The Path to Net-Zero Energy Manufacturing

John Seryak, George Mertz and Gregory Raffio, Go Sustainable Energy LLC

ABSTRACT

Within several decades, manufacturing facilities will need to achieve net-zero energy status in order to achieve climate and energy goals that are being discussed by the scientific and legislative community. Successfully overcoming the associated technical, economic, and policy challenges requires that potential paths to achieving net-zero energy manufacturing (NZEM) and their costs be conceptualized and discussed now. Despite the critical importance, relative immediacy, and difficulty of achieving NZEM, there has been little direct discussion or pursuit of how to achieve this end.

In this paper, definitions of NZEM will be discussed along with related terms. Next, several small light-manufacturing facilities that have or are attempting to achieve net-zero energy use, and the technologies and strategies these facilities used will be briefly reviewed. Then, a methodology for examining industrial processes for NZEM will be proposed. Finally, this paper will discuss potential paths and corresponding project economics towards net-zero manufacturing for several anonymous but real manufacturing processes. Concepts from the literature such as lean energy and theoretical minimum energy use will be involved. Additionally, this paper will discuss technological and financial challenges for each example process. For each case, approximate implementation costs and savings will be discussed.

Definition of Net-Zero Energy Manufacturing

Net-zero energy manufacturing (NZEM) is a logical extension of net-zero energy buildings (NZEB). NZEBs are generally defined as buildings that produce as much energy through renewable energy generation as they consume from the electrical grid throughout the year. Pless and Torcellini (2010) described four classifications of NZEB, with the sighting of renewable energy generation determining the classification. It is generally accepted that a NZEB combines maximum energy efficiency with on-site renewable energy generation, and is one tool to achieving a renewable energy grid. There are other, related terms which are slightly different than a NZEB, but which may be thought of as a similar tool in achieving a renewable energy grid. There are seemingly slight, but important nuances. Examples include:

- Off-the-Grid – An off-the-grid facility is a standalone building which can fully meet its energy needs through on-site renewable energy generation. An off-the-grid building is different than an NZEB in that it must match renewable energy generation to energy demand for every instance. An NZEB may overproduce during one time to compensate for underproduction at another time. Thus, while off-the-grid and NZEB both contribute to renewable energy and climate goals, they require distinctly different design approaches.
- Net-zero Emissions – A net-zero emissions building converts energy to carbon dioxide emissions in the net-zero analysis. Thus, if the source of grid electricity is more carbon intense than the site production, the on-site renewable energy would have to produce

more energy to make up this gap. That is, the accounting is not for kWh or Btu used and produced but on pounds of CO_2 emissions.

These approaches and terms are often used interchangeably, though each approach has unique design constraints and contributes to the ultimate societal climate and energy goals differently. In fact, the design approach may suggest differences in the ultimate vision of a clean energy world. For example, off-the-grid design if used en-masse suggests a future in which every facility is energy self-sustaining. This would require smaller, distributed renewable energy technologies appropriate to a variety of weather climates. Buildings in the desert southwest US may implement photovoltaics (PV) and battery storage systems, while buildings in northern Ohio may require a mix of PV, small wind and biomass or fuel cell systems. In contrast, the NZEB approach recognizes the role of large-scale, centralized renewable energy plants and storage systems in a clean energy world. In this scenario, during periods of underproduction, a building may use grid energy produced cleanly elsewhere. This allows for flexibility in time of energy production, place of production, and ultimately the cost of implementation. The appropriateness of each approach should be considered by every design team and facility owner.

NZEM envisions a manufacturing facility that produces as much on-site renewable energy generation as it uses from the electrical grid, for a net-zero energy balance over the course of the year. Our definition assumes that at some point in the future all electricity on the grid could be renewable, and thus an NZEM in the future will be synonymous with a net-zero emission manufacturing facility. This is important for a design goal, as it excludes the use of natural gas and other fossil fuels as an energy source in manufacturing, exempting methane or biomass from agriculture waste, waste-water or landfills. The reason for adopting this constraint is to fully capture the costs of achieving zero carbon-dioxide emissions goals for manufacturing, which may require conversion of energy sources.

