
by

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# Table of Contents

**Acknowledgements** ........................................................................................................... 4  
**Abstract** ............................................................................................................................. 5  
**Problem** ............................................................................................................................... 6  
**Objective** ............................................................................................................................. 9  
**Background** ......................................................................................................................... 9  
  Waste-Heat-to-Power Systems .................................................................................................. 9  
  Source and Quality of Waste Heat ............................................................................................ 10  
  Heat Capture Technologies ....................................................................................................... 11  
  Power Generation Technologies ............................................................................................... 12  
**WHtP System Installation at a Cement Plant** ....................................................................... 14  
**Cement Plant WHtP Feasibility Analysis (Methods and Data)** ................. 17  
  Control Case: Cement Plant Costs and Carbon Intensity before ORC Project ................. 18  
  Cost of ORC WHtP System and Resulting Savings ............................................................... 20  
  Internal Rate of Return Calculation ....................................................................................... 21  
  Carbon Dioxide Mitigation Calculation ............................................................................... 22  
  Sensitivity Analyses .............................................................................................................. 22  
**Results** ................................................................................................................................ 24  
  IRR and Carbon Savings ......................................................................................................... 24  
  Savings in Context .................................................................................................................. 25  
**Discussion** ............................................................................................................................ 27  
  Barriers to adoption ............................................................................................................... 27  
  Practical Approaches to Encourage Adoption ....................................................................... 30
List of Figures

Figure 1: Key Industries from DOE Study, by Amount of Useable Waste Heat .................7
Figure 2: Finned Tube Heat Exchanger .................................................................12
Figure 3: Power Generating System manufactured by Turbine Air Systems, Inc. ..........13
Figure 4: View Inside Cement Kiln ........................................................................15
Figure 5: View Outside Cement Kiln .....................................................................15
Figure 6: Schematic of Clinker Cooler ..................................................................15
Figure 7: Schematic Identifying Tow Sources of Waste Heat from Cement Plant ....15
Figure 8: Schematic of Organic Rankine Cycle Installation at Industrial Plant ..........16
Figure 9: Variable Costs for Typical 1MM TPY Cement Plant ..................................19
Figure 10: Example Breakdown for CO₂ Emissions from a Cement Plant ..............19
Figure 11: eGrid Regional Map ...............................................................................23
Figure 12: Feasibility Analysis Model Results ..........................................................24
Figure 13: Net Savings from WtP for a Typical 1MM TPY Cement Plant .................26
Figure 14: CO₂ Emissions Savings resulting from WtP System at a Cement Plant ...26
Figure 15: Average WtP Generation Capacity per Site (MW, estimated) .....................29

List of Tables

Table 1: Key Industries from DOE Study .................................................................7
Table 2: Options for Heat Recovery via Power Generation .......................................13
Table 3: Control Case Parameters for Plant (before WtP System Installed) .............18
Table 4: Feasibility Analysis Parameters for ORC Plant ........................................20
Table 5: Components of Internal Rate of Return Calculation ...............................21
Table 6: Parameters Defining Sensitivity Analyses ...............................................23
Acknowledgements

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Abstract

The United States Department of Energy ("DOE") highlighted in 2008 the existence of nearly 1.5 quadrillion British Thermal Units ("QBtu", or "quads") of harvestable waste heat from eight key domestic industries. The key industries contain tens of thousands of industrial locations where waste-heat-to-power ("WHTP") systems could be installed, but less than 50 such systems have been installed at MW-scale to-date. To better understand the factors limiting adoption, this project conducted a detailed feasibility analysis of a hypothetical WHTP system at a cement plant. The feasibility analysis utilized a financial and engineering model that calculated the internal rate of return ("IRR") for the project and the metric tonnes of carbon dioxide (CO₂) mitigated by the system. Key inputs to the model included (i) cost of grid electricity, (ii) carbon-intensity of grid electricity, (iii) cost of the WHTP system, and (iv) power generating capacity of the system. The analysis considered how results would vary geographically as (i) cost and (ii) carbon-intensity of grid electricity varied across 6 randomly-selected U.S. locations. IRRs varied from 4.3% in Washington State to 18.6% in California. Carbon mitigation potential varied from 7,638 metric tonnes of CO₂ per year in California to 16,773 metric tonnes of CO₂ per year in South Carolina. Even though positive, the relative magnitude of these results is small – power costs savings represent less than 5% of annual plant costs and emissions reductions address only 2% of annual plant CO₂ emissions. The project concludes by discussing in detail barriers to adoption for WHTP systems, including (i) small relative magnitude of financial and carbon savings from such projects and resulting lack of demand from customers, (ii) irrationally-inflated perception of operational and financial risks among potential customers, and (iii) small number of legitimate WHTP system opportunities due to the diffuse nature of most waste heat point sources. Finally, the paper suggests approaches to overcome these barriers, including (i) creative business models using third party management and financing, (ii) construction of demonstration systems to prove that irrationally-inflated perception of operational risks is unfounded, and (iii) additional research and development regarding power conversion technologies, to lower the costs, and therefore increase the IRRs, of WHTP systems.
Problem

The DOE released in 2008 a summary report that detailed the significant potential to recover waste heat from industrial processes in the U.S.A\(^1\). The study suggested that generally between 20% and 50% of the 20 Quadrillion Btu ("QBtu")\(^2,3\) of the energy input used by industrials is wasted, so the opportunity for waste heat capture is massive. The DOE analysis focused attention by identifying eight industries (see figure and chart, next page) that offered the most-concentrated waste heat opportunities, and suggesting in summary that approximately 1.5 QBtu/year of wasted heat could be practically harvested from these industries\(^4\). The report also highlighted the thermodynamic processes that already exist today to convert such wasted heat – if it can be captured – into power. Given conservative assumptions, the 1.5 QBtu mentioned above could be mathematically assumed to create approximately 7.5GW of power generation capacity\(^5\).

