Improving Energy Efficiency
(Turning Wasted Heat into Cash Flow)

by

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Abstract

The following gaps in critical goals are derived through a direct comparison of the Needs to Goals transformation versus the current waste heat recovery solutions and their stated goals.

1. Critical: Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery
2. Critical: Deployment of waste heat recovery strategies for reducing greenhouse emissions

A proposed solution to achieve these two goals would be:

1. Purchasing waste heat from industries.
2. Storing this energy with our proprietary thermal storage materials.
3. Selling the stored energy at either industrial sites or to pricier markets.

New thermal-storage materials and a mini-sized combined heat and power (CHP) system have been further developed. This system will be the first to involve the arbitrage of waste heat energy by using cheap thermal storage material (made with zero greenhouse emissions) and a mini generator. This system could play an important role in providing economic incentives for industries that wish to recover waste heat.

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Chapter 1: Introduction
SCOPE OF PROBLEM

Energy and the environment have been two of the most critical issues facing the U.S. scientific and business communities over the past four decades. The improvement of energy efficiency has been suggested by some (Granade, 2009) (Lester & Hart, 2012) as a priority for a U.S. energy strategy. At present, energy efficiency opportunities are worth more than $130 billion a year to the U.S. economy (Granade, 2009). In the United States, about 60% of energy produced is not utilized (calculated from the Exhibit 1). This unutilized energy often comes in the form of waste heat. In 2013, waste heat energy in the U.S. totaled about 59 Quads, or 517 billion gallons of gasoline, as estimated by the Lawrence Livermore National Laboratory. This waste heat, if utilized, could potentially benefit the U.S. economy to the tune of $1.8 trillion per year (given gas price is $3.5 per gallon).

Exhibit 1: Estimated U.S. energy flow in 2013 by Lawrence Livermore National Laboratory

This figure shows the U.S. energy flow from upstream energy sources (the left of the chart) to downstream energy usages (the right of the chart). In the energy

1 Quad = $10^{15}$ British thermal units (about 1.055 exajoule (EJ) or $1.055 \times 10^{18}$ J) = 8.77 billion gallons of gasoline
usages part, the number 59.0 indicated in the light gray box refers to the amount of unutilized energy, while the number 38.4 in the dark gray box refers to the amount of utilized energy. As the total amount of energy in the downstream energy usages is the sum of both unutilized and utilized energy, the share of the unutilized (or waste) energy over entire downstream energy usage equals $\frac{59.0}{59.0 + 38.4}$, which is 60.6%.

**WHAT IS WASTE HEAT**

Waste heat can be generated either by way of equipment inefficiencies or thermodynamic limitations on equipment and processes or both. We can cite as a good example (BCS, 2008) of this, the reverberatory furnace, a process furnace frequently used in aluminum melting operations. Generally speaking, the temperature of input gases in the reverberatory furnace is around 2,500K\(^1\) while the temperature of immediate exhaust gases in the furnace can stay as high as -1,500K. The exhaust gases have high heat content and carry away as much as 60% of furnace energy input, based on the First Law of Thermodynamics. If the heat of these exhaust gases is cooled by water but isn’t utilized further, this heat can be defined as waste heat.

Examples of waste heat sources (BCS, 2008) are as follows:

- **Combustion Exhaust**
  - Glass melting furnaces
  - Cement kilns
  - Fume incinerators
  - Aluminum reverberatory furnaces
  - Boilers

- **Exhaust gases**
  - Steel electric arc furnaces
  - Aluminum reverberatory furnaces

- **Water cooling**
  - Furnaces
  - Air compressors

\(^1\) $^\circ C = [K] - 273.15; ^\circ F = [K] \times 9/5 - 459.67$
Chapter 1: Introduction

- Internal combustion engines
  - Conductive, convective, and radiative losses from equipment
    - Hall-Hèroult cells
  - Conductive, convective, and radiative losses from heated products
    - Heated coke
    - Blast furnace slag

OBJECTIVES OF THIS THESIS

This thesis would like to explore new ways to improve energy efficiency not only from the perspective of technology but also from a systems point of view, taking into account technological, social and business concerns. The objectives of this thesis are as follows,

- Identify the current situation including barriers to waste heat recovery in U.S. and abroad.
- Describe the quantity and quality of key industrial waste heat sources.
- Suggest new Research and Development (R&D) efforts that can further advance waste heat recovery.
- Develop a product prototype through the application of the above R&D suggestions.

Exhibit 2 summarizes the scope the problem and the way this thesis would like to tackle it. Major energy consumer categories include: industrial, transportation, commercial, and residential. This thesis would like to explore a way to increase energy efficiency by turning waste heat into useful energy. This thesis will focus on proposing a new solution to this problem with high-level analysis and validation.

Exhibit 2: Approaches for addressing waste heat recovery issues in this thesis
Chapter 1: Introduction

Major Energy Consumers

- Wasted Heat 60.60%
- Energy Used 39.40%

Innovation → Energy Recovered
CURRENT SOLUTIONS

Current solutions that deal with the waste heat issue can be divided into the following three categories as follows,

- Developing technologies for re-generating energy from waste heat.
- Increasing the price of electricity.
- Prompting greenhouse gas emissions trading.

An overview of pre-existing literature on major solutions involves in the above three categories reveals the following:

**Waste Heat Recovery Technologies**

Unutilized energy is eventually exhausted in the environment, either dissipating into the atmosphere or into water, in the form of waste heat.

Heat recovery technologies can generally be classified in the following three ways.

1. Recycling energy back into the manufacturing process.
2. Recovering energy for other on-site uses.
3. Using unutilized energy to generate electricity in combined heat and power (CHP) systems.

From an energy-flow standpoint, technologies can also be classified using the following two categories.

1. Passive recovery: Transferring heat from a higher temperature source to a lower temperature stream by various heat exchangers.
2. Active recovery: Upgrading the waste heat from a low temperature (grade) to a higher one, which can generate cheaper electricity on site. These technologies include heat pumps and CHP systems.

Generally speaking, waste heat recovery options can be categorized by dividing temperature ranges into low, medium, and high quality of waste heat (BCS, 2008) sources as follows:

<table>
<thead>
<tr>
<th>Quality of heat sources</th>
<th>1,200°F [649°C] and higher</th>
</tr>
</thead>
</table>

Table 1: Quality of heat sources
Table 2 summarizes the typical sources of low, medium, and high temperature waste heat and their related recovery advantages, disadvantages, and applicable technologies (BCS, 2008). As shown in table 2, technologies for waste heat recovery opportunities depend mainly upon temperature.

