Importance of Energy Service Demand Representation to Consideration of Range of Technology Choices in Manufacturing

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Introduction

The concept of an energy service demand is a powerful concept in the modeling of energy use. By representing end-use service demand robustly, an analyst or modeler can explore the relative importance of various energy uses and how different energy resources can be used to satisfy these energy needs, allowing various energy future scenarios to be considered. However using a limited representation, as is seen in many models can unnecessarily restrict the resource and technology options available to satisfy service demands, locking in current energy and technology use patterns in the forecasts of the future, limiting the ability to consider alternative energy paths that could offer improved economic and environmental performance.

Making good estimates of energy service demand is particularly challenging for the manufacturing sub-sector of industry[1] because of the diversity in energy requirements within the sub-sectors, and the limited quality and resolution of the data available. These challenges have discouraged robust representations of energy service demands, resulting in rigid representations of the sector. This rigidity is pronounced with respect to the switching between various energy resources – particularly between purchased electricity and direct application of fuels. While data problems may limit the precision of energy service representations, using more rigid representations of energy use limit the range of technology futures that can be envisioned. This limited approach also may result in an apparent limitation of industry to adapt to policy signal such as energy price increases or carbon emissions caps, making these policies appear more costly to the economy than in fact they may be.

These limitations in the representation of service demand becomes particularly pronounced when estimating the future potential for combined heat and power (CHP, also known as Cogeneration). The CHP approach of transforming energy resources to satisfy multiple service demands offers significant opportunities for improvements in energy efficiency and carbon reduction (see Elliott and Spurr 1999 for a future discussion of CHP). Many of the barriers to expanded use of CHP exist from market and regulatory barriers, not limitations in the technology, so policy changes should have significant impact the deployment of the technologies. However, because CHP is not endogenously represented in most models, the transformative impacts of expanded CHP on manufacturing cannot be fully appreciated.

This paper will explore how manufacturing energy use is currently represented in many models, propose an approach to estimating energy service demands, incorporate these estimates into a representation of manufacturing energy use that integrates the energy flows between resources and service demands, and explores the ramification of this alternative representation. As an example, energy service demands are estimated for food products manufacturing (NAICS 311).[2] In addition, this paper will also consider how energy service demands might evolve in the future

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[1] In this context the NAICS definition of industry sector is used, which is made up of four sub-sections: agriculture, mining, construction and manufacturing.

[2] NAICS – the North American Industrial Classification System has been adopted for categorizing economic activity in the United States, Canada and Mexico, and conforms with international classifications. The system allows comparability of statistics about business activity across North America. See http://www.census.gov/epcd/www/naics.html.

and the ramifications of how these alternative futures might impact energy use and technology requirements.

Characterization on Industrial Energy Use in Models

The author has reviewed a range of energy models that provide a disaggregated, bottom-up representation of the manufacturing sub-sector. These include the U.S. Department of Energy's Energy Information Administration's (DOE/EIA) *National Energy Modeling System, Industrial Demand Module* (NEMS/IDM) (OIAF 2006), the CIMS model developed at Simon Fraser University that was derived from the ISTUM model developed at DOE in the 1980s (Bataille et al. 2006, EMRG 2006 and Jaccard 2005), and the MARKAL model that is used extensively around the world (OIAF 2003, Bataille et al. 2006 and Greening 2006). None of these models cleanly define service demands for the manufacturing sector. In part, this lack of clear definition likely results from data availability issues and the need to simplify the representation of industrial energy use that is inherently complex. While this representation is quite satisfactory to understanding how energy is currently used in manufacturing, it may not provide adequate flexibility to explore alternative future energy technology paths that diverge significantly from current practice.

