Ways to Improve Energy Efficiency: Roadmap to Sustainable Manufacturing

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What on Earth Are These?

World Energy Use

World Population

World Gross Income
Converting Heat to Work

Since pre-history we knew how to:

<table>
<thead>
<tr>
<th>Work</th>
<th>Heat</th>
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Industrial Revolution to:

<table>
<thead>
<tr>
<th>Work</th>
<th>Heat</th>
<th>Work</th>
<th>Heat</th>
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</table>
Newcomen’s Steam Engine
~1712
Energy Revolution Creates Modern World
Most Important Event in Human History
We’ve Come a Long Way…

- Newcomen’s steam engine: 0.5%
- Watt’s steam engine: 1%
- Gasoline engines: 30%
- Coal Rankine cycles: 35%
- Turbines: 40%
- Diesel engines: 50%
- Combined-cycle turbine/Rankine engines: 60%
But Energy Conversion Largely Unchanged...

1. Use hydrocarbon fossil fuels

   
   \[
   \text{CH}_4 + 2(\text{O}_2 + 3.76 \text{N}_2) = \text{CO}_2 + 2\text{H}_2\text{O} + (\text{NOx} + \text{SOx} + \ldots)
   \]

2. Employ combustion to release heat

3. Convert heat to work via thermal expansion
84% of world energy from fossil fuels

- In U.S. 86% from non-renewable fossil fuels
Resource Constraints: World Oil Peak
Greenhouse Gas Trends

Intergovernmental Panel on Climate Change, 2001, “Summary for Policymakers”
Coincident Global Warming

Hansen, J., “Is There Still Time to Avoid Dangerous Anthropogenic Interference with Global Climate?”, American Geophysical Union, 2005.
Mechanism Well Understood

“Changing Climate”, Stephen Schneider, Scientific American, 10/1989
Linear Model of Production

Running Out of Energy Resources While Atmosphere Filling Up
Our Challenge: Sustainable Prosperity
US CO$_2$ Stabilization Scenario

Manufacturing Efficiency: Large Gains Possible

• Manufacturers make money, making it easier to spend money
• Energy costs are only 2% of gross income
• Technologies improve faster than obsolete factories replaced
• Manufacturing is inherently inefficient
Manufacturing Efficiency??

- 1 kg paper requires 100 kg of resources
- 1 liter OJ requires 1,000 liters of water
- 1 semiconductor chip generates 100,000 times its mass in waste
- US industry mines, burns, pumps, disposes of 4 M lb of material per family per year
Disruptive Technologies: Energy Efficiency

• **New technologies** (lights, VSDs, fuel cells, ...)
• **New processes** (biological engineering, ...)
• **New controls** (local feedback, nn, fl, ...)
• **New materials**: substitution and reduction (near net shape, dematerialization, remanufacturing, ...)
Evolutionary Approach to Energy Efficiency

Integrated Systems + Principles Approach
Energy Systems

– Lighting
– Motor drive
– Fluid flow
– Compressed air
– Steam and hot water
– Process heating
– Process cooling
– Heating, ventilating and air conditioning
– Cogeneration
Principles of Energy Efficiency

- Apply Inside Out Analysis
- Maximize Control Efficiency
- Maximize Counter-flow
- Avoid Mixing
- Match Energy Source to End Use
- Consider Theoretical Minimum Energy Use
- Consider Whole System
- Consider Whole Time Frame
## Integrated Systems + Principles Approach

- Integrated systems + principles approach (ISPA) = Systems approach + Principles of energy efficiency

