thermal energy and electricity consumed to produce one ton of clinker among its reporting companies was 3,510 MJ and 104 kWh, respectively, although these values can vary greatly depending on the age and configuration of clinker kilns[4]. Clinker production is the most energy-intensive stage in cement production, accounting for more than 90 percent of the total energy use and virtually all of the fuel use in the industry. Clinker is produced by pyro-processing the raw materials in large kilns. Three important processes occur with the raw material mixture during pyro-processing. First, all moisture is driven off from the materials. Second, the calcium carbonate in limestone dissociates into carbon dioxide and calcium oxide (free lime); this process is called calcination. Third, the lime and other minerals in the raw materials react to form calcium silicates and calcium aluminates, which are the main components of clinker. This third step is known as clinkering or sintering.

The main kiln type in use throughout the world is the rotary kiln (see Figure 1). In rotary kilns, a tube with a diameter of up to eight meters is installed at a three- to four-degree angle that rotates one to five times per minute. The kiln is normally fired at the lower end, and the ground raw material is fed into the top of the kiln, from where it moves down the tube countercurrent to the flow of gases and toward the flame end of the kiln. As the raw material passes through the kiln, it is dried and calcined, then finally enters into the sintering zone. In the sintering (or clinkering) zone, the combustion gas reaches a temperature of 1,800 to 2,000°C. Hot clinker is discharged from the lower end of the kiln and is immediately cooled in large air coolers to ensure clinker quality and to lower the clinker temperature to reach handling temperature in downstream equipment. Cooled clinker is combined with gypsum and other additives and ground into a fine powder called cement. Many cement plants include the final cement grinding and mixing operation at the site. Others ship some or all of their clinker production to standalone cement-grinding plants situated close to markets.

[3] United States Geological Survey, 2017. USGS estimated Turkish cement production in 2016 at 77 million metric tons. The Turkey Cement Manufacturers Association (TCMA) reported 2016 cement production of 75.4 million metric tons and clinker production of 67.9 million metric tons, http://www.tcma.org.tr.

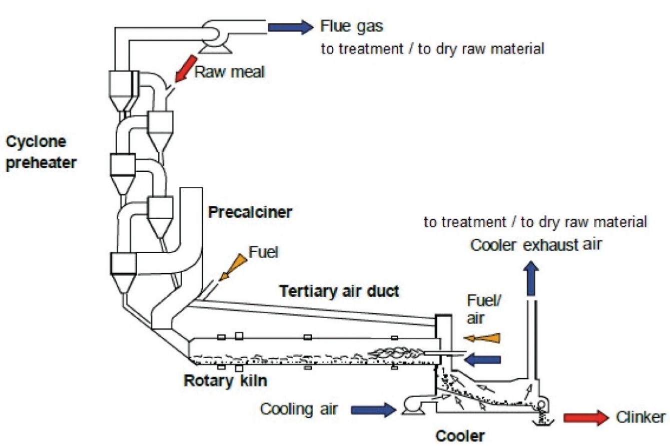
[4] GNR Database, 2017, World Business Council for Sustainable Development, Cement Sustainability Initiative, http//www.wbcsdcment.org/GNR-2014/.

TABLE 1. SPECIFIC THERMAL ENERGY CONSUMPTION BY ROTARY KILN TYPE	
Kiln Type	**Heat Input (MJ/ton of clinker)**
Wet	5,860–6,280
Long Dry	4,600
1-Stage Cyclone Suspension Preheater	4,180
2-Stage Cyclone Suspension Preheater	3,770
4-Stage Cyclone Suspension Preheater	3,550
4-Stage Cyclone Suspension Preheater plus Calciner	3,140
5-Stage Cyclone Suspension Preheater plus Calciner plus High-Efficiency Cooler	3,010
6-Stage Cyclone Suspension Preheater plus Calciner plus High-Efficiency Cooler	<2,930

Source: Based on N. A. Madlool et al., "A Critical Review on Energy Use and Savings in the Cement Industries," Renewable and Sustainable Energy Reviews 15, no. 4 (2011): 2,042–60.

Rotary kilns are divided into two groups, dry process and wet process, depending on how the raw materials are prepared. In wet process systems, raw materials are fed into the kiln as slurry with a moisture content of 30 to 40 percent. Wet process kilns have much higher fuel requirements due to the amount of water that must be evaporated before calcination can take place. To evaporate the water contained in the slurry, a wet process kiln requires additional length and nearly 100 percent more kiln thermal energy compared to the most efficient dry kiln (see Table 1). Wet process kilns tend to be older operations.

FIGURE 1. ROTARY CEMENT KILN (FIVE-STAGE CYCLONE SUSPENSION PREHEATER PLUS CALCINER PLUS HIGH-EFFICIENCY COOLER)



Source: U.S. Department of Energy, "Energy and Emissions Reduction Opportunities for the Cement Industry" (2003). Deployment of CCS in the Cement Industry, Report 2013/19 (2013).

Three major variations of dry process systems are used worldwide: long dry kilns without preheaters, suspension preheater kilns, and preheater/precalciner kilns. In suspension preheater and preheater/precalciner kilns, the early stages of pyro-processing occur in the preheater sections, a series of vertical cyclones (see Figure 1), before materials enter the rotary kiln. As the raw material is passed down through these cyclones, it comes into contact with hot exhaust gases moving in the opposite direction, and, as a result, heat is transferred from the gas to the material. Modern preheater/precalciner kilns also are equipped with a precalciner, or a second combustion chamber, positioned between the kiln and preheaters that partially calcines the material before it enters the kiln so that the necessary chemical reactions occur more quickly and efficiently. Depending on the drying requirements of the raw material, a kiln may have three to six stages of cyclones with increasing heat recovery with each extra stage. As a result, suspension preheater and preheater/precalciner kilns tend to have higher production capacities and greater fuel efficiency compared to other types of systems, as shown in Table 1.

Waste Heat Recovery for Power Production

State-of-the-art suspension process rotary kilns include multi-stage preheaters and pre-calciner to preprocess raw materials before they enter the kiln, and an air-quench system to cool the clinker product (clinker cooler). Kiln exhaust streams, from the clinker cooler and the kiln preheater system, contain useful thermal energy that can be converted into power. Typically, the clinker coolers release large amounts of heated air at 250 to 340°C directly into the atmosphere. At the kiln charging side, the 300 to 450°C kiln gas coming off the preheaters is typically used to dry material in the raw mill and/or the coal mill and then sent to electrostatic precipitators or bag filter houses to remove dust before finally being vented into the atmosphere. Although maximizing overall kiln efficiency is paramount, it is also essential to recover remaining waste heat from the preheater exhaust and clinker cooler to provide low-temperature heating or generate electricity. Typically, cement plants do not have significant low-temperature heating requirements, so most waste heat recovery projects have been for power generation. Waste heat recovery can provide up to 30 percent of a cement plant's overall electricity needs and offers a number of advantages[5,6].

- Reduces purchased power consumption (or reduces reliance on captive power plants), which in turn reduces operating costs.
- Mitigates the impact of future electric price increases
- Enhances plant power reliability.
- Improves plant competitive position in the market.
- Lowers plant grid energy consumption, reducing greenhouse gas emissions (based on credit for reduced central station power generation or reduced fossil-fired captive power generation at the cement plant).

In dry process cement plants, nearly 40 percent of the total heat input is available as waste heat from the exit gases of the preheater and clinker cooler. The quantity of heat from preheater exhaust gases ranges from 750 to 1,050 MJ per ton of clinker while the quantity of heat from the clinker cooler ranges from 330 to 540 MJ per ton of clinker from the exhaust air of the cooler. The amount of waste heat available for recovery depends on a number of factors including kiln design and production, the number and efficiency of preheater/precalciner stages[7], kiln operation (amount of excess air and air infiltration), configuration of the clinker cooler, the moisture content of the raw materials, and the amount of heat required for drying in the raw mill system, solid fuel system for cement mill. A portion of the available waste heat is usually used to dry raw materials and/or solid fuel, and because raw material drying is important in a cement plant, heat recovery has limited application for plants with higher raw-material moisture content. Often drying of other materials needed for cement production such as slag or fly ash also requires hot gases from the preheater or cooler; in that case, opportunities for waste heat recovery will be further decreased.

[5] Lawrence Berkeley National Laboratory (LBNL), 2008, "Energy Efficiency Improvement Opportunities for the Cement Industry," Worrell, Galitsky, Price, January 2008.

[6] Environmental Protection Agency (EPA), 2010, "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry," October 2010.

[7] The number of preheater stages in a cement plant has significant bearing on the overall thermal energy consumption and waste heat recovery potential. The higher the number of stages, the higher the overall thermal energy efficiency of the kiln and the lower the potential for waste heat recovery. Selection of the number of preheater stages is based several factors such as cooler efficiency, restrictions on preheater tower height, or heat requirements for the mill itself..

It should be noted that WHR is an energy efficiency and cost savings measure that can be retrofitted relatively easily on existing kilns lines. Over the long term, the Turkish cement industry is expected to continue its investment in new technologies and kiln upgrades to remain competitive with industry best practices. One example is the use of state-of-the-art low pressure cyclone preheater towers and precalciners. While the number of preheater stages for clinker kilns is typically driven by raw material drying requirements, kiln systems with five preheater stages and precalciner are considered 'standard' technology for today's modern, dry-process plants. Although the average thermal energy consumption per ton of clinker for the Turkish cement industry compares favorably with the EU average[8], there are still a number of less-efficient kilns operating with three and four preheater stages. Retrofitting existing preheater towers with additional stages of low pressure drop cyclone preheaters and precalciners can increase production, reduce fuel use and lower emissions, and is a recommended long term upgrade for most kilns. Preheater tower retrofit costs, however, can be significantly higher than the costs of implementing a WHR project (four to six times higher), particularly if the existing preheater tower foundation must be replaced. Preheater retrofits also require a significant amount of downtime for the kiln (8 to 12 weeks), resulting in lost revenues in addition to retrofit equipment and construction costs[9]. For these reasons, preheater upgrades are usually conducted in conjunction with major kiln renovations. In the interim, and depending on age and condition of the kiln, WHR can represent an economic option to increase energy efficiency and lower production costs for many cement plants.

Waste Heat Recovery Is a Proven Efficiency Measure for Cement Plants

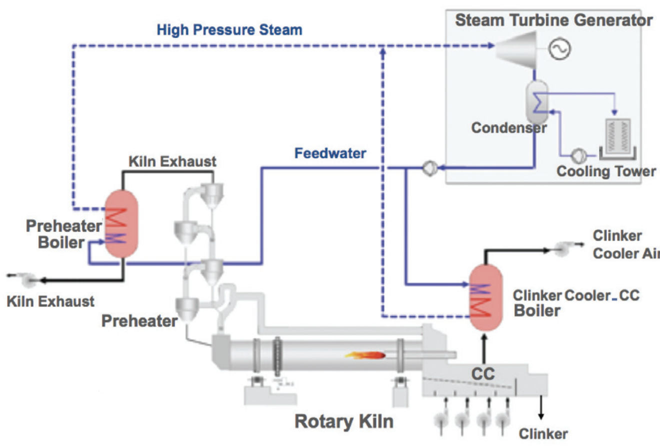
Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle[10]. This thermodynamic cycle is the basis for conventional thermal power generating stations and consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapor (steam, in a power station) that is then expanded through a turbogenerator producing power. Low-pressure vapor exhausted from the turbogenerator is condensed back to a

[8] World Business Council for Sustainable Development, Cement Sustainability Initiative, Getting Ready Now (GNR) Database, http://www.wbcsdcement.org/GNR-2014/index.html.

[9] LBNL, "Guidebook for Using the Tool BEST Cement: Benchmarking and Energy Savings Tool for the Cement Industry", LBNL-1989E, 2008.

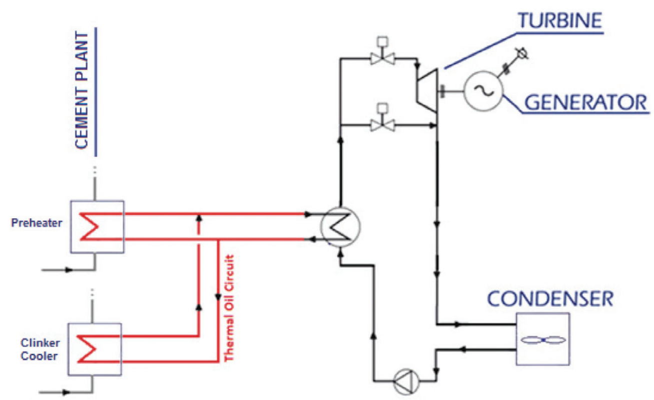
[10] The Rankine cycle is a thermodynamic cycle that converts heat into work. Central station power plants that generate electricity through a high-pressure steam turbine are based on the Rankine cycle..

FIGURE 2. TYPICAL WASTE HEAT RECOVERY SYSTEM USING STEAM RANKINE CYCLE (SRC)



Source: *Adapted from Holcim, 2012–2013 and revised.*

FIGURE 3. WASTE HEAT RECOVERY SYSTEM USING ORGANIC RANKINE CYCLE (ORC)



liquid state, with condensate from the condenser returned to the boiler feedwater pump to continue the cycle. Waste heat recovery Rankine cycles can be based on steam or on an organic compound used as the working fluid[11]. In each case, the working fluid is vaporized in heat recovery boilers or steam generators (HRSGs) by the hot exhaust gases from the preheater and hot air from the cooler, and then expanded through a turbine that drives a generator.

Steam Rankine Cycle (SRC) Is the Most Common WHR System in Cement

As shown in Figure 2, in the steam waste heat recovery cycle, the working fluid – water – is first pumped to elevated pressure before entering waste heat recovery boilers. The water is vaporized into high-pressure steam by the hot exhaust from the preheater boiler and clinker cooler boiler and then expanded to lower temperature and pressure in a turbine, generating mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapor is condensed to low-pressure liquid and returned to the feedwater pump and boiler[12]. The steam turbine system is best known from power plants. While the electric efficiency of a steam Rankine cycle can reach 45 to 46 percent in modern power plants, the relatively low temperature level of heat from the cooler (250 to 340°C) limits the efficiency of waste heat recovery systems in cement kilns to a maximum of 18 to 25 percent[13].

Organic Rankine Cycle (ORC) Utilizes Lower Temperature Heat for Power Generation

Organic compounds with better generation efficiencies at lower heat-source temperatures are used as the working fluid in Organic Rankine Cycle (ORC) systems. ORC systems typically use a high-molecular-mass organic working fluid such as butane or pentane that has a lower boiling point, higher vapor pressure, higher molecular mass, and higher mass flow compared to water. Together, these features enable higher turbine efficiencies than those offered by a steam system. ORC systems can be used for waste heat sources as low as 150°C, whereas steam systems are limited to heat sources greater than 260°C. ORC systems typically are designed with two heat transfer stages. The first stage transfers heat from the waste gases to an intermediate heat transfer fluid (for example, thermal transfer oil). The second stage transfers heat from the intermediate heat transfer fluid to the organic working fluid. A heat exchanger (regenerator or recuperator) may also be added to the cycle represented in Figure 3, to preheat organic liquid with turbine exhaust vapor before condenser. ORCs have commonly been used to generate power in geothermal power plants and, more recently,

[11] A third type of Rankine cycle is based on a mixture of water and ammonia and is called the Kalina cycle. Application of the Kalina cycle to the cement industry is still in the demonstration phase.
[12] Institute for Industrial Productivity/International Finance Corporation (IIP/IFC), "Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis" (2014).
[13] CSI, "Existing and Potential Technologies for Carbon Emissions Reductions in Indian Cement Industry".

in pipeline compressor heat recovery applications in the United States. ORC systems have been widely used to generate power from biomass systems in Europe.

Market Interest for WHR Increases as Feasibility of Technology Improves

The Turkish cement industry was an early adopter of WHR, with the first installation commissioned in 2011. As of the end of 2016, there were 10 clinker plants operating WHR systems with a total design capacity of 98 MW. Interest in waste heat recovery among cement industries is mainly driven by:

- Rising prices for power and fuel, particularly where captive power plants prevail.
- Concerns about grid power reliability, particularly in developing countries where the electricity supply is often controlled by local, state-owned monopolies and the cost of power can represent up to 25 percent of the cost of cement manufacture.
- Industry commitment to and government support and policies for sustainable development.

On the technology supply side, Japanese companies spearheaded the introduction of waste heat recovery power systems in the cement industry and introduced the technology to China in 1998. Since then, China has become the market leader as technology supplier for steam-cycle waste heat recovery installations, both in the number of systems installed domestically and in the number of systems installed internationally by Chinese companies (particularly in Asia). Initially, waste heat recovery development in China was driven by incentives such as tax breaks and Clean Development Mechanism (CDM) revenues for emissions reductions from clean energy projects. In 2011 a national energy efficiency regulation mandated waste heat recovery on all new clinker lines built after January 2011. These drivers were reinforced when multiple Chinese waste heat recovery suppliers entered the market, lowering waste heat recovery capital and installation costs by adopting domestic components and design capability, which developed the technology for the Chinese market, and by 2012 over 700 units were operating in that country. The bulk of recent market activity has been in Asia, where Chinese companies or joint ventures are the primary suppliers. The experience of China in using waste heat recovery for power has shown that, in large plants, about 22 to 36 kWh per ton of clinker (25 to 30 percent of total power requirements) can be generated, depending on kiln configuration and drying requirements. This power is considered sufficient to operate the kiln section on a sustained basis[14]. The leading manufacturers of waste heat recovery systems using conventional steam system technology are now marketing systems with improved performance due to higher steam temperatures and pressures as well as higher component efiiciencies that can reach output levels as high as 45 kWh/t of clinker under certain conditions.

Organic Rankine Cycle systems have started to be applied successfully in the cement industry, especially in recent years, in addition to a portfolio of applications such as biomass recovery, geothermal power, and compressor stations.

Waste Heat Recovery Feasibility Requires Rigorous Analysis

The project economics of waste heat power generation depend on a number of site-specific and project-specific factors, including the following considerations:

- The amount of heat available in waste gases (exhaust gas volume and temperature) and conditions of such gases determine the WHR system’s size, potentially its technology (for example, ORCs are more applicable to lower-temperature exhaust streams and lower gas volumes), and its overall generation efficiency (including the amount of power that can be produced). The amount of heat available and at what temperature is determined by the size and configuration of the kiln (that is, its capacity in tons per day and number of preheater/precalciner stages) and the raw material moisture level (which determines the percentage of hot exhaust gases needed for drying).
- Capital cost of the heat recovery system, which generally depends on size, technology used, and equipment supplier.
- System installation costs (design, engineering, construction, commissioning, and training) depend on the installation size, technology, complexity, supplier, and degree of local content.

[14] CSI, “Existing and Potential Technologies for Carbon Emissions Reductions in Indian Cement Industry”.

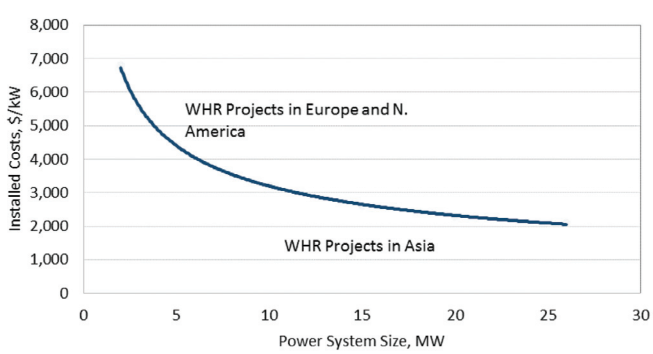
- System operating and maintenance costs are affected by size, technology, site-specific operational constraints or requirements. They are also influenced by staffing – whether the system can be handled by existing operating staff, new staff that require training, or be outsourced.
- Operating hours of the kiln and availability of the heat recovery system.
- Displaced power prices based on grid electricity no longer purchased, or reduced dependence on captive power plants and associated costs.
- Net power output of the WHR system. Net output is more important in determining project economics than gross power output. The impact of auxiliary power consumption and process/booster fans must be included in efficiency and economic calculations.
- Availability of space in close proximity to the preheater, cooler, and air-cooled condensers.
- Availability of water.

A WHR installation is a relatively complex system with multiple interrelated subsystems. The basic package for a steam-based system[15] consists of heat recovery boilers or heat exchangers, steam turbine, gearbox, electric generator, condenser, steam and condensate piping, lubrication and cooling systems, water-treatment system, electrical interconnection equipment and controls. Total installed costs, which include design, engineering, construction, and commissioning, can vary significantly depending on the scope of plant equipment, country, geographical area within a country, competitive market conditions, special site requirements, and availability of a trained labor force and prevailing labor rates. Total capital cost (equipment and installation) is strongly influenced by size – smaller WHR systems will have a higher cost per kW of generation capacity. Engineering, civil work, and construction costs can represent as much as 34 to 45 percent of total project cost. Costs in Western countries are at the high end of the range[16]. Figure 4 shows industry estimates of total installed costs for cement WHR projects on a $/kWe basis and illustrates how costs depend heavily on project size (MW), local cost variations (region of the installation), and type of technology (systems lower than 2 to 3 MW tend to be ORC systems). Hence, total installed costs for WHR systems are affected by all of the factors mentioned above, but costs can range from 7,000 $/kWe for 2-MW systems (ORC) in Europe to 2,000 $/kWe for 25-MW systems (steam) in Asia. IFC's experience over the last few years is that costs can be lower than indicated in Figure 4, as also demonstrated by more recent experience in the Turkish cement industry (see Figure 16). Note that since 2013, the leading suppliers of waste heat recovery systems using conventional steam circuit technology have now been marketing second-generation systems with improved efficiencies, resulting in somewhat lower costs on a $/kW basis.

[15] The discussion of system costs and project economics focuses primarily on steam systems, which represent the vast majority of installed technology – conventional steam systems account for 99 percent of existing WHR installations in the cement industry worldwide.