Existing Efforts and Methodologies for Achieving NZEM

NZEM is not new; it is a logical extension of NZEB and is in fact being pursued by a number of light manufacturing facilities. These manufacturing facilities are not energy intensive, and typically the manufacturing component is assembly. There is often a large percentage of office space within the project boundary. In this way, the approaches to achieving these early NZEMs are closer to an NZEB than for what would be appropriate for more typical manufacturing. Following is a summary of early NZEM facilities, or more appropriately facilities that have set NZEM goals.

- NRG Systems in Hinesburg, VT has plans to become a NZEM facility. A 31,000 square foot manufacturing and office facility, NRG uses a large PV array to generate electricity. Hot-water and space heating needs are met with a combination of geothermal wells, solar hot water generation and wood-pellet stoves (Environmental Leader, 2010).
- Melink Corporation in Cincinnati, OH is actively pursuing NZEM for its office headquarters and light manufacturing facility. Manufacturing comprises only 6,450-ft^2 of the total 31,237-ft^2 of the facility. Minor and Hallinan (2011) describe a strategy of cost optimization for both NZEB and off-grid status. Melink Corporation has implemented a variety of renewable energy generation technologies, including PV, small wind turbines and solar thermal hot-water panels.

- Frito-Lay planned to achieve net-zero energy at its Casa Grande plant by 2011, delayed from a 2010 earlier target date. According to news publications, plans are to install a large PV array for electricity and generate methane from plant waste to power the facility's boilers (Environmental Leader, 2007).

There are several items of note from these early attempts. First, the Frito-Lay Casa Grande plant is by far the most typical and true manufacturing plant. Even so, it has the fortunate ability to have combustible plant waste generated from the plant, which can be used to power the facility's boilers. This strategy for on-site generation certainly reduces costs of conversion to electric hot-water generation and is appropriate for this facility. However, most industrial facilities will not have on-site biomass waste, and will thus need a different and perhaps more costly solution. Biomass generation of heat is also a strategy employed by NRG Systems. It may not be feasible for every manufacturing facility to use biomass as a source of renewable energy. Thus, these facilities do not necessarily offer a template strategy for broader replication.

Ball et. al. (2009) described a method by which to evaluate a "zero carbon manufacturing facility". Their approach considered a large system boundary for the facility, evaluating material flows, transportation of material to and from the facility, and even the supply chain. In their paper, they advocate "treating individual process as 'black boxes'" and considering material or energy outputs as inputs elsewhere in the process, instead of as waste. As such, any efficiency improvements to the processes are neglected.

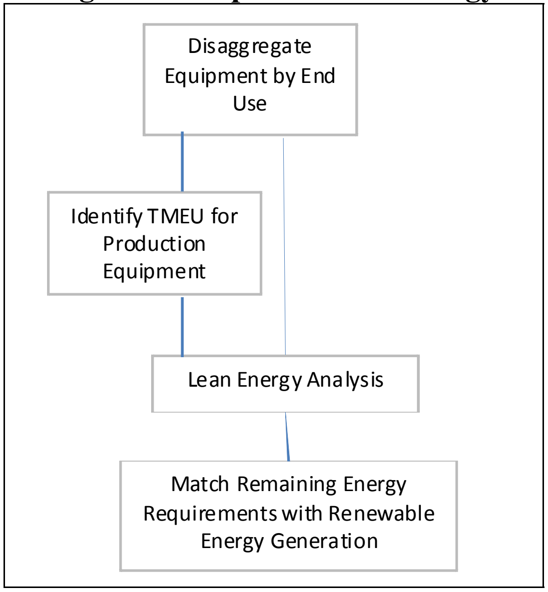
Anderson et. al. (2006) developed an approach for analyzing the least-cost solution for residential NZEB using multiple energy simulations with discrete choices for various energy-efficiency technologies, such as insulation thickness, SEER rating of air-conditioning equipment, etc. Energy efficiency measures were utilized first, so long as they were less expensive to implement than on-site renewable energy generation.