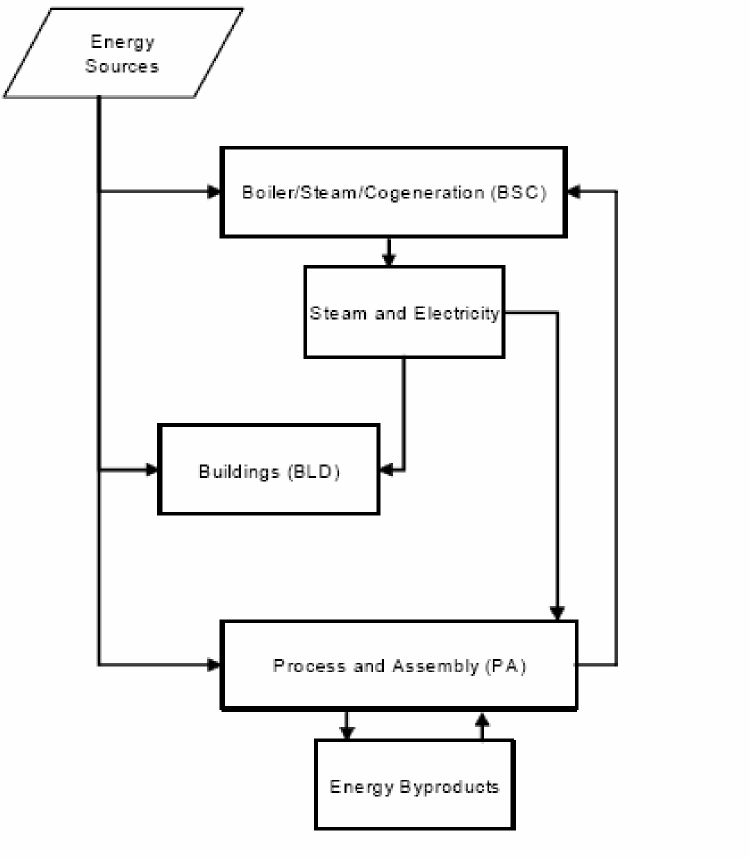
The primary data source for U.S. manufacturing energy use is DOE/EIA's *Manufacturing Energy Consumption Survey*, or MECS (EIA 2006). This report uses a end-user survey instrument sent to a representative subset of manufacturing facilities to collect data on energy use and related information. The MECS reports an estimated end-use breakdown for fuel consumption for three-digit North American Industrial Classification System (NAICS) Codes, as well as several important four-digit codes (see Table 1). These end-uses are broadly divided into three categories: indirect, direct process and direct non-process. These groupings do not correspond directly to service demands, but rather represent a hybrid that appears driven by the ability to collect data from the survey instrument. For example, it has been noted by EIA staff that MECS is unable to identify with confidence what end uses steam is put to from the survey data (EIA 1994). This observation of the limitation of the MECS data should not be taken as a criticism of the survey, which represents one of the best and most important manufacturing data sources anywhere. Rather, this observation applies to the application of data for analysis and forecasting, and the need to extend this data to provide a level of insights beyond energy end-uses.

Table 1. End Uses within NAICS Codes Reported in MECS

Indirect Uses-Boiler Fuel
Conventional Boiler Use
CHP and/or Cogeneration Process
Direct Uses-Total Process
Process Heating
Process Cooling and Refrigeration
Machine Drive
Electro-Chemical Processes
Other Process Use
Direct Uses-Total Non-process
Facility HVAC (g)
Facility Lighting
Other Facility Support
Onsite Transportation
Conventional Electricity Generation
Other Non-process Use
End Use Not Reported
Source: 2002 MECS, Table 5.2 (EIA 2006)

The MECS data serves as the basis for the end-use breakdown in almost all of the models of the U.S. manufacturing sector that the author has reviewed, and in particular the NEMS/IDM. Based on MECS data, the NEMS/IDM provides one of the most detailed representations of industrial end-use energy. The NEMS/IDM makes an estimation of the break down of these end-uses into more of an approximation of service demands using addition data sources to pars the MECS data. Energy use in the NEMS/IDM is segregated into primary model components (see Figure 1): a *buildings* (BDL) component that is further broken down into end-use categories that are common to all manufacturing and addresses the regional climate effects; and a *process and assembly* (PA) component that breaks down the end-use into industry-specific, end-use categories for energy intensive industries and into more general categories for metals-based durables (MBD) and balance of manufacturing (BOM). In addition, NEMS/IDM also introduces two sub-modules, *Boiler/Steam/Cogeneration* and *Steam and Electricity* that address the indirect conversions of fuel into steam