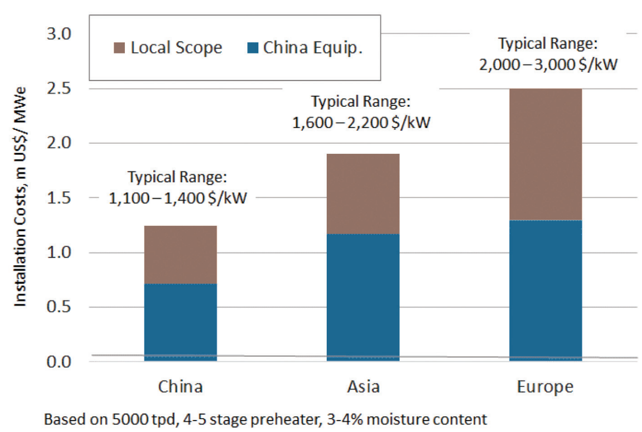
[16] Holcim, 2013, "Experience and Challenges in Waste Heat Recovery," Urs Herzog, Thomas Lamare, 2nd Global CemPower, London, June 2013

FIGURE 4. WHR INSTALLED COSTS, USD/KW



Source: Holcim 2013, OneStone Research 2012, 2013.

FIGURE 5 – INSTALLED COSTS FOR CHINESE WHR SYSTEMS (STEAM CYCLE)*



Source: Holcim 2013, OneStone Research 2013; IFC 2014.

** The above capex estimates are based on Chinese WHR equipment. Experience from WHR project in various regions suggest that installation costs are often higher, and in certain cases reach up to $5,000 per kWe depending upon WHR power technology type and installed capacity. For instance, European-manufactured WHR power systems could cost up to $3,800 per kW_e.*

Technology Supplier Is Also a Capex Factor

In addition to factors discussed above, the supplier is a key determinant in total capital cost for steam WHR systems in the cement sector. Due to its extensive domestic installed base, China is by far the major player in WHR for the cement industry in terms of installations, equipment supply, and developer experience. Faced with near market saturation at home, and building on the advances Chinese firms have made in the global cement market, Chinese WHR suppliers and developers are actively marketing WHR systems in Asia and branching out into Africa, the Middle East, and other regions. Initially, Chinese suppliers faced concerns about the reliability and quality of some of their WHR systems, as well as their ability to provide adequate start-up and training support[17]. Nevertheless, Chinese suppliers are active in a number of countries, including Turkey, where they are establishing partnerships and alliances with national resources for marketing and local project scope. Key to the Chinese success is their commanding price advantage over Western suppliers. Figure 5 provides an estimate of total project costs for Chinese WHR systems installed in China, other parts of Asia, and Europe. Note that while the figure depicts relative cost differences for Chinese WHR systems across these three regions, the range of reported total installation costs varies widely and can be impacted by a variety of site- and project-specific factors[13,18].

Main SRC system suppliers other than China are from Japan, India, and Denmark. ORC systems, on the other hand, are mainly supplied by US, Japanese, and Swiss companies. There are hundreds of successful ORC references in many types of applications throughout the world, and waste heat recovery in cement is rapidly becoming one of them.

Cement Industry in Turkey Is One of the Largest in the World

The Turkish cement industry is the fourth largest in the world, and the largest producer in Europe, with reported 2017 production of 80.5 million tons of cement and 70.8 million tons of clinker[19]. The industry began in 1911 with 20,000 tpy of capacity and saw large development starting in 1953, when the Turkish Cement Industry Company (ÇISAN), a public enterprise, was set up to commission 15 new cement plants throughout Turkey. A total of 17 more plants were added between 1963 and 1980 by the national and regional governments to support regional development. The Turkish Manufacturer's Association (TCMA) was formed in 1957 to represent the interests of the growing industry. In 1989 cement industry privatization began in the west of Turkey, where greater demand and higher efficiency meant plants were more likely to be attractive acquisition targets. Plants in the east were restructured and consolidated prior to privatization, which occurred rapidly by 1997. By this time, Turkey was the third-largest cement producer in Europe after Germany and Italy. By the end of the privatization process, Turkey had 40 cement plants producing a total of 33.3 Mt/yr of cement; eight plants were wet process and the rest were dry kilns. Driven by an expanding economy, the Turkish cement industry more than doubled in size in just 15 years; 33 percent of all Turkish capacity in 2010 was less than six years old[20].

By the end of 2017, the Turkish cement industry has a total of 54 active integrated cement plants with 83.6 Mt/yr of clinker production capacity and 14 cement grinding facilities with 8.1 Mt/yr of grinding capacity.[19] An additional three integrated plants are under construction with 5.5 Mt/yr of clinker capacity, and an existing plant is expanding with an additional 1.0 Mt/yr clinker capacity. Table 2 lists the largest clinker producers in 2017. The majority of cement producers are Turkish companies, including Akçansa Çimento, Oyak Group, Çimsa Çimento, Askale Çimento, and Limak Çimento. Multinational producers include Heidelberg (a joint venture in Akçansa), Votorantim Cimentos, Cementir Holding, Titan and Vicat.

Domestic cement sales were 72.2 million tons in 2017[21]. Domestic consumption is forecast to increase in the near term with the undertaking of new infrastructure projects, including highways, stadium construction, and new metro lines. Turkey is also constructing one of the world's largest airports in Istanbul. As noted earlier, Turkish producers are expanding existing plants to meet planned consumption levels. Turkey is a key exporter of cement, shipping 7.9 million tons of cement and 4.9 million tons of clinker to over 80 countries in 2017, including Libya, Iraq, Russia,

[17] IFC 2014, "Waste Heat Recovery for the Cement Sector".
[18] For example, Sinoma Energy Conservation Ltd. estimates the costs of a 9 MW system installed on a 5,000 tpd kiln in Asia (outside China) to be $18 million to $19 million, or about $2000/kW (Sinoma 2013).
[19] TCMA , http://www.tcma.org.tr.
[20] International Cement Review (ICR), 2103, "The Global Cement Report" 10th Edition, March 2013.
[21] TCMA, "Cement Sector Waste Heat Recovery," June 2017.

TABLE 2. MAJOR CEMENT COMPANIES – INTEGRATED PRODUCERS (2017)*

Group	# of plants	Clinker Capacity
OYAK	6	10.05
Akcansa	3	7.03
Limak	7	6.60
CIMSA	5	5.70
Askale	5	5.20
Nuh	1	4.40
AS Cimento	1	4.30
Cementir	4	4.22
Votorantim	4	3.88
Medcem	1	3.50
Vicat	2	3.20
Sanko	2	3.10
Kipas	1	2.90
Bati Anadolu	2	2.40
Goltas	1	2.20
Others	9	14.9
TOTAL	54	83.6

** IFC.*

and Israel as well as growing markets in Africa and Europe. Turkey is also one of the world's most significant producers of white cement, produced by Cimsa Cimento in Mersin (1.10 Mt/yr) and Adana Cimento (Oyak Group) in Adana (0.35 Mt/yr)[22].

Cement Production Is the Second Biggest Industrial Energy Consumer in Turkey

The cement industry is one of the largest energy consumers in the Turkish economy, with a total consumption of 6426 thousand TOE in 2016, representing about 6 percent of Turkey's total energy use[23]. Energy comprises a significant portion of the cost of producing cement, and the industry continues to make efforts to reduce energy use to control costs and meet national sustainability and environmental goals. Waste heat recovery can be an important factor in reducing energy use, costs, and greenhouse gas emissions at cement plants by utilizing waste energy normally vented into the atmosphere to produce up to 25 to 30 percent of a cement plant's electricity needs.

[22] Egypt is the world's largest producer of white cement, followed by Spain and Turkey. In 2014 there were 31 global producers of white cement operating 45 integrated plants in 29 countries with a combined production capacity of 13.3 Mt/yr. Çimsa Çimento, part of Hacı Ömer Sabancı Holding A.Ş., was the second-largest white cement producer in 2014 with its plant in Mersin, and exports its white cement to more than 60 countries around the world. "White Cement Report," Global Cement, Nov. 2015.

[23] TCMA, "Cement Sector Waste Heat Recovery," June 2017.

2. Waste Heat Recovery in the Turkish Cement Industry: Current Status and Project Experience

Forty Percent of Existing Clinker Capacity Has Implemented WHR

Efficiency and productivity improvements remain very important for the Turkish cement sector, and the industry was an active early adopter of WHR. As shown in Table 3, 100.7 MW of WHR capacity was installed during 2011–2015 at 10 plants, representing 21.7 Mt/yr of clinker capacity (26 percent of Turkey's total clinker capacity of 83.6 Mt/yr). Another 34 MW of WHR capacity is currently in the construction phase at four additional plants, representing 8.9 Mt/yr of clinker capacity (an additional 11 percent of total clinker capacity). Together, the 14 plants that have implemented or are in the process of installing WHR to date account for 37 percent of Turkey's total clinker production capacity, and 88 percent of clinker capacity at plants 1.0 Mt/yr or greater.

To date, all the WHR units installed or currently in the investment phase have been steam cycle systems. As such, the waste heat recovery power market for the Turkish cement industry has been served primarily by Chinese and Chinese/Japanese joint venture suppliers, which have extensive experience in steam-cycle WHR applied to the cement industry[24]. Some of the suppliers

[24] Institute for Industrial Productivity/International Finance Corporation (IIP/IFC), "Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis" (2014).

TABLE 3. EXISTING WHR SYSTEMS IN TURKEY

	Plant	Clinker Capacity (Mt/yr)	Number of Lines#	Commis-sioned	Technology Provider	WHR Capacity
1	Akcansa Çimento - Canakkale	4.45	2	2011	Sinoma EC	15.2 MW
2	Aşkale Çimento - Erzurum	1.95	2	2011	AVIC / GTE Endüstri	7.5 MW
3	Cimsa Çimento - Mersin	2.47	2	2012	Anhui Conch / Kawasaki / Marubeni	9.8 MW
4	Bati Çimento Anadolu	1.40	2	2012	Sinoma EC	9.0 MW
5	Bati Soke Çimento	1.00	1	2012	Sinoma EC	5.5 MW
6	Nuh Çimento	4.40	3	2013	Sinoma EC	17.7 MW
7	Bursa Çimento - Kestel	1.40	2	2013	STEC/Mitsubishi	9.0 MW
8	Bolu Çimento - Oyak Group	1.20	1	2014	STEC/Mitsubishi	7.5 MW
9	Aslan Çimento - Oyak Group	1.25	1	2014	STEC/Mitsubishi	7.5 MW
10	Goltas Çimento	2.17	2	2015	AVIC / GTE Endüstri	12.0 MW
11	Aşkale Çimento – Van*	1.05	1 line	-	Feasibility Done – Investment decision is pending	7.5 MW
12	Aşkale Çimento – Gumushane*	1.40	1 line	-	Feasibility Done – Investment decision is pending	7.5 MW
13	KCS Çimento*	2.90	2 lines	-	Commissioning in Feb 2018	9.0 MW
14	Medcem Çimento*	3.50	1 line	-	Commissioning in 2018	10.0 MW

Source: Based on spesific company inputs and company annual reports.

** Investment Phase.*

 # Number of clinker lines incorporated into WHR system.

have partnered with Turkish firms for local engineering support and installation. Major participants include:

- Anhui Conch / Kawasaki Engineering is a joint venture of the Chinese cement company Anhui Conch and the Japanese equipment and engineering company Kawasaki Plant Systems. Anhui Conch / Kawasaki is a leading WHR supplier in China and has installed a number of systems in other countries – including India, Pakistan, and Vietnam – and one system in Turkey.
- Sinoma Energy Conservation (Sinoma EC) is a leading Chinese supplier of waste heat recovery power generation systems. Sinoma EC has also installed over 20 WHR systems in other countries – including Vietnam, The Philippines, India, Pakistan, Thailand, Angola, the UAE, and Saudi Arabia – and four systems in Turkey. Sinoma EC has partnered with SC Endustri AS for WHR applications in Turkey.
- STEC (Shanghai Triumph Energy Conservation) / Mitsubishi is a joint venture of China Triumph International Engineering Company (CTIEC) and Mitsubishi Corporation. Shanghai Triumph specializes in medium- and low-temperature flue-gas waste heat recovery for power generation from glass and cement kilns. As of 2013 the company had 28 EPC projects in production, primarily in China and including three systems in Turkey.
- SinoPES International Engineering Company is a Chinese engineering company that focuses on cement plant design, engineering, procurement, construction, commissioning, operation and maintenance, and waste heat recovery. SinoPES has partnered with GTE Endüstri Sistemleri for WHR applications in Turkey.

Turkey's Cement Industry Has Seen Substantial Adoption of Waste Heat Recovery and Has Further Potential

IFC's Energy and Water Advisory Team[25] recently launched a review of WHR investments to analyze the operational and financial performance of WHR installations, identify lessons learned during implementation/operation, and assess what is needed to utilize the full potential for WHR.

[25] IFC, a member of the World Bank Group, is the largest global development institution focused on the private sector in developing countries. IFC's Energy and Water Advisory Team works with private and sub-national clients to facilitate adaption of clean energy and resource efficiency solutions.

The team had three specific objectives for the review:

- To conduct a post-investment review of existing WHR installations to evaluate their current state and operational performance.
- To identify possible bottlenecks for capacity utilization and adoption of small- to mid-size installations (less than 5 MW) in the cement sector in Turkey and
- To evaluate the remaining economically viable potential for steam-cycle and ORC WHR installations in Turkey's cement sector.

As part of this review, the IFC Team gathered raw data from a representative group of 12 integrated cement plants in Turkey – of which six had already installed WHR systems, and six had not yet made a decision on implementing WHR. The survey sample was selected based on broad outreach to plants that had operational WHR systems in 2015 and companies with plants producing 1 MT/yr or more that were not currently utilizing WHR. The survey sought to gather information at the plant level on plant operations relevant to WHR potential, such as design/operating capacity, kiln operation data, waste heat parameters, moisture content of raw materials/fuels, current energy use, and alternative fuels. For plants that had already installed WHR, the survey requested information on WHR system type, design characteristics, actual performance, project costs and financing, project implementation, and overall satisfaction with the project development process and WHR installation. For plants that had not installed WHR, the survey requested information on the level of familiarity or experience with WHR. The survey ended with questions for all participants on priorities for future efficiency and productivity investments.

Survey Coverage is Representative of the Turkish Cement Industry

Surveyed Plants Represent a Larger than Statistically Relevant Proportion of Industry Capacity

The plants participating in the WHR survey represent a total clinker production capacity of 21.2 Mt/yr, accounting for 25.3 percent of the total 83.6 Mt/yr clinker production capacity for the industry. Survey coverage by clinker capacity ranges is presented in Figure 6 below and reflects the survey's wide representation of the Turkish cement industry. Design clinker capacities of the 12 surveyed plants ranged from 0.435 Mt/yr to over 4.4 MT/yr and, as shown in the figure, covered roughly 20 percent or more of each capacity segment of the industry. Evaluating a variety of plant-level performance parameters indicates that the 12 surveyed plants are statistically relevant and representative of the Turkish cement industry:

Clinker Utilization of Surveyed Plants Is in Line with Overall Sector

As shown in Figure 7, reported annual capacity utilization of the surveyed plants for 2015 ranged from a low of 87 percent to a high of 130 percent based on actual production versus maximum design capacity, and from 87 percent to 99 percent based on planned operating hours. The production-based utilization rate for the Turkish cement industry as a whole was 85 percent in 2015 and 88.7 percent in 2016[26].

Variation in Moisture Content Affects WHR Performance

Raw material and fuel moisture content are critical factors affecting WHR performance, since most plants use the preheater exhaust to dry raw feed and fuel before they enter the kiln. Using waste heat to dry excessive moisture content in the raw feed or fuel reduces the amount of heat available in the exhaust stream entering the WHR boilers, reducing the amount of power produced by the WHR unit. All 12 of the surveyed plants used preheater exhaust, and sometimes clinker cooler exhaust, to dry raw material. Figure 8 shows the reported average raw material moisture content on an annual basis for 11 of the survey plants, ranging from a low of 3 percent to a high of 10 percent. While the average raw material moisture content as reported by the companies is within industry norms, subsequent communication with the survey respondents highlighted that moisture content can vary widely over the course of a year due to variations in weather, changes in raw material sourcing, and variations in mining conditions. According to discussions with cement plant managers, seasonal or periodic variations in moisture content can have a significant impact on WHR performance.

Thermal Energy Use of the Plants Is Representative

Figure 9 shows the average thermal energy consumption per ton of clinker produced for each of the survey plants. It also includes the Best Available Technology (BAT) average, which is approximately 3.0 GJ/ton, and

[26] TCMA.

FIGURE 6. WHR SURVEY COVERAGE VS CLINKER CAPACITY

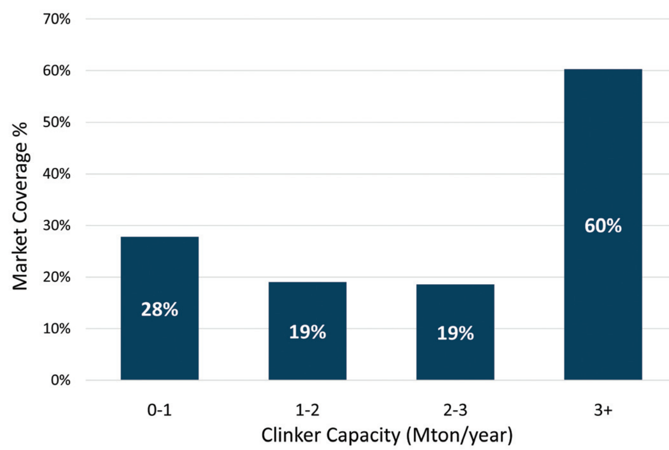


FIGURE 7. REPORTED ANNUAL CLINKER CAPACITY UTILIZATION, 2015

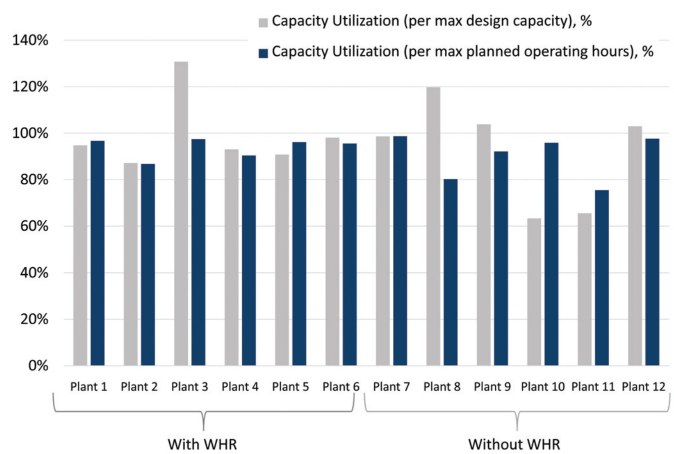
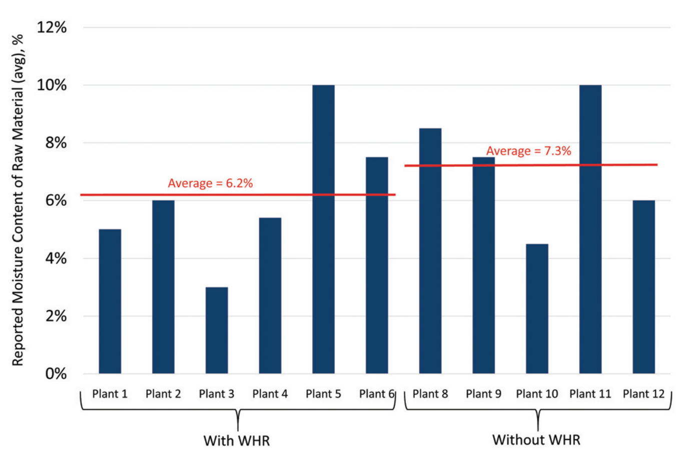


FIGURE 8. REPORTED RAW MATERIAL AVERAGE MOISTURE CONTENT



the 2011 average for the entire Turkish cement industry, which was just below 3.5 GJ/ton. In addition, the World Business Council for Sustainable Development's Cement Sustainability Initiative reports the 2014 EU average thermal energy consumption as 3.51 GJ/ton[27]. The reported thermal energy consumption of all 12 of the survey plants were higher than the BAT average, but in line with the 2011 Turkish and 2014 CSI EU averages. Seven of the plants had kilns with four preheater stages, and five plants had at least one kiln with five preheater stages. All 12 plants used coal as the primary fuel for their kilns, and seven of them supplemented coal with natural gas firing.

In comparing Figures 6 and 7, note that there does not appear to be a direct correlation between thermal energy use and reported raw material moisture content in the survey plants. Raw material is typically dried to specifications before entering the kiln, either through direct fuel dryers or the use of waste heat, so moisture content in the as-delivered raw material is not a factor in kiln operation. As noted above, all survey plants use a portion of the waste heat for drying. While the use of waste heat for drying has no direct impact on kiln thermal energy use itself, it does impact the overall plant fuel use – waste heat used for drying eliminates or reduces the need for separate fuel-fired dryers and would affect overall plant thermal performance accordingly. As noted earlier, the use of waste heat for drying also impacts the performance of WHR systems, reducing the amount of heat available for power generation.

Electricity Requirements Vary Based on Individual Plant Operations

Figure 10 shows the total electricity requirements of each plant, ranging from 85 to 140 kWh/ton of cement. Electricity requirements in terms of kWh per ton of cement can vary widely based on plant specific parameters such as the amount of raw material and finishing grinding conducted on-site, the grinding technologies used, and the type of cement itself. The CSI 2014 EU average electricity use is reported as 118 kWh/ton of cement, with an overall range of 40 to 180 kWh/ton. Figure 10 also shows that for those plants that had already implemented WHR, the WHR systems on average provided 23 percent of total plant electricity needs, with individual levels ranging from 18 to 31 percent.