The appeal of capturing this wasted thermal energy and re-purposing it onsite at an industrial only grows with time, for two main reasons: (i) increasing energy costs, and (ii) the need to abate carbon emissions. As energy costs increase, it becomes more costly to create Btus or power, and it therefore becomes more attractive to spend money on systems to capture and reuse waste heat. Separately, as pressure from emission regulators increases, industries fall under increasing scrutiny from regulatory institutions and

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3 Note: 20QBtu is the amount of thermal energy consumed by industrial users. This number is reported on page 37 of the Annual Energy Review, and does not include an additional approximately 10 QBtu of energy that is consumed as electricity, which is shown on page 3 of the Annual Energy Review.
4 The estimate of 1.5 QBtu per year was estimated in the Choate / DOE Waste Heat paper according to a 77°F reference case.
5 7.5GW estimate generated by the following arithmetic: assumed 15% efficiency converting thermal energy to electrical energy, resulting in 65 million MWhs, which is equivalent to 7.5GW of baseload capacity if spread equally across the 8,760 hours in every year.
Table 1: Key Industries from DOE Study\(^6,7,8,9\)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Waste Heat (TBtu/yr, est.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Boilers</td>
<td>1,170</td>
</tr>
<tr>
<td>Paper Boilers</td>
<td>398</td>
</tr>
<tr>
<td>Chemical Boilers</td>
<td>316</td>
</tr>
<tr>
<td>Food Boilers</td>
<td>99</td>
</tr>
<tr>
<td>Other Boilers</td>
<td>357</td>
</tr>
<tr>
<td>Cement Mfg.</td>
<td>82</td>
</tr>
<tr>
<td>Iron and Steel Mfg.</td>
<td>79</td>
</tr>
<tr>
<td>Ethylene Crackers</td>
<td>61</td>
</tr>
<tr>
<td>Glass Mfg.</td>
<td>43</td>
</tr>
<tr>
<td>Metal Casting</td>
<td>33</td>
</tr>
<tr>
<td>NatGas Pipeline Compressors</td>
<td>17</td>
</tr>
<tr>
<td>Aluminum Mfg.</td>
<td>9</td>
</tr>
<tr>
<td><strong>TOTAL Waste Heat</strong></td>
<td><strong>1,500 TBtu</strong></td>
</tr>
<tr>
<td><strong>Power Equivalent</strong></td>
<td><strong>7.5GW</strong></td>
</tr>
</tbody>
</table>

environmental groups to curb their CO\(_2\) emissions. As a result, the concept of using a waste-heat-to-power ("WHtP") system to mitigate fuel- and power-related emissions liabilities has become more attractive to industrial customers. The DOE report, and other related reports, suggest that investing in a WHtP system at a large industrial site can indeed (i) reduce overall energy costs with an attractive payback period, and (ii) mitigate meaningful amounts of CO\(_2\) emissions.

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9 Note that the table and chart listed on this page represent data that was combined from the three studies listed in the footnotes above. The combination was conducted by the author of this paper to provide a more-holistic picture of the waste heat related opportunity.
Unfortunately, however, waste-heat-to-power ("WHtP") projects have only been built in very small numbers to date, even though enthusiasm has existed for some time (both before and after the DOE report) around the idea. In 2008, Greentech Media referred to the concept of WHtP as, “America’s secret power source”, but cited the difficulties in capturing waste heat in an economical manner.\textsuperscript{10} Separately, tens of millions of dollars have been invested via venture capital over the last few years in companies that are aiming to capitalize on this opportunity. However less than 50 WHtP plants that are megawatt-scale or greater have been installed domestically to date, according to an industry advocacy organization\textsuperscript{11}.

Some authors have hypothesized as to why there more systems haven’t yet been installed. Obvious potential reasons include: (i) the need for the cost of WHtP systems to be reduced significantly, (ii) the fact that grid-based power is very cheap and very reliable, and therefore a preferential source of power when compared to a stand-alone, self-managed WHtP system, and (iii) the lack of education related to the potential benefits of WHtP systems among potential industrial customers. Less obvious reasons include, (i) the fear that the systems may reduce the operating efficiency of the industrial plants by distracting workers and requiring more operational staff, (ii) the concern that financial returns may not be as strong as advertised given the significant investment in needed in such a system – often $10MM+, and (iii) the worry that installation and maintenance may increase the annual downtime for the industrial plant under consideration. These hypotheses will be explored in more detail in this paper in an attempt to explain the disconnect between the massive opportunity outlined above and the lack of projects being installed domestically.