Proposed Engineering Methodologies for NZEM Analysis

Our proposed methodology follows a similar path as that set forth by Anderson et. al. with important differences. The approaches are similar with the intent that the least-cost solution for net-zero energy is being explored. As with the Anderson paper, our approach will largely assume PV as the default on-site renewable energy technology which would meet any energy needs that efficiency cannot eliminate. We select PV for simplicity; certainly wind could be implemented for some facilities. This is unlike the light-industrial efforts underway, nearly all of which utilize some form of biomass generation and/or small wind turbines in addition to PV. While Anderson considered a limited number of energy-efficiency technologies, this is not possible with manufacturing. Each industrial facility is unique, and thus a computer simulation may not be possible in determining least-cost solutions. Each and every manufacturing facility may require its own engineering study.

We propose integrating several different analytical tools previously described in the literature. First, we propose disaggregating the facility's equipment into process equipment, work environment equipment and independent equipment. Next, theoretical minimum energy use (TMEU) would be defined for the production process only (Fruehan, et. al., 2000). The difference between actual energy use and the TMEU is the energy bandwidth, and is equivalent to the theoretical maximum gains through energy efficiency (Energetics, 2004). Constraints on the maximum efficiency gains will be limited by the best available technology (BAT) for each category of equipment. We propose using the Lean Energy conceptual framework to maximize efficiency returns (Kissock and Seryak, 2004). Finally, remaining energy consumption will be matched with an appropriate renewable energy technology. Figure 1 presents a flow chart of the proposed methodology.

Figure 1. Proposed Methodology



Equipment Disaggregation

Energy-using equipment in a manufacturing facility should be disaggregated into categories based on purpose, as energy use for each category would be considered differently. Categories are described as follows:

- Production equipment – This category includes equipment that directly or indirectly supports production. Direct production equipment would include stamping presses, injection molding machines, forges, annealing furnaces, quench baths, etc. Indirect production equipment would include air compressors, process chillers, cooling water circulation pumps, conveyor belts, etc.
- Work environment equipment – This category includes equipment that provides heating, cooling, ventilation or lighting for the plant environment. Equipment would include air-conditioning units, space heating boilers, furnaces, make-up air units and lighting.
- Independent equipment – This category includes equipment that does not contribute mainly to production or the work environment, such as computers, exit signs, etc.

Theoretical Minimum Energy Use & Energy Bandwidth

To bracket energy efficiency potential, the DOE has sponsored several studies on the theoretical minimum energy use (TMEU) for various manufacturing processes. TMEU is the thermodynamic minimum energy use for a process. It does not establish minimum energy use using the best available technology (BAT) or take economics into consideration. These studies conclude that theoretical minimum energy use (TMEU) is far less than actual energy use. For example, Ayers (1989) estimated that only 2.5% of US primary energy consumption is used to provide energy services. Table 1 shows the TMEU as either an absolute and unitized quantity and also as a percent of current energy requirements for the aluminum, steel and ammonia industries as described by Choate and Green (2003), Fruehan, et al. (2000), and Worrell, et al. (2000), respectively.

Table 1: Theoretical Minimum Energy Use

Industrial Process Aluminum[1]	**Theoretical Minimum Energy Requirement (kWh 10^9/year)**	**Theoretical Minimum Energy (% of Actual Energy)**
Alumina Refining	0.56	3.4%
Anodes Production	9.77	44.7%
Aluminum Smelting	22.41	19.3%
Primary Casting	1.23	27.0%
Secondary Casting	1.15	11.9%
Rolling	1.76	26.4%
Extrusion	0.75	29.0%
Shape Casting	0.84	12.7%
Total Aluminum Shape Casting	38.47	20.8%
Steel[2]	**GJ/ton product**	
Liquid Hot Metal	9.8	72.6%
Liquid Steel (BOF)	7.9	71.8%
Liquid Steel (EAF)	1.3	57.8%
Hot Rolling Flat	0.03	1.4%
Cold Rolling Flat	0.03	2.5%
Ammonia[3]		
Ammonia Steam Reforming	21.6	60.8%

[1] Choate & Green [2] Fruehan, et al. [3] Worrell, et al.