[27] World Business Council for Sustainable Development, Cement Sustainability Initiative, Getting Ready Now (GNR) Database, http://www.wbcsdcement.org/GNR-2014/index.html.

FIGURE 9. REPORTED THERMAL ENERGY REQUIRED PER TON CLINKER PRODUCED

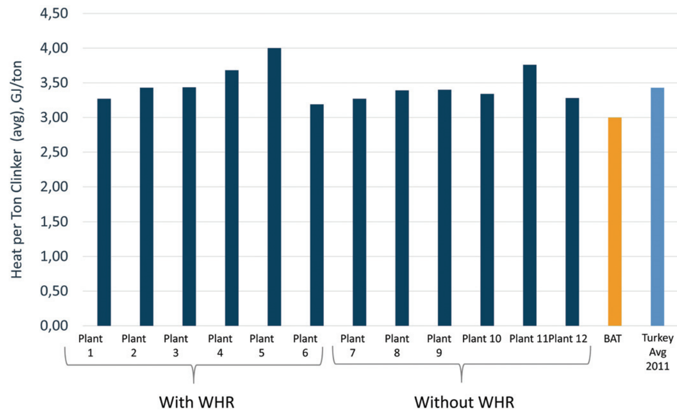
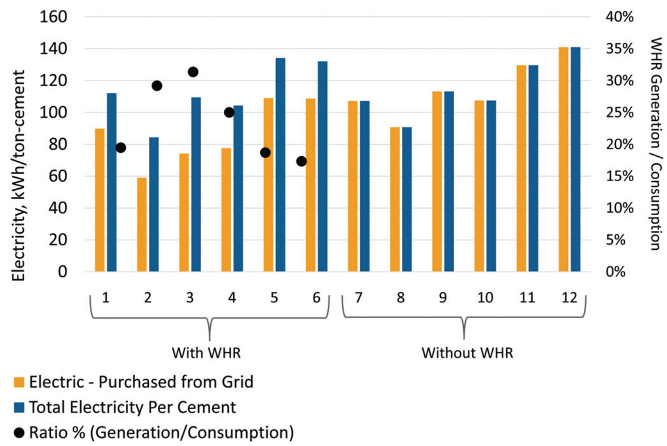


FIGURE 10. ELECTRICITY CONSUMPTION FOR CEMENT (KWH/TON CEMENT)



Correct Assessment of Design Capacity Is Key for Project Financial Performance

An initial modeling exercise estimated the financial performance of the existing WHR systems included in the industry survey. The clinker capacities of the six plants with WHR ranged from 0.61 to 4.45 Mt/yr. The WHR systems were all steam Rankine cycles (SRC) installed between 2011 and 2014, and ranged in design capacity from 5.5 to 17.7 MW. Two financial analysis cases were evaluated for these existing projects:

1. Planned Performance – Design conditions based on the maximum planned operating hours of clinker lines in a given year with 100% WHR capacity utilization.

2. Actual Performance – Operations based on reported actual operating hours of clinker lines and actual WHR capacity utilization in a given year.

The financial performance analysis was based on data reported by the individual companies for their operations in 2015. No adjustments were made to primary data received. In case no data was provided for select questions, estimates were made based on other relevant plant parameters and responses of comparable companies within the survey sample. Key assumptions used in the financial analysis are included in Annex C. The results of the analysis summarized below stress that correct assessment of available waste heat at the design stage, followed by operation at high-capacity utilization, are key parameters for better return on investment.

Actual WHR Performance Was Lower than Design Performance, but Still Boosted Bottom Lines

As shown in Figure 11, the WHR design capacities of the existing WHR systems were all within international practice standards of generating between 25 and 45 kWh/ton of clinker. Actual WHR generation, however, was lower than design estimates for five of the plants, though still within the range of international practice expectations. Design conditions are based on upfront projections of available waste heat, annual kiln and WHR operating hours, current and future electricity prices, and project capital costs. Actual WHR system performance can fall below design performance for a variety of reasons, including variations in moisture content of raw materials or coal, the specifics of drying practice at a given plant that may reduce available heat to the WHR system, changes in kiln operations that reduce the number of WHR operating hours, extended downtime on the WHR sys tem itself due to operational issues, or oversizing of the WHR system in the initial design. Actual project economics can vary from design conditions due to unexpected changes in cost factors, including displaced electricity costs or project capital expenses. Potential performance and cost uncertainties underscore the need for adequate upfront preparation and project analysis based on longer-term measurements and realistic projections of key performance and cost parameters.

Levelized cost of electricity (LCOE) is often used as a convenient measure of the overall competitiveness of a generation investment compared to other electricity supply options. LCOE (as described in detail in Annex C, page 79) represents the per-kWh cost (in discounted real dollars and discounted kWhs) of installing and operating a generating asset over an assumed financial life and duty cycle or capacity utilization. For technologies such as solar or WHR generation that have no fuel costs and relatively low O&M costs, LCOE changes in rough proportion to the capital cost and utilization rate of the system. As with any projection, there is uncertainty about these factors and their values can vary with unanticipated changes in project operating parameters or project costs. Figure 12 shows the planned and actual LCOE's of the existing WHR systems. The figure shows the influence of capital costs on LCOE, and highlights the differences between planned and actual LCOEs for the six systems, primarily impacted by actual capacity utilization compared to planned capacity

FIGURE 11. WHR DESIGN AND WHR ACTUAL PRODUCTION VS CLINKER DESIGN CAPACITY

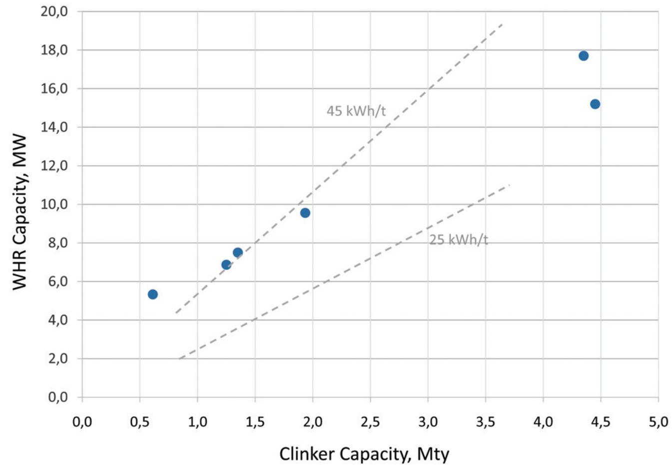
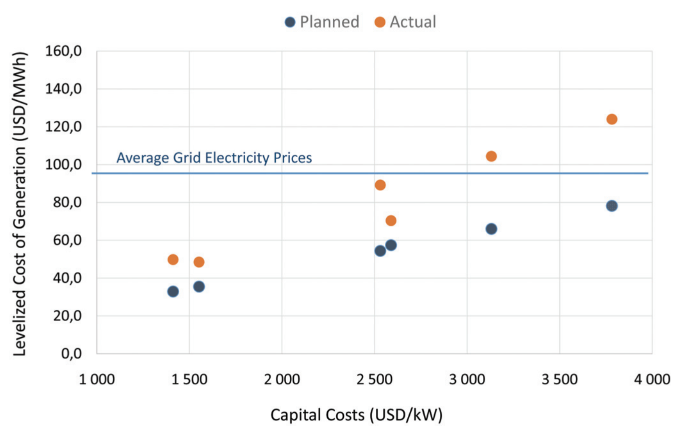


FIGURE 12. PLANNED AND ACTUAL LEVELIZED COST OF ELECTRICITY (LCOE)



utilization for each of the projects. Planned LCOE's were all well below the average delivered grid price of electricity of 96 USD/MWh. Actual LCOE's were consistently higher than planned, with four of the six LCOE's still well below the grid price of electricity, again underscoring the need for adequate upfront preparation and realistic projections of key performance and cost parameters.

Even with the reduced performance of actual operation compared to design conditions, the WHR systems on average provided 23 percent of total plant electricity needs, with individual levels ranging from 18 percent to 31 percent (Figure 13). As a result, all six plants realized sizeable savings on their purchased electricity costs, boosting their economic bottom lines – the estimated cost of electricity for the WHR systems, including operating and capital expenses, ranged from 18 to 45 $/MWh, compared to current purchased electricity prices which range from 91 to 106 $/MWh[28].

FIGURE 13. WHR GENERATION AS A SHARE OF TOTAL PLANT ELECTRICITY USE

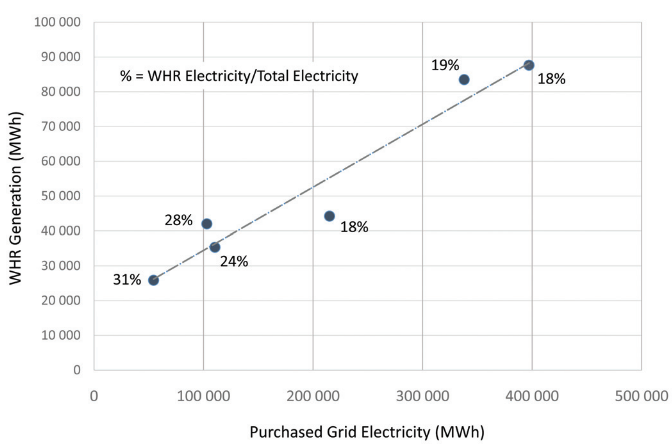
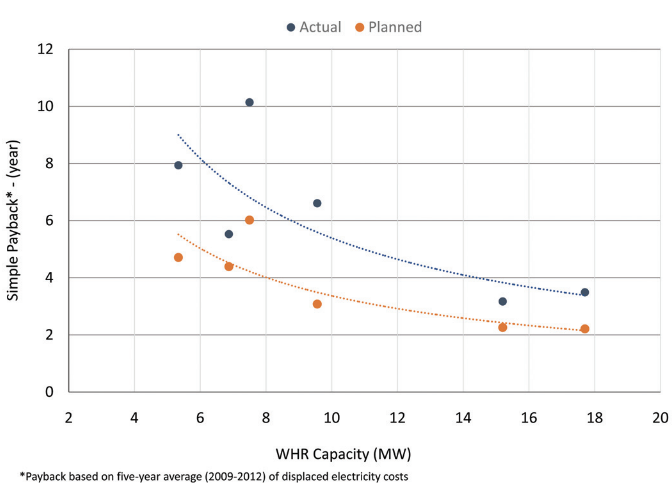


FIGURE 14. SIMPLE PAYBACK – ESTIMATED ACTUAL VS ESTIMATED PLANNED



Actual Project Paybacks Were Longer than Planned Paybacks due to Reduced WHR Capacity Utilization and Lower-than-Expected Grid Electricity Costs

Figure 14 provides a summary of the projects' financial performance based on estimated simple payback[29] of the six existing WHR systems for both the planned and actual cases. As shown in the figure, planned system paybacks ranged from 2.2 years to just over six years, driven primarily by differences in system capital costs. The actual case paybacks are based on the reported gross electricity generated at each plant, and estimates range from 3.1 to 10.1 years – 40 to 70 percent longer than planned paybacks under design conditions. The difference in financial performance between planned and actual is primarily due to the reduced capacity utilization of the WHR units (as shown in Figure 13) and grid electricity prices that were lower than originally projected. Estimated payback for one plant that reported electricity prices 30 percent below design projections was 50 percent longer than the planned design payback.

High WHR Capacity Utilization Is Key to Project Success

WHR system capacity utilization is a key performance parameter for project returns, and can be affected by a combination of factors including kiln utilization, kiln operation and raw material and fuel moisture content. Figure 15 presents the actual capacity utilization factors for WHR systems based on reported gross generation values for each plant. As shown, actual WHR utilization ranged from a high of 94 percent to a low of 63 percent with an average of 73 percent, even though clinker production capacity utilization for all plants was relatively high (87 percent to 130 percent of planned kiln production capacity). WHR system availability for all installations was reported to be in the 95+ percent range, indicating that the lower WHR utilization rates shown in Figure 15 were not due to the systems being unable to operate when

[28] The estimated cost of electricity for WHR projects includes operating costs and the 20-year net present value of capex expenses. The estimated cost of electricity including operating expenses only ranged from 9.1 to 14.4 $/MWh.

[29] Paybacks presented are simple paybacks for the WHR system using a five-year average (2009–2012) of displaced electricity costs.

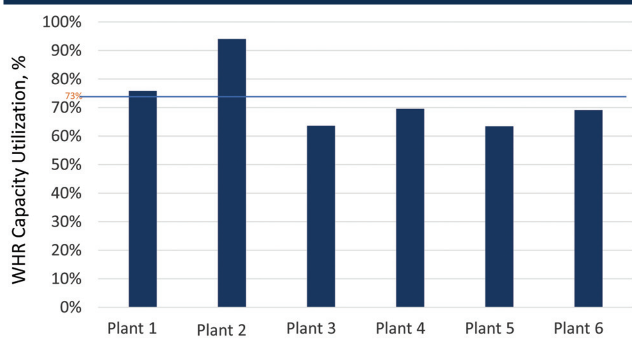
needed[30]. Low utilization rates are primarily as a result of higher than expected raw material/fuel moisture content, especially in winter due to seasonal variations, which leads to more heat used for drying and less heat available for power generation. However, as shown in Figure 15, there is little correlation of the WHR utilization rates with either kiln capacity utilization or average raw material moisture content over the year. This leaves the possibility that the WHR systems may have been oversized in the original designs, or there may be site-specific conditions such as seasonal variations in raw material moisture content that reduced the amount of heat available for power generation for certain periods. Other site-specific operational issues may also impact WHR performance.. As an example, Turkey is a leading supplier of white cement on the world market, and one of the survey plants is a key provider of this product. White cement production has different thermal and kiln residence time requirements than gray cement, resulting in reduced thermal energy in the preheater exhaust[31]. Annexes A and B provide guidance on best practices for accurately estimating waste heat availability and WHR system sizing.

Project IRRs are a Function of WHR Utilization and Investment Costs

All six of the plants that had installed WHR identified saving costs and improving efficiency as the primary drivers for installing the systems. Secondary reasons for implementing WHR included environmental considerations and implementing industry best practices to remain economically competitive. In fact, even with the reduced WHR utilization rates, the experience of the six plants shows that average electricity costs can be reduced by 1.4 to 2.7 $/ton of clinker, contributing to better EBITDA per ton of clinker produced. As shown in Figure 16, estimated project IRRs of the six installations ranged from 6 to 27 percent, driven largely by significant differences in investment costs. The range of WHR investment costs in terms of $/kW identified in the figure reflect the wide range of reported total investment for the plants. While total installed costs for WHR systems are generally a function of economies of scale (larger systems applied to larger kilns generally have lower per-kW costs), site-specific installation issues and differences in system suppliers can significantly impact total investment requirements.

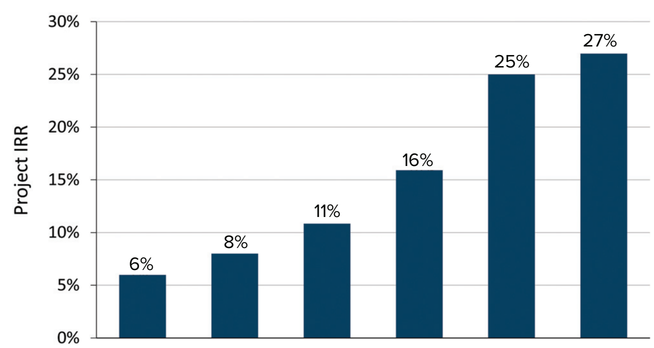
The existing WHR systems included in the survey were all commissioned between 2011 and 2014 and reflect prevailing installed costs of systems in that time period. Anecdotal information from more recent projects indicate that WHR investment costs are decreasing in Turkey. Figure 17 shows reported investment costs for the six survey installations and two estimates from recent WHR installations currently in the construction phase. Reported investment costs for the two recent installations are 20 to 25 percent lower than the average cost line for surveyed

FIGURE 15. WHR CAPACITY UTILIZATION



Clinker production capacity utilization						
By Production	95%	87%	130%	93%	91%	98%
By Hours	97%	87%	97%	90%	96%	96%

FIGURE 16. PROJECT IRRS ARE A FUNCTION OF INVESTMENT COSTS



Investment cost, USD/kWe	3,782	3,131	2,531	2,589	1,551	1,412
Clinker Capacity, Mton/yr	1-2	0-1	2-3	1-2	3+	3+

[30] Availability is defined as the ability of the WHR system to operate during the time period it is expected to operate (that is, when the clinker production line is operating).
[31] White cement requires raw materials with much lower iron and alumina content resulting in low melt liquid flow. Melt liquid acts as a solvent in final reactions in the kiln. Lower solvent flow results in longer residence time in the kiln, requiring higher fuel consumption per ton of clinker. This is coupled with higher radiant heat loss in the kiln due to reduced coatings forming on the kiln refractories, resulting in less heat available for recovery in white cement production.

plants. The cost decrease is a combination of lower costs from the system supplier and local scope providers, and recent adjustments to currency valuations.

Implementing WHR Projects May Require Dealing with Issues Unfamiliar to Cement Plants

The WHR installations all saved costs and generated reasonable returns on investment; however, the project development process itself was not without issues. As shown in Figure 18, responses from the facilities all indicate some difficulties with project implementation ranging from problems with suppliers not meeting project milestones on time, difficulties in the construction and commissioning of the system, integration issues with the cement process,

FIGURE 17. WHR INVESTMENT COSTS

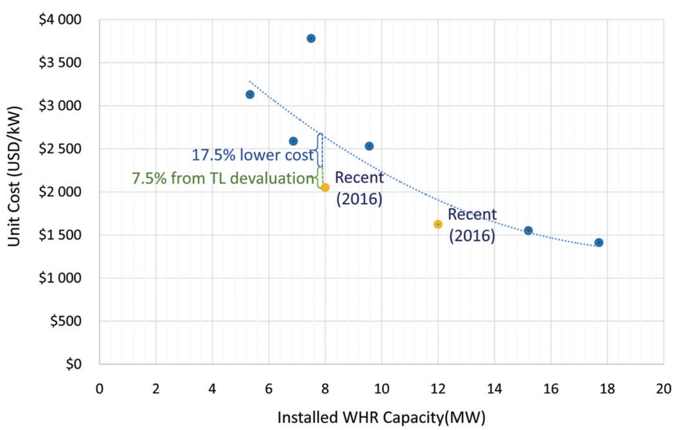
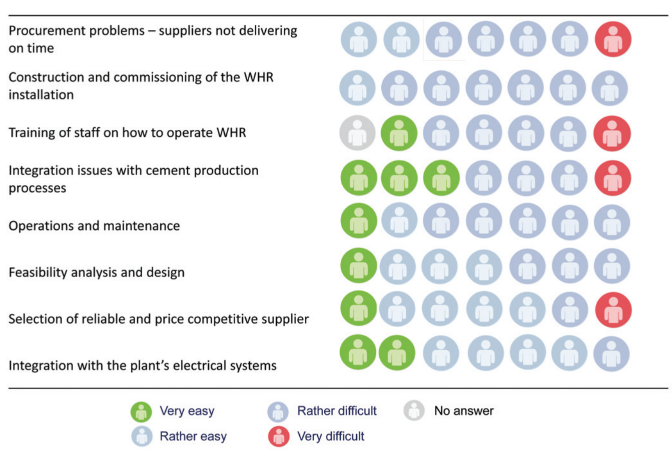


FIGURE 18. PERCEIVED DIFFICULTIES WITH EXISTING WHR INSTALLATIONS



operations and maintenance concerns, and issues with training staff to operate the WHR system. While concerns about the impact of WHR on kiln operations – kiln stability, clinker quality, production rate, and fuel consumption – are often cited as barriers to project implementation, none of the surveyed plants reported any significant operational issues in these areas.

Specific project development and operational issues commonly cited include:

- *System design issues*: Positive project economics depends on appropriate WHR system sizing and design. This requires accurate measurement of key baseline process parameters such as preheater and clinker exhaust flows and temperatures, thorough understanding of expected kiln utilization and the moisture content of raw material and fuel, and consideration of potential variations in these parameters over time. Positive project economics also depends on quality system components and equipment installation.
- *Water conditioning*: Required for both boiler feedwater and condenser cooling water, surveyed plants highlighted the need to utilize high-quality water conditioning chemicals to avoid erosion and corrosion problems, and to contract with reputable suppliers that not only provide quality chemicals, but that provide a full-service package that includes such tasks as daily tracking of conditioning equipment, water quality lab tests, online monitoring with analyzers, and corrosion measurements.
- *Training*: Proper training of plant personnel on WHR system operation and maintenance as well as system performance monitoring was a critical need identified by multiple survey participants. WHR system O&M is unlike normal cement plant operations and may require new personnel with different technical skills and salary requirements.
- *Communication*: The existing WHR systems were all installed by project teams led by foreign equipment vendors and engineering firms, with support from local companies for engineering support and installation. Communication can become complicated with multinational project teams such as this, particularly when there are language issues.

Implementation of Operational Best Practices Can Enhance WHR Performance

While the plants had positive returns on their WHR investments and received substantial benefits in terms of lower production costs, implementation of best practices to better control factors that affect WHR performance could further enhance their bottom lines. One example is management of the moisture content of raw materials. Cement raw materials are received with an initial moisture content varying from 1 to more than 50 percent, depending on source and season. Moisture is usually reduced to less than 1 percent before entering the kiln by use of preheater exhaust (and in some plants, clinker cooler exhaust) during grinding. Variations in the amount of exhaust gas used for drying affects WHR performance by limiting the amount of waste heat available for power generation. While the moisture content of delivered raw material may be beyond the control of plant operators, applying an understanding of the historical range and seasonal occurrence of variations in WHR system sizing and operational planning will ensure optimum utilization of the equipment. Historical data on as-received moisture content could potentially be used to reduce seasonal variations by planned blending of different sources. Applying proper storage and moisture management controls for materials stored on-site prior to grinding could further mitigate moisture issues and promote optimum WHR performance. Annex B contains a summary of best practices for both design and operation of WHR systems.