\textsuperscript{11} Southerland, Kelsey. Heat is Power Association. Personal interview via e-mail. 19 March 2012.
Objective

The goal of this project is to better understand why WHtP systems are not being installed domestically. In order to accomplish this goal, a cement plant WHtP system was selected for a feasibility analysis for two specific reasons: (i) as shown in Figure 1 on page 7, the cement industry is one of the largest waste heat sources identified by the DOE study, and (ii) WHtP systems have been installed at cement plants in countries abroad\textsuperscript{12,13,14} but not been in the U.S. If private capital was deployed abroad to pay for WHtP systems abroad, a clear business rationale must have existed to justify those investments. Therefore an analysis of a similar, hypothetical system here in the U.S. was chosen in an attempt to reveal factors that could be limiting the broader domestic rollout of WHtP systems at both cement plants and the other key industries identified above by the DOE.

Background

Waste-Heat-to-Power Systems

WHtP systems require three main components to be viable: (i) an accessible and capture-able source of waste heat, (ii) a technological approach for capturing the heat, and (iii) a technological approach for converting the captured thermal energy into electrical power. Such a system may seem straightforward because it is similar to the traditional, steam-cycle approach used at thermal power plants for the last 100+ years. However, the complexities related to WHtP systems make generating power from waste heat anything but straightforward due to the fact that the heat source is not intentionally created (and,

\textsuperscript{12} "US$18.6 M waste heat-to-energy power plant to be built in CEMEX plant in the Philippines". Cemex, Inc. press release. Released 20 March 2012. Web. 28 March 2012. \\
\textsuperscript{13} Sharma, R.A. Co-Generation & Success Story In Indian Cement Industry. Web. 15 February 2012. \\
therefore, engineered and processed) for the purpose of generating electricity. Instead, WHtP systems must capture heat from existing industrial plant systems and processes, and doing so can be difficult. The following paragraphs explain each of the three components in greater detail in an attempt to inform the reader about the physical requirements for a WHtP system to successfully integrate within and industrial plant. In turn, these physical requirements will be discussed as one of the potential factors that may be limiting demand from industrial customers such systems.

Source and Quality of Waste Heat

Industrial waste heat must be practically capture-able at relatively high temperatures in order to be useful. The requirement for practical capture-ability reflects the need for the waste heat source to be concentrated. For example, the high temperature flue gasses at a cement plant provide a concentrated source of heat that can be accessed and captured via the smokestack. On the other hand, other industrial plants dissipated heat in a much more diffuse manner (e.g., as finished products cool on a factory floor, heat lost from the sidewalls of furnaces, etc.). When the heat is difficult to capture it isn’t useful for WHtP systems.

Waste heat must also be high quality, both in terms of temperature and cleanliness, to be useful for WHtP. The need for high temperature speaks to the fact that the work potential of such systems increase in direct correlation with the temperature differential between the captured, useable waste heat and the ambient air. In thermodynamic terms, the need for high temperatures is illustrated by the equation below for the maximum Carnot efficiency of a system:

\[
\text{Maximum Carnot Efficiency: } \eta_{\text{max}} = 1 - \frac{T_c}{T_h}
\]

Carnot efficiency measures the efficiency with which thermal energy can be converted to useable work, and the efficiency of a system will increase as the \( T_h \) of
the system increases, assuming $T_c$ is constant (i.e., ambient air). The concept of Carnot efficiency suggests that low waste heat temperatures may not generate enough work potential to drive a WHtP system. Additionally, if waste heat streams are dirty (e.g., chemically corrosive, etc.), they will obviously be difficult to use. Of note, the DOE study mentioned above highlighted only industries where the waste heat met the requirements described in this paragraph: capture-able, high temperature, and clean.

**Heat Capture Technologies**

Heat capture technologies physically harvest the useable waste heat so the corresponding WHtP system can convert the thermal energy to electrical power. These technologies can take many forms: one common approach is a finned-tube heat exchanger (i.e., a similar system used in a car’s radiator). An example of an industrial-scale, finned-tube heat exchanger is shown below. Other examples include furnace regenerators or heat wheels that cycle heat-sink materials (e.g., ceramics) into and out of a waste heat stream. These technologies act as important intermediaries in WHtP systems by transferring Btus from the captured waste heat to a power generation system. In the context of this project, it is important to realize that useable waste heat is not actually useable unless a heat capture system can be incorporated into the industrial plant to capture and transfer the Btus.
Power Generation Technologies

Power generation technologies take the captured Btus and convert them into electricity. This final component of the WHTP system can take many forms, and the table on the following page outlines the main technologies for WHTP generation. Importantly, operating such a power generation system is equivalent to having a power plant onsite at the industrial plant, and can require complicated engineering and construction related to integration and balance of plant. Even if a WHTP system is largely automated, its presence can add additional operational responsibilities to the industrial plant managers. Therefore, the ease of use for such systems must be considered when considering impediments to broader adoption of WHTP projects.