<table>
<thead>
<tr>
<th>Inside Out</th>
<th>Electrical</th>
<th>Lighting</th>
<th>Motors</th>
<th>Fluid Flow</th>
<th>Comp Air</th>
<th>Steam</th>
<th>Proc Heat</th>
<th>Proc Cool</th>
<th>HVAC</th>
<th>CHP</th>
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<tbody>
<tr>
<td>Control Efficiency</td>
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<td>Counter-flow</td>
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<tr>
<td>Avoid Mixing</td>
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<td>Match Source Energy to End Use</td>
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<tr>
<td>Theoretical Minimum Energy Use</td>
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<td>Whole-system, Whole-time Frame Analysis</td>
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- ISPA is both effective and thorough.
1. Inside-out Approach
Inside-out Approach

Conversion Distribution Use

Energy Supply Savings

End–Use Savings

Inside-Out Analysis Approach
Inside-out Amplifies Savings

Reduce pipe friction: Savings = 1.00 kWh
Pump 70% eff: Savings = 1.43 kWh
Drive 95% eff: Savings = 1.50 kWh
Motor 90% eff: Savings = 1.67 kWh
T&D 91% eff: Savings = 1.83 kWh
Powerplant 33% eff: Savings = 5.55 kWh
2. Maximize Control Efficiency

- Systems designed for peak load, but operate at part load
- System efficiency generally changes at part load
- Recognize and modify systems with poor part-load (control) efficiency
Control Efficiency

Energy

Production

Poor

Excellent
Air Compressor Control

\[ FP = FP_0 + FC (1 - FP_0) \]
Pump System Control
3. Maximize Counter-flow

- Parallel Flow
- Counter Flow
Counter-flow Furnace Pre-heats Charge

Reverb Furnace Efficiency = 25%    Stack Furnace Efficiency = 44%
(Eppich and Nuranjo, 2007)
Counter-Flow Cooling

Counter flow enables 50 F to 70 F water saves 10x
4. Avoid Mixing

• Availability analysis...
  Useful work destroyed with mixing

• Examples
  – CAV/VAV air handlers
  – Separate hot and cold wells
HVAC Applications

Cooling Energy Use

Heating Energy Use
Cooling Applications

Separate tank into hot and cold sides
5. Match Energy Source and End Use

- Compressed air
- Open loop cooling
- Chillers
- Cooling towers

$/mmBtu cooling

Compressed air
Open loop cooling
Chillers
Cooling towers
Use Cooling Tower When Possible

Fraction of year cooling tower can deliver water at Tc (Assume Tr = 10 F in Dayton OH)

<table>
<thead>
<tr>
<th>Tc (F)</th>
<th>Twb (F)</th>
<th>Fyr (%)</th>
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<tbody>
<tr>
<td>75</td>
<td>65</td>
<td>72%</td>
</tr>
<tr>
<td>70</td>
<td>57</td>
<td>61%</td>
</tr>
<tr>
<td>65</td>
<td>50</td>
<td>53%</td>
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<tr>
<td>60</td>
<td>42</td>
<td>40%</td>
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</tbody>
</table>
Air Pumps Use 7x More Electricity
Natural Lighting: Eyes See Best in Sunlight
6. Theoretical Minimum Energy Use