The United Nations Development Programme (UNDP) defines several useful forms of minimum energy use (1997). First, the theoretical minimum specific energy use is "for processes that reach the final state of equilibrium at an infinitely slow rate." Industry is not economically viable functioning at an infinitely slow rate, leading UNDP to define technically achievable minimum energy use, where "technically" indicates that time constraints of the process are taken into account. Finally, the cost of technology is accounted for in economically achievable minimum energy use.

While TMEU has been studied as a goal for large-scale energy-reduction efforts, it has not been widely adopted as a guide. Instead, targeted industrial energy assessments have been shown to provide more practical advice for individual facilities seeking to reduce energy use. However, to determine the least-cost implementation of NZEM, approximating TMEU is a useful tool. An in-depth engineering analysis is not necessarily needed to determine TMEU – engineering approximations can be completed at relatively low-cost and are very informative. We will present several process-specific analyses utilizing this method.

Lean Energy

Lean Energy follows Lean Manufacturing in that "any action that does not add value to the product or plant environment is waste" (Kissock and Seryak, 2004). Thermodynamically speaking, anything above the TMEU would be waste. Thus, TMEU is essentially the "lean" energy, or that which adds only value. In quantifying the TMEU, all other uses of energy are waste, including friction, bypassing of fluids, heat loss and others. What differentiates Lean

Energy from TMEU is that TMEU is a specific quantity that could be used as a benchmark, while Lean Energy is a mindset which encourages an engineer or evaluator to view the process' energy use through the Lean manufacturing paradigm.

NZEM Process-Specific Examples

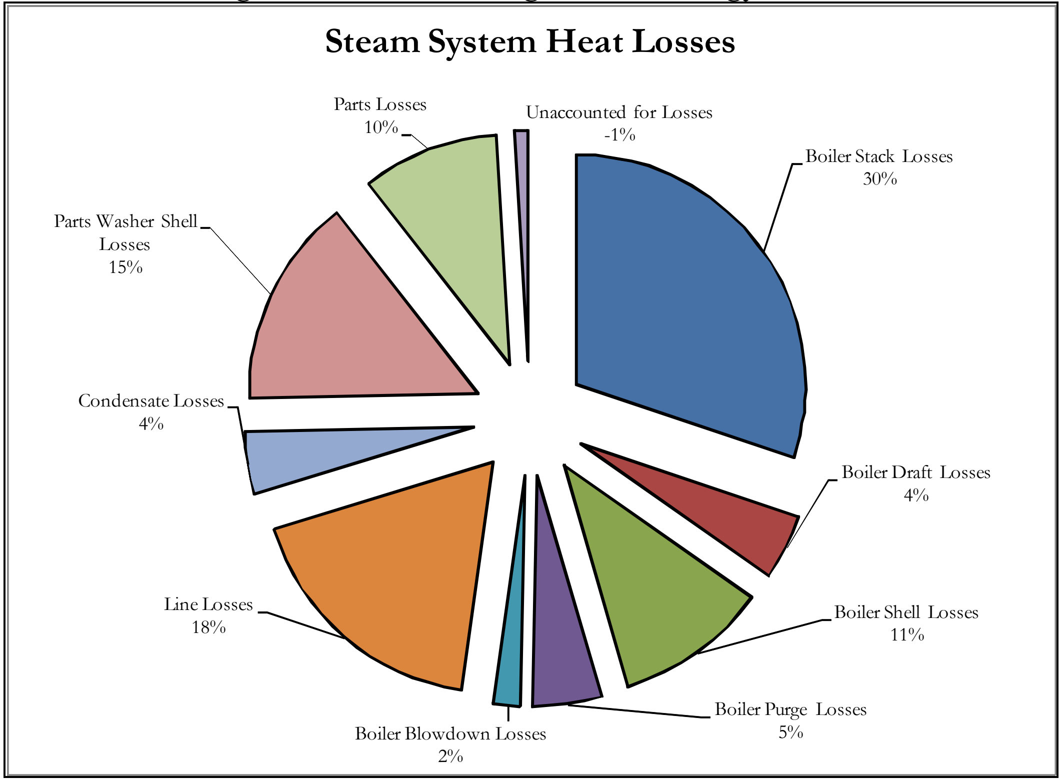
The following analyses are for two real but anonymous processes. Cost economics for NZEM are presented in terms of simple payback and/or 30-year cost equivalents. The rationale is that NZEM projects would likely need to be financed over a 30-year period, similar to home mortgages, to be cost competitive with traditional uses of energy. Interest rates are accounted for, though escalating energy costs, the tax effect of depreciation, and ancillary benefits to production, labor and maintenance costs are not.