### Table 2: Advantages and disadvantages of heat recovery technologies

<table>
<thead>
<tr>
<th>Temp Range</th>
<th>Example Sources</th>
<th>Temp (°F)</th>
<th>Temp (°C)</th>
<th>Advantages</th>
<th>Disadvantages/Barriers</th>
<th>Typical Recovery Methods/Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (&gt;1,200°F) [&gt;650°C]</td>
<td>Nickel refining furnace</td>
<td>2,500-3,000</td>
<td>1,370-1,650</td>
<td>High-quality energy, available for a diverse range of end-uses with varying temperature requirements</td>
<td>High temperature creates increased thermal stresses on heat exchange materials</td>
<td>Combustion air preheat</td>
</tr>
<tr>
<td></td>
<td>Steel electric arc furnace</td>
<td>2,500-3,000</td>
<td>1,370-1,650</td>
<td></td>
<td></td>
<td>Steam generation for process heating or for mechanical/electrical work</td>
</tr>
<tr>
<td></td>
<td>Basic oxygen furnace</td>
<td>2,200</td>
<td>1,200</td>
<td></td>
<td></td>
<td>Furnace load preheating</td>
</tr>
<tr>
<td></td>
<td>Aluminium reverberatory furnace</td>
<td>2,000-2,200</td>
<td>1,000-1,200</td>
<td></td>
<td></td>
<td>Transfer to mid-low temperature processes</td>
</tr>
<tr>
<td></td>
<td>Copper refining furnace</td>
<td>1,400-1,500</td>
<td>760-820</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel heating furnace</td>
<td>1,700-1,900</td>
<td>930-1,040</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper reverberatory furnace</td>
<td>1,650-2,000</td>
<td>900-1,090</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen plants</td>
<td>1,200-1,800</td>
<td>650-980</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Furnace incinerators</td>
<td>1,200-2,600</td>
<td>650-1,430</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass melting furnace</td>
<td>2,400-2,800</td>
<td>1,300-1,540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coke oven</td>
<td>1,200-1,800</td>
<td>650-1,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iron cupola</td>
<td>1,500-1,800</td>
<td>820-980</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium 450-1,200°F [230-650°C]</td>
<td>Steam boiler exhaust</td>
<td>450-900</td>
<td>230-450</td>
<td>More compatible with heat exchanger materials</td>
<td></td>
<td>Combustion air preheat</td>
</tr>
<tr>
<td></td>
<td>Gas turbine exhaust</td>
<td>700-1,000</td>
<td>370-540</td>
<td></td>
<td></td>
<td>Steam/power generation</td>
</tr>
<tr>
<td></td>
<td>Reciprocating engine exhaust</td>
<td>600-1,100</td>
<td>320-590</td>
<td></td>
<td></td>
<td>Organic Rankine cycle for power generation</td>
</tr>
<tr>
<td></td>
<td>Heat treating furnace</td>
<td>800-1,200</td>
<td>430-650</td>
<td></td>
<td></td>
<td>Furnace load preheating, feed/water preheating</td>
</tr>
<tr>
<td></td>
<td>Drying &amp; baking ovens</td>
<td>450-1,100</td>
<td>230-590</td>
<td></td>
<td></td>
<td>Transfer to low-temperature processes</td>
</tr>
<tr>
<td></td>
<td>Cement kiln</td>
<td>840-1,150</td>
<td>450-620</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low 450°F [230°C]</td>
<td>Exhaust gases exiting recovery devices in gas-fired boilers, ethylene furnaces, etc.</td>
<td>150-450</td>
<td>70-230</td>
<td>Large quantities of low-temperature heat contained in numerous product streams.</td>
<td>Few end uses for low temperature heat</td>
<td>Combustion air preheat</td>
</tr>
<tr>
<td></td>
<td>Process steam condensate</td>
<td>130-190</td>
<td>50-90</td>
<td></td>
<td></td>
<td>Steam generation for process heating or for mechanical/electrical work</td>
</tr>
<tr>
<td></td>
<td>Cooling water from:</td>
<td>90-130</td>
<td>30-50</td>
<td></td>
<td></td>
<td>Furnace load preheating</td>
</tr>
<tr>
<td></td>
<td>furnace doors</td>
<td>150-450</td>
<td>70-230</td>
<td></td>
<td></td>
<td>Transfer to mid-low temperature processes</td>
</tr>
<tr>
<td></td>
<td>annealing furnaces</td>
<td>80-120</td>
<td>30-50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>air compressors</td>
<td>150-250</td>
<td>70-120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>internal combustion engines</td>
<td>90-110</td>
<td>30-40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>air conditioning and refrigeration condensers</td>
<td>200-450</td>
<td>90-230</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drying, baking, and curing ovens</td>
<td>90-450</td>
<td>30-230</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hot processed liquids/solids</td>
<td>90-450</td>
<td>30-230</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In table 2, four things worth noting about low temperature heat recovery are:

1. Much of the recovered energy is non-usable.
2. Power re-generation has a low efficiency rate.
3. Energy recovery is often not cost-effective due to acidic condensation and corrosion in heat exchangers, in addition to items 1 and 2.
4. A large quantity of heat at this temperature range is being contained rather than used.

The first three above items lead to higher costs in power re-generation. The cost of power re-generation is usually more than $0.50 per kWh, according to heat recovery experts. Meanwhile, in U.S., the industrial electricity price is around $0.06 per kWh and residential electricity price is around $0.20 per kWh. The higher cost of low temperature heat recovery inhibits industries and residents in their efforts to save the energy and leads to energy waste even though the waste heat still can be recovered by current available technologies.

As can be seen in item 4, a lot of energy is contained in low-temperature heat. This may suggest that huge research opportunities could be further explored at this temperature range.

Electricity Pricing

The price of electricity varies from country to country. Electricity prices depend not only on the type and market price of fuel but on government policies as well. The implementation of a creative pricing policy should include the following,

- The providing of economic incentives for industries to recover more energy from waste heat
- The allocation of subsidies to both users and producers of green energy, such as solar and wind
- The implementation of an electricity supply-and-demand matching system to encourage energy efficiency

For waste heat recovery, policies which favor higher electricity prices assume that manufacturers will benefit from re-generating more electricity from medium or even low temperature waste heat, from which they often lost money at lower electricity prices. Also, higher prices may spur investment in the renovation of old, low-efficiency manufacturing equipment.

Although some studies show higher prices may aid in recovering waste heat and increase energy efficiency, some studies suggest that the regulated electricity price conflicts with free-market principles. Also, the higher electricity price may eliminate competitive advantages for industries internationally due to higher operational costs from pricier electricity. For example, as a result of these policy differences, electricity prices in Europe now are far higher than those in the United States, for industrial and residential users alike. European steelmakers pay twice as much for their electricity as U.S. manufacturers. Residential

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1 Data source: EIA
electricity prices in Germany are presently three times higher than those of the U.S.

Exhibit 2 demonstrates the average price\(^1\) for electricity in different countries/territories worldwide. In the upper chart, the lighter color shows the lower electricity price and vice versa. The numbers for each country are shown in numeric order on the lower chart. As should be evident, prices vary from country to country. For example, the price for electricity in Kuwait averages out to be only 1 cent per kWh in U.S. dollars, but totals as much as 94 cents in Solomon Islands. Worth noting on this chart is the fact that in most countries, the price of electricity is lower than $0.50 per kWh. This represents a key economic threshold regarding low-temperature waste heat recovery. Heat recovery in general tends to only make economic sense when the price of electricity exceeds $0.50 per kWh. When electricity prices are lower than this number, such efforts tend to not be cost effective. However, current costs for recovering electrical energy from low-temperature waste heat are usually higher than $0.50. This may explain why efforts to recover energy from low-temperature waste heat have gone slowly.

Exhibit 3: Worldwide average electricity price

\(^1\) It covers the electricity price in both industrial and residential sectors.
Greenhouse Gas Emission Trading (Cap and Trade)

The policy of Emission Trading, or so-called Cap and Trade, aims to reduce greenhouse gas emissions which are viewed as the primary driver of global warming.

This policy sets a limit (Cap) on the amount of emissions being released into the atmosphere over a given time period. The cap sets a maximum allowable level of greenhouse gas emissions and penalizes companies that exceed their allowance.

In addition, this policy creates a market (Trade) for greenhouse emission allowances. This gives economic incentives to companies, allowing them to meet their allocated “Cap”, as the less they emit, the more they can earn from the market. For example, some companies will find it easy to reduce their emissions to meet their cap quota and can then sell their remaining allowance to other companies who need it. Supporters of this policy believe that implementing Cap and Trade can lead to more cost-effective greenhouse gas cuts and also create incentives for investing in cleaner technology.

Many EU countries have supported and implemented Cap and Trade policies, some over a ten-year time period. Most (Germany excepted) experience a modest drop in greenhouse gas emissions. The U.S., however, has demonstrated that Cap and Trade is not the only way to go. The country has achieved greater success than the EU countries by utilizing non-Cap and Trade methods. We may conclude from this information that Cap and Trade policies can serve a useful purpose but other methods and policies must be considered as well.

WASTE HEAT ENERGY: INNOVATION OPPORTUNITIES

Currently available methods for dealing with the above-mentioned issue are: 1) Developing cheaper technologies for re-generating electricity from low-grade
heat. 2) Increasing the price of industrial electricity. 3) Prompting greenhouse gas emissions trading.

All of these solutions have their advantages. But they do progress slowly, often conflicting with free-market principles or increasing the cost of manufactured goods, which can slow their development in some countries, such as the U.S.

In addition, current solutions to waste heat issues tend to be fragmented. They depend heavily upon case studies and anecdotes with insufficient syntheses of findings.

Based on my previous working experience in the military, and in the consumer goods, software, semiconductor and consulting industries, I learned that innovation in interdisciplinary fields relies heavily both on a deep understanding of a benchmark industry and a systematic understanding of stakeholders’ needs and goals. Therefore, unlike currently used methods, a systematic approach for examining the waste heat challenge will be further explored. Applying system theory tools, such as Systems Architecture, System Dynamics, and Clockspeed-based strategies, we expect the holistic methods of decomposition and re-integration of a system for waste heat recovery solutions could provide researchers different insights for innovating this variegated field.

External analysis: A case study of the semiconductor industry

Introduction

The information technology (IT) industries are among the fastest growing businesses reshaping the current technological, business, and political world. The key part of IT industries is the semiconductor industry. With the advances in semiconductor technologies, computing speed doubles every two years. This growth trend has been observed for more than forty years.

Just as geneticists study the fruit fly to gain insight into the evolutionary paths of all animals, Professor Charles H. Fine (Fine, 1998) suggests system designers in any industry can learn from outside factors: Observing quickly developing industries, which can be likened to industrial fruit flies, could help us better design effective models for new businesses.