3. There Is Potential for Additional WHR in the Turkish Cement Industry

The survey gathered data on annual clinker design capacity and production as well as on preheater and cooler exhaust conditions from six plants currently without WHR. Based on this information, and using baseline assumptions on WHR performance (see Annexes A and C), a high-level feasibility analysis was conducted on each plant to estimate the potential heat available for recovery, and the size, cost, and baseline performance of applicable WHR systems. As a group, these six plants were smaller than the plants surveyed with existing WHR systems, ranging from 0.435 to 1.88 Mt/yr clinker design capacities compared to 0.612 to 4.45 Mt/yr for the plants with WHR. Only three of the plants had clinker capacities greater than 1.0 Mt/yr, compared to five of the six plants with WHR, and two of these plants with WHR had design capacities greater than 4.0 Mt/yr.

Given the relatively small size of the plants in the group without WHR, the relatively higher raw material moisture content for these plants (Figure 6), the use of clinker cooler exhaust for raw material drying by five of the plants, and the reported preheater and cooler exhaust temperatures of 285°C to 350°C for this group (the six plants had a combined total of seven clinker lines: four with five preheater stages and three with four preheater stages), the feasibility analysis was based on application of organic Rankine cycle (ORC) WHR. As discussed in Annex A, there is overlap between application of SRC and ORC systems when the exhaust temperatures are between 300 and 350°C and WHR system capacities are between 4 and 10 MW. While selection of the appropriate WHR system in this range can be affected by a variety of site conditions and requires a direct comparison of cost, performance, and benefits based on expected plant operation, ORC technology was selected as the appropriate option for the feasibility analysis given that five of the six plants would utilize systems below 6 MW.

ORC WHR Is Economically Viable in the Turkish Cement Industry

A Base Case technical feasibility and financial analysis was conducted for each plant based on their reported operating data for 2015, including information on kiln utilization and operation, exhaust temperatures and flows from the preheaters and clinker coolers, and the amount of heat used for drying raw material and fuel. ORC WHR systems were sized for each plant based on the preheater and clinker cooler exhaust conditions, and the technical and financial feasibility was estimated based on typical cost and performance assumptions for ORC systems applied to cement plants. The basic assumptions used for the feasibility analysis are detailed in Annex C. Chapter 4 includes a sensitivity analysis on key factors impacting project economics, including WHR system utilization rates, kiln operating hours, total investment cost, grid electricity prices, currency exchange rates, WHR O&M costs, and WHR auxiliary power requirements.

The Base Case scenario is based on the maximum planned kiln operating hours in a given year as reported by the plants, and does not account for potential variability in the amount of heat available throughout the year due to variations in moisture content or kiln operation. The model further assumes that all heat at the exit of preheater and cooler is available for WHR, and the design is based on a highly efficient integration with the plant, absence of leaks, and the utilization of exhaust heat for drying materials only after the WHR, which may not always be the case. Table 4 presents the key plant parameters, estimated WHR design sizing, and financial modeling results of the Base Case analysis. The ORC design capacities are estimated based on average temperature and flowrate data provided by the companies, although for appropriate sizing a precise metering of the exhaust streams for an extended period is needed.

TABLE 4. BASE CASE RESULTS								
	Clinker Kiln Capacity, Mt/yr	**Maximum Kiln Operation, hrs/yr**	**Preheater Exhaust Used for Drying?**	**Cooler Exhaust Used for Drying?**	**WHR Capacity, kW**	**IRR, %**	**Payback*, years**	**Cost of Generated Electricity**, USD/MWh**
Plant 7	>1.0 < 2.0	8,300	Yes	Yes	5,460	24%	4.8	20.3
Plant 8	<1.0	7,920	Yes	Yes	2,150	12%	8.7	33.8
Plant 9	<1.0	8,592	Yes	No	4,150	19%	6.1	25.2
Plant 10	1.0 to 2.0	8,000	Yes	Yes	5,790	23%	5.0	21.0
Plant 11	<1.0	8,000	Yes	No	4,230	17%	6.6	27.1
Plant 12	1.0 to 2.0	8,000	Yes	Yes	6,000	23%	5.0	21.0

** Simple Paybacks based on a five-year average (2016–2020) of displaced electricity costs.*

*** Cost of Generated Electricity including both operating expenses and the 20 year Net Present Value of capital expense.*

Figure 19 shows the Base Case WHR design capacities are within the international practice standard of 25 to 45 kWh/t clinker. In the Base Case, WHR systems provide from 13 to 58 percent of the total electricity use depending on WHR system size and the extent of finish grinding at each plant, resulting in an estimated savings of 11 to 50 percent of annual electricity charges. (The higher-end estimates on percent of total electricity use and percent of electric bill savings are from Plant 11 in Figure 19, which is the outlier in the survey data provided. Without Plant 11 the higher ends are 30% and 27%, respectively). While ORCs are only beginning to be applied in the cement industry, they are extensively used worldwide in geothermal applications and in biomass heat recovery in Europe, and their capital and maintenance costs are relatively well understood. Total investment costs used in the feasibility analysis range from 2,500 USD/kW for the largest system of 6.0 MW to 3,800 USD/kW for the smallest system of 2.2 MW. The estimated cost of electricity produced from the WHR systems varies between 21 and 34 USD/MWh compared to an assumed cost of grid electricity of 78 USD/MWh[32]. This results in a reduction in electricity costs of 1.3 to 8.0 USD/t clinker. (The range is $1.30 to $2.60 per ton of clinker when outlier Plant 11 is excluded.)

FIGURE 19 – ESTIMATED WHR DESIGN CAPACITY VS CLINKER DESIGN CAPACITY

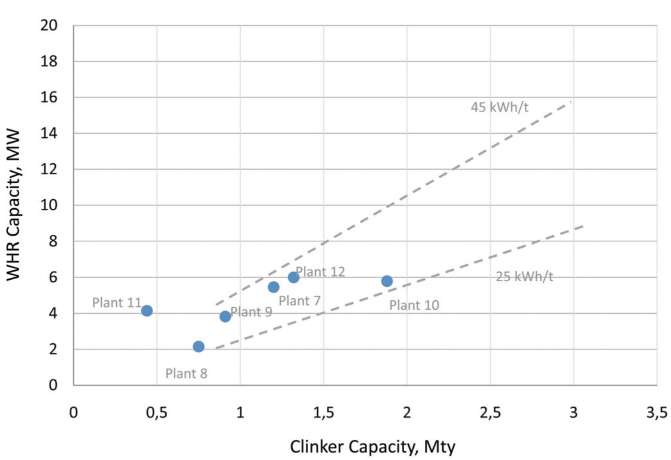


Figure 20 shows the estimated simple payback periods [33]from the analysis as a function of WHR design capacity. As shown, the payback periods are driven largely by the range in the total installed costs of the system used in the analysis, which is a strong function of system size. Payback periods range from 4.8 years for a 5.5-MW system to just under nine years for the smallest system (2.2 MW). Payback periods for systems in the 4 to 6 MW range were estimated at 5 to 7 years. Estimated IRRs ranged from 12 percent for the smallest system to 24 percent for systems larger than 5.5 MW as shown in Figure 21.

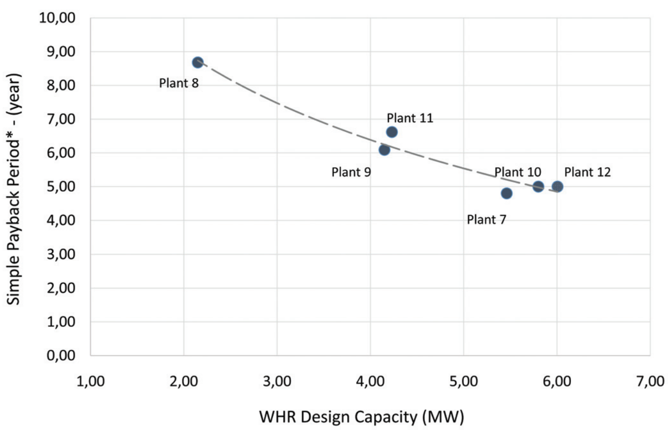
The Turkish Cement Industry Still Has 125 to 230 MW of Feasible WHR Potential

By the end of 2017, the Turkish cement industry has 54 active integrated cement plants with a total of 83.6 Mt/yr of clinker production capacity. An additional three

[32] The cost of electricity values of 21 to 34 USD/MWh include operating costs and the 20-year net present value of capex expenses. The Base Case estimated costs of electricity based on WHR operating costs only range from 7 to 17 USD/MWh.

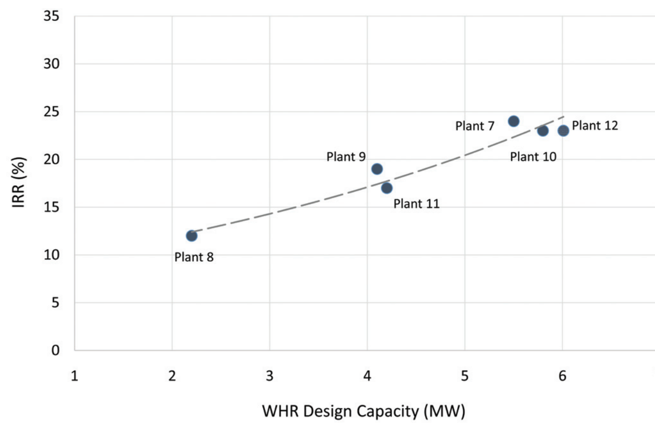
[33] Simple paybacks are based on a five-year average (2016 – 2020) of displaced electricity costs

FIGURE 20. ESTIMATED PAYBACK



*Payback based on five-year average (2012-2016) of displaced electricity costs

FIGURE 21. ESTIMATED PROJECT IRRS



integrated plants are under construction with total 5.5 Mt/yr of clinker capacity, and an existing plant is expanding with an additional 1.0 Mt/yr of clinker capacity. Average clinker capacity of the 54 plants is 1.55 Mt/yr. The smallest plant has a clinker capacity of 0.43 Mt/yr, with the largest at 4.45 Mt/yr, and 15 of the plants have capacities below 1.0 Mt/yr. Fourteen of the plants ranging in size from 0.68 to 4.45 Mt/y have already installed, or are in the process of installing, a total 130 MW of steam-cycle WHR capacity, representing 30.6 Mt/yr, or 40 percent, of total existing clinker capacity. While successful application of WHR depends on a variety of site-specific parameters, the review of existing WHR systems and the feasibility analysis of plants currently without WHR indicate that WHR is technically, and potentially economically, applicable to plants with more than 1 Mt/yr clinker capacity, adding up to 125 to 250 MW of remaining WHR potential (25 plants, 43 Mt/yr clinker capacity).

The analysis also verified that the existing industry standard of WHR producing between 25 and 45 kWh/t of clinker is broadly applicable to the Turkish cement industry. Applying this standard to the 39 clinker plants that have not implanted WHR results in an estimate of additional WHR potential ranging from 158 to 283 MW, with the corresponding range of investment potential totalling $450 million to $630 million, as shown in Table 5 below.

The largest potential market, in terms of total remaining WHR capacity of 88 to 158 MW (250 to 350 million USD), is in the 20 plants with clinker capacities of 1.0 to 1.99 Mt/yr. These plants could support WHR systems of 5 to 7 MW capacity. While, as noted throughout this report, project economics are driven by a number of site-specific factor such as number of preheater stages, raw material drying requirements and number of individual kiln lines, systems of this size had estimated simple payback periods of around 5 years in the feasibility analysis. Both SRC and ORC WHR systems could be applied in this size range depending on plant specific parameters. The estimates of potential investment in this capacity range are based on a mix of 50 percent ORC and 50 percent SRC capital costs. The five plants with clinker capacities greater than 2.0 Mt/yr represent a potential market of 41 to 73 MW (90

TABLE 5. REMAINING TECHNICAL POTENTIAL FOR WHR IN TURKISH CEMENT INDUSTRY

Plant Clinker Capacity, Mt/yr	Number of Plants	Total Clinker Capacity (Mt/yr)	Potential Capacity @ 25 kWh/t (MW)	Potential Investment @ 25 kWh/t (Million $)	Potential Capacity @ 45 kWh/t (MW)	Potential Investment @ 45 kWh/t (Million $)
<0.99	14	9.88	29.4 MW	$111.5	52.9 MW	$167.2
1.0 – 1.99	20	29.41	87.5 MW	$247.7	157.6 MW	$349.0
>2.0	5	13.60	40.5 MW	$89.7	72.9 MW	$116.6
	39	52.89	157.4 MW	$448.8	283.3 MW	$632.8

to 115 million USD). This is a particularly significant market because of the more compelling project economics of larger WHR systems. These plants could support WHR systems in a range of 7 to 15 MWs. WHR systems of this size would have expected payback periods of 4 years or less due to economies of scale and the ability to utilize SRC technology. The estimates of potential investment for this capacity range are based on SRC system costs.

4. Key Factors Impacting WHR Feasibility

WHR Project Economics Are Driven by Factors that Impact the Amount of WHR Power Generated and Affect Project Costs

As described in Chapter 3, a technical feasibility and financial analysis was conducted for each plant, with Base Case performance based on reported operating data for 2015. ORC WHR systems were sized for the analysis based on preheater and clinker cooler exhaust conditions, and financial feasibility was estimated based on typical cost and performance assumptions for ORC systems. A series of analyses were then performed to assess the financial sensitivity of WHR projects to variations in key plant and system operating and financial parameters, as described in Table 6. Detailed assumptions used in the sensitivity analysis are presented in Annex C.

Figure 22 presents the results of the sensitivity analysis on project paybacks for a single plant (Plant 10), but are representative of the results for the entire survey group. As shown, WHR capacity utilization and kiln operating hours have the greatest impact on project economics as these factors drive the amount of electricity produced by the WHR system. Cost factors such as WHR capital expenses, displaced electricity prices, and variations in currency exchange rates also have significant impact on project financial performance. Reasonable variations in WHR operating and maintenance costs and in WHR auxiliary power requirements have more modest impact on project performance.

Specific details on each of the sensitivity factors are presented below in order of greatest to least impact on project financial performance:

TABLE 6. DESCRIPTION OF FINANCIAL ANALYSIS SCENARIOS FOR ORC WHR

Scenario	Description
Base Case	Operations as per maximum planned operating hours of cement plant in given year at 100% WHR capacity utilization, with heat used for drying limiting available heat for WHR as per typical drying practice and as reported by each plant.
1	WHR Capacity Utilization: -30% / +5%
2	Clinker Kiln Operating Hours: 6034 hours, 8595 hours
3	Total Capital Cost: -10% / +20%
4	Electricity Prices: +10% / -10%
5	TL/$ Exchange Rate: -10% / +10%
6	WHR O&M Expenses: -130% / +30%
7	WHR Auxiliary Power: 8%, 10% (base case), 12%

WHR Capacity Utilization Is a Key Determinant of Power Generated and Project Economics

Variations in WHR capacity utilization have the most significant impact on WHR project economics, as Figure 23 shows. WHR system capacity utilization can be affected by a number of factors including: (i) changes in kiln operations, (ii) variations in raw material and fuel moisture that reduce available heat to the WHR system, (iii) extended downtime on the WHR system itself due to operational issues, (iv) oversizing the WHR system in the initial system design, (v) less production in different terms depending on sales.

FIGURE 22. SENSITIVITY ANALYSIS ON WHR PROJECT PAYBACKS

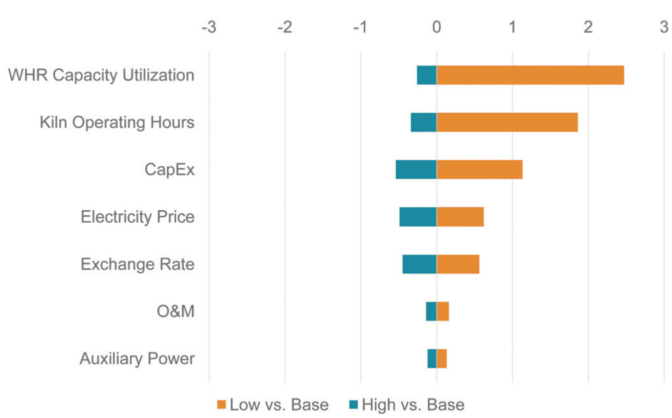


FIGURE 23. IMPACT OF WHR CAPACITY UTILIZATION RATES ON PROJECT PAYBACK

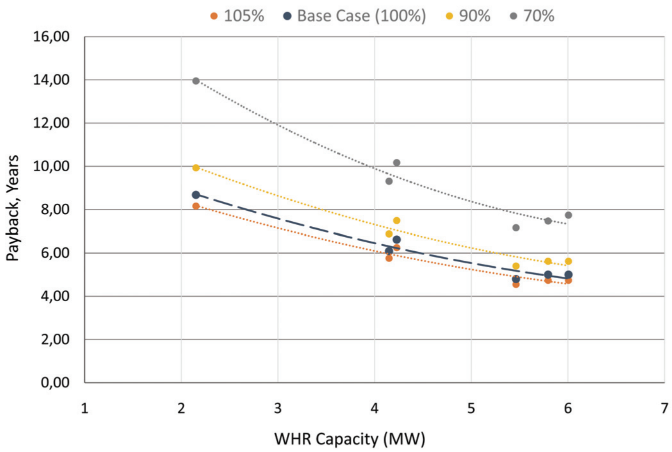


FIGURE 24. IMPACT OF KILN OPERATING HOURS ON PROJECT PAYBACK

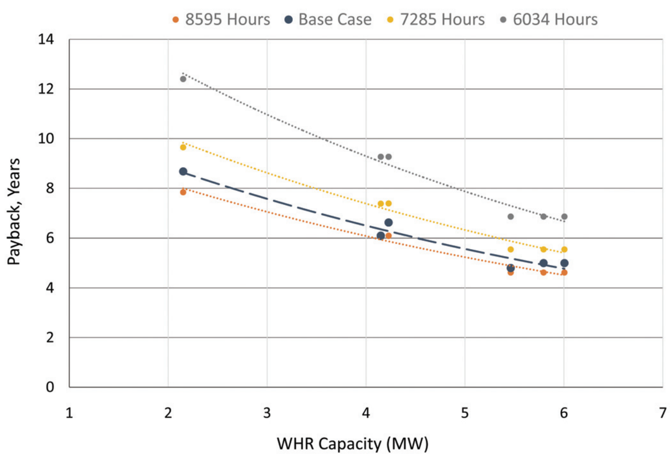
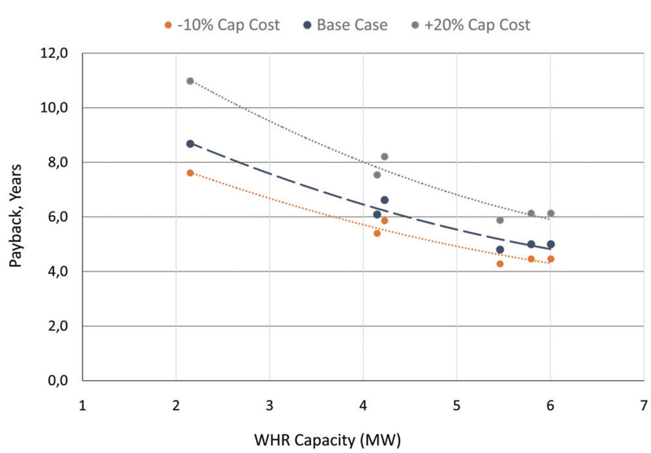


FIGURE 25 – IMPACT OF CAPEX ON PROJECT PAYBACK



A WHR capacity utilization of 70 percent (the Base Case is 100 percent) increases paybacks by 5.3 years for the smallest WHR system and 2.4 years for systems greater than 5 MW. A WHR capacity utilization of 105 percent, which could represent increased kiln operating hours or additional waste heat availability, improves Base Case paybacks by 0.25 to 0.5 years.

Kiln Operating Hours also Drive WHR Project Performance

Similar to WHR utilization, kiln operating hours also have a significant impact on WHR project economics, as shown in Figure 24. The Base Case kiln operating hours were the maximum operating hours reported by each plant and ranged from 7,902 to 8,592 hours per year. Applying 6,034 annual kiln operating hours to each plant (this is the lowest actual operating hours for 2015 reported in the survey) increases paybacks by 3.7 years for the smallest WHR system and by 1.6 years for the largest. Conversely, applying 8,595 annual kiln operating hours (close to the maximum annual hours achievable, considering required downtime for annual maintenance on the kiln) shows a decrease in payback by up to 0.8 years.

Not surprisingly, WHR Capital Cost (CapEx) Has Significant Impact on Project Economics

Variations in the total investment cost of WHR systems also have a substantial impact on project economics, and differences in actual project capital costs from industry averages are commonplace due site-specific conditions and site limitations that can subtract, or more often, add to, projected investment costs. Figure 25 shows the effect of variations in total project capital costs (equipment and installation/construction costs) on financial performance. A 10 percent decrease in total investment costs from the Base Case decreases paybacks from 0.5 to 1.0 years. A 20 percent increase in total investment cost increases paybacks by 2.3 years for the smallest WHR system and 1.1 year for the largest. It should be noted that capex can vary significantly depending on the technology provider used, which may have a direct impact on the payback periods and overall feasibility of the project.