Parts Washing Process

Two boilers orginally provided steam for process heating, with insulated steam lines routed throughout the multi-acre plant. However, as is with many manufacturing facilities, the original manufacturing process is no longer in place, and the boiler plant currently provides heat to two parts-washers only. While not all manufacturing systems are so oversized, many are. Approximately 9.7% of the energy being utilized is for the actual washing process, and, it is likely that the actual TMEU needed to break the molecular bonds to wash the metal parts of lubricants is much less. However, as we previously noted an engineering approximation is actually sufficient and far less costly than a comprehensive study that would establish TMEU with a high degree of accuracy.

Areas of inefficiency for the parts-washing process are expected. The boiler combustion efficiency is not quite 70%, and thus more than 30% is lost to the atmosphere up the boiler stack. There are additional boiler losses from purging, blowdown, drafts during non-firing periods, and heat loss through the boiler shell. Still more large sources of energy losses are from heat loss of the steam lines and part washer, and unreturned condensate, all shown in Figure 2. While many energy-efficiency opportunities exist with the boiler efficiency and steam distribution losses, the greatest opportunity is addressing inefficiency at the point of use first. For this parts-washing system, there is an opportunity to use heating elements at the point-of-use. By providing heat directly at the wash tank, all "outside" heating components can be eliminated; including steam generation and distribution.

Figure 2. Parts Washing Process Energy Losses



The parts-washing process currently uses 6,103 mmBtu/year at a cost of $7.1 /mmBtu, or $43,331 per year. The 30-year cost of this process would thus be $1,299,930. Energy efficiency opportunities with the parts-washer include insulating the parts-washer, using insulative ball floats to cover the open tank and installing better controlled valves. These opportunities combined with elimination of the boiler and distribution lines would reduce annual energy use to 595 mmBtu/year, or 166,007 kWh/year. The total implementation cost for these efficiency opportunities is $8,000. At this point, the efficiency economics are remarkably favorable, with a simple payback of 0.2 years. However, to achieve net-zero energy for this process, renewable energy must make up the difference. We used PVWatts and found that a 147 kW PV array could produce 167,000 kWh/year. The combination of efficiency and renewable energy would make this a net-zero energy manufacturing process.

The cost of PV installation varies widely dependent on array size, mounting, local conditions and other factors, and today can vary. Because this would be a larger installation, we will use an installation cost of $5 /peak-watt. At this level, the 147 kW PV array would cost $735,000 to install, with no incentives. If the total project cost of $735,000 were financed at 6% interest over 30 years, the total cost would be about $1.323 million, just over the total 30-year cost of energy.