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Table 2: Options for Heat Recovery via Power Generation

<table>
<thead>
<tr>
<th>Thermal Conversion Technology</th>
<th>Temp. Range</th>
<th>Typical Sources of Waste Heat</th>
<th>Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Steam Cycle</td>
<td>M,H</td>
<td>Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces.</td>
<td>$1,100 to $1,400/kW</td>
</tr>
<tr>
<td>Kalina Cycle</td>
<td>L,M</td>
<td>Gas turbine exhaust, boiler exhaust, cement kilns</td>
<td>$1,100 to $1,500/kW</td>
</tr>
<tr>
<td>Organic Rankine Cycle</td>
<td>L,M</td>
<td>Gas turbine exhaust, boiler exhaust, heated water, cement kilns</td>
<td>$1,500 to $3,500/kW</td>
</tr>
<tr>
<td>Thermoelectric Generation</td>
<td>MH</td>
<td>Not yet demonstrated in industrial applications</td>
<td>$20,000 to $30,000/kW</td>
</tr>
<tr>
<td>Piezoelectric generation</td>
<td>L</td>
<td>Not yet demonstrated in industrial applications</td>
<td>$10,000,000/kW</td>
</tr>
<tr>
<td>Thermal Photovoltaic</td>
<td>MH</td>
<td>Not yet demonstrated in industrial applications</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Literature review suggests that the most common approach for WHtP power generation in the cement industry is the organic Rankine cycle ("ORC"). Therefore, the feasibility analysis described later in this paper evaluates an ORC system. An example of an ORC system is shown in the figure below.

Figure 3: Power Generating System manufactured by Turbine Air Systems, Inc.  

WHtP System Installation at a Cement Plant

A WHtP system installed at a modern cement plant would harvest waste heat from both the clinker cooler and the preheater exhaust streams to maximize its effectiveness. The following paragraphs describe (i) how such a system would be integrated into a cement plant’s workflow, and (ii) how an organic Rankine cycle could be used to turn the captured waste heat into power. These descriptions are offered here to provide appropriate background before the feasibility model is described in the next section of the paper.

Cement Plant Workflow

Portland cement plants create cement by heating a mixture of clay and limestone at extremely high temperatures (up to 2,000°C). The first source of waste heat from the process is the hot air that exists the rotary kiln where the mix is heated convectively – significant waste Btus are still present in exhaust air. This hot air is often used to preheat the incoming mix of raw materials, but still can be as hot as 400°C when leaving the preheater\(^\text{18}\). The second source of hot air comes from the portion of the plant is used to cool the finished cement product, called clinker. This “clinker cooler” generates significant waste heat because air is blown over the molten limestone/clay mix to cool it quickly – immediate cooling is a key part of the cement manufacturing process.

The next page contains four pictures that illustrate the workflow described above:

1) Cement kiln from the inside, while being fired
2) Cement kiln from the outside, showing the smokestack and preheater tower
3) Schematic of a clinker cooler, including identification of waste heat source
4) Schematic of manufacturing process, indentifying sources of waste heat

Organic Rankine Cycle WhtP System

The Organic Rankine Cycle (“ORC”) is the generation technology most often used in WhtP systems at cement plants. The ORC is a derivation of the traditional Steam Rankine Cycle that is used at most thermal (e.g., coal-fired) power plants. In Steam Rankine Cycles, water is used as the working fluid and is converted into high-temperature, high-pressure steam to generate power. After leaving the generator,

the steam is then cooled and condensed and the cycle starts again. Temperatures required to drive this process can be as high as 700°C\textsuperscript{23}. However, the temperature range of waste heat from cement plants (e.g., 400°C) is not sufficient to drive such generation if water is the working fluid in the system. If an organic fluid with lower boiling point is used instead, however, the Rankine cycle can still hold and power can be generated with efficiency up to 20\%\textsuperscript{24}. Organic working fluids allow the Rankine Cycle to be driven by waste heat temperatures as low as 100°C\textsuperscript{25}. Therefore, the Organic Rankine Cycle is well suited for cement plants.

The schematic above shows how an ORC system would be installed at a cement plant. Of interest, the ORC power plant is shown to be a stand-alone unit that is dis-


\textsuperscript{24} Examples of organic fluids used in these types of systems are n-pentane, benzene, and toluene


integrated from the plant - the only interaction with the industrial process is the heat exchanger within the waste heat stream, also referred to as the intermediate cycle (show in orange coloring in the schematic). This disintegration illustrates how similar WHtP systems could be installed at many other industrial plants across the U.S. The only custom work that would be required for installation at each plant would be the integration of the intermediate cycle into the plant’s waste heat stream.

Cement Plant WHtP Feasibility Analysis (Methods and Data)

This analysis used a financial and engineering model to evaluate (i) financial data related to costs, benefits, and investment returns, and (ii) amount of carbon mitigation that could be attained by the WHtP system at the cement plant. To better understand the quantitative results, an interview was conducted with a cement plant manager from a major Portland cement production company. He provided industry-specific knowledge about (i) how a WHtP system would be installed and staffed within his plant, and (ii) how a purchase decision for such a system might be made by his corporation. Outputs from the analyses, and learning form the interview, allowed for clear understanding of what may be hindering the broader rollout of WHtP systems among industrial customers. These key takeaways will be discussed in the Results and Discussions sections later in this paper.

The following section describes in detail how the model was built. The data used to define the control case (i.e., before a WHtP system was installed) was attained from the interview with the cement plant manager. The subsequently feasibility analysis of the WHtP system was based on data that came from significant literature review and primary research. Sensitivity analyses were included in the model (described later in this section) to examine
how the base-case outputs from the feasibility and would vary geographically as grid electricity price and carbon intensity varies from region to region.