Displaced Electricity Prices Drive Project Savings

Figure 26 shows the sensitivity of project paybacks to a +/- 10 percent variation in electricity prices over the Base Case projection. A 10 percent decrease in price results in an increase in project paybacks by 0.62 years for the largest system and 1.25 for the smallest. A 10 percent increase in price results in a decrease in project paybacks ranging from 0.49 years for the largest system to 0.97 for the smallest. WHR provides costs savings for cement plants by replacing electricity purchases from the grid with an upfront capital investment and modest ongoing O&M costs for the WHR system. As such, the price of grid electricity, and the price outlook into the future, has significant impact on net savings and WHR project economics. The cost of electricity paid by cement plants in each year was assumed

FIGURE 26. IMPACT OF ELECTRICITY PRICES ON PROJECT PAYBACK

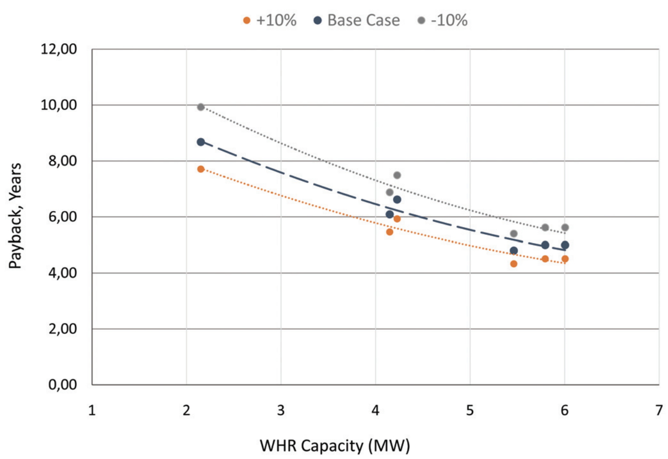
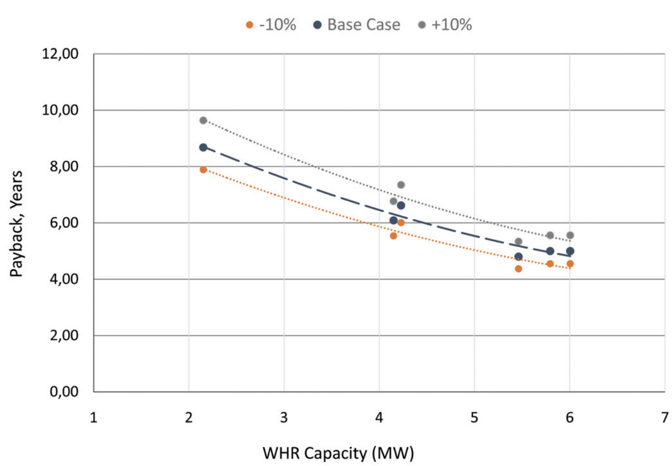


FIGURE 27. IMPACT OF CURRENCY EXCHANGE RATES ON PROJECT PAYBACK



at the level of yearly average wholesale market prices in Turkey during that year, including fees for transmission, distribution, and renewable energy support. The Base Case assumes a 2018 price for electricity to industrial users of 0.289 TL/kWh (0.078 USD/kWh at the Base Case exchange rate). The rate of increase for the out-years is based on forecasts developed in Mercados Market Report, March 2017. Mercados' price forecast is influenced by assumptions on fuel price outlook, planned capacity additions, attractiveness of new investments, future carbon prices, growing demand, decreasing efficiency gains in new thermal power plants over time, and decreasing costs of renewable power. The forecast projects substantial price increases in the near term (through 2020) due to rising oil prices and depreciation of existing natural gas power plants. Current over-capacity ends in 2021 as a tighter demand-supply balance is reached due to strong market fundamentals, and new capacity is needed. The forecast projects the industrial electricity rate to increase at an average annual rate of 9.4 percent between 2018 and 2023, reaching a price of 0.447 TL/kWh (0.103 $/kWh at the Base Case exchange rate) in 2023. Prices continue to increase more gradually from 2023 onward (average annual rate of 1.9 percent between 2024 and 2040) due to forecasts of gradually increasing global oil prices and gradually increasing carbon costs starting in 2025.

Variations in Currency Exchange Rates Affect Project Costs

Since the leading suppliers of ORC WHR systems are foreign entities, volatility in the currency exchange rate between the Turkish lira and U.S. dollar creates uncertainty in the financial evaluation of potential WHR projects. Empirical studies have also shown a negative relation between exchange rate volatility and plant level investment, particularly for industries with significant export exposure. The Turkish lira experienced a significant depreciation against hard currencies over the past two years. The exchange rate has ranged from 2.335 TL/$ in January 2015 to 3.779 TL/$ in February 2017. The Base Case assumption for the financial analysis is 3.698 TL/$ for 2018. Forecasted values of the exchange rate are based on estimates by the Economist Intelligence Unit, accessed on July 21, 2017. The forecast projects the exchange rate increasing at an average annual rate of 3.2 percent for the first five years of the forecast, and then ramping down over the long term to a 2.0 percent annual increase in 2040. Figure 27 shows the sensitivity of project paybacks to a +/-10 percent variation in exchange rate over the Base Case. A 10 percent increase in the exchange rate, to 4.068 TL/$, results in an increase in project paybacks from 0.54 years for the larger systems to 0.96 for the smallest. A 10 percent decrease in the exchange rate, to 3.328 TL/$, results in a decrease in project paybacks ranging from 0.43 years for the larger system to 0.79 for the smallest.

Variations in O&M Costs (Opex) Have Only a Modest Impact on Financial Performance

Because WHR generates power by recovering heat normally wasted in the cement plant and does not rely on any additional fuel consumption, the only costs for operating the WHR system are the operating and maintenance (O&M) costs related to ongoing system maintenance, day-to-day monitoring and control, and servicing. WHR O&M includes daily, monthly, and annual equipment inspection and adjustments, periodic preventive maintenance and refurbishment, and restoration and repair from unplanned equipment failures, as well as daily control and monitoring of system performance. O&M costs can vary based on whether services are provided by a third party or by in-house staff. The Base Case assumed annual O&M costs at 3 percent of system investment cost for systems of 2-3 MW capacity, 2.5 percent for systems of 3-5 MW capacity, and 2.0 percent for systems of > 5 MW. Figure 28 shows the relatively modest impact of +/- 30 percent variations in these Base Case levels, with paybacks decreasing or increasing from 0.15 to 0.7 years depending on WHR system capacities.

Reasonable Variations in Auxiliary Power Requirements Have Minimal Impact on Project Performance

WHR systems have significant auxiliary power requirements to operate the controls, pumps, blowers, and cooling towers necessary for system operation. Auxiliary power requirements typically range from 8 to 12 percent of gross generation depending on system configuration and whether condensers are air cooled or water cooled. The Base Case assumption was 10 percent. Figure 29 shows the relatively modest impact of variations in auxiliary power consumption of 8 percent and 12 percent of gross generation, with paybacks decreasing or increasing from 0.1 to 0.25 years depending on WHR system capacities.

Subsidies and Financing Mechanisms May Improve Feasibility for WHR Investments

All the financial analysis in the report has been done assuming no incentives are used in the project cycle. However, there are many incentives that can be considered which may substantially improve the feasibility of a WHR investment. In this section a specific incentive has been analyzed in detail. Further information regarding other incentives and financing mechanisms is provided in Annex C.

On May 9, 2014, the 2014/6058 Decision in the 28995 Number Official Gazette further clarified that energy efficiency and waste heat recovery investments are added

FIGURE 28. IMPACT OF O&M COSTS ON PROJECT PAYBACK

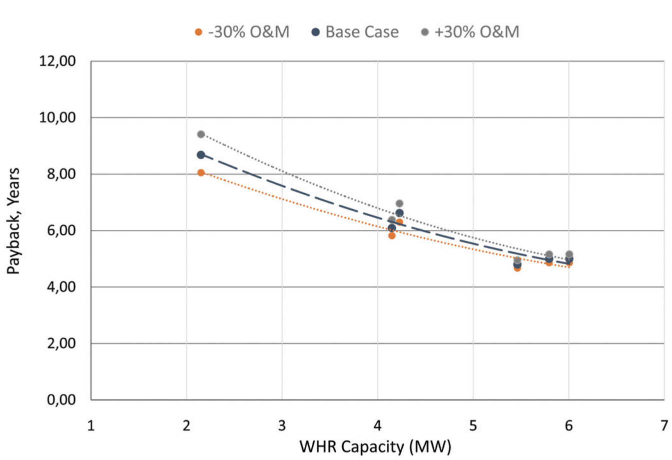


FIGURE 29. IMPACT OF AUXILIARY POWER REQUIREMENTS ON PROJECT PAYBACK

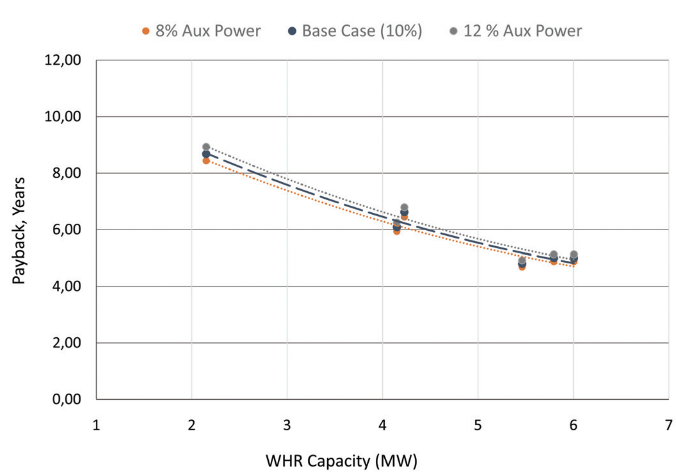


TABLE 7. INCENTIVES AND STATE GRANTS IN INVESTMENTS SCHEME

Regional Investment Incentives Scheme Instruments									
Incentive Instruments				Region					
				I	II	III	IV	V	VI
VAT Exemption				YES					
Customs Duty Exemption				YES					
Tax Reduction	Tax Reduction Rate (%)			50	55	60	70	80	90
	Reduced Tax Rate (%)			10	9	8	6	4	2
Rate of Contribution to Investment (%)	Out of OIZ*			15	20	25	30	40	50
	Within OIZ*			20	25	30	40	50	55
Social Security Premium Support (Employer's Share	Support Period	Out of OIZ*		2 years	3 years	5 years	6 years	7 years	10 years
		Within OIZ*		3 years	5 years	6 years	7 years	10 years	12 years
		Upper Limit for Support (%)	Out of OIZ*	10	15	20	25	35	No limit
			Within OIZ*	15	20	25	35	No limit	No limit
Land Allocation				YES					
Interest Rate Support	TRY Denominated Loans (points)			N/A	N/A	3 points	4 points	5 points	7 points
	FX Loans (points)					1 point	1 point	2 points	2 points
Social Security Premium Support (Employee's Share)				N/A	N/A	N/A	N/A	N/A	10 years
Income Tax Withholding Allowance				N/A	N/A	N/A	N/A	N/A	10 years

Source: Investment Support and Promotion Agency Turkey.

** OIZ: Organized Industrial Zone.*

to the top priority list, and all priority investments will be supported with "5th region" incentives (independent of location) under the Ministry of Economy's "Incentives and State Grants in Investments Scheme." Under this scheme, the investor does not pay value-added tax (VAT) for the WHR equipment; the investor will not pay customs tax for imported equipment; the social security premiums for WHR operating staff is supported by the ministry; the ministry will cover five percentage points of bank loan interest in the first year; and the tax is reduced during the investment period by up to 40 percent of the total WHR investment (and by up to 50 percent in an organized industrial zone).

As shown in the example above, for a theoretical 40 million TL WHR investment and total investment incentive certificate period of two years, a cement company can save up to 16 million TL on taxes, with the exact amount depending on the company's income. The maximum benefit limit here is the cap of 40 percent of investment (or 50 percent if plant is located in an OIZ). The same plant can at the same time benefit from interest rate support if the loan is taken for investment and other relevant items, as presented in Table 7.

Example (1): Interest rate support

Principal = 1 million TL

Interest Rate = 15%

First Payment is 180 days later

Interest = (Principal * Int. Rate * Days) / (days in year)

= 1,000,000 * 0.15 * 180 / 360

= 75,000 TL is the interest cost

With incentive:

= 1,000,000 * 0.05 * 180 / 360

= 25,000 TL will be paid by ministry

Example (2): Tax reduction

Total WHR Investment = 40 million TL

Assuming company EBITDA of 50 million TL

And annual tax (20%) payment of 10 million TL

Incentives will lead to a reduced tax of (4%) = 2,000,000 TL

The difference of 8 million TL is called deferred tax and it will not be paid until reaching the amount of contribution cost (40% of investment cost), which makes 16 million TL total, during investment period.

Annex A – Waste Heat Recovery Technologies

Introduction

Waste heat recovery for power (WHR) is the process of capturing heat discarded by an industrial process or prime mover and using that heat to generate electricity. Energy-intensive industrial processes – such as those in refineries, steel mills, glass furnaces, and cement kilns – all release hot waste streams that can be harnessed with well-established technologies to generate power. To be effective, WHR must have a source of waste heat that is of sufficiently high temperature for the waste heat recovery system to be both thermodynamically and economically feasible. In addition, the best sources of waste heat for bottoming cycles are high-volume and high-load factor so that the power generation equipment can operate with economies of scale and the capital cost can be offset by nearly constant output throughout the year. The key advantage of waste heat recovery systems is that they utilize heat that would otherwise be wasted from an existing thermal process to produce power, as opposed to directly consuming additional fuel, displacing higher-priced purchased electricity for the user, and reducing overall energy use and emissions.

At the project level, a number of factors in addition to the temperature of the waste heat must be considered to determine the feasibility of power generation from waste heat sources. While many high-temperature waste heat sources are straightforward to capture and use with existing technologies, other sources are filled with contaminants and can be expensive to recover because the waste streams must be cleaned prior to use. Not only can the cleaning process be expensive, but removing contaminants prior to use often removes heat at the same time. Other waste heat sources are difficult to recover because of equipment configuration or operational issues. Along with temperature, a project developer would need to consider a number of questions about the candidate waste heat source:

- What is the availability of the waste heat – is it continuous, cyclical, or intermittent?
- What is the load factor of the waste heat source – are the annual operating hours sufficient to amortize the capital costs of the WHR system?
- Does the temperature of the waste stream vary over time?
- What is the flow rate of the waste stream and does it vary?
- Is the waste stream at a positive or negative pressure, and does this vary?
- What is the composition of the waste stream?
- Are there contaminants that may corrode or erode the heat recovery equipment?
- Is there space available in or close to the waste heat stream for recovery and generation equipment?

The answers to these questions affect technology choice, system design and, ultimately, the economic viability of the waste heat recovery application. This Annex describes the basic requirements of heat engine systems to produce power in the context of utilizing industrial waste heat streams, and provides details on two commonly used technologies for producing power from waste heat.

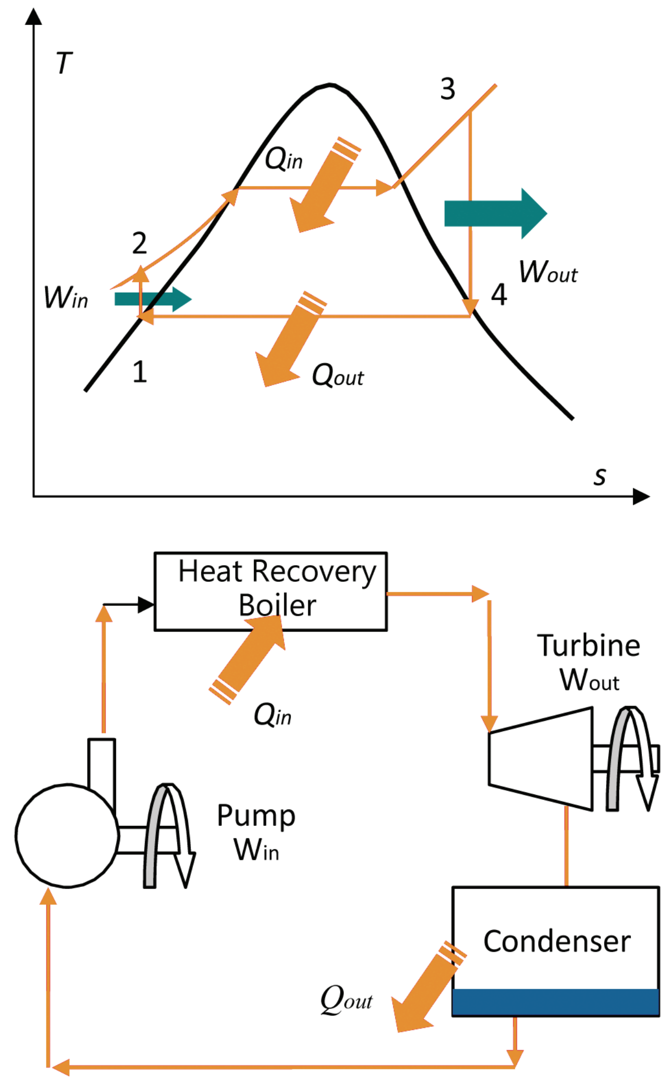
Rankine Cycle

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle[34]. In a Rankine cycle, heat is supplied externally to a fluid in a closed loop. Water is the most commonly used fluid – steam turbines found in thermal power generation plants produce most of the electricity in the world, including power from coal, biomass, solar thermal, and nuclear energy. However, systems using other fluids or combinations of fluids have been developed that have advantages over water in certain WHR applications.

In a heat recovery Rankine cycle, a working fluid in the liquid state is first pumped to elevated pressure before entering a heat recovery boiler (as illustrated in Figure

[34] The Rankine cycle, named after William John Macquorn Rankine, is a thermodynamic cycle that converts heat into mechanical work.

FIGURE A-1. RANKINE CYCLE HEAT ENGINE



A-1). The pressurized fluid is vaporized by the hot exhaust, and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low-pressure working fluid is then exhausted to a condenser at vacuum conditions where heat is removed by condensing the vapor back into a liquid. The condensate from the condenser is then returned to the pump for continuation of the cycle.

By condensing the working fluid to a liquid, the work required by the pump consumes only 1 to 3 percent of the turbine power and contributes to a higher cycle efficiency[35]. However, the range between the heat source and heat sink temperatures is typically much lower than for an open cycle combustion turbine, limiting both theoretical and practical efficiencies of the Rankine cycle. In addition, as a result of irreversibility in various components such as fluid friction and heat loss to the surroundings, the compression by the pump and the expansion in the turbine are not isentropic, somewhat increasing the power required by the pump and decreasing the power generated by the turbine, and the actual cycle efficiency deviates from the ideal Rankine cycle efficiency. For WHR applications, the achievable Rankine cycle efficiency typically ranges from 30 to 50 percent of the Carnot efficiency. Commercially available waste heat recovery Rankine cycles are based on steam or an organic compound as the working fluid[36].

Steam Rankine Cycle (SRC)

Steam Rankine cycles are the most common waste heat recovery systems in operation in cement plants and have the following attributes:

[35] One of the principal advantages of the Rankine cycle compared to other thermodynamic cycles is that during the compression stage relatively little work is required to drive the pump, since the working fluid is in the liquid (nearly incompressible) phase. The energy required for raising the pressure of the fluid is a function of the change in volume; therefore, raising the pressure of a compressible gas as is required in a combustion turbine (Brayton Cycle) requires much more energy than raising the pressure of an incompressible liquid.

[36] A third type of Rankine cycle is based on a mixture of water and ammonia and is called the Kalina cycle. Application of the Kalina cycle to the cement industry is still in the demonstration phase.

TABLE A-1. STAGES OF THE RANKINE CYCLE

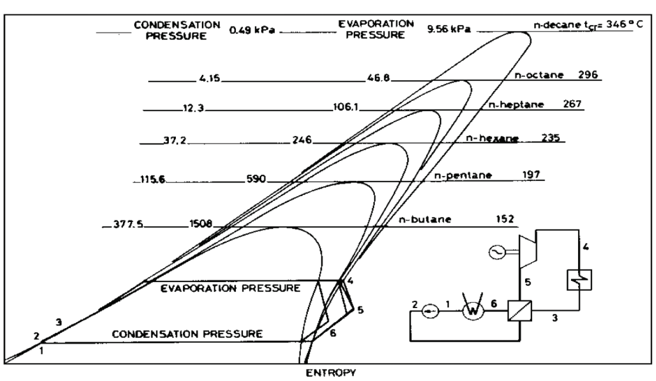
1-2:	Isentropic compression (pumping)	The working fluid enters the pump as saturated liquid (state 1) and is compressed isentropically to the operating pressure of the boiler (state 2)
2-3:	Constant pressure heat addition	Saturated liquid (state 2) enters the boiler and leaves it as superheated vapor (state 3)
3-4:	Isentropic expansion (turbine generator)	Superheated vapor expands isentropically in a turbine and produces work, and exits the turbine as low-pressure, lower-temperature saturated vapor (state 3 to state 4)
4-1:	Constant pressure heat rejection	Low-pressure steam (state 4) is condensed in the condenser to a saturated liquid (state 1)

- Most familiar to the cement industry and are generally economically preferable where source heat temperature exceeds 350°C.
- Based on proven technologies and generally simple to operate.
- Widely available from a variety of suppliers.
- Generally have lower installation costs than other Rankine cycle systems on a specific cost basis ($/kW).
- Need higher-temperature waste heat to operate optimally (minimum 260°C); generation efficiencies fall significantly at lower temperatures, and steam conditions with lower pressure and temperature can result in partially condensed steam exiting the turbine, causing blade erosion.
- Usually require a full-time operator, depending on local regulations.
- Require feedwater conditioning systems.
- Generally require a water-cooled condenser; air-cooled condensers can be used but create a performance penalty due to higher condenser vacuum pressures.
- In general, match well with large kilns and systems with low raw-material water content (resulting in higher exhaust gas temperatures).