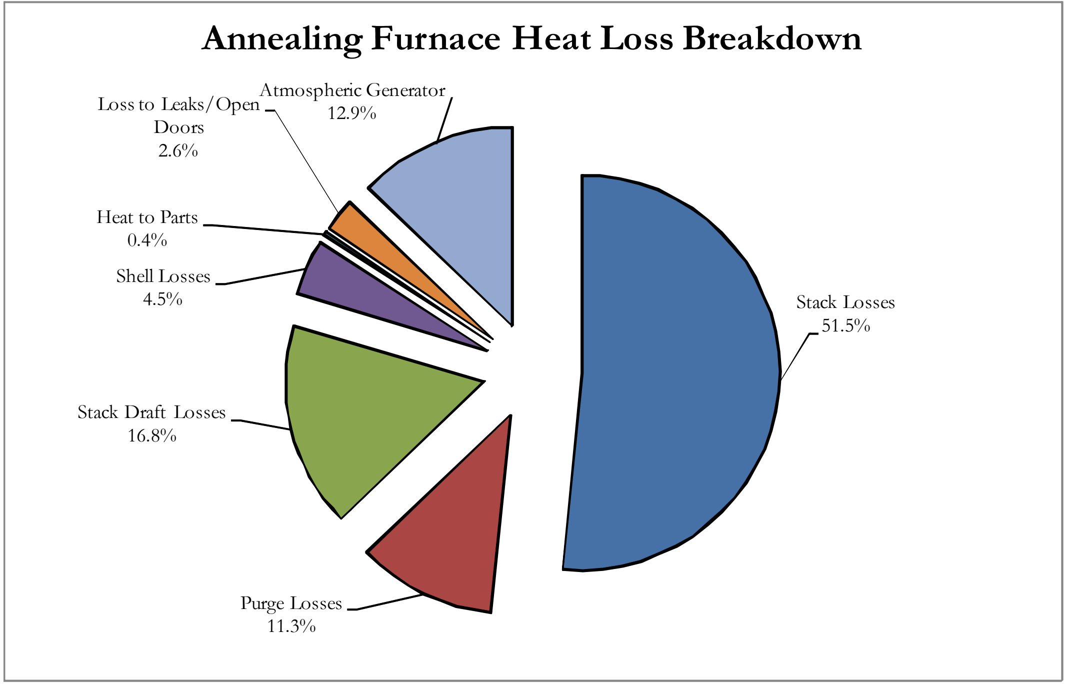
The immediate challenge presented is that of the capital expenditure for PV. This warrants a deeper evaluation of efficiency opportunities, which are far less expensive, and consideration of other, less expensive renewable energy technologies. The original efficiency evaluation considered the installation of insulation for the parts-washer tank and also using ball floats to reduce heat loss and evaporation from the open tank top. In fact, both of these efficiency opportunities could be more aggressive. If side insulation were doubled, and a lid used instead of ball floats, required electricity use would then be 139,818, or 84% of the previous estimate. Even if the cost of the efficiency opportunities tripled, which is unlikely, the cost of PV would be reduced to $619,046, for a total project cost of $643,046. At the identical interest and loan duration terms, the 30-year cost would be just under $1.16 million. Therefore, reducing the cost of NZEM will likely require aggressive implementation of energy efficiency.

After efficiency opportunities are exhausted, to further reduce the cost of the renewable energy generation one would examine the technology used for reducing costs. For example, because the parts-washer requires 180 F hot water, there is an opportunity for solar thermal panels to augment the PV. Because solar hot water generation could not produce net energy use for others, it cannot be considered by itself as a generation technology, but would reduce the energy required from the PV array.

Annealing Process

An annealing process was evaluated that operates intermittently and consumes 8,919 mmBtu/year at a cost of about $63,325 /year at $7.10 /mmBtu. At this consumption and energy cost, the 30-year energy cost of operation would be close to about $1.9 million. As Figure 3 shows below, very little of this energy consumption is actually absorbed by the parts being annealed. Because the annealing furnace must be kept at around 1,500 F, and is heated with gas combustion, a considerable amount of heat is exhausted through the stack – over 50%. Other sources of losses including purge, stack draft, convection and radiation from the furnace shell and infiltration account for about another 35% of energy consumption. While gas is also consumed by an atmospheric generator, less than 1% of the energy consumed is absorbed by the parts.