**Control Case: Cement Plant Costs and Carbon Intensity before ORC Project**

The control case for evaluating an ORC WHtP system was defined as a “typical” cement plant, with “typical” revenues, variable costs, and fixed costs. Industry professionals define the “typical” plant as producing one million metric tons (1MM tonnes) of Portland cement per year\(^{27}\). Of course, there is no such thing as a “typical” plant, and performance characteristics, cost of inputs, and efficiency will vary from plant to plant. That said, the analysis contained herein will allow for directionally correct, if not perfectly accurate, evaluation of an ORC WHtP system, and the results of the model will be useful for generating insights. The control case characteristics are defined as follows:

**Table 3: Control Case Parameters for Plant (before WHtP System Installed)**\(^{28,29}\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td>1MM tonnes production capacity per annum</td>
</tr>
<tr>
<td><strong>Electricity Demand</strong></td>
<td>Electricity demand for process = 80kWh/tonne; at 95% capacity utilization, this equates to a run-rate baseload demand of 8.67MW</td>
</tr>
<tr>
<td><strong>Exhaust gas Temperature</strong></td>
<td>Exhaust gases assumed to be 400˚C (i.e., enough temperature and mass flow rate to drive an ORC WHtP system)</td>
</tr>
<tr>
<td><strong>Costs of Production</strong></td>
<td>Variable Costs = $40MM per year&lt;br&gt;30% = Fuel for kiln&lt;br&gt;23% = Production costs (i.e., labor, raw materials, etc.)&lt;br&gt;21% = Maintenance costs&lt;br&gt;&lt;strong&gt;12.5% = Power for process&lt;/strong&gt;&lt;br&gt;14% = Overhead and Other</td>
</tr>
<tr>
<td><strong>Carbon Intensity of Plant</strong></td>
<td>Carbon intensity = 1 tonne CO(_2) per tonne clinker; = 1MM tonnes CO(_2) per year per plant. CO(_2) emissions break down as follows:&lt;br&gt;52% from chemical reaction related to limestone treatment&lt;br&gt;42% from fuel burned in the kiln&lt;br&gt;&lt;strong&gt;6% from electricity consumption&lt;/strong&gt;</td>
</tr>
</tbody>
</table>

\(^{27}\) Cement Plant Manager. Personal interview. 25 March 2012.  
\(^{28}\) ibid  
The following two charts provide a visual representation of the control case parameters related to operating costs and carbon emissions for the plant.

Two parameters above are most relevant to the feasibility analysis for a WHtP system: (i) annual cost for power used in the production process is assumed to be $5MM/year\textsuperscript{32} and (ii) CO\textsubscript{2} emissions from the electricity consumed onsite, which are assumed to be 6\% of total CO\textsubscript{2} related to cement manufacturing\textsuperscript{33}. The relative magnitude of these costs and emissions illuminates the relative benefit that is offered by WHtP systems, which will be discussed in greater detail later in this paper.

\textsuperscript{30} Cement Plant Manager. Personal interview. 25 February 2012.


\textsuperscript{32} $5MM per year calculation based on the following assumptions: industrial grid average electricity price of 6.6 cents/kWh (according to EIA as of 2011), 95\% up time for the plant per year creating 1MM tonnes of Portland cement, 90 kWh/tonne-klinker, 1MM tonnes per year.

\textsuperscript{33} Choate, William. Energy and Emission Reduction Opportunities for the Cement Industry. (see above)
Cost of ORC WHtP System and Resulting Savings

ORC system costs, and the resulting operational savings at the plant, were compared against the control case defined above. Primary and secondary research suggests that the cost of such a project would be $3MM/MW-capacity\textsuperscript{34,35}, and that the efficiency of the system would allow $\sim$33\% of onsite power usage to be generated by the ORC system\textsuperscript{36}. These data points are, of course, subject to change based on the specificities of each plant and potential ORC WHtP.

The specific inputs that were used in the feasibility model are defined as follows.

<table>
<thead>
<tr>
<th>Table 4: Feasibility Analysis Parameters for ORC Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size and Capacity</strong></td>
</tr>
<tr>
<td>• 3MW</td>
</tr>
<tr>
<td>(i.e., $\sim$33% of the run-rate electrical load for the plant)</td>
</tr>
<tr>
<td>• 97% capacity utilization</td>
</tr>
<tr>
<td><strong>WHtP System Cost</strong></td>
</tr>
<tr>
<td>• $9MM</td>
</tr>
<tr>
<td>• $3MM/MW</td>
</tr>
<tr>
<td><strong>Electricity Savings</strong></td>
</tr>
<tr>
<td>• $1.7MMM per annum</td>
</tr>
<tr>
<td>= 33% of control case electricity bill of $5MM</td>
</tr>
<tr>
<td>• Calculation based on</td>
</tr>
<tr>
<td>\quad o 80kW per tonne clinker (from Table 3)</td>
</tr>
<tr>
<td>\quad o U.S. average price for industrial electricity in Dec 2011 = 6.60 cents/kWh\textsuperscript{37}</td>
</tr>
<tr>
<td><strong>Project Life</strong></td>
</tr>
<tr>
<td>• 15 year life assumed for project (conservative)\textsuperscript{38}</td>
</tr>
<tr>
<td><strong>Operation and Maintenance Costs</strong></td>
</tr>
<tr>
<td>• $90,000 per annum\textsuperscript{39}</td>
</tr>
</tbody>
</table>