Organic Rankine Cycle (ORC)

Organic compounds with better generation efficiencies at lower heat-source temperatures are used as the working fluid in organic Rankine cycle (ORC) systems. The most widely used organic fluids are hydrocarbons (such as pentane), siloxanes (employed also in cosmetic products), and refrigerants (more common in HVAC systems and refrigeration). In Figure A-2, saturation curves for several organic fluids are shown: as the shape of curves suggest,

FIGURE A-2. SATURATION CURVES FOR SEVERAL ORGANIC FLUIDS



Source: Turboden.

if compared to water, organic fluids do not need to be superheated to avoid condensation in the turbine during expanding stage; moreover, the organic fluids have higher molecular weight, lower boiling point, and higher vapor pressure than water. All these features lead to some key technical advantages compared to conventional steam cycles in certain applications:

- Higher turbine efficiency.
- Low mechanical stress on the turbine (low tip speed, moderate temperature).
- No blade erosion (no liquid particles during expansion, due to the shape of saturation curve).
- No oxidation (some organic fluids can even be considered as lubricants themselves).
- Higher efficiency with low and moderate temperature sources (for example, 24% with a 300°C heat source).

ORC systems can be utilized for waste heat sources as low as 150°C, whereas steam systems are limited to heat sources greater than 260°C[37]. The ORC systems are typically designed with two heat transfer stages. The first stage transfers heat from the waste gases to an intermediate heat transfer fluid (such as thermal transfer oil). The second stage transfers heat from the intermediate heat transfer fluid to the organic working fluid. The ORCs have commonly been used to generate power in geothermal power plants, and more recently, in pipeline compressor heat recovery applications. ORC systems have been widely used to generate power from biomass systems in Europe. A growing number of ORC systems have been installed on cement kilns[38].

The actual configuration of ORC systems can be different depending on the specific application and site conditions, such as type of heat source, demand for low temperature heat, availability of water, space constraints. Usually, when the primary heat sources are hot, and dusty combustion

[37] Low-pressure, low-temperature steam produced from lower temperature heat sources will partially condense in the last stages of the steam turbine, resulting in low efficiency and potential blade erosion.

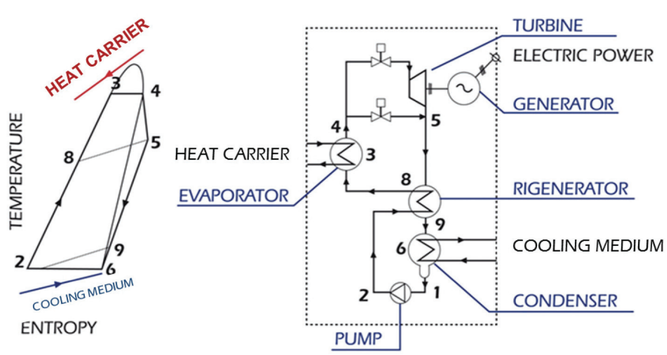
[38] Two ORC systems began operating in the late 1990s in cement plants: a 1.2 MW system installed in 1999 at the Heidelberg Cement plant at Lengfurt, Germany, recovers heat from the clinker cooler vent air; the second ORC system is a 4.8 MW unit located at AP Cement (now Ultra Tech Cement), Tadipatri, Andhra Pradesh, India. ORC system (2 MW) at Italcementi's Ait Baha plant in Morocco in 2010 (5,000 tpd clinker line). In 2012, 4 MW unit at a Holcim Romani plant in Alesd (4,000 tpd clinker line); Holcim Slovakia (5 MW at 3,600 tpd line at the Rohoznik plant) and an undisclosed North American plant (7 MW). Holcim is installing another 4.7 MW ORC system at its Mississauga, Canada plant from an undisclosed provider. Jura cement 2.0 MW ORC system at the Wildegg AG plant in Switzerland.

gases and cooling water are available, the heat recovery systems consist essentially of a primary heat exchanger (the ORC unit) and a cooling system for dissipating heat of condensation downstream (the ORC turbo-generator). As mentioned earlier, the primary heat exchanger transfers the waste heat from the exhaust gas to the ORC unit by means of a heat carrier (typically thermal oil, pressurized water, or saturated steam). This is one of the main differences with conventional steam Rankine cycles – while the waste heat recovery boiler evaporates steam directly using the heat of the exhaust, in ORC systems the heat is transferred from the waste heat recovery units through a heat carrier, which is heated by the hot exhaust, and transfers the heat to the organic fluid in the closed-loop ORC.

The ORC unit converts the incoming thermal energy into electricity and heat at relatively low temperature. The heat discharged from the power cycle during condensation is then released to the environment by means of an intermediate water circuit (or mixture of water and glycol to prevent freezing in winter). The dissipation of this heat can be in the form of a dedicated system: this can be either a dry system, with air-coolers, or a wet system with evaporative cooling towers. As an alternative, direct condensation of the working fluid through an Air Cooled Condenser (ACC) is often preferable, for both operational and technical reasons – first, avoiding one heat transfer passage increases the overall efficiency of the system; and second, an ACC does not require any water supply and/or water treatment.

Figure A-3 shows a simplified scheme for a typical waste heat recovery ORC system. Following the cycle schematic, the working fluid is first pre-heated (7-3) and evaporates (3-4) by means of the heat carried in the intermediate heat

FIGURE A-3. TYPICAL ORC SCHEME AND THERMODYNAMIC CYCLE



transfer fluid (thermal oil, hot water, or steam), and then expands in a turbine (4-5), which is usually directly coupled to the generator. Condensation (8-1) is performed by a cooling medium (air or water) after the regenerator. The cycle is closed when liquid from the condenser is pumped (1-2) to reach the evaporation pressure. An internal heat exchanger (the "regenerator") is placed downstream of the turbine in order to achieve higher efficiency (5-8, 2-7).

Specific features impacting ORCs in cement industry applications include the following:

- Simple start-stop procedures, with quiet running as well as automatic and unattended operation.
- High availability (about 98%).
- High flexibility (good efficiency at partial load, with possible operation as low as 10% or less of nominal power).
- Long life and reduced O&M requirements.
- Can recover heat from gases at lower temperatures than is possible with conventional steam systems, enabling ORCs to utilize all recoverable heat from the air cooler.
- Operate with condensing systems above atmospheric pressure, reducing risk of air leakage into the system and eliminating the need for a de-aerator.
- Not susceptible to freezing.
- Because ORCs operate at relatively low pressure, they can operate unattended and fully automated in many locations depending on local regulations.
- Can utilize air-cooled condensers without negatively impacting performance.
- Lower-speed (rpm) ORC turbine allows generator direct drive without the need for and inefficiency of a reduction gear.
- ORC equipment (turbines, piping, condensers, heat exchanger surface) is typically smaller than that required for steam systems, and the turbine generally consists of fewer stages.
- Although ORCs can provide generation efficiencies comparable to a steam Rankine system, ORCs are typically applied to lower temperature exhaust streams, and limited in sizing and scalability, and generally are smaller in capacity than steam systems.
- Depending on the application, ORC systems often have a higher specific cost ($/kW) than steam systems
- The two-stage heat transfer process creates some system inefficiencies.

- The heat transfer fluids and organic fluids normally used in ORCs are combustible, requiring fire protection measures and periodic replacement over time. Also, there may be environmental concerns over potential system leaks.
- In general, ORC systems are well-matched with small- to medium-size, high-efficiency kilns or kilns with elevated raw-material moisture content (resulting in lower waste gas temperatures due to increased preheating or raw material drying).

WHR Technology Selection

The amount of heat available for waste heat recovery, in combination with the temperature at which the heat is available, are the main drivers for the choice between SRC and ORC technologies. In general, ORC technologies are often a preferred choice for projects with up to 5 MW of power output and when heat is rejected at lower temperatures (less than 300°C), while steam cycles are normally preferred for larger systems and when heat is available at higher temperature (above 350°C). However, there are a variety of other considerations that can further impact technology choice, such as availability of water, kiln operation, raw-material moisture and resulting drying needs, and system capital costs. In addition, any anticipated changes to the cement production process should be considered, as they may affect the potential and performance of any installed WHR system. Relevant operational changes to be considered in advance include, for example, any planned increase or decrease of production capacity over the long term; increase or modification of pre-heater stages; or the introduction or increase in use of alternative fuels (for example, refused derived fuel).

Comparative advantages and disadvantages of SRC and ORC systems that could impact technology choice for cement applications are summarized in Table A-2:

Figure A-4 is a simple decision tree that presents guidelines for selecting the appropriate WHR system based on key threshold questions, including water availability at the plant, amount of waste heat available in the preheater and cooler exhaust streams, and the temperature of the exhaust streams. Note that there is some overlap between application of SRC and ORC systems when the exhaust

TABLE A-2. COMPARISON OF SRC AND ORC TECHNOLOGY

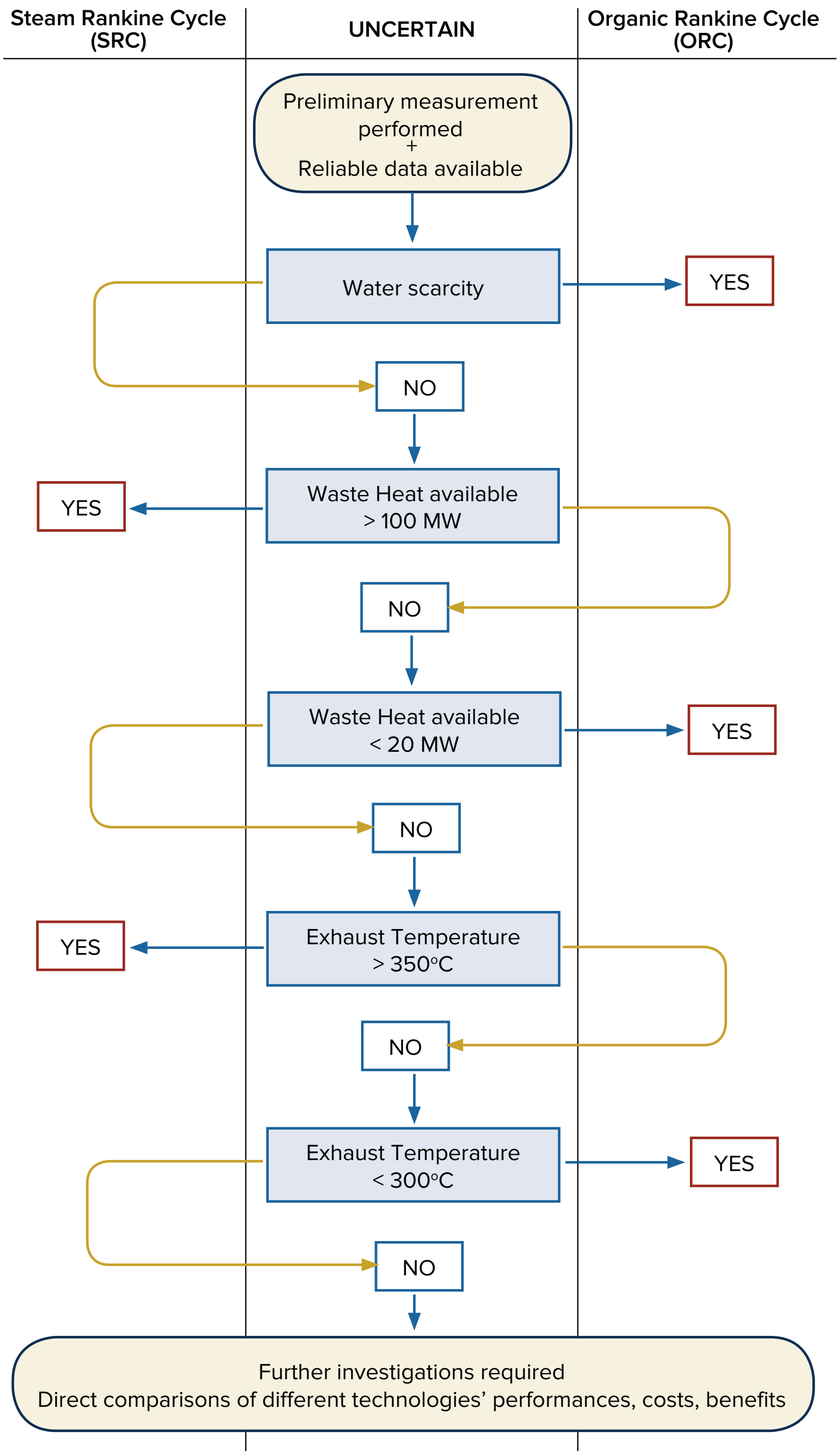
COMPARISON BETWEEN ORC AND SRC CHARACTERISTICS		
TECHNOLOGY	**ADVANTAGES**	**DISADVANTAGES**
ORC	• Applicable to medium-low temperature applications (heat source <300°C) • Better choice for small installations (<2-5 MW power output) • Very high turndown ratio (power production is possible at ratios as low as 10% of nominal heat input) • Better choice if water is not easily and abundantly available • Unattended operation (no dedicated supervision or operators required) • Low turbine maintenance requirements	• Less efficient than SRC in medium-high temperature applications (heat source >350°C) • Higher capital cost on a USD/kW basis • Higher auxiliary power requirements due to increased pump and fan power • Organic fluids can be expensive and require more attention than water when handled (they may be harmful to environment or flammable) • Leakage detection is a must, to avoid losses of expensive fluid • Emerging technology with limited installations worldwide in cement plants
SRC	• Well-known and reliable technology, with many installations worldwide in cement plants • Lower USD/kW CapEx for systems of equal size; Chinese suppliers have quoted 4 to 6 MW systems at 2,000 USD/MW installed • More efficient than ORC in medium-high temperature applications (heat source >350°C) • Better choice for large installations (>5 MW power output) • Water is normally easily available and environmentally friendly	• Requires large amounts of water • Requires expensive equipment and chemicals for water treatment • Less flexible and efficient at part load operation (at input loads <60-70%) • Turbine more prone to maintenance requirements (for the effects of corrosion or erosion)

TABLE A-3. WHR SYSTEM & TECHNOLOGY SUPPLIERS

STEAM SYSTEMS	
Japan	Kawasaki Plant Systems Ltd. (JPN) (Dual Pressure Steam System)
China	Anhui Conch/Kawasaki Engineering Co., Ltd. (CHN/JPN) (Dual Pressure Steam System)
	Sinoma Energy Conservation Ltd. (CHN) (Single Pressure Steam System)
	Nanjing Triumph Kenen Environment & Energy Co., Ltd. (CHN) Nanjing Triumph (Kesen)
	Dalian East New Energy Development Co., Ltd. (CHN) (Dual pressure steam system)
	CITIC Heavy Industries Co., Ltd. (CHN) (Dual-pressure steam system)
	China National Building Materials Group (CNBM) (CHN) (Single-pressure steam system)
	Hefei Cement Research Design Institute (HCRDI) (CHN)
	Shanghai Triumph (Kesen) Energy Conservation (STEC) – JV between China Triumph International Eng. (CTIEC) and Mitsubishi (CHN/JPN)
	China National Building Materials Group (CNBM) (CHN) (Single-pressure steam system)
India	Transparent Energy Systems Private Limited (IND)
	Tecpro Systems Limited/NTK (IND/CHN)
	Thermax/Taiheyo Engineering (IND/JPN)
FLSmidth (DEN) and others...	
ORGANIC RANKINE CYCLE SYSTEMS	
ORMAT (USA) Turboden / Mitsubishi (JPN) ABB (CHE) Exergy (ITA) Opcon Energy and others...	
KALINA CYCLE SYSTEMS	
Wasabi Energy (Australia) And others...	

FIGURE A-4. COMPARISON OF SRC AND ORC TECHNOLOGY

Simple decision-making tree for waste heat recovery projects



temperatures are between 300 and 350°C and the available waste heat is between 20 and 100 MW. Selection of the appropriate system in this range can be affected by a variety of site conditions and requires a direct comparison of cost, performance, and benefits based on expected plant operation.

WHR System Suppliers

The report maps out major WHR system suppliers, which are divided into three groups according to the technology. The detailed information about the suppliers can be seen in "Waste Heat Recovery for the Cement Sector" report published on June 2014, that can be found in IFC website.

Annex B – Best Practices in WHR Design and Operation

Application of waste heat recovery power systems to cement kilns can be challenging. The exhaust gases from the kiln preheaters and clinker cooler typically contain relatively high dust concentrations that sometimes exceed 50 grams per nanometer cubed and the waste gas temperatures can fluctuate widely during kiln operation. Furthermore, many plants utilize a portion of the preheater exhaust gas to dry raw materials, and the amount available for heat recovery can vary widely depending on the moisture content of the raw feed[39,40].

Evaluating Recoverable Waste Heat and Power Generation Potential

The amount of waste heat recoverable from a cement kiln depends on the volume, temperature, and composition of the preheater exhaust and the air cooler exhaust. Exhaust flows and temperatures are, in turn, influenced by a number of factors including:

- Number of preheater/precalciner stages.
- Configuration of the clinker cooler system.
- Moisture content of the raw-material feed (determines heat requirement for the kiln and the amount of preheater exhaust needed for drying).
- Moisture content of the fuel to the kiln.
- Efficiency of the top-stage cyclone (determines dust content in the preheater exhaust).
- Amount of excess air in the kiln.
- Amount of air infiltration.
- Annual operating hours and capacity factor of the kiln.

It is critical to properly analyze each of these parameters in establishing a baseline for evaluating waste heat potential and project feasibility. Care must be taken to ensure that baseline assumptions reflect the actual operating conditions expected during annual operation. Seasonal or daily variations, or design changes, in any of these factors can significantly impact WHR performance and the amount of power produced, affecting project economics and expected paybacks.

[39] Lawrence Berkeley National Laboratory (LBNL), "Energy Efficiency Improvement Opportunities for the Cement Industry, Worrell, Galitsky," Price, January 2008.
[40] "Desk Study on Waste Heat Recovery in the Indian Cement Industry," Confederation of Indian Industry, Final Report, April 2009.

TABLE B-1. TYPICAL AVAILABLE HEAT FROM PREHEATER FOR DRY PROCESS KILNS

Parameter	Unit	Preheater kilns	Preheater with precalciner (number of stages)		
Number of cyclone stages		4	4	5	6
Kiln capacity range	TPD	1000 - 2500	2000 – 8000		
Top-stage exit temperature	Deg C	400	340	300	260
Heat available in preheater exhaust	GJ / tonne clinker (kcal/kg)	0.904 (216)	0.771 (184)	0.678 (162)	0.586 (140)
	GJ / hr for 1 MTPA* (Mkcal/hr)	113.0 (27.0)	96.4 (23.0)	84.7 (20.3)	73.3 (17.5)
Specific thermal energy consumption	GJ / tonne clinker (kcal/kg)	3.55 (850)	3.14 (750)	3.01 (720)	2.93 (700)

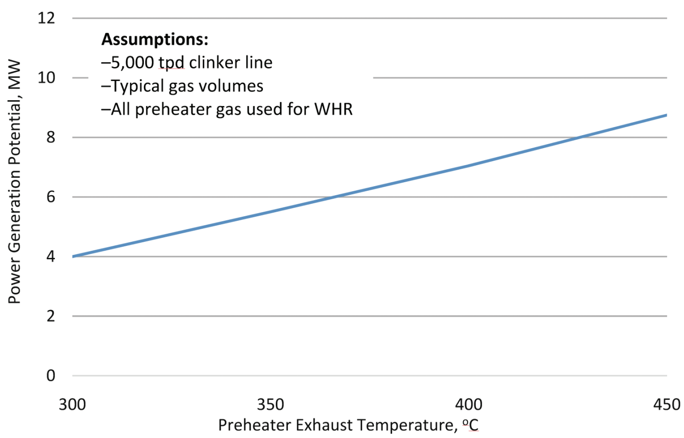
Source: "Desk Study on Waste Heat Recovery in the Indian Cement Industry," Confederation of Indian Industry, Final Report, April 2009.

** MTPA – million metric tons per annum.*

Preheater Stages

The number of preheater stages in a cement plant has significant bearing on the overall thermal energy consumption and waste heat recovery potential. The higher the number of stages, the higher the overall thermal energy efficiency of the kiln and the lower the potential for waste heat recovery. Selection of the number of preheater stages is based on several factors, such as cooler efficiency, restrictions on preheater tower height, or heat requirements for the mill itself. Table B-1 summarizes the efficiency (specific heat consumption) and quantity of waste heat recoverable from state-of-the-art kilns. Preheater exhaust temperatures range from 400°C for small kilns with four preheater stages, to below 300°C for large kilns with six preheater stages.

FIGURE B-1. POWER GENERATION POTENTIAL AS A FUNCTION OF PREHEATER EXHAUST TEMPERATURE



Source: PENTA Engineering 2013.

Figure B-1 shows the power generation potential for a steam waste heat recovery system applied to the exhaust of a typical 5,000 tpd clinker line for exhaust temperatures ranging from 300 to 450°C.

Air Cooler Configuration

The clinker cooler design also impacts waste heat availability. The basic cooler function is to remove heat from hot clinker discharged from the kiln so that the clinker can be handled by subsequent equipment. Rapid cooling also improves clinker quality and grindability. Typically, state-of-the-art coolers are grate coolers, which have various stages of development. Table B-2 summarizes the heat available in different generations of grate coolers. Exhaust air temperatures from the clinker cooler range from 250 to 340°C depending on cooler configuration and recuperation efficiency. Waste heat recovery potential depends on the type and generation of cooler and the extent of utilization of cooler exhaust for the raw material or coal mills.

Power Generation Potential

Table B-3 shows the total heat available from both the preheater exhaust and clinker cooler air for a typical 5,000 tpd clinker plant. Power conversion efficiencies range from 18 to 25 percent, resulting in potential power capacities of 6 to 9 MW.