I worked in a value-added full-service house for the manufacture of semiconductors with operations in East and Southeast Asia. The company provided both manufacturing equipment and process technologies to its clients. Its business model included machine sales, machine financing, technology transfer, and value added business services (i.e. start up & trouble shooting services, modification & relocation, spare parts support, and training services, etc.

The architecture part in my area of business means both thinking of a product design and development plan that matches a company’s business model and
works out how the plan can be implemented. Herein, “the product” refers to both the machine and its service related businesses. With this experience, I have had the privilege of meeting clients from various disciplines in the semiconductor industry.

The characters of the semiconductor industry

Since semiconductor industries are to a high extent technology and capital driven, the “goals” of an architecture case in the area of business typically are aimed at catching up with the worldwide technology benchmark while averting follow-up capital risks. Currently, most semiconductor industries view the trend of ITRS as a reliable benchmark. Herein, the ITRS refers to the International Technology Roadmap for Semiconductors, which is a fifteen-year assessment of the semiconductor industry’s future requirements, entailing joint efforts by industry, government, universities, and various consortia. In order to stand out in this industry, system designers need to work hard to keep up with contemporary trends, identify each company’s competitive advantage, and then seek strategic partners to reduce potential financial risks.

Based on previous experience, semiconductor industries have found that the ITRS is quite straightforward and matches real world demands. Therefore, architecture ambiguity seems to not be a big concern in this industry.

As for “platform alignment,” the industry adopts a standard clean room as its platform for product design and development. Hardware and services are conducted in a clean room with specific ISO clean room standards (Appendix 1). Figuring out the necessary standards is the only iteration the architecture part has to deal with.

Derived architecture and its system dynamics of the semiconductor industry

Unlike cost leadership, technology leadership plays an important role in the evolution of system architecture in my area of business. Herein, technology leadership means a competitive advantage which requires firms to compete on an ITRS, while averting follow-up capital risks.

Although cost is not an important factor in the semiconductor industry, the benefits from this industry are still huge. Revenues, which are expected to reach $348 Billion1 in 2015, would be due to companies’ business models stimulating and fulfilling customers’ strong demands.

Last but not least, social factors play important roles as well in moving this industry forward. For example, as the manufacturing scales of the semiconductor being reduced (presently they are in the nano meter scale), the regulations for environmental safety concerns must be followed and updated over time.

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1 Information credit: www.gartner.com

Based on the above observation, the semiconductor industry’s high-level architecture intangibles can be visualized in Exhibit 4. Three drivers, including technological, business and social, are postulated in Exhibit 4 to form a dynamic system\(^1\) driving the industry and other societal advances moving forward over time. Analogizing these as three wheels interacting with each other, social, technological, and business architecture cases form a feedback loop. The faster the loop runs, the faster the semiconductor industry (or societal advances) moves forward. If any wheel (or driver) cannot keep up with the speed of the others, the wheel will be the bottleneck slowing down the evolution of the whole system.

Exhibit 4: A holistic point of view for societal advances

Factors of the first pass: external opportunity scans

Based on the above architecture, the semiconductor industry places great emphasis on opportunity/threat scans of new technology through the first pass. The underlying principle of that external environmental scan is that many companies have to form as many strategic alliances so as to be able to survive worldwide technological competition. Indeed, as semiconductor manufacturing processes become more and more sophisticated and expensive as well, the

\(^1\) System Dynamics (SD) is a methodology for framing, understanding, and discussing a complex system. Four factors, including internal feedback loop, flow, stock, and time delay, are usually used in the SD. Herein, this thesis would like to apply high-level factors, i.e. internal feedback loop, and flow, to the waste heat recovery system.
business model of running a vertically- or horizontally-integrated semiconductor company seems to become almost impossible. For example, a new semiconductor foundry may cost up to $11 billion (for a 18 inch fab) with current manufacturing technology, not to mention that the lifetime of each foundry is just about ten years. The huge capital investment required, therefore, encourages companies to seek strategic partners to mitigate potential market fluctuations.

Along with the business case, the technological and social cases of the semiconductor industry evolve with the driver of the first pass: the assessment of the external environment. The external information may come either from the outline of an architecture case, such as technology, regulation, supply chain, customer needs, competitive environment, etc.

Integrated within the framework of Systems Architecture (Crawley, 2007), more detailed system dynamics of the semiconductor industry (and other society advances) illustrate how both business and architecture cases evolve over the first pass in the semiconductor industry is demonstrated in Exhibit 5. Please note, for simplicity purposes, the Systems Architecture depicted in Exhibit 5 includes both the Technological Case and the Social Case mentioned in Exhibit 4.

Exhibit 5: First pass of the evolution of systems architecture – A case from the semiconductor industry

--------- First pass: external opportunity scan

Factors of the second pass: opportunity evaluation

After the first pass, many of the opportunities collected from the systems architecture and business case may not worth following up. Some of these opportunities do not match my company’s core competence; others, in most cases, are because a company can’t afford to possess so many opportunities at the
same time. In the second pass, therefore, system designers evaluate the most promising opportunities.

The evaluation process combines two attributes obtained in the first and second passes, respectively. The first attribute is “attractiveness,” which is quantified by answering the following two questions.

Can the opportunity meet the trend of the roadmap?
Can the opportunity deliver benefits better than presently existing options?

If an opportunity satisfies both of these questions, a “High” will be noted in its “attractiveness” attribute. If only one, a “Low” will be noted.

The second attribute is “success probability,” which is assessed by experienced managers. Exhibit 6 shows the evaluation matrix, where only #1 (upper-left cell) is the best external opportunity, which will later move on to the third pass.

Exhibit 6: Evaluation matrix for the second pass

<table>
<thead>
<tr>
<th>Success Probability</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attractiveness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Low</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The three-iteration chart of the semiconductor industry

Based on the above discussion, the three-iteration chart describing the semiconductor industry is summarized in table 3.

Table 3: The three-iteration chart for the semiconductor industry

<table>
<thead>
<tr>
<th>Item</th>
<th>First Pass</th>
<th>Second Pass</th>
<th>Third Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factors causing the industry to focus on certain items in the first two passes</strong></td>
<td><strong>external opportunity scan</strong></td>
<td><strong>opportunity evaluation</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Architecture Case</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goals</td>
<td>Meet the trend of ITRS</td>
<td>Validate company’s core competence</td>
<td>Evaluate possible strategic alliance scenarios</td>
</tr>
<tr>
<td>Context (whole product, and use)</td>
<td></td>
<td>Make prototypes</td>
<td>Evaluation by lead users</td>
</tr>
<tr>
<td>Architecture (Function, Concept, Form)</td>
<td>Function</td>
<td>Concept</td>
<td>Form</td>
</tr>
<tr>
<td>Technology</td>
<td>Assess technologies</td>
<td>Validate company’s technology strategy in terms of competitive advantage</td>
<td>Acquire the technology by either outsourcing or in-house R&amp;D</td>
</tr>
<tr>
<td>Regulation</td>
<td>Identify regulation</td>
<td>Validate regulation</td>
<td>Update and revalidate regulation</td>
</tr>
<tr>
<td>Legacy/Supply Chain</td>
<td>Identify obvious and latent resources</td>
<td>Manage resources and understand their constraints</td>
<td>Identify company’s core competence</td>
</tr>
<tr>
<td>Platform Alignment</td>
<td></td>
<td></td>
<td>Identify clean room standard</td>
</tr>
<tr>
<td>Plans (Design, Implementation, Operations, Upgrade)</td>
<td>Define customers’ and company’s needs with Business team</td>
<td>First draft finished by Architecture team</td>
<td>Evaluation by business team</td>
</tr>
<tr>
<td>Interface and Architecture Control Plans</td>
<td>Goal setting</td>
<td>Performance diagnosis</td>
<td>Corrective action</td>
</tr>
<tr>
<td><strong>Business Case</strong></td>
<td>Identify needs</td>
<td>Validate needs</td>
<td>Update, and</td>
</tr>
</tbody>
</table>

21
### Chapter 2: Analysis of Current Solutions for Waste Heat Recovery – A Systemic Approach

<table>
<thead>
<tr>
<th></th>
<th>and refine</th>
<th>revalidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Analysis</td>
<td>Identify market and its characteristics</td>
<td>Define market and its characteristics</td>
</tr>
<tr>
<td>Competitive Analysis</td>
<td>Identify competitive products</td>
<td>Characterize your product vs. competitors</td>
</tr>
<tr>
<td>Strategy</td>
<td>Be guided by enterprise strategy</td>
<td>Identify alignment and issues with strategy</td>
</tr>
<tr>
<td>Product Line Alignment</td>
<td>Identify possible product line alignment</td>
<td>Resolve product line alignment</td>
</tr>
<tr>
<td>Channels</td>
<td>Identify likely channels and distribution plans</td>
<td></td>
</tr>
<tr>
<td>Organization</td>
<td>Identify and recruit core team</td>
<td>Identify larger team and consider organization</td>
</tr>
<tr>
<td>Schedule</td>
<td>Develop preliminary schedules</td>
<td>Refine schedules</td>
</tr>
<tr>
<td>Resources</td>
<td>Identify needed space and capital resources</td>
<td>Refine requirements for resources</td>
</tr>
<tr>
<td>Revenue Projection</td>
<td>Preliminary volume estimates</td>
<td>Refine volume and revenue projections</td>
</tr>
<tr>
<td>Earnings and Financial</td>
<td>Prepare preliminary financials</td>
<td>Prepare detailed financial analysis</td>
</tr>
</tbody>
</table>