\textsuperscript{35} Boerrnerrt, Thomas. Personal Interview. 1 Feb 2012.
\textsuperscript{37} EIA – Electricity – Wholesale Market Data. Available online: http://www.eia.gov/electricity/wholesale/index.cfm. Prices listed are for December 2011 (i.e., latest data available when this report was written).
\textsuperscript{38} Saleeby, John. Personal Interview. 15 March 2012.
\textsuperscript{39} Boerrnert, Thomas. Personal Interview. 1 March 2012
Internal Rate of Return Calculation

Internal Rate of Return ("IRR")\(^\text{40}\) is a financial calculation that best represents the financial return of an investment. The feasibility model calculated the IRR of the project to evaluate the financial attractiveness of the ORC WHtP installation. The following outputs from the financial model were used to calculate the IRR:

**Table 5: Components of Internal Rate of Return Calculation**

<table>
<thead>
<tr>
<th>Project Timeframe</th>
<th>15 years = conservative assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs (one-time; at time T=0)</td>
<td>Cost at T={0} = $9.0MM</td>
</tr>
<tr>
<td>Returns (annually; T=1 to T=15)</td>
<td>Return at T={1, 2, 3,..., 15} = Function of the following elements:</td>
</tr>
<tr>
<td></td>
<td>• Electricity savings = constant at $1.7MM per annum</td>
</tr>
<tr>
<td></td>
<td>• O&amp;M costs = constant at $90,000 per annum</td>
</tr>
<tr>
<td></td>
<td>• Revised tax liability = varies by year, as a function of:</td>
</tr>
<tr>
<td></td>
<td>o Increased profits from electricity savings (taxes go up)</td>
</tr>
<tr>
<td></td>
<td>o Depreciation charge for ORC plant in give year, according to IRS double-declining-balance (&quot;DDB&quot;) schedule (taxes go down, albeit not enough to offset effect from increased profits)</td>
</tr>
<tr>
<td></td>
<td>• Tax Credit, if applicable</td>
</tr>
<tr>
<td></td>
<td>o Political proposals exist for an investment tax credit or a production tax credit to encourage ORC WHtP projects, but legislation has not yet been signed</td>
</tr>
<tr>
<td></td>
<td>o The model was built to accommodate consideration for such tax credits, but this portion of the model is currently “zeroed out”, due to lack of in-place policy</td>
</tr>
</tbody>
</table>

\(^{40}\) A note about IRR: To better understand IRR, the reader should know that the IRR of a stream of cash flows is equal to the discount rate that would make the net present value ("NPV") of those cash flows equal to zero. Separately, from a corporate finance perspective, the discount rate used to evaluate a project is usually equal to the weighted average cost of capital ("WACC") for the firm. As a result, a positive IRR might have a negative NPV, if the IRR for a project is not larger than the discount rate used by the firm to evaluate projects. Any reader must keep this perspective in mind because a positive IRR for a project is not necessarily an indication that the project is attractive to a firm.
Carbon Dioxide Mitigation Calculation

The model also calculates the potential for mitigating CO₂ emissions. This calculation uses data from the Emissions & Generation Resource Integrated Database (“eGRID”), which tracks the regional carbon intensity of electricity (i.e., lbs-CO₂ per kWh). The average carbon intensity for the U.S. grid in 2007 (i.e., the most recent data series available from eGrid) was 1,300 lb. CO₂ per kWh⁴¹.

The model calculates CO₂ emissions reduced (in metric tonnes) as a result of the installation of an ORC project by considering the reduction in electricity used onsite. More specifically, the model was set up to calculate power costs usage at the plant based on a key quantitative assumption: the kWh per ton of clinker consumed by the plant. This number, combined with the eGrid data mentioned above, can be used to calculate the CO₂ emissions per ton clinker due to electricity consumption (i.e., not including emission related to fuel for the kiln and limestone conversion). Subsequently, the emissions reductions can be calculated by (i) estimating the reduction in power demand that will come about due to the WHtP plant (i.e., 33% in this case), and (ii) multiplying that reduction percentage across the annual total for emissions related to power consumption.

Sensitivity Analyses

The IRR and the carbon mitigation amounts will vary with geography. Industrial electricity prices vary by state, and higher prices will therefore lead to larger benefits from installing the WHtP plant – in turn, this will create a higher IRR. Similarly, carbon intensity varies by region (more specifically, by power pool⁴²), and the carbon savings will be higher in “dirtier” regions. The model therefore included a sensitivity analysis that evaluated the magnitude

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⁴² Powerpools are regional distinctions within the electrical grid, and each power pool’s carbon intensity is a result of the mix of fuels used for electrical generation within the pool.
of these changes across six diverse regions within the U.S. The table and figure below show the inputs that were used for the six regions.