Typically, the potential power generation, depending on waste heat losses and the number of preheater cyclone stages, ranges from 25 45 kWh/t of clinker. Assuming a typical plant electrical power requirement of 106 kWh/t

TABLE B-2 – TYPICAL AVAILABLE HEAT FOR GRATE CLINKER COOLERS

Parameter	Unit	1st Generation	2nd Generation	3rd Generation
Grate Plate Type		Vertical aeration with holes in plate	Horizontal aeration	Horizontal aeration
Cooling Air Input	Nm3/kg clinker	2.0 – 2.5	1.8 – 2.0	1.4 – 1.5
Exhaust Air Volume	Nm3/kg clinker	1.0 – 1.5	0.9 – 1.2	0.7 – 0.9
Heat Available in Exhaust	GJ / Tonne clinker (kcal/kg	0.419-0.502 (100 – 120	0.335-0.419 (80 – 100)	0.293-0.335 (70 – 80)
	GJ / hr for 1 MTPA* (Mkcal/hr)	52.3-62.8 (12.5 – 15.0)	41.9-52.3 (10.0 – 12.5)	36.6-41.9 (8.8 – 10.0)
Recuperation Efficiency	%	<65	<70	>73

Source: "Desk Study on Waste Heat Recovery in the Indian Cement Industry", Confederation of Indian Industry, Final Report, April 2009 (CII 2009).

** MTPA – million metric tons per annum.*

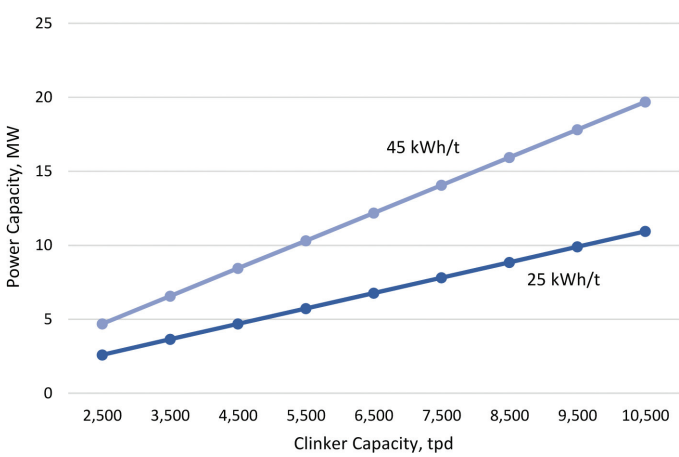
TABLE B-3. TYPICAL AVAILABLE HEAT AND POWER GENERATION FROM PREHEATER/GRATE CLINKER COOLER	
5000 tpd clinker line, 100% utilization of available waste heat	
Input Heat to PH and AQC Boilers	0.963 GJ / Tonne clinker (230 kcal/kg)
Output Heat in Boiler Exhaust Gas	0.379 GJ / Tonne clinker (90 kcal/kg)
Heat Available for Power (Input – Output)	0.583 GJ / Tonne clinker (140 kcal/kg)
Power Conversion Efficiency	18 – 25%
Potential Power Generation	6 – 9 MW

Source: Adapted from PENTA Engineering, 2013.

of cement and a clinker factor of 0.75, approximately 20 to 30 percent of the required electricity for the cement production process can be generated from the waste heat. Figure B-2 shows the band of expected power generation for a range of kiln capacities.

Heat recovery and heat transfer ultimately are a function of the quantity of hot exhaust and the temperature difference between the two fluids entering the waste heat boiler. The improved design characteristics of preheater stages with more effective heat transfer have resulted in lower exhaust temperature – exhaust temperatures in a modern five-stage preheater can vary between 290 to 320°C, depending on capacity utilization, operating efficiency and dust concentration, opening opportunities for organic Rankine cycle systems capable of producing power from lower temperatures (as low as 150°C).

FIGURE B-2. WASTE HEAT POWER GENERATION CAPACITIES AS A FUNCTION OF KILN CAPACITY



Variations in preheater exhaust temperature are normally within +/-5°C during normal operation, assuming other process parameters such as oxygen content and kiln feed remain constant. Clinker cooler temperatures, on the other hand, can vary +/-20°C and can exceed 350°C. The heat availability is also affected by clinker dust carry-over, clinker bed thickness, and variations in clinker quality.

Note that many plants have two or more kilns at the same site. Although the heat availability in any single kiln or cooler may be below an economic size threshold, the total heat available in multiple lines can often be consolidated to support a viable WHR project.

Raw Material Moisture Content

An additional limiting factor to the heat available for effective recovery is the moisture content of the raw material entering the kiln. Moisture content of limestone deposits can range from 2 to 15 percent depending on the limestone origin. The amount of moisture present in the feed material entering the kiln preheater influences specific thermal energy consumption in the kiln and the kiln production rate. Typical practice is to limit moisture content entering the kiln to less than 1.0 percent[41]. To achieve this level, raw feed material is normally dried during grinding by utilizing preheater exhaust gas and/or cooler exhaust as the heat source.

Theoretically about 2.26 GJ is required to evaporate or remove one tonne of moisture from raw feed or limestone (540 kcal/kg water). However, in practice, vertical roller mills require 3.77 to 4.61 GJ of heat per tonne of moisture removed (900 to 1100 kcal/kg water), and ball mills require about 3.14 to 3.56 GJ of heat per tonne of moisture due to losses in mill outlet gas, radiation losses, and air infiltration (750 to 850 kcal/kg water). To illustrate the impact of moisture on drying requirements, Table B-4 gives the heat requirements in terms of kcal//kg clinker for different limestone moisture levels based on the following assumptions:

- Raw meal to clinker factor of 1.55.
- Heat requirement of 3.98 GJ / ton of water for raw mill (950 kcal/kg).

As shown in Table B-4, substantial heat can be required to dry raw material with high moisture levels. Table B-5

[41] "Desk Study on Waste Heat Recovery in the Indian Cement Industry," Confederation of Indian Industry, Final Report, April 2009.

shows the heat available in preheater exhaust at different preheater exit temperatures ranging from 280°C to 400°C. A comparison of the two tables shows that high moisture content in the raw feed can significantly reduce the heat available for WHR in the preheater exhaust; raw feeds with very high moisture rates essentially eliminate the potential for effective heat recovery. As shown, if the preheater exit temperature is less than 340°C (heat available of 0.77 GJ/ton), waste heat is available for recovery only if the moisture content of the raw feed is less than 10 percent (<0.75 GJ/ton heat required for drying). Waste heat is available for the entire range of preheater exit temperatures if the raw feed has a moisture content of 4 percent (0.28 GJ/ton heat required for drying). Raw material moisture content plays a major role in the viability of applying WHR by affecting the heat available from the preheater. Care must be taken to understand the variations in raw material moisture that is likely to be encountered over the year, and to base system design and performance projections on a reasonable baseline.

Another area of drying requirements are cement additives. Wet fly ash and slag specifically often need to be dried during grinding, typically with clinker cooler exhaust[42]:

- Wet fly ash – 0.40 GJ of heat for every ton of cement based on 30 percent wet fly ash addition and 25 percent moisture in fly ash and an evaporation rate of 3.98 GJ/ton water.
- Slag – 0.27 GJ heat for every ton of cement based on 50 percent wet fly ash addition and 12 percent moisture in fly ash and an evaporation rate of 3.98 GJ/ton water.

[42] "Desk Study on Waste Heat Recovery in the Indian Cement Industry," Confederation of Indian Industry, Final Report, April 2009.

Influence of Dust on WHR

Dust in the hot exhaust from the preheater affects both kiln efficiency and operation of the waste heat recovery boilers. As shown in Figure B-3, raw material feed typically enters the riser duct (connecting duct) coming from the Stage 2 cyclone preheater and is carried by the gas to the top stage cyclone where it is separated. Raw material dust is carried downward and the gas from Cyclone 1 goes to the preheater fan. Depending on the efficiency of the top stage cyclone, part of the kiln feed remains in the gas stream. This adds to the specific heat consumption as heated material leaves the kiln system and also increases the power consumption of the preheater fan as the presence of dust increases both the density and pressure drop. Dust also results in formation of coating in the preheater fan impeller during operation due to it clay content.

Cyclone efficiency can vary from 88 percent to as high as 97 percent, resulting in dust concentration varying 0.125 kg/Nm3 to 0.035 kg/Nm^3 [43] . The normal range of operation is 0.070 to 0.080 kg/Nm^3. Preheater dust is sticky by nature and can affect WHR performance by decreasing the heat transfer rate by forming a coating over the heat transfer surfaces in the waste heat recovery boiler, which in turn affects the efficiency of the cycle and may eventually cause blockage. To address these conditions, waste heat boiler tubes are usually in a vertical arrangement, and suitable cleaning systems should be installed to avoid dust adherence to the tube walls. Available cleaning systems are sonic cleaners, soot blowers, mechanical (or pneumatic) rapping, and steel shot cleaning (the last two being the most commonly employed). Preheater dust can

[43] "Desk Study on Waste Heat Recovery in the Indian Cement Industry", Confederation of Indian Industry, Final Report, April 2009.

TABLE B-4. HEAT REQUIRED FOR RAW MATERIAL DRYING

Moisture Content	2%	4%	6%	8%	10%	12%	14%	16%
Heat Required, GJ/ton	0.14	0.28	0.43	0.58	0.75	0.92	1.09	1.28

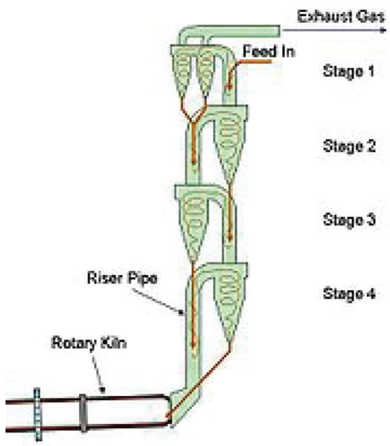
Source: "Manual on Waste Heat Recovery in the Indian Cement Industry", Confederation of Indian Industry, 2009.

TABLE B-5. HEAT AVAILABLE AT DIFFERENT PREHEATER EXIT TEMPERATURES

Exit Temperature, °C	260	280	300	320	340	360	380	400
Heat Available, kcal/kg	140.4	151.2	162.0	172.8	183.6	194.4	205.2	216.0

Source: Based on "Manual on Waste Heat Recovery in the Indian Cement Industry", Confederation of Indian Industry, 2009.

FIGURE B-3. DUST COLLECTION IN PREHEATER/ CYCLONE TOWERS



also be reduced by installing a high-efficiency cyclone at the top stage or improving the efficiency of the existing cyclones.

Cooler exhaust contains dust, which is highly abrasive to steel and capable of eroding the heat transfer area in the boiler, negatively affecting system operation. Waste heat recovery boilers for cooler exhaust typically use horizontal tube arrangements and generally do not require cleaning systems. A portion of the duct content settles inside the waste heat boilers, reducing the dust load at downstream filters or electrostatic precipitators. Bottom dust removal is usually required and typically done by screw conveyors or drag chain conveyors. Many installations install a dust separation system on the cooler gas before it enters the waste heat boiler.

Project Feasibility Analysis

All projects should start with precise analysis of all aspects and factors involved in a potential installation, and include technical evaluations of the viability of WHR implementation at the site. The issues and variables to be considered are typically:

- The size of the plant.
- Process characteristics and plant layout.
- Heat available from exhaust gas (from kiln and clinker cooler).
- Power supply situation (availability of grid power, presence of gen-sets in constant operation or used during power interruption or shortage, etc.).

As outlined above, the most important information required to perform an accurate assessment of power production potential is the heat available for waste heat recovery from kiln exhaust and cooler air. The remaining information is more relevant in the next stages of basic and detail engineering of the power plant. Therefore, it is necessary to collect a comprehensive set of data records including:

- Gas temperature.
- Gas composition (and dust content).
- Gas flow rates.

As noted earlier, the heat available for waste heat recovery is the difference between the heat content in the exhaust of the preheater and the cooler air, minus the heat required for drying or heating raw material and/or fuel (coal, heavy fuel oil, refused derived fuel, etc.), as this use of heat has priority over power production, and provides a clear advantage in terms of increased process efficiency (internal heat needs should, in general, be preferred to power production).

Accurate measurement and analysis of exhaust temperatures, flows, and composition is key to determining available waste heat. Gas temperatures and flows can be directly and easily measured on-line, downstream of all internal heat use for waste heat. Preheater exhaust gas composition can be estimated if an on-line analyser is present, for example, at the stack. If fresh air is mixed upstream of the analyser, the mixing proportion must be known and weighted quantities of components must be subtracted from the gas composition at the stack. Clinker cooler air composition is easier to evaluate, as it is normally just affected by moisture content. Gas flows can be calculated indirectly by measuring flows at stack. Again, if fresh air is mixed upstream of the measurement point, the mixing proportion must be known, and fresh air quantity must be subtracted from the total measure.

WHR Project Risks

There are a number of potential risks related to implementing WHR that could impact the ability of projects to meet projected performance levels. These risks can be summarized by the following categories:

TABLE B-6. DESIGN PHASES AND INFORMATION REQUIRED FOR EACH PHASE		
DESIGN PROCESS PHASES, OBJECTIVES, INFORMATION REQUIRED		
DESIGN PHASE	**OBJECTIVES**	**INFORMATION REQUIRED**
Feasibility assessment	• Collect basic process information • Evaluate WHR potential • Evaluate power output • Compare technologies and performances	• Plant size and production capacity and operation data • Potential reuse of heat (to increase the production efficiency) • Temperature, flow rate, chemical composition, dust content of exhaust gases available for WHR • Maximum and minimum temperature of exhaust gases acceptable after WHRU • Ambient conditions (localization, height above sea level, climate data) • Potential use for low-grade heat • Plans for plant revamping or other modifications • Market and production forecast
Basic design	• Define the budget • Define and size the main components for WHR system • Draft a preliminary layout • Define the requirements for WHR system (water, fuel, devices, dedicated personnel) • Draft a procurement and erection programme	• Plant layout • Tie-in details • Local regulations to fulfil (for pressure parts, environmental, seismic, grid code, firefighting, health and safety) • Company specifications for civil, mechanical, electrical supply and works
Detail design	• Finalize the layout of WHR system • Finalize the design of WHR system components • Finalize the procurement and erection programme	• Calendar of plant stops for programmed maintenance

Design Risk

The risks related to system design center on whether the waste heat recovery system is adequately designed and engineered to achieve the projected performance levels outlined in the project agreement and to withstand the rigors of extended operation in the industrial environment of an operating cement plant. Minimizing these risks depends on careful vetting of the equipment suppliers and designers and of the local construction content in terms of previous experience and any performance guarantees. It is also critical that the design be based on a complete understanding of the expected operating conditions including: raw material and fuel composition and moisture content; accurate exhaust gas flow, temperature, and composition measurements and/or estimates under varying operating conditions; potential changes in kiln operation and/or product mix over time; and projections of fuel and electricity prices over time.

Construction Risk

The risks related to construction center on whether the waste heat recovery system is installed according to specifications, the overall project schedule is realistically planned and followed, tie-ins to and alterations to existing plant equipment are scheduled around planned downtime, and start-up and commissioning are adequately supported.

Typical construction times can be as short as six months. Installation should be scheduled to ensure there is no interruption to cement production. However, individual construction schedules can vary depending on plant conditions and supplier schedules.

The commissioning process can last four to six weeks and includes check-out of the waste heat recovery system and controls. Commissioning should also include a one- to two- week performance test before final sign-off. System power production should be measured and compared to the design targets (kWh per ton of clinker). While the performance test is intended to verify that design targets can be met (performance goals sometimes need to be adjusted to reflect the actual operating conditions of the production line at the time of testing), it should also be understood that it normally takes a number of months before the systems are routinely operating at highest efficiency and power output over the range of kiln conditions experienced in daily operation.

Operational Risk

The risks related to waste heat recovery system and kiln operations center on whether adequate training, operating procedures, and maintenance programs are in place to ensure that the system performs as expected over the long term.

Operational risks relate also to the impact on system performance by planned or unplanned outages of the cement production line or the waste heat recovery system itself, and to the ability of the integrated kiln and waste heat recovery system to operate at levels or conditions as projected in the PDDs. Along with performance guarantees that are verified during commissioning, most suppliers provide a system availability guarantee (often around 97%). Availability is defined as the ability of the system to operate during the time period it is expected to operate (that is, when the cement production line is operating)[44]. Similarly, target availabilities for the clinker production lines also must be considered, including annual planned maintenance shutdowns and a review of historical unplanned outages.

Finally, there is the risk of not achieving the full power production levels projected in project design. Performance projections are based on specific design conditions of both the cement kilns and the waste heat recovery systems. There are two conditions where the projected production levels or design conditions may not be achieved. One reflects the time needed for a system to gradually come up to optimum operating conditions after initial installation. This is a normal operational issue for initial startup of any complicated thermal system, as it takes time for the operating staff to get a feel for the system and its response to changes in the operating conditions of the kilns. This becomes a risk to achieving projected performance only if the ramp-up periods are extensive (greater than six months).

The more critical risk has to do with the month-to-month, or day-to-day, variations in kiln operating conditions. Projected project performance is normally based on design heat recovery system power generating capacities at nominal kiln conditions (nominal exhaust gas temperatures and flows). Variations in either exhaust temperatures or flow rates impact the amount of heat available for recovery in the waste heat boilers and, in turn, the amount of power produced by the heat recovery systems. Actual heat recovery system output could be higher or lower than design conditions depending on a variety of factors that affect kiln operation. As noted earlier, the factors that could impact exhaust temperature and flows, and the heat available for recovery, include:

- Fuel quality and moisture content.
- Raw-material quality, temperature, and moisture content.
- Modifications to kiln operations to maximize throughput, enhance fuel utilization efficiency, or maintain product quality.
- Changes in operating conditions or inconsistent operation related to process control or maintenance issues.

WHR design is often based on best-case scenarios – high-quality fuel, nominal limestone conditions, set production mix, etc. However, variations should be expected as the primary objective of the kiln operator is to optimize kiln operation for a given fuel composition, clinker quality, and production level. System design should incorporate an understanding of potential off-design conditions likely to occur, and the potential impact on power production.

[44] Availability Factor (AF) measures on a percent basis the unit's "could run" capability. Impacted by scheduled outage hours (SOH) and Forced Outage Hours (FOH). AF = (Scheduled Run Hours - SOH - FOH)*100 / Scheduled Run Hours.

WHR Maintenance Requirements

TABLE B-7. MAINTENANCE REQUIREMENTS FOR DIFFERENT FREQUENCIES					
Boiler Checklist		**Maintenance Frequency**			
Description	**Comments**	**Daily**	**Weekly**	**Monthly**	**Annually**
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	x			
Follow manufacturer's recommended procedures in lubricating all components	Compare temperatures with tests performed after annual cleaning	x			
Check steam pressure	Variation in steam pressure as expected under different loads; wet steam may be produced if the pressure drops too fast	x			
Check unstable water level	Unstable levels can be a sign of contaminates in feedwater, overloading of boiler, equipment malfunction	x			
Check motor condition	Check for proper function temperatures	x			
Boiler blowdown	Verify the bottom, surface, and water column blowdowns are occurring and are effective	x			
Boiler logs	Keep daily logs on: • Exhaust gas temperature • Makeup water volume • Steam pressure, temperature, and amount generated Look for variations as a method of fault detection	x			
Check oil filter assemblies	Check and clean/replace oil filters and strainers	x			
Check boiler water treatment	Confirm water treatment system is functioning properly	x			
Check flue gas temperatures and composition	Measure flue gas composition and temperatures at selected situation		x		
Check all relief valves	Check for leaks		x		
Check water level control	Stop feedwater pump and allow control to stop fuel flow to burner. Do not allow water level to drop below recommended level.		x		
Inspect system for water/steam leaks and leakage opportunities	Look for: leaks, defective valves and traps, corroded piping, condition of insulation		x		
Inspect all linkages on waste gas dampers and valves	Check for proper setting and tightness		x		
Check all blower belts	Check for tightness and minimum slippage.			x	
Check all gaskets	Check gaskets for tight sealing; replace if do not provide tight seal			x	
Inspect boiler insulation	Inspect all boiler insulation and casings for hot spots			x	
Steam control valves	Calibrate steam control valves as specified by manufacturer			x	
Perform water quality test	Check water quality for proper chemical balance			x	

Boiler Checklist		Maintenance Frequency			
Description	Comments	Daily	Weekly	Monthly	Annually
Inspect and repair refractories on boiler side	Use recommended material and procedures				x
Relief valve	Remove and recondition or replace				x
Feedwater system	Clean and recondition feedwater pumps. Clean condensate receivers and deaeration system				x
Electrical systems	Clean all electrical terminals. Check electronic controls and replace any defective parts.				x
Hydraulic and pneumatic valves	Check operation and repair as necessary				x

Turbine Checklist	Maintenance Frequency			
Description	Daily	Weekly	Monthly	Annually
Conduct visual inspection of the unit for leaks (oil and steam), unusual noise/vibration, plugged filters, or abnormal operation	x			
Cycle non-return valves	x			
Trend unit performance and health. Hand-held vibration readings should be taken from the steam turbine and gearbox if permanent vibration monitoring system is not installed		x		
Test emergency backup and auxiliary lube oil pumps for proper operation		x		
Test the main lube oil tank and oil low-pressure alarms		x		
Test the simulated over-speed trip if present		x		
Cycle the main steam stop or throttle valve		x		
Cycle control valves if steam loads are unchanging		x		
Cycle extraction/admission valves if steam loads are unchanging.		x		
Sample and analyze lube oil and hydraulic fluid for water, particulates, and contaminants			x	
Deferred weekly tests or valve cycling that experience has indicated sufficient reliability to defer them to a one month interval.			x	
Conduct visual inspection and functional testing of all stop, throttle, control, extraction, and non-return valves including cams, rollers, bearings, rack and pinions, servomotors, and any other pertinent valves or devices for wear, damage, and/or leakage.				x
Conduct visual inspection of seals, bearings, seal and lubrication systems (oil and hydraulic), and drain system piping and components for wear, leaks, vibration damage, plugged filters, and any other kinds of thermal or mechanical distress.				x
Conduct visual, mechanical, and electrical inspection of all instrumentation, protection, and control systems. Includes checking alarms, trips, filters, and backup lubrication and water cooling systems				x