### Internal analysis: Needs to goals

**Introduction**

A good way to design an effective system is through the process of “needs to goals” (Crawley, 2007). The definition (Crawley, 2007) of “needs,” “goals,” and “stakeholders” could be summarized as follows,

**Needs**

- Needs exist in the hearts and minds of beneficiaries
- They exist outside the enterprise
- They are fuzzy, ambiguous and ill-stated
- They must be identified and understood

Goals

- A goal is what an effective system intends to accomplish
- A goal is what the designer of the system hopes to achieve or obtain

Stakeholder

- A stakeholder is an independent party involved in the system
- A stakeholder often has more than one need to be met by a product system
- There is usually more than one stakeholder in the system

Stakeholders and their needs

- Generation Waste Heat Providers
  - Financial sustainability
  - Safety
- Industrial Waste Heat Providers
  - Maintenance of quality standards and output of original industrial processes
  - Financial sustainability
  - Safety
- Transportation Waste Heat Providers (Autos, Airplanes, Boats)
  - Maintenance of vehicle performance
  - Financial sustainability
  - Safety
  - Comfort
- Commercial Waste Heat Providers (Shopping Malls, Offices)
  - No drop-off of space heating services
  - Financial sustainability
  - Safety
  - Comfort
- Residential Waste Heat Providers (Houses, Apartments)
  - No drop-off of space heating services
  - Financial sustainability
  - Safety
- On-grid Electricity Users (Industrial and Residential)
  - Low costs
  - Stability of electricity supplied
  - Safety

- Off-grid Electricity Users (Battery)
  - Carrying convenience
  - Low cost
  - Safety
  - Adequate supply of electricity when needed
- Industrial Process Heat Users
  - Stability
  - Low costs
  - Safety
- Climate Control Heat Users
  - Low costs
  - Safety
- Co-generators
  - Financial sustainability
  - Safety
- Scientific Researchers
  - Financial sustainability
  - Impact
- Government Funding Bodies
  - Leadership
  - Incentives management
- Environmental Organizations
  - Pollution management
  - Clean energy
  - Climate change preparation
- Departments of Energy
  - Addressing each host country’s specific energy challenges
  - Addressing each host country’s specific environmental challenges
- Voters
  - Paying lower living costs while maintaining same living quality
  - Increase of earnings
  - Enjoyment of a better environment

Stakeholder Goals

Stated Goals

Primary Goal: To improve energy productivity by installing or developing technologies for waste heat recovery.

Other Goals include:

1. Increasing electricity and fuel prices in order to prevent from wasting energy, including waste heat.
2. Reduce waste heat by regulating waste heat amount over time.
3. Reduce waste heat by implementing cap and trade policy.
Derived Goals

In order to critique the architecture, the following Needs to Goals transformation must be performed. This transformation will then be used to derive goals and subsequently identify potential gaps in these goals of waste heat recovery solutions.

Based on the above analysis, there are eighteen major stakeholder needs required to be addressed in this waste heat recovery system. Applying a concept shown in Exhibit 4, all needs are evaluated from three perspectives, i.e. technological, social, and business, seen in table 4.

Table 4: Ranking of Needs

<table>
<thead>
<tr>
<th>Needs</th>
<th>Technological</th>
<th>Social</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial sustainability</td>
<td>Must be</td>
<td>Must be</td>
<td>Must be</td>
</tr>
<tr>
<td>Safety</td>
<td>Should be</td>
<td>Must be</td>
<td>Should be</td>
</tr>
<tr>
<td>Maintenance of quality standards and output of original industrial processes</td>
<td>Must be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance of vehicle performance</td>
<td>Must be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfort</td>
<td>Should be</td>
<td></td>
<td>Must be</td>
</tr>
<tr>
<td>Low costs</td>
<td>Might be</td>
<td></td>
<td>Might be</td>
</tr>
<tr>
<td>Stability of electricity supplied</td>
<td>Must be</td>
<td></td>
<td>Must be</td>
</tr>
<tr>
<td>Carrying convenience</td>
<td>Should be</td>
<td></td>
<td>Must be</td>
</tr>
<tr>
<td>Adequate supply of electricity when</td>
<td>Should be</td>
<td></td>
<td>Must be</td>
</tr>
</tbody>
</table>
### Chapter 2: Analysis of Current Solutions for Waste Heat Recovery – A Systemic Approach

<table>
<thead>
<tr>
<th>Needed</th>
<th>Goal Criticality</th>
<th>Goal Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact</td>
<td>Should be</td>
<td>Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery</td>
</tr>
<tr>
<td>Leadership</td>
<td>Must be</td>
<td></td>
</tr>
<tr>
<td>Incentives management</td>
<td>Must be</td>
<td></td>
</tr>
<tr>
<td>Pollution management</td>
<td>Should be</td>
<td></td>
</tr>
<tr>
<td>Clean energy</td>
<td>Might be</td>
<td></td>
</tr>
<tr>
<td>Climate change preparation</td>
<td>Should be</td>
<td></td>
</tr>
<tr>
<td>Addressing each host country's specific energy challenges</td>
<td>Should be</td>
<td>Must be</td>
</tr>
<tr>
<td>Addressing each host country's specific environmental challenges</td>
<td>Should be</td>
<td>Must be</td>
</tr>
<tr>
<td>Enjoyment of a better environment</td>
<td>Should be</td>
<td>Must be</td>
</tr>
</tbody>
</table>

Goals interpreted from the above needs are then prioritized in the table 5.

Table 5: Needs to Goals and their prioritization

<table>
<thead>
<tr>
<th>Financial sustainability</th>
<th>Goal Criticality</th>
<th>Goal Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Goal</td>
<td>Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery</td>
<td></td>
</tr>
</tbody>
</table>
### Chapter 2: Analysis of Current Solutions for Waste Heat Recovery – A Systemic Approach

<table>
<thead>
<tr>
<th></th>
<th>Goal Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Critical Goal</td>
<td>All solutions to waste heat recovery must be validated and use proven technologies</td>
</tr>
<tr>
<td>Pollution management</td>
<td>Critical Goal</td>
<td>All solutions for waste heat recovery must follow pollution regulations</td>
</tr>
<tr>
<td>Climate change</td>
<td>Critical Goal</td>
<td>Deployment of waste heat recovery strategies for reducing greenhouse emissions</td>
</tr>
<tr>
<td>preparation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability of</td>
<td>Important Goal</td>
<td>To recover electricity by using reliable resources from waste heat</td>
</tr>
<tr>
<td>electricity supplied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact</td>
<td>Important Goal</td>
<td>To increase the amount of waste heat recovery by Y% by year Z</td>
</tr>
<tr>
<td>Enjoyment of a</td>
<td>Important Goal</td>
<td>Raising of awareness of waste heat recovery issues</td>
</tr>
<tr>
<td>better environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrying convenience</td>
<td>Desirable Goal</td>
<td>Considering user-friendly design when product available.</td>
</tr>
<tr>
<td>Adequate supply of</td>
<td>Desirable Goal</td>
<td>Considering high energy density design when such a product is available.</td>
</tr>
<tr>
<td>electricity when</td>
<td></td>
<td></td>
</tr>
<tr>
<td>needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leadership</td>
<td>Desirable Goal</td>
<td>Making a vibrant effort to use technological, social and business as</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cornerstones of national economic growth with clear leadership in strategic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>areas</td>
</tr>
<tr>
<td>Clean energy</td>
<td>Desirable Goal</td>
<td>Recovery of W% more clean energy from waste heat by year T</td>
</tr>
<tr>
<td>Addressing each</td>
<td>Desirable Goal</td>
<td>Establishment of an operational and adaptable framework that utilizes the</td>
</tr>
<tr>
<td>country’s specific</td>
<td></td>
<td>combined wisdom of all department stakeholders to maximize mission success</td>
</tr>
<tr>
<td>energy challenges</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Addressing each</td>
<td>Desirable Goal</td>
<td>Establishment of an operational and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Country’s specific environmental challenges | Adaptable framework that utilizes the combined wisdom of all department stakeholders to maximize mission success |
| Comfort | Desirable Goal | No change of user experience while driving or using space heat |
| Maintenance of quality standards and output of original industrial processes | Desirable Goal | No change of user experience while utilizing current manufacturing processes |
| Maintenance of vehicle performance | Desirable Goal | No change of user experience while driving |
| Incentives management | Desirable Goal | Catalyzing the timely, material, and efficient transformation of the nation’s energy system |
| Low costs | Desirable Goal | Access to electricity at a affordable price |

The key goals identified are:

- **Critical**: Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery
- **Critical**: All solutions to waste heat recovery must be validated and use proven technologies
- **Critical**: All solutions for waste heat recovery must follow pollution regulations
- **Critical**: Deployment of waste heat recovery strategies for reducing greenhouse emissions
- **Important**: To recover electricity by using reliable resources from waste heat
- **Important**: To increase the amount of waste heat recovery by Y % by year Z

- **Important:** Raising of awareness of waste heat recovery issues

**Identified Gaps in Goals**

The key goals identified above show ideal targets for a waste heat recovery system. In examining these goals, Table 6 reveals the discrepancy between ideal and reality.