Table 6: Parameters Defining Sensitivity Analyses

<table>
<thead>
<tr>
<th>State</th>
<th>e- Price (cents/kWh)</th>
<th>C intensity (lb-CO₂/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX</td>
<td>5.91¢</td>
<td>1,252.57 (ERCT)</td>
</tr>
<tr>
<td>CA</td>
<td>9.73¢</td>
<td>681.01 (CAMX)</td>
</tr>
<tr>
<td>SC</td>
<td>5.90¢</td>
<td>1,118.41 (SRVC)</td>
</tr>
<tr>
<td>AL</td>
<td>6.64¢</td>
<td>1,495.47 (SRSO)</td>
</tr>
<tr>
<td>NY-Upstate</td>
<td>7.16¢</td>
<td>683.27 (NYUP)</td>
</tr>
<tr>
<td>WA</td>
<td>4.10¢</td>
<td>858.79 (NWPP)</td>
</tr>
<tr>
<td>U.S. Average</td>
<td>6.6¢</td>
<td>1299.66 (eGRID)</td>
</tr>
</tbody>
</table>

Figure 11: eGrid Regional Map

Across all the scenarios evaluated, all other inputs were held constant, and the only inputs that were adjusted were carbon intensity and price. The results of the sensitivity analyses are presented and discussed below in the results section.

43 eGRID Subregion Map. Online: https://www.energystar.gov/istar/pmpam/help/eGRID_Subregion_Map.htm
44 EIA – Electricity – Wholesale Market Data. Available online: http://www.eia.gov/electricity/wholesale/index.cfm. Prices listed are for December 2011 (i.e., latest data available when this report was written).
Results

IRR and Carbon Savings

The base-case IRR for the ORC WHtP project, given all the assumptions defined above, was calculated to be 11.3%. The base-case CO₂ mitigation calculated by the model was calculated to be 14,577 tons per year.

The base case scenarios reported above utilized data for the average electricity cost and carbon intensity across the U.S. grid. The previous section described how the model expanded upon the base case results to consider six specific regions within the U.S. via a sensitivity analysis that accounted for geographical variations in electricity cost and carbon intensity. The following chart displays the results of the model base case, and the six additional scenarios evaluated under the sensitivity analysis.

![Sensitivity Analysis Across Six Plant Locations: Project IRR and Tonnes CO₂ Reduced Per Year](image)

**Figure 12: Feasibility Analysis Model Results**
The U.S. Grid (Average) column at the right of the chart represents the results of the base case scenario, as reported above: 11.3% IRR and ~15,000 metric tonnes of CO\textsubscript{2} reduced.

The IRR in California was highest, at 18.6%. The IRR in Washington State was lowest, although still positive, at only 4.3%. The IRR results for the other four cases were predictable, as the IRR declined in direct correlation with declining power prices.

The carbon savings are highest in Alabama, and lowest in California. These results are intuitive, as the savings are directly correlated to the carbon intensity data from eGrid.

**Savings in Context**

The base case IRR for the ORC WHtP project, given all the assumptions defined above, was calculated to be 11.3%. Even though this figure represents an attractive annualized return on a percentage basis, the return is less attractive on an absolute basis. More specifically, the net annual savings of $1.6MM offered by the WHtP system only represents a 4% overall savings when compared to the annual plant operating budget costs of $40MM (please revisit Figure 9 on page 19 for perspective).

The base-case CO\textsubscript{2} mitigation calculated by the model was calculated to be 14,577 tons per year. Even though this figure represents an attractive annualized return on an absolute basis, the return is less attractive on a percentage basis. More specifically, this number of tonnes is equivalent to a 33% reduction of the carbon emissions related to electricity consumption at the cement plant, which is therefore equivalent to a 2% reduction in overall emissions from the plant (please revisit Figure 10 on page 19 for perspective).
The relatively small magnitude of these savings has implications for industrial customer demand (or lack thereof) for WHtP systems. WHtP systems require significant investment (i.e., $9MM base case cost in this model) and risks. If such risks do not lead to statistically significant reductions in cost or emission on an *overall* basis, then plant managers will be reticent to take such risks. The small relative size of the savings is displayed in the two figures below, which mirror Figures 9 and 10 from Page 19. The figures provide a visual representation of a potential limiting factor re: demand for WHtP systems – the savings is just too small to be meaningful. This limiting factor will be discussed further in the next section of this paper.

**Figure 13:** Net Savings from WHtP for a Typical 1MM TPY Cement Plant

(note: this is an updated version of Fig. 9 on page 19)

**Figure 14:** CO2 Emissions Savings resulting from WHtP System Installation at a Cement Plant

(note: this is an updated version of Fig. 10 on page 19)
Discussion

The results of the feasibility analysis suggest that ORC WHtP can have real and tangible benefits. However, in spite of these benefits, ORC WHtP plants are not being installed in significant numbers at domestic cement plants or in other industries. The following discussion will (i) clearly explain the barriers to adoption, and (ii) discuss approaches that may overcome these obstacles.

Barriers to adoption

1. Savings Are Not Significant Enough

   Large scale WHtP ORC projects cost millions of dollars, but the savings they drive are often relatively small with respect to both carbon dioxide mitigation and dollars saved. As a rule, industrial customers will consider all projects that are accretive to their profits, but they will not prioritize such projects for action unless they are convinced that the benefits outweigh the costs. The lack of WHtP installations suggest that potential customers perceive that (i) the potential benefits are not large enough (relative to other potential investments at the firm) to motivate a purchase decision, or (ii) other operational areas are simply higher priority, even though WHtP systems may have attractive financial returns and carbon-mitigating potential.