Figure 3. Annealing Process Energy Losses



We evaluated several energy efficiency opportunities which would reduce gas consumption considerably. Table 2 presents these opportunities and their associated energy and cost savings, estimate implementation cost and simple payback.

Table 2: Annealing Furnace Energy Efficiency Opportunities

Description	Gas Savings (ccf/year)	Cost Savings ($/year)	CO_2 Savings (lbs CO_2 /year)	Imp. Cost ($)	Simple Payback (years)	Rate of Return (%)
Annealing Furnace Recommendations						
Reduce Excess Combustion Air	10,132	$7,194	114,492	$2,500	0.3	287.7%
Preheat Combustion Air	27,565	$19,571	311,485	$70,000	3.6	28.0%
Install Modulating Burners for Annealing Furnac	12,778	$9,072	144,391	$52,800	5.8	17.2%
Insulate Annealing Furnace	6,030	$4,281	68,139	$30,840	7.2	13.9%
Install Heat Exchanger Tube Inserts	8,919	$6,332	100,785	$100,800	15.9	6.3%
Comment: Reduce Turnover of Atmospheric Gas						
Comment: Insulate Atmospheric Generator End Cap						
Interactive Savings - (All Furnace Recommendations)	37,664	$26,741	425,603	$256,940	9.6	10.4%
Annealing Furnace Sub-Total	**37,664**	**$26,741**	**425,603**	**$256,940**	**9.6**	**10.4%**

If these efficiency opportunities were implemented, the resulting gas consumption of the annealing furnace would be 5,153 mmBtu/year at an implementation cost of $256,940. If this energy load were met with PV, the electrical equivalent of 1,510,795 kWh/year would need to be generated, and this could be accomplished by a 1,337 kW array of PV. At $5 /peak-watt, the cost of a PV array this large would be almost $6.7 million. The total cost of NZEM would be almost $7.0 million. At 6% interest over 30 years, the total cost would be $12.6 million. This does not even include the cost to convert the furnace to electrical resistance heat. Compared to the 30-year operational cost of $2.5 million, NZEM is prohibitively expensive.

Moreover, other serious issues exist. In the parts-washing example, the existing equipment could be retrofit to be more efficient and use renewable electrical energy relatively cost effectively. The annealing process is different in that the NZEM simple payback is about 110 years. While additional energy efficiency measures could be explored, the existing list of opportunities already includes relatively long payback opportunities (heat exchanger tube inserts is over 12 years). Thus, retrofitting this system to be NZEM is unlikely. With the efficiency opportunities diminished, to make NZEM cost-competitive over a 30-year timeframe would require an installed PV cost of $0.6 /peak-watt.

As an NZEM retrofit for this system in the near future is unlikely, we suggest two alternate paths or a combination thereof. First, an industrial process like this would not convert to NZEM until renewable energy costs were very inexpensive and/or fossil fuel costs very expensive. Such a scenario could be likely after 2020, which is the DOE target date to achieve $0.06 /kWh for unsubsidized solar electricity generation as part of their Sunshot program (DOE, 2011). At this time, it is likely that centralized PV or wind turbine power plants would provide electricity via the grid to industrial processes such as this, and thus manufacturing facilities such as this may never truly be NZEM.