Table 6: Evaluation of current solutions to waste heat recovery along with derived goals

<table>
<thead>
<tr>
<th>Current Solutions</th>
<th>Waste Heat Recovery Technologies</th>
<th>Electricity Pricing</th>
<th>Cap and Trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>All solutions to waste heat recovery must be validated and use proven technologies</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>All solutions for waste heat recovery must follow pollution regulations</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Deployment of waste heat recovery strategies for reducing greenhouse emissions</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>To recover electricity by using reliable resources from waste heat</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>To increase the amount of waste heat recovery by Y % by year Z</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Raising of awareness of waste heat recovery issues</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

The following gaps in critical goals are derived through a direct comparison of the Needs to Goals transformation versus the current waste heat recovery solutions and their stated goals.

- **Critical**: Implementation of a sustainable financial plan which can help to initiate an increase in waste heat recovery

  This goal is essential to different stakeholders, especially for a self-sustained approach to the waste heat recovery system. By redesigning the system’s missing factor, i.e. business architecture, the whole system could move along much faster. This system can be seen in Exhibit 4.

- **Critical**: Deployment of waste heat recovery strategies for reducing greenhouse emissions

  The goal will be for all stakeholders to work together to take on climate change challenge, which not only affects all stakeholders but future generations as well. Related actions should have good leadership and sound systems thinking.

**System Problem Statement (SPS)**

The system problem statement (SPS) (Crawley, 2007) is defined as a single assertion of a system that is intended to deliver value, representative of real success. It is highly desirable that the above statement be described in a single statement in order to maintain focus and organizational unity.

Our proposed SPS for waste heat recovery system can be seen in Table 7.

<table>
<thead>
<tr>
<th>Proposed SPS</th>
<th>Current SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>To improve energy efficiency and reduce carbon emissions</td>
<td>To improve energy productivity</td>
</tr>
<tr>
<td>By initiating an increase in waste heat recovery</td>
<td>By recovering waste heat energy</td>
</tr>
<tr>
<td>Using financial-sustained solutions</td>
<td>Using technological and/or pricing and/or cap and trade solutions</td>
</tr>
</tbody>
</table>
Identified opportunities: Financial-sustained solutions

Based on the proposed SPS, financial-sustained solutions would be innovation opportunities for improving current waste heat recovery system. Along with the external and internal analysis conducted in this chapter, waste heat recovery solutions should take consideration in not only technological and social sectors, but business sector as a whole as well. Herein, business means financial-sustained consideration. Indeed, today, there are technologies on the market for recovering low-grade waste heat. However, in order to recover this heat, industries need economic incentives for applying such technologies in a practical way. As an example, the price of industrial electricity is about $0.06 per kilowatt-hour (kWh) in the U.S. If electricity re-generated by any other technology were to cost more, industries wouldn’t invest in it.

As we can see, all of current solutions have their advantages. But they do progress slowly, often conflicting with free-market principles or increasing the cost of manufactured goods, which can slow their development in some countries, such as the U.S.

Proposed solution: Energy Arbitrage

Based on the opportunities identified, along with electricity price difference in different market, such as daytime/nighttime and on-grid/off-grid, this thesis would propose a new approach for tackling the waste heat challenge by

- Purchasing waste heat from industries.
- Storing this energy with our proprietary thermal storage materials.
- Selling the stored energy at either industrial sites or to pricier markets.

With buying low and selling high, this proposed solution could take advantage of price difference in two or more markets, providing more economic incentives for all stakeholders to improve energy efficiency and reduce carbon emissions.

The related technologies and use case would be discussed in the next chapter. A market analysis would be conducted as well.
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery
BUSINESS MODEL

Our team has lately been working on a new approach for bridging the gap between waste heat and mobile energy. About 60% of all energy produced is not utilized. Our platform, as proposed, will be the first to involve the arbitrage of waste heat energy by using cheap thermal storage material (made with zero greenhouse emissions) and a mini generator. The resulting stored energy will then emerge in the form of electricity and high-grade heat coming from the mini generator, made with currently available technologies. As the cost of mobile energy is 10,000 times higher than the cost of energy that industries purchase, our solution could play an important role in providing economic incentives for industries that wish to recover waste heat.

We are developing proprietary thermal-storage materials and a mini-sized combined heat and power (CHP) system that can collect and sell waste heat either in different markets or the same one in a different time frame in order to take advantage of price differentials for the same asset. In our approach, electricity and heat re-generated by waste heat will be applied to the following two markets:

1. Industries: Our system can store the waste heat with our proprietary materials and re-generate energy into high-grade heat with our catalytic combustion devices. These devices can be further integrated with on-site steam turbine systems and re-generate electricity when necessary. The cost of this industry system is about $0.04 per kWh. Therefore, the profit is about $0.02 per kWh (assuming industrial electricity price is $0.06 per kWh.)

2. General individual users: The mobile electricity/heat market where costs for electricity and heat generated by batteries can be as high as $600 per kWh (10,000 times higher than the cost of industrial electricity ($0.06 per kWh)). Currently, we are inventing a mini-sized CHP platform that utilizes waste heat for use in both mobile electricity and heating markets. This platform can be essential for industrial designers to create innovative products that address the market needs they find. These use-cases could include: new snow plows, snow shovels, cheaper water heaters for developing countries or products designed for outdoor activities in cold weather, such as snow sports, hunting, camping, and motorcycling. The cost will be about $2 per kWh for this mini-sized platform. The profit will generally be about $18 per kWh (assuming mobile heat and electricity price is $20 per kWh) or $598 (assuming mobile heat and electricity price is $600 per kWh).

The business model is visualized in Exhibit 7.

Exhibit 7: Energy arbitrage business model
WASTE HEAT SOURCE CONCERNED: INDUSTRIAL

There are five waste heat sources:

1. Waste in generation
2. Residential waste
3. Commercial waste
4. Industrial waste
5. Transportation waste

Industrial sector would be the major source to be evaluated by this research.

The amount of waste heat from each source is from 2011 can be seen in Exhibit 8. In Exhibit 8, even though the amount of industrial waste heat is just the third largest since the past four years, we chose this sector for reasons;

1. Energy cost in generation sector (around $0.01 per kWh) is lower than our ($0.04 per kWh). Therefore, it would be difficult practicing arbitrage in the generation sector. Although arbitrage could be practiced between generation and mobile markets, we would like to pass it until our proposed solution could be realized from the industrial sector.

2. Transportation sector is another story. Due to the emerging electric vehicle, and possibility that fossil fuel would running out, the amount of waste heat in this sector would be expected to reduce significantly due to the high energy-work efficiency from battery-powered vehicles.

Exhibit 8: Waste heat sources (unit: Quads)
Electricity prices in different markets

The mobile electricity market is potentially the most valuable one for the proposed solution as shown in Table 8.

Table 8: Electricity prices in different markets

<table>
<thead>
<tr>
<th></th>
<th>On grid electricity</th>
<th>Mobile electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Co-gen</td>
<td>Industrial</td>
</tr>
<tr>
<td>Cost/kWh</td>
<td>$0.03</td>
<td>$0.07</td>
</tr>
</tbody>
</table>

TECHNOLOGIES

Our system will include two major units: 1) A heat storage pack and 2) A generator (for both heat and electricity.) The heat storage pack will store heat in such sources as industrial funnels, and the heat exchangers at solar thermal and geothermal facilities. This pack can also be further developed to be applied to refrigerators and motorcycle exhaust systems. Our proprietary heat storage material in the pack can store thirty times more energy than Lithium Ion batteries of a similar size. Once mounted with the heat-storage pack, the mini generator can generate heat and electricity for mobile use.