Turbine Checklist	Maintenance Frequency			
Description	Daily	Weekly	Monthly	Annually
Test the mechanical over-speed for proper operation annually unless the primary system is electronic and has an OS test switch. For that system, electronic over-speed simulations should be conducted weekly while mechanical and electrical over-speed tests should be conducted every three years. For electronic systems without an OS test switch, an over-speed test should be conducted annually.				x
Conduct visual inspection of gearbox (if installed) teeth for unusual wear or damage, and gearbox seals and bearings for damage.				x
Internally inspect non-return valve actuators for wear				x

Steam Traps		Maintenance Frequency			
Description	Comments	Daily	Weekly	Monthly	Annually
Test steam traps	weekly/monthly/annually test recommended for low-pressure trap		x	x	x
Repair/replace steam traps	When testing shows problems. Typically, traps should be replaced every 3-4 years.				x

Cooling Tower		Maintenance Frequency			
Description	Comments	Daily	Weekly	Monthly	Annually
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	x			
Inspect for clogging	Make sure water is flowing in tower	x			
Fan motor condition	Check the condition of the fan motor through temperature or vibration analysis and compare to baseline values		x		
Test water samples	Test for proper concentrations of dissolved solids, and chemistry. Adjust blowdown and chemicals as necessary.		x		
Operate make-up water	Operate switch manually to ensure proper float switch operation		x		
Vibration	Check for excessive vibration in motors, fans, and pumps		x		
Check tower structure	Check for loose fill, connections, leaks, etc.		x		
Check belts and pulleys	Adjust all belts and pulleys		x		
Check lubrication	Assure that all bearings are lubricated per the manufacture's recommendation			x	
Check drift eliminators, louvers, and fill	Look for proper positioning and scale build up			x	
Clean tower	Remove all dust, scale, and algae from tower basin, fill, and spray nozzles				x
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.				x

Building Automation Systems		Maintenance Frequency			
Description	**Comments**	**Daily**	**Weekly**	**Monthly**	**Annually**
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place.	x			
Verify control schedules	Verify in control software that schedules are accurate for season, occupancy, etc.	x			
Verify set-points	Verify in control software that set-points are accurate for season, occupancy, etc.	x			
Time clocks	Reset after every power outage	x			
Check all gauges	Check all gauges to make sure readings are as expected		x		
Control tubing (pneumatic system)	Check all control tubing for leaks		x		
Check set-points	Check set-points and review rational for setting		x		
Check schedules	Check schedules and review rational for setting		x		
Check dead bands	Assure that all dead bands are accurate and that the only simultaneous heating and cooling is by design		x		
Check sensors	Conduct thorough check of all sensors – temperature, pressure, humidity, flow, etc – for expected values			x	
Calibrate sensors	Calibrate all sensors: temperature, pressure, humidity, flow, etc.				x

ANNEX C – Key Assumptions for the WHR Financial Model and Performance Analysis

Financial Analysis of Existing WHR Systems

An initial modeling exercise estimated the financial performance of the existing WHR systems included in the survey under two financial analysis cases:

1. Planned Performance – operations based on design conditions, including the maximum planned operating hours of clinker lines in a given year with 100% WHR capacity utilization.
2. Actual Performance – operations based on reported actual operating hours of clinker lines and actual WHR capacity utilization in a given year.

Key assumptions used in the financial analysis include:

- The data used were collected in a survey, with questionnaires completed by individual companies based on their operations in 2015 to ensure consistency within the group. No adjustments were made to primary data received. In case no data was provided for select questions, estimates were made based on other relevant plant parameters and responses of comparable companies within the sample.
- Planned clinker kiln operating hours were based on the maximum annual operating hours reported for each plant. Actual kiln operating hours were based on the reported kiln operating hours for 2015.
- Planned WHR operating hours were estimated using a 100 percent WHR system availability, as a percent of maximum kiln operating hours, as typically guaranteed by the suppliers. In a plant operating 8,000 hours a year this corresponds to 240 hours of WHR downtime, which is typical given the annual hours of planned and unplanned outages for maintenance and service. Actual WHR operating hours were based on the reported WHR system operating hours for 2015.
- Auxiliary power requirements were set at an average value of 10 percent of total WHR power generation. This is a conservative estimate, considering a wide variation in values observed in the survey, with the lowest value reported of 5.5 percent of total power generation.
- Information on annual O&M costs was not provided by all companies. For the purpose of consistency, an estimate was developed based on partial reporting and industry best practices: annual O&M costs equal to $70/kW for systems <7.5 MW, $60 /kW for systems >7.5 MW and <10 MW, and $50 /kW for systems >10 MW.
- Performance of WHR systems during the first year of operations was set to 94 percent in the model, based on industry experience that WHR plants may be operating at 85-92 percent of capacity during the first three to six months until the system operations are optimized.
- For the financial analysis, equity-only financing was assumed for all companies to ensure ease of comparisons. Consequently, a discount rate of 12.5 percent was applied to all companies. It was further assumed that the full investment cost was paid within one year prior to start-up.
- Economic lifetime for WHR systems was set to 20 years in the model. Best practices in operations and maintenance can extend the lifetime of WHR systems up to 30 years. Yearly degradation rate is highly dependent on quality of operation and was not considered in the analysis.
- The cost of electricity paid by cement plants in each given year was assumed at the level of yearly average wholesale market prices in Turkey during that year, including fees for transmission, distribution, and renewable energy support. The rate of increase for the out-years was based on forecasts in Mercados Market Report of March 2017.

- Historical and forecasted values of exchange rates (Turkish lira vs the US dollar and euro) and inflation were based on Economist Intelligence Unit estimates, accessed on July 21, 2017[45].

Sensitivity Analysis of ORC WHR for Plants without Existing WHR Systems

A sensitivity analysis was conducted to identify the key performance and financial factors that could impact the financial performance of potential ORC WHR projects in the Turkish cement industry. In the analysis, a Base Case technical feasibility and financial analysis was conducted for each plant based on their reported operating data for 2015, including information on kiln utilization and operation, exhaust temperatures and flows from preheaters and clinker coolers, and the amount of heat used for drying of raw material and fuel. ORC WHR systems were sized for each plant based on the preheater and clinker cooler exhaust conditions, and technical and financial feasibility was estimated based on typical cost and performance assumptions for ORC systems applied to cement plants. A number of scenarios were then conducted to assess the financial sensitivity of ORC projects to variations in key plant and ORC system operating and financial parameters as described in Table C-1.

[45] Economist Intelligence Unit, http://www.eiu.com/home.aspx.

TABLE C-1. DESCRIPTION OF FINANCIAL ANALYSIS SCENARIOS FOR ORC WHR

Scenario	Description
Base Case	Operations as per maximum planned operating hours of cement plant in given year with 100% WHR capacity utilization, with heat used for drying limiting available heat for WHR as per typical drying practice and as reported by each plant.
1	WHR Capacity Utilization: -30%/+5%
2	Clinker Kiln Operating Hours: 6034 hours, 8595 hours
3	Total Capital Cost: -10% / +20%
4	Electricity Prices: +10% / -10%
5	TL/$ Exchange Rate: -10% / +10%
6	WHR O&M Expenses: -130% / +30%
7	WHR Auxiliary Power: 8%, 10% (base case), 12%

Key assumptions used in the financial analysis include:

- The data used were collected in a survey, with questionnaires filled by individual companies based on their operations in 2015 to ensure consistency within the group. No adjustments were made to primary data received. In case no data was provided for select questions, estimates were made based on other related plant parameters and responses of comparable companies within the sample.
- The potential for additional WHR application was calculated assuming the start-up of new WHR plants in early 2018.
- Base Case clinker kiln operating hours were based on the maximum annual kiln operating hours reported for each plant.
- Base Case WHR operating hours were based on a WHR system availability of 96 percent applied to maximum kiln operating hours. In a plant operating 8000 hours a year, 96 percent availability corresponds to 320 hours of WHR system downtime, which is typical of the annual hours of planned and unplanned outages for maintenance and service. Suppliers of ORC suppliers generally guarantee and availability of 95-98 percent.
- Heat available for waste heat recovery was calculated based on average temperatures and flowrates of the exhaust gases and air at the pre-heater and clinker cooler exits as reported by the companies surveyed.
- The composition of gases assumed was in line with industry practice at the preheater with 64% N_2, 28% CO_2, 4% H_20, 4% O_2 and clinker cooler with 72% N2 and 21% O_2. The normal exhaust gas density for preheater exhaust was 1.438 and 1.276 Nm^3/kg for clinker cooler exhaust air. Specific heat capacities were calculated based on gas density and temperature.
- The temperatures of exhaust gas and air at the exit of the WHR heat exchangers applied to the preheater and clinker cooler were based on usual cement industry practice. A temperature of 230°C at the exit of preheater and/or cooler was assumed where heat was being used for raw material or fuel drying as reported in the survey. In case of limited or no secondary use of heat after the WHR, 160°C temperature was assumed at the exit of the preheater recovery unit (the minimum temperature required to stay above condensation temperature for combustion gases to reduce heat exchanger corrosion); 120°C

was assumed at the exit of the cooler recovery unit since the exhaust is primarily air and does not contain condensable corrosive elements. The ability to recover heat from streams as low as 120°C is one of the advantages of ORC systems.

- Heat transfer losses were assumed at 2%, in line with industry practice. Gross electric efficiency of the ORC unit was set to 21%, which is an upper-range value for ORC plants currently in place, considering that ORC solutions of higher efficiency are under development and should be more readily available in the near future.
- Auxiliary power requirements tend to vary between 9 and 12 percent based on site and design conditions; 10 percent was assumed for the Base Case.
- Total investment costs were estimated based on average market prices in Europe during the first quarter of 2017 with respect to system capacity: €3500 per kW for installations of 2-3 MW capacity, €2915 per kW for 3-5 MW, €2335 per kW for 5-10 MW, and €2105 per kW for installations above 10 MW capacity.
- Annual O&M costs were assumed at 3 percent of investment cost for systems of 2-3 MW capacity, 2.5 percent for systems 3-5 MW capacity, and 2.0 percent for systems above 5 MW. These are typical of usual O&M costs in existing applications, and include spare parts, personnel, and the cost of a major overhaul that can be expected around the mid-life of the plant.
- Performance of the WHR system during the first year of operations was assumed to be 94% in the model, as during first three to six months after the start-up WHR plants may be operating at 85-92% of capacity, until the system operations are optimized.
- Equity-only financing was assumed for all of the companies, although loans and several incentive programs are currently available to finance WHR projects in the cement sector in Turkey. A discount rate of 12.5% was applied to all companies, and it was further assumed that the full investment cost was paid within one year prior to start-up.
- Economic lifetime for WHR systems was set to 20 years in the model. Best practices in operations and maintenance can extend the lifetime of WHR systems up to 30 years. Yearly degradation rate is highly dependent on quality of operation and was not considered in the analysis.
- Cost of electricity paid by cement plants in each given year was assumed at the level of yearly average wholesale market prices in Turkey during that year, including fees for transmission, distribution, and renewable energy support. The rate of increase for the out-years is based on forecasts in Mercados Market Report, March 2017.
- Historical and forecasted values of exchange rates (Turkish lira vs. U.S. dollar and euro) and inflation were based on Economist Intelligence Unit estimates, accessed on July 21, 2017.

Levelized Cost of Electricity

Levelized cost of electricity (LCOE) is a convenient measure of the overall competitiveness of a generation investment compared to other electricity supply options. LCOE represents the per-kWh cost (in discounted real dollars and discounted kWhs) of installing and operating a generating asset over an assumed financial life and duty cycle or capacity utilization:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

lifetime (a)
initial investment cost (€)
Annual costs ($/a) (expected-estimated)
discount rate (%)
Levelised Cost of Electricity ($/MWh)
output (MWh/a), annual electricity generation (expected-estimated)

Key inputs to calculating LCOE for a project include capital costs, fuel costs, operating and maintenance (O&M) costs, financing costs, and an assumed utilization rate. The importance of each of these factors varies among generating technologies. For technologies such as solar or WHR generation that have no fuel costs and relatively low O&M costs, LCOE changes in rough proportion to the capital cost and utilization rate of the system. For technologies with significant fuel cost, both fuel cost and capital cost estimates significantly affect LCOE. The availability of various incentives, including regional or national tax credits, can also impact the calculation of LCOE. As with any projection, there is uncertainty about these factors and their values can vary regionally and across time as technologies evolve and fuel prices change. While LCOE can be an important measure in considering the economic viability of a WHR project, it is important to base the calculation on adequate upfront preparation and realistic projections of key performance and cost parameters .

Detailed Sensitivity Analysis Results

TABLE C-2. SENSITIVITY ANALYSIS RESULTS

	Plant 7 5,462 kW				Plant 8 2,151 kW				Plant 9 4,149 kW				Plant 10 5,794 kW				Plant 11 4,228 kW				Plant 12 12,897 kW			
	Payback (years)	IRR	COE w/CapEx (USD/MWh	COE w/OpEx only (USD/MWh	Payback (years)	IRR	COE w/CapE x (USD/MWh	COE w/OpEx only (USD/MWh	Payback (years)	IRR	COE w/CapE x (USD/MWh	COE w/OpEx only (USD/MWh	Payback (years)	IRR	COE w/CapE x (USD/MWh	COE w/OpEx only (USD/MWh	Payback (years)	IRR	COE w/CapEx (USD/MWh	COE w/OpEx only (USD/MWh	Payback (years)	IRR	COE w/CapEx (USD/MWh	COE w/OpEx only (USD/MWh)
Base Case	**4.80**	**23.9%**	**20.3**	**7.1**	**8.68**	**12.0%**	**33.8**	**16.6**	**6.09**	**18.6%**	**25.2**	**10.6**	**5.00**	**22.9%**	**21.0**	**7.3**	**6.62**	**16.9%**	**27.1**	**11.4**	**4.47**	**25.6%**	**19.0**	**6.6**
Kiln Operating Hours																								
6034 hrs	6.86	16.3%	27.9	9.7	12.40	6.5%	44.4	21.8	9.27	11.1%	35.9	15.1	6.86	16.3%	27.9	9.7	9.27	11.1%	35.9	15.1	6.10	18.6%	25.1	8.8
7285 hrs	5.55	20.6%	23.1	8.0	9.65	10.3%	36.8	18.1	7.39	14.9%	29.7	12.5	5.55	20.6%	23.1	8.0	7.39	14.9%	29.7	12.5	4.95	23.2%	20.8	7.3
8595 hrs	4.62	24.8%	19.6	6.8	7.84	13.7%	31.2	15.3	6.09	18.6%	25.2	10.6	4.62	24.8%	19.6	6.8	6.09	18.6%	25.2	10.6	4.13	27.7%	17.6	6.1
WHR Capacity Utilization																								
70%	7.16	15.6%	28.9	10.1	13.95	4.8%	48.3	23.8	9.31	11.0%	36.0	15.2	7.47	14.8%	30.0	10.5	10.17	9.6%	38.7	16.3	6.64	17.0%	27.1	9.4
90%	5.40	21.2%	22.5	7.8	9.93	9.8%	37.6	18.5	6.88	16.2%	28.0	11.8	5.62	20.3%	23.4	8.1	7.49	14.6%	30.1	12.7	5.01	22.9%	21.1	7.3
105%	4.55	25.2%	19.3	6.7	8.16	13.0%	32.2	15.8	5.67	19.7%	24.0	10.1	4.74	24.2%	20.0	7.0	6.25	18.1%	25.8	10.9	4.24	27.0%	18.1	6.3
CapEx																								
+20% Capex	5.88	19.4%	24.3	8.5	10.98	8.3%	40.6	20.0	7.54	14.5%	30.2	12.8	6.13	18.5%	25.2	8.8	8.21	13.0%	32.5	13.7	5.46	20.9%	22.7	7.9
-10% Capex	4.28	26.3%	18.2	6.4	7.61	15.3%	30.5	15.0	5.4	21.1%	22.7	9.6	4.46	25.7%	18.9	6.6	5.86	19.4%	24.4	10.3	3.99	26.7%	17.1	5.9
O&M																								
+30% O&M	4.95	23.1%	21.0	9.2	9.41	10.4%	35.6	21.6	6.38	17.5%	26.4	13.8	5.16	22.1%	21.8	9.5	6.96	15.6%	28.3	14.9	4.59	24.9%	19.7	8.6
-30% O&M	4.67	24.6%	19.5	4.9	8.05	13.5%	32.0	11.6	5.82	19.6%	24.0	7.4	4.86	23.7%	20.2	5.1	6.30	18.0%	25.8	8.0	4.35	26.4%	18.2	4.6
Auxiliary Power																								
12% Aux Power	4.92	23.3%	20.7	7.2	8.93	11.5%	34.6	17.0	6.25	18.1%	25.8	10.9	5.13	22.3%	21.5	7.5	6.79	16.4%	27.7	11.7	4.58	25.0%	19.4	6.8
8% Aux Power	4.69	24.4%	19.8	6.9	8.44	12.5%	33.1	16.3	5.94	19.1%	24.7	10.4	4.88	23.5%	20.6	7.2	6.45	17.4%	26.5	11.2	4.36	26.3%	18.5	6.5
Electricity Price																								
+10% Elect Price	4.33	26.4%	20.3	7.1	7.71	14.0%	33.8	16.6	5.46	20.9%	25.2	10.6	4.51	25.4%	21.0	7.3	5.93	19.1%	27.1	11.4	4.03	28.1%	19.0	6.6
-10% Elect Price	5.40	21.2%	20.3	7.1	9.93	9.8%	33.8	16.6	6.88	16.2%	25.2	10.6	5.62	20.3%	21.0	7.3	7.49	14.6%	27.1	11.4	5.01	22.9%	19.0	6.6
Exchange Rate																								
+10% Exchange Rate	5.34	21.5%	20.0	6.4	9.64	10.4%	33.2	15.0	6.77	16.6%	24.8	9.6	5.56	20.6%	20.8	6.6	7.35	15.0%	26.7	10.3	4.96	23.1%	18.7	5.9
-10% Exchange Rate	4.37	26.2%	20.5	7.8	7.89	13.6%	34.4	18.3	5.54	20.6%	25.6	11.7	4.55	25.2%	21.3	8.1	6.01	18.8%	27.5	12.6	4.06	28.1%	19.2	7.3

ANNEX D – Subsidies and Financing Mechanisms for WHR Investments

Various financing mechanisms are provided by the international and national institutions and organizations to support new investments in Turkey. Because there are many incentives for special investments in the industry such as WHR, it is useful to review available incentives and financial grants before the investment stage.

Many of the Incentives vary according to investment region of the county:

The specific support instruments provided within the framework of the four investment incentives schemes are summarized in Table C-1; WHR investments would qualify under Regional Investment Incentives Schemes.

Regional Investment Incentives Scheme

The sectors to be supported in each region are determined in accordance with regional potential and the scale of the local economy, while the amount of support varies depending on the level of development in the regions. The minimum fixed investment amount is defined separately for each sector and region with the lowest amount being TL 1 million in Region 1 and 2, and TL 500,000 in the remaining regions.

Incentives

First, the company must apply to the Ministry of Economy to get an investment incentive certificate. After that application, the ministry prepares an investment incentive certificate to support the company for the related investment(s). The certificate initiates the support for investors; the level of support varies from region to region.

VAT Exemption

The generally applied VAT rate is set at 1 percent, 8 percent, and 18 percent. Commercial, industrial, agricultural, and

FIGURE D-1. TURKISH INVESTMENT REGION MAP

Source: investinturkey.com

independent professional goods and services, goods and services imported into the country, and deliveries of goods and services as a result of other activities are all subject to VAT.

Customs Duty Exemption

Customs duty is not paid for machinery and equipment provided from abroad (imported) within the scope of the investment incentive certificate.

Social Security Premium Support (Employer's Share)

This measure stipulates that, for additional employment created by the investment, the employer's share of the social security premium on portions of labor wages corresponding to the legal minimum wage will be covered by the ministry.

Interest Rate Support

Interest support is provided for loans with at least a one-year term obtained within the frame of the Investment Incentive Certificate. The interest/dividend can be covered by the government for the portion of the loan that covers 70% of the investment budget. On 9 May 2014 the 2014/6058 Decision in the 28995 Number Official Gazette further clarified that energy efficiency and waste heat recovery investments are added to the top priority list, and all priority investments will be supported with 5th region incentives (independent of location) under "Incentives and State Grants in Investments Scheme" (see Chapter 3 Table-X for detailed analysis).

References

1. Invest in Turkey, http://www.invest.gov.tr/en-US/investmentguide/investorsguide/Pages/Incentives.aspx.

TABLE D-1. SUPPORT INSTRUMENTS WITHIN INVESTMENT INCENTIVES SCHEMES

Support Instruments	General Investment Incentives Scheme	Regional Investment Incentives Scheme	Large-Scale Investment Incentives Scheme	Strategic Investment Incentives Scheme
VAT Exemption	X	X	X	X
Customs Duty Exemption	X	X	X	X
Tax Reduction		X	X	X
Social Security Premium Support (Employer's Share)		X	X	X
Income Tax Withholding Allowance *		X	X	X
Social Security Premium Support (Employee's Share) *		X	X	X
Interest Rate Support **		X		X
Land Allocation		X	X	X
VAT Refund***				X

**Provided that the investment is made in Region 6.*

***Provided that the investment is made in Regions 3, 4, 5, or 6 within the framework of the Regional Investment Incentives Scheme.*

****For construction expenditures of strategic investments with a minimum fixed investment amount of TL 500 million.*