The second scenario would be that a much more efficient, new electrical annealing furnace is installed. This would likely need to correspond with alterior motives from the manufacturing company, such as a need for increased production, improved annealing quality, or reduction in maintenance issues. Dramatic reductions in energy use and converting from gas consumption to electric consumption, while improving quality, increasing production and reducing maintenance and labor costs are actually common in high-heat industrial applications. A good example are newer electric aluminimum melt furnaces which have substantially reduced energy consumption over older gas reverb aluminum melt furnaces (DOE, 2009). In this scenario, the cost of energy conversion and efficiency is included with strategic capital expenditures the company is making for other reasons. In other words, significant energy-efficiency improvements would be an ancillary benefit to some other purpose, and not the primary criteria in the decision making process. However, the promise is that such equipment change-outs and total redesign may further reduce energy consumption of the equipment. This highlights the need for industrial equipment designers and manufacturers to consider energy consumption as a criteria in design. Additionally, in this scenario an NZEM plan for industrial facilities will likely need to be integrated with the capital improvement plans and broader strategic investments of the company.

Barriers to Adoption

The above analyses show that manufacturing processes can have net-zero energy use over a 30-year period at a financed cost equivalent to traditional energy. Thus, overall project investment may not always be a barrier - certainly thousands of homes are purchased and financed over a 30-year period. The barriers to adoption, then, are more specific to different economic horizons and criteria for industry, which we discuss below:

- Investment timeline threshold – As mentioned, a 30-year timeframe is adequate for some capital expenditures, such as home purchasing. Home buyers and banks, however, are often confident of their earning power for the next 30 years, in addition to the ability of the home to hold its value. This is not the case with manufacturing. Industrial facilities have a much lower payback threshold, as many manufacturing facilities may switch production processes, may change location, or may not even be in business within a few years. Thus, there is virtually no investment from industrial facilities on projects that take 30 years to recoup. More typically, industrial facilities require a 1-3 year maximum simple payback period. In other words, the low payback threshold is a result of high business uncertainty. Moreover, industrial equipment depreciates, losing its value over time while homes have until recently appreciated.
- Capital availability – While some manufacturing processes can achieve net-zero energy with less than a 30-year simple payback, this requires the equivalent cost of energy for up to 30 years to be paid up front in capital expenditure. It is unlikely that most manufacturing facilities have this quantity of capital available for NZEM projects.
- Engineering information – Another obstacle to adoption of NZEM is simply available information. Very few plant-specific studies have been conducted to identify TMEU and fully analyze all efficiency and renewable energy options for a manufacturing plant. It is more likely that facilities have received the equivalent of an ASHRAE Level II energy audit. A more thorough NZEM study is likely to be much more costly. Additionally, there is likely a lack of engineering teams capable of providing such a study.

Conclusions

We have shown that NZEM can be achieved in certain manufacturing processes at a simple payback of 30 years, while others have a much higher simple payback, though this is not a comprehensive set of examples. Manufacturing companies face several real barriers to adopting these practices, such as uncertainty in future business, capital availability and engineering information.

Our analysis was limited, and did not take the entire facility into consideration. If the entire facility were within the scope of our analysis, additional practical issues would likely arise, such as foot-print constraints for the renewable energy generation.

It is unlikely that NZEM could be realized with traditional financing mechanisms and engineering workforce skills. Obviously, adoption of NZEM will quicken with such market forces as rising energy prices, falling renewable energy costs, and increased knowledge in the engineering workforce. However, taking all of this together, adoption of NZEM will likely still fall significantly short of what is needed for national and international climate and energy goals without innovative financing for these projects. While any one manufacturing facility or process may change in the short-term, many industries do stay in business for years utilizing similar equipment and processes. Thus, pooling the risk of investment across many industrial facilities may alleviate the short payback threshold of such projects.

Further Study

There is ample opportunity for further study in the area of NZEM. Key areas of interest include:

- Obtaining a broader sample of NZEM economics for various industrial processes.
- Establishing cash flows for NZEM investment, including loan interest rates, a range of energy cost escalation factors and equipment value depreciation.
  - Comparison of proposed NZEM cash-flows to other financing mechanisms would be valuable.
- Determining change-over rates of industrial plants and processes to derive a theoretical persistence rate of NZEM projects.

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