The related technologies and performance will be discussed here. However, for patent application concerns, our thermal storage materials would just be shown on some use case without further technological explanation.
Thermoelectric technology

Introduction

Thermoelectric technology can directly generate electricity from heat and vice versa. This technology can further be developed through solid-state energy converters, such as generators or refrigerators. By transforming heat into electricity, thermoelectric technology can convert part of the waste heat energy into electricity and is hence a potential solution for improving energy efficiency. In addition, thermoelectric technology can provide electricity by using a smaller and quieter generator than the traditional thermal one that depends upon moving parts.

Moreover, the thermoelectric technology has a long lifetime and requires low maintenance. For example, the lifetime for the thermoelectric generators that have been used on NASA’s 67 deep space missions totaled more than 30 years (Fleurial, 2009).

Currently, a news item attracting attention is the exploration of Pluto by the New Horizons spacecraft (NASA, 2015). Its electrical power comes from a single radioisotope thermoelectric generator. Since it was launched in 2006, New Horizons’ thermoelectric generator has provided electric power through the natural radioactive decay of plutonium dioxide fuel, which creates a huge amount of heat. Unlike fission-based nuclear reactors, the radioisotope thermoelectric generator simply harnesses the heat it produces and turns it into electricity. The thermoelectric generator is provided by the U.S. Department of Energy and carries approximately 11 kilograms (24 pounds) of plutonium dioxide. Onboard systems manage the spacecraft’s power consumption so it doesn’t exceed the steady output from the thermoelectric generator, which has decreased by about 3.5 watts per year since its initial launch. Typical of thermoelectric-based systems, as on past deep space missions, New Horizons does not have a battery for storing power. At the start of the Pluto mission, New Horizons’ thermoelectric generator supplied approximately 245 watts (at 30 volts of direct current). The spacecraft’s shunt regulator unit maintains a steady input from the thermoelectric generator and dissipates power the spacecraft cannot use at a given time. Presently (July 2015), as the New Horizons spacecraft has reached Pluto, that supply has decreased to about 200 watts at the previously noted voltage (30 volts).

Last but not least, thermoelectric technology is environmentally adaptable. Unlike traditional refrigerators, thermoelectric refrigerators can be operated without compressed gases or chemicals. The following six unique properties (alternative energy efficiency, compact size, silent performance, high reliability, low maintenance requirement, and environmental compatibility) enhance the application opportunities for developing special products that fulfill customers’ needs. These factors create viable business opportunities for the development of thermoelectric technology.
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

Thermoelectric technology attracts a lot of attention from researchers; more than three thousand papers on this topic were published between 2008 and 2011 (Zebarjadi, Esfarjani, Dresselhaus, Ren, & Chen, 2012). Furthermore, recent advances in thermoelectric materials have created higher efficiency in thermoelectric systems. However, identifying strategies for the pursuit of such opportunities is rarely discussed in these publications. Therefore, further research is needed.

Cost of thermoelectric generation

The cost of thermoelectric generation would be around $0.50 per kWh, estimated by a steel refinery company. The breakdown of costs for the thermoelectric generator is shown in Exhibit 9.

Exhibit 9: Breakdown of costs for the thermoelectric generator

<table>
<thead>
<tr>
<th>Breakdown of costs for TEG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Price T.E. Electricity</strong> = <strong>Price T.E. System</strong> + <strong>Price Heat</strong></td>
</tr>
<tr>
<td>$0.50 – 0.52 per kWh</td>
</tr>
</tbody>
</table>

- **Heat** (4%)
- **TEG Integration** (24%)
- **TEG Module** (23%)
- **Labor** (49%)
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

Thermoelectric energy conversions

Thermoelectric energy conversions are emerging energy technologies. With no moving parts or vibration, a thermoelectric generator module (shown in Exhibit 10) can, on the one hand, generate electricity directly from heat flux, thus working as a power generator. This process is known as the “Seebeck effect.” On the other hand, a thermoelectric cooling/heating module (shown in Exhibit 11) can generate a temperature gradient from electrical energy, thus working as a cooler or heater. This process is called the “Peltier effect.”

Exhibit 10: Schematic representation of a thermoelectric generator module

A thermoelectric module is usually computer-chip-sized, with dimensions of 40mm (length) X 40mm (width) X 3.5mm (height). Other common dimensions are 30mm X 30mm X 3.5mm and 56mm X 56mm X 5mm. The power output of each module ranges from several mW up to 20 W.

Exhibit 11: Schematic representation of a thermoelectric cooling module

The dimensions of commercially available thermoelectric cooler/heater modules vary from about 50mm X 50mm X 5mm (height) to around 4mm X 4mm X 3mm. In the future these modules can be even smaller, and the concept of the microcooler can be realized, due to ongoing technological progress.

Device physics
The thermoelectric generator (the Seebeck Effect)

In 1821, Thomas Johann Seebeck, a German physicist, discovered that the junction of two different metals produces an electric current in a closed circuit when exposed to a temperature gradient. Illustrated in Exhibit 12, the Seebeck Effect can be thought of as a circuit built by two different conductors, a and b, which are connected electrically in series but thermally in parallel (Rowe, 2005).

Exhibit 12: Schematic representation of the Seebeck effect; photo credit: (Rowe, 2005)

An open circuit voltage, $V$, is generated between C and D, if the junctions at A and B are maintained at different temperatures, $T_1$ and $T_2$ ($T_1 > T_2$). This phenomenon can be mathematically expressed as:

$$V = S_{ab} (T_1 - T_2)$$

(Eq. 1–1)

Herein, $S_{ab}$ is the Seebeck coefficient between the elements a and b.

Shown in Exhibit 13, a thermocouple, a device that can measure temperature, is a good application of the Seebeck Effect. A thermocouple is typically made from metal or metal alloys. When connected to an electric resistive load, a thermocouple can generate a small amount of voltage when there is a temperature difference between one junction and the other reference junction. The amount of voltage per one Kelvin difference, or Seebeck coefficient, for metals or metal alloys is roughly a few tens of microvolts (Rowe, 2005).

Exhibit 13: Conventional thermocouple; photo credit: (Rowe, 2005)
By using semiconductor materials rather than metals and metal alloys, modern thermoelectric technology has raised the previously mentioned amount of voltage per centigrade to hundreds of microvolts (Rowe, 2005). This makes the application of the thermoelectric generator feasible. For example, NASA adopted thermoelectric generators to provide electrical power from the heat generated from radioisotope decay and nuclear reactors on their missions (Bennett, 2006). The Galileo spacecraft, for instance, was equipped with two 290-Watt thermoelectric generators for its interplanetary mission, the duration of which was too long for fuel cells or batteries, and for which solar power was not sufficient.

There are two types of semiconductor materials, N-type and P-type, which provide free electrons and holes respectively; electrons and holes function as carriers for both charges and heat. The reason why N-type semiconductors can create free electrons to allow an electric current to flow through them is that a small quantity of an impurity with a movable electron in the semiconductor lattice has been added to them. As electrons have a negative charge, the semiconductors are named N-type. On the other hand, in P-type semiconductors, a small amount of an impurity (a so-called “hole”) that can host an additional movable electron is added to the semiconductor lattice to provide a positive charge. A hole attracts an electron from a neighbor, the result of which is that the hole moves over to the space from which the electron originated. This creates the absence of an electron function as a positive charge so the holes can conduct electric current. As holes create a positive charge, the semiconductors are named P-type.

In addition to carrying a charge, holes and free electrons in the thermoelectric semiconductors can carry heat if there is a temperature gradient, where heat transfers from the hot end to the cold end. In other words, in such materials, free electrons and holes carry not only charges but also thermal energy. This can be explained as follows. In thermoelectric semiconductors, the holes and free electrons, i.e. charged particles, move faster in the hot end than in the cold. As the hot particles diffuse more than the cold, they end up having a larger particle number in the cold end. This will result in heat and charges being carried by the

---

1 The thermal vibrations of the atoms in a crystal can also carry heat. However, we’ll forgo further technical discussion here, as phonon conduction and drag are not directly related to this research.
particles from the hot end to the cold end. The gathering of charges in the cold end, therefore, will create electric potential. In the P-type, the free positive charges, i.e. holes, are gathering in the cold end, producing a positive electrostatic force, or positive potential. Likewise, in the N-type, the free negative charges are generating a negative potential in the cold end. Herein, the electric potential, i.e. voltage, induced by the temperature differential will be called the Seebeck Effect.

The concept of a thermoelectric generator with semiconductor materials is depicted in Exhibit 14.

Exhibit 14: Diagram of a thermoelectric generator

The Seebeck effect in semiconductors can be thought of as a circuit built by one N-type and one P-type semiconductor, both connected electrically in series but thermally in parallel. Whenever there is heat flux flowing from the hot junction to the cold, an electric current is generated by this process and flows through the whole circuit.

There are five parts assembled here as a thermoelectric generator. In Exhibit 14, from top to bottom, these parts are: heat source contact material (shown in red), the hot end junction (dark gray), the N- and P-type semiconductors (light gray), the cold end junctions (dark gray), and the low temperature contact material (blue). Heat from the high temperature surface drives both the free electrons (in the N-type semiconductor) and the holes (in the P-type semiconductor) toward the low temperature surface. At the cold end junctions, since there are a positive and a negative electric potential in the P-type semiconductor and N-type semiconductor respectively, an electric current can be generated if there is a metal wire with a load (or electric resistance), connecting both cold junctions. The metal wire creates the closed circuit, where the positive electrical current will flow from the P-type cold junction to the N-type cold junction. Driven by this electric potential, the current will flow through the entire closed circuit from the N-type semiconductor to the hot junction, and from the P-type semiconductor all the way back to the wire again, creating a closed circuit. The thermoelectric
semiconductors shown in Exhibit 14, together with the heat differential, can create a feasible thermoelectric generator.

The thermoelectric cooler/heater (the Peltier Effect)

The thermoelectric generator can use heat flux to force the flow of electrical charges. Inversely, Jean Charles Athanase Peltier, a French physicist, discovered in 1834 that by using two different thermoelectric materials, an external electric potential can force electrical charges to carry heat, driving heat from one end of a thermoelectric device to another. In other words, when an electric current is applied, the thermoelectric materials can function as a heat pump moving heat away from one end, where heat is absorbed, to the other, where heat is dissipated. The first is the cooling side because the heat there will be transported by electric charges to the other end where the heat has accumulated and dissipated. Since an electric current can heat one side of thermoelectric materials and cool the other side, the Peltier Effect can be applied both to the thermoelectric cooler and heater.

More specifically, the thermoelectric cooler/heater is illustrated in Exhibit 15. A thermoelectric cooler/heater includes five parts. In Exhibit 13, from top to bottom, these five parts include: #1 the heat-absorbing end (blue), #2 the cooling junction (dark gray), #3 the N- and P-type semiconductors (light gray), #4 the heating junctions (dark gray), and #5 the heat-dissipating end (red). When an electric current is forced to flow through the entire circuit, heat will be transported from the heat-absorbing end toward the heat-dissipating end by free electrons and holes in N-type and P-type semiconductors respectively. As heat is continually removed from the blue color end shown in Exhibit 13, that end will absorb heat from its top and sides. A thermoelectric cooler can use the heat-absorbing end to cool an object, such as a bottle of wine, whose heat will be transported and then dissipate in the heat-dissipating end. On the other hand, if an object is attached to the heat-dissipating end, the device will become a thermoelectric heater.

Exhibit 15: Diagram of a thermoelectric cooler/heater
The Peltier effect in semiconductors can be thought of as a circuit built by one N-type and one P-type semiconductor, which are connected electrically in series but thermally in parallel. Whenever there is an electric current forced through the whole circuit, the heat is transported by electric charges from the heat-absorbing end to the heat-dissipating end. This device can be further developed to function as a thermoelectric cooler or heater.

Mathematically, the Peltier Effect can be illustrated as follows,

\[ Q = \Pi_{ab} I = (\Pi_b - \Pi_a) I \]  

(Eq. 1.2)

wherein,

\( Q \): the rate of the Peltier heat dissipated by the heating junction; on the contrary, \(-Q\) refers to the rate of the Peltier heat absorbed by the cooling junction.

\( a \) and \( b \): two dissimilar thermoelectric materials

\( \Pi_{ab} \): the Peltier coefficient for the thermoelectric materials \( a \) and \( b \). The Peltier coefficients represent how much heat is carried per unit charge through a given material.

\( \Pi_b \) and \( \Pi_a \): the Peltier coefficients of materials \( a \) and \( b \) respectively.

\( I \): electric current

**Link between the thermoelectric generator and cooler/heater (the Kelvin Relationships)**

In 1854, the British physicist William Thomson, better known as Lord Kelvin, derived the following two relationships. Experiments have confirmed them.\(^1\)

\(^1\) Lord Kelvin didn’t provide valid proof for the Second Kelvin Relationship. The most convincing support for the relationship is based on vast experimental data.
The First Kelvin Relationship:
\[
\tau = T \frac{dS}{dT} \tag{Eq. 1 - 3}
\]

wherein,
\(\tau\): the Thomson coefficient\(^1\)
\(T\): the absolute temperature

The Second Kelvin Relationship:
\[
\Pi = ST \tag{Eq. 1 - 4}
\]

The Second Kelvin Relationship provides a fundamental link between thermoelectric power generation and thermoelectric cooling/heating.

**Efficiency limitation of thermoelectric converters**

A thermoelectric converter is either a heat engine or a heat pump, which obey the laws of thermodynamics. The maximum efficiency of the previously mentioned thermoelectric converters depends not only upon properties of the thermoelectric materials but also upon Carnot efficiency as well.

**\(ZT_m\), the efficiency property of thermoelectric materials**

For thermoelectric materials, the efficiency of energy conversion depends on five factors: The Seebeck (or Peltier) coefficients \(S\) or \(\Pi\), electrical conductivity \(\sigma\), thermal conductivity \(K\), high temperature \(T_h\) and low temperature \(T_l\). These material properties all appear together and thus form a dimensionless material property called \(ZT_m\). Generally, \(ZT_m\) is used as a given material’s thermoelectric figure of merit.

In the expression of \(ZT_m\), \(Z\) is a function of the Seebeck (or Peltier) coefficient, electrical conductivity, and thermal conductivity. \(T_m\) is the mean temperature between the high \((T_h)\) and the cold \((T_c)\) under the absolute temperature system, Kelvin.

The previously referred to dimensionless expression is demonstrated as follows:

\(^1\) Unlike the Peltier and Seebeck coefficients, for which only the net effect of two different materials can be measured, the Thomson coefficient can be measured directly with one material via the Thomson Effect; the effect describing the internal heating or cooling of a current-carrying conductor with a temperature gradient. The Thomson Effect was forecasted by and subsequently observed by Lord Kelvin in 1851. According to both the Thomson Effect and the Kelvin Relationships, the Thomson coefficient can help to compute the Seebeck and Peltier coefficients without involving a second material.
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

\[ ZT_m = \frac{S^2 \sigma}{\kappa} T_m = \frac{\Pi^2 \sigma}{\kappa T_m^2} \]  
\text{(Eq. 1 - 5)}

whereas

\[ \Pi = ST \]  (The Second Kelvin Relationship)

\[ Z = \frac{S^2 \sigma}{k} = \frac{\Pi^2 \sigma}{k T_m^2} \]

\[ T_m = \frac{(T_h + T_c)}{2} \]

The higher the value of \( ZT_m \), the higher the efficiency of the thermoelectric energy conversion.

Carnot efficiency

The efficiency of all heat engines (or heat pumps) cannot exceed Carnot efficiency. Carnot efficiency is defined as the most efficient cycle for converting thermal energy into work (such as thermoelectric generation), or by contrast, creating temperature differential caused by a given amount of work (such as thermoelectric refrigeration).

For a heat engine, Carnot efficiency (\( \eta \)) is defined as follows,

\[ \eta = \frac{W}{Q_h} \]  \text{(Eq. 1 - 6)}

Wherein, \( W \) is the work transferred from the amount of heat energy utilized; \( Q_h \) is the heat energy entering the system.

Carnot efficiency can be further analyzed by using a temperature-entropy (TS) diagram shown as follows.

\textbf{Exhibit 16: Temperature-entropy (TS) diagram}
Demonstrated in Exhibit 16, the thermodynamic state of a heat engine (or a heat pump) is specified by a point on a graph with entropy (S) as the horizontal axis and temperature (T) as the vertical axis.

A Carnot cycle will consist of horizontal (isothermal) and vertical (isentropic) lines connecting an initial state (α) and a final state (β). The area (blue and green shown in Exhibit 16) under the upper horizontal line between an initial state and a final state will be:

\[ Q_h = T_h(S_\beta - S_\alpha) \]  \hspace{1cm} (Eq. 1 - 7)

The total amount of thermal energy transferred between the heat in system and the cooler environment (green) will be:

\[ Q_c = T_c(S_\beta - S_\alpha) \]  \hspace{1cm} (Eq. 1 - 8)

Based on the First Law of Thermodynamics, energy is conserved as follows (blue):

\[ W = Q_h - Q_c \]  \hspace{1cm} (Eq. 1 - 9)

Plug (Eq. 1 - 7)(1 - 8)(1 - 9) into (Eq. 1 - 6), the efficiency \( \eta \) can be rearranged to be:

\[ \eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{T_c(S_\beta - S_\alpha)}{T_h(S_\beta - S_\alpha)} = 1 - \frac{T_c}{T_h} \]  \hspace{1cm} (Eq. 1 - 10)

wherein,
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

$T_c$: the absolute temperature of the cooler environment

$T_h$: the absolute temperature of the external heat coming into the system

$S_p$: the maximum system entropy

$S_a$: the minimum system entropy

Thermal and work losses can further reduce the efficiency of a heat engine (or a heat pump) from this ideal thermodynamic efficiency.

Efficiency limitation of thermoelectric generators

Combined with thermoelectric properties, the maximum efficiency of the thermoelectric generator can be further developed as follows,

$$\eta_{\text{max}} = \left(1 - \frac{T_c}{T_h}\right) \left(\frac{\sqrt{1 + ZT_m} - 1}{\sqrt{1 + ZT_m + \frac{T_c}{T_h}} + 1}\right) \quad (\text{Eq. 1 - 11})$$

In the above equation, the first half term, i.e. $(1 - \frac{T_c}{T_h})$, represents the Carnot efficiency of an ideal heat engine. The second half, $\left(\frac{\sqrt{1 + ZT_m} - 1}{\sqrt{1 + ZT_m + \frac{T_c}{T_h}} + 1}\right)$, shows the correction factor for the efficiency of thermoelectric generators. Please note $0 \leq \left(\frac{\sqrt{1 + ZT_m} - 1}{\sqrt{1 + ZT_m + \frac{T_c}{T_h}} + 1}\right) < 1$

As $T_c$ is usually in ambient temperature, based on the (Eq. 1 - 11), there are two general strategies to develop the high-efficiency thermoelectric generator systems:

1. Keep the external heat ($T_h$) coming into the systems as high as possible.

2. Choose high $ZT_m$ thermoelectric materials.

Efficiency limitation of thermoelectric refrigerators

For a heat pump, Carnot efficiency ($\eta$) is defined as follows,

$$\eta = \frac{Q_c}{W} = \frac{T_c}{T_h - T_c} \quad (\text{Eq. 1 - 12})$$

In order to prevent confusing about definition of efficiency between a heat engine and a heat pump, the efficiency for a heat pump is generally named Coefficient of Performance (COP).

Combined with thermoelectric properties, the maximum COP of the thermoelectric refrigerator can be derived as follows,
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

\[ COP_{max} = \left( \frac{T_c}{T_h - T_c} \right) \left( \frac{\sqrt{1 + ZT_m} - \frac{T_h}{T_c}}{\sqrt{1 + ZT_m} + 1} \right) \]  

(Eq. 1 - 13)

In the above equation, the first half term, i.e. \( \frac{T_c}{T_h - T_c} \), represents the Carnot efficiency of an ideal heat pump. The second half, \( \frac{\sqrt{1 + ZT_m} - \frac{T_h}{T_c}}{\sqrt{1 + ZT_m} + 1} \), shows the correction factor for the efficiency of thermoelectric refrigerators.

As \( T_h \) and \( T_c \) are usually fixed parameters for thermoelectric refrigerators, based on (Eq. 1 - 13), developing high \( ZT_m \) thermoelectric materials is the strategy for increasing the efficiency of the thermoelectric refrigeration systems.

Derived operands for processing waste heat recovery solutions

Applying the above equations, potential waste heat recovery sources could be visualized in Exhibit 17 and 18. As seen in Exhibit 18, forest product, chemicals, and petroleum refinery would be potential operands for applying our solutions. This result would later apply on the OPM visualization in Chapter 4.

Exhibit 17: Ratio of energy recovered by thermoelectric technologies (industrial sectors)

Exhibit 18: Potential for energy recovery through the use of thermoelectric technologies (industrial sectors)
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

Potential for Energy Recovery in Using Thermoelectric Technologies

- Forest Products
- Chemicals
- Petroleum Refining
- Food & Beverage
- Iron & Steel Mills
- Mining
- Alumina & Aluminum
- Transportation Equipment
- Textile

Energy Losses (Tbtu) - Industrial Sectors

Average Operating Temperature (K)

0 200 400 600 800 1000 1200 1400 1600

400 600 800 1000 1200 1400 1600

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USE CASE (PROTOTYPE)

Three current available prototypes are shown here for further reference in Exhibit 19, 20, and 21.

**Mini Generator®**

Exhibit 19: Mini-sized combined heat and power generators and high-performance thermo-storage materials

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**Thermoelectric coffee cup**

Exhibit 20: Thermoelectric coffee cup
Chapter 3: Energy Arbitrage – A Financial-Sustained Solution for Waste Heat Recovery

CHP air drone

Exhibit 21: CHP air drone
OBJECT-PROCESS METHODOLOGY (OPM) (CRAWLEY, 2007)

OPM is a means of representing systems. It is a system development methodology that integrates many system attributes into one model. In particular, one that explicitly represents objects, processes and their links. Herein, OPM can provide us a framework for rigorous qualitative systems thinking.

OPM's legends can be further defined as follow,

**Object**

- Defined: An object is that which has the potential of stable, unconditional existence for some positive duration of time
- Can be physical: visible or tangible and stable in form
- Can be informational: anything that can be apprehended intellectually
- Objects have states (which can be changed by processes)
- Objects are linked to nouns

**Processing**

- Defined: A process is the pattern of transformation applied to one or more objects
- Cannot hold or touch a process - it is fleeting
- Generally creation, change, or destruction
- A process relies on at least one object in the pre-process set
- A process transforms at least one object in the pre-process set
- A process takes place along a time line
- A process is associated with a verb

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Function

- **Operand** is the object which is acted upon by the process, which may be created, destroyed, or altered:
  - *Image* is captured
  - *Signal* is amplified
  - *Array* is sorted
- You often do not supply the operand, and there may be more than one operand to consider
- The double arrow is the generic link, called “effecting”
- A single headed arrow can be used to represent “producing” or “consuming”

Form

- Architecture is made up of operands + processes (functions) plus instrument object (form)
- Examples:
  - Image is captured by digital camera
  - Low frequency signal is amplified with an operational amplifier
  - Tone is created by whistle
Chapter 4: Systems Visualization – An OPM Approach

- Characterization/Exhibition
  - The relation between an object and its features or attributes
  - Some attributes are states

- Specialization/Generalization
  - The relationship between a general object and its specialized forms
**Enabler**
- Defined: Enablers of a process is an object that must be present for that process to occur, but does not change as a result of the occurrence of the process

**Agent**
- Defined: Agent is an intelligent enabler
  - A human or organization of humans
  - Autonomous devices (animals, real-time computing services)

**Instruments**
- Defined: Instruments is a non-agent enabler

---

**OPM Process Links**

- **P changes O** (from state A to B).
- **P affects O**
- **P yields or creates O**
- **P consumes or destroys O**
- **O is an agent of P (agent)**
- **O is and instrument of P**
- **P occurs if O is in state A**
- **P1 invokes P2 directly**
MAJOR CONCEPT

In order to fulfill the two gaps identified in the above analysis, a new concept is to be proposed in the following chart. As shown as SPS in Table 7, this new concept focuses on the financial sustainability of all stakeholders. By doing so, more economic incentives can be created for stakeholders to help to increase the amount of waste heat recovery, which of course can help to reduce greenhouse emissions. In Chapter 3, industrial stakeholders are identified as the specific operands in this concept. In addition, a potential arbitrage practice has been evaluated as a specific system form.

All the concept-related findings from previous chapters have been listed as follows,

- Value related operand = amount of waste heat recovery
- Solution neutral process = Increase
- Specific system operating = To achieve financial sustainability
- Specific operand = Industrial stakeholders
- Generic concept form = Financial-sustained solutions
- Specific system form = Arbitrage practices

This major concept then can be visualized in Exhibit 22 for documentation and further systems thinking.

Exhibit 22: Major concept visualized by OPM
WHAT IS THE HIGH LEVEL ARCHITECTURE?

Based on the previous discussion and the above introduction, the proposed architecture of waste heat recovery solutions can be further developed and summarized as follows:

- **Beneficiary:** Energy efficiency and greenhouse emissions
- **Need:** Improvement
- **Attribute of operating =** Business Societal technology
- **Beneficial attribute =** Performance doubled every two years (Moore’s Law)
- **Attribute of form =** Thermal storage materials and mobile mini generators
Chapter 4: Systems Visualization – An OPM Approach

This high level Functions to Forms architecture can be further visualized in Exhibit 23.

Exhibit 23: Functions to Forms Architecture visualized by OPM
Appendix 1: ISO 14644-1 clean room standard

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Data are cited from http://en.wikipedia.org/wiki/Clean_room#US_FED_STD_209E_cleanroom_standards)
References