<table>
<thead>
<tr>
<th>Industrial Process</th>
<th>Theoretical Minimum Energy Requirement $(\text{kWh} \times 10^8 \text{year})$</th>
<th>Total US Gross Energy Required $(\text{kWh} \times 10^8 \text{year})$</th>
<th>Theoretical Minimum Energy % of Actual</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Alumina Refining</td>
<td>0.56</td>
<td>16.24</td>
<td>3.4%</td>
<td>Choate &amp; Green</td>
</tr>
<tr>
<td>Anodes Production</td>
<td>9.77</td>
<td>21.86</td>
<td>44.7%</td>
<td></td>
</tr>
<tr>
<td>Aluminum Smelting</td>
<td>22.41</td>
<td>116.36</td>
<td>19.3%</td>
<td></td>
</tr>
<tr>
<td>Primary Casting</td>
<td>1.23</td>
<td>4.56</td>
<td>27.0%</td>
<td></td>
</tr>
<tr>
<td>Secondary Casting</td>
<td>1.15</td>
<td>9.64</td>
<td>11.9%</td>
<td></td>
</tr>
<tr>
<td>Rolling</td>
<td>1.76</td>
<td>6.66</td>
<td>26.4%</td>
<td></td>
</tr>
<tr>
<td>Extrusion</td>
<td>0.75</td>
<td>2.59</td>
<td>29.0%</td>
<td></td>
</tr>
<tr>
<td>Shape Casting</td>
<td>0.84</td>
<td>6.63</td>
<td>12.7%</td>
<td></td>
</tr>
<tr>
<td>Total Aluminum Shape Casting</td>
<td>38.47</td>
<td>184.54</td>
<td>20.8%</td>
<td>Choate &amp; Green</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Hot Metal</td>
<td>9.8</td>
<td>13.5</td>
<td>72.6%</td>
<td>Fruehan, et al.</td>
</tr>
<tr>
<td>Liquid Steel (BOF)</td>
<td>7.9</td>
<td>11</td>
<td>71.8%</td>
<td></td>
</tr>
<tr>
<td>Liquid Steel (EAF)</td>
<td>1.3</td>
<td>2.25</td>
<td>57.8%</td>
<td></td>
</tr>
<tr>
<td>Hot Rolling Flat</td>
<td>0.03</td>
<td>2.2</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>Cold Rolling Flat</td>
<td>0.03</td>
<td>1.2</td>
<td>2.5%</td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia Steam Reforming</td>
<td>21.6</td>
<td>35.5</td>
<td>60.8%</td>
<td>Worrell, et al.</td>
</tr>
</tbody>
</table>


- 2.5% of primary energy used to provide energy services Ayers (1989)
TME: Parts on UV Curing Oven

Slowed belt, shut off excess lamps, saved 50%
7. Whole-System Design

• Design heuristic derived from natural evolution
• Nothing evolves in a vacuum, only as part of a system
• No optimum tree, fan, ...
• Evolutionary perspective: ‘optimum’ synonymous with ‘perfectly integrated’
• Optimize whole system, not components
• Design for whole time frame, next generation
Whole System “Lean” Manufacturing

400 ft/min  200 ft/min

200 ft/min
Whole System Pumping
“Optimum Pipe Diameter”

- $D_{\text{opt}} = 200 \text{ mm when Tot Cost} = \text{NPV}(\text{Energy}) + \text{Pipe}$
- $D_{\text{opt}} = 250 \text{ mm when Cost} = \text{NPV}(\text{Energy}) + \text{Pipe} + \text{Pump}$
- $\text{Energy}_{250} = \frac{\text{Energy}_{200}}{2}$
8. Whole-Time Frame Analysis: “Efficiency Gap”

- “Numerous studies conclude 20% to 40% energy savings could be implemented cost effectively, but aren’t…..”

- Discrepancy between economic and actual savings potential called “efficiency gap”.

- Puzzled economists for decades: “I can’t believe they leave that much change lying on the table.”
Whole Time Frame Accounting: “Don’t Eat Your Seed Corn”

- SP = 2 years (10 year life) is ROI = 49%
- SP = 5 years (10 year life) is ROI = 15%
- SP = 10 years (20 year life) is ROI = 8%
Integrated Systems and Principles Approach

• Principals of energy efficiency
  – Global, applied to all manufacturing processes
  – Can be taught and mastered
  – Build an ethic of energy/environmental awareness: “Rather do 100 kaizans that save 1 second each than 1 kaizan that saves 100 seconds.”
Leveraging Energy Efficiency to Pay for Renewable Energy

Reduce CO$_2$ by 20% at “Negative Cost”

Conclusion

• Net-zero energy house analogy
  – Solar array won’t fit on roof of standard energy efficient house
  – Solar array easily fits on roof of energy efficient house
• Energy efficiency and renewable energy closely linked.
• Manufacturing: Energy efficiency savings can drive renewable energy
Thank you!