2. Perceived Risks Are Too Large

   Industrial customers feel that they must hire and train staff to run a power plant on site. For example, a Cement Plant manager at an international cement company stated in an interview that he was concerned that installing a WHtP system would significantly increase his staffing needs. He felt that running a WHtP system is a

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45Cement Plant Manager. Personal interview. 25 February 2012.
non-core activity, and that plant employees may not be able to manage the WHtP system well in addition to their status quo responsibilities. When compared to the reliability and consistence of grid electricity, the risk of the WHtP system is perceived to be high. This barrier to adoption is qualitative, but significant – no matter how attractive a project is financially, potential customers will not pursue the project if they worry that it could compromise the workflow of their plant.

3. WHtP Opportunities Not as Plentiful as DOE Suggests

The DOE study mentioned in the introduction of this report outlined a large opportunity for WHtP in eight key industries. The study did not, however, include data related to the number of sites in each industry across which the WHtP opportunity is distributed. Further research and analysis reveals that some of the industries are comprised of many locations, and that the WhtP opportunity *per site* is relatively small. The chart on the following page reveals this fact by showing the per-site power generating capacity in the eight key industries from the DOE study.

WHtP systems take significant effort to build, whether large or small, and such effort is not justifiable if the power generating opportunity is not significant. Therefore, expectations for the potential number of WHtP systems should be aligned with this reality – there are a limited number of industries with significant WHtP generating capacity per site, and these industries have relatively few sites where such systems could be installed.
Figure 15: Average WHtP Generation Capacity per Site (MW, estimated)\textsuperscript{46,47,48,49}

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline
Potential Power Gen Per Site (MW) & Ethylene Crackers & Iron & Steel Mfg. & Cement Mfg. & Glass Mfg. & NatGas Pipeline Compressors & Paper Industry & Metal Casting & Food Boilers & Other Boilers & Chemical Boilers & Aluminum Production & Total Power Gen Potential (MW) \\
\hline
6.8 & 3.5 & 3.0 & 1.9 & 0.8 & 0.6 & 0.2 & 0.1 & 0.1 & 0.1 & 0.0 & & 306 & 396 & 412 & 216 & 83 & 1,995 & 45 & 1,587 & 1,791 & 166 & 499 \\
\hline
Number of Sites & 45 & 113 & 135 & 115 & 100 & 3,460 & 300 & 11,980 & 16,935 & 2,190 & 10,610 & & \\
\hline
Total Power Gen Potential (MW) & 306 & 396 & 412 & 216 & 83 & 1,995 & 45 & 1,587 & 1,791 & 166 & 499 & & 1.4 GW potential* & ~500 sites & 6.1 GW potential* & ~45,000 sites \\
\hline
\end{tabular}
\end{center}


\textsuperscript{49} The arithmetic used to define the generating capacity per site was as follows: estimates were generated by assuming 15% efficiency converting thermal energy to electrical energy, resulting in MWhs, and then converted to MW of baseload capacity if spread equally across the 8,760 hours in every year.
Practical Approaches to Encourage Adoption

1. New Business Models Including Third-Party Involvement

Some industrial customers are reticent to install WHtP systems due to perceived risk and concern about distractions from current plant operations. If a third party was allowed to (i) finance, (ii) install, and (iii) manage the WHtP system, these obstacles could be overcome. Of course, the industrial host of the project will only allow a third party to install a WHtP system onsite if the industrial host is incentivized to do so (i.e., due to provision of discounted electricity by the third party, or a similar incentive). And, such an arrangement would require clear contractual agreements regarding management and cash flows. However, such an arrangement could potentially overcome the hesitation among industrial customers and lead to the successful installation and commissioning of many WHtP systems.

2. Demonstration Plants

WHtP systems are reported to operate with minimal oversight and maintenance, but industrial customers still worry about the risk from such systems related to (i) causing plant downtime, and (ii) causing a significant distraction for plant staff. To address these worries, example WHtP systems should be commissioned and operated here in the U.S. to provide a performance record to the contrary. As these demonstration systems build a record of successful and trouble-free operation, industrial customers will lower their perceived risk profile of such systems.

Private investors are unlikely to put millions of dollars to risk for the purpose of a demonstration project. As a result, government funding or self-funding by WHtP system providers may be necessary to increase the number of demonstration plants.
3. Research to Lower the Cost of WHtP Systems and/or Higher-Cost Grid Electricity

The decision to buy and install a WHtP system is clearly a cost-benefit tradeoff. Although this feasibility analysis shows a positive IRR for all regions of the country, it is clear from the lack of current WHtP installations the IRRs are not high enough to attract customers at this time. As the sensitivity analysis shows, higher electricity costs in the model lead to a higher IRR. Moreover, IRRs will increase if the cost of the system, and therefore the initial investment, goes down. Additional research and development on WHtP systems can potentially lower the costs of these systems. As the cost of the systems comes down, or the cost of grid electricity goes up, the demand for WHtP systems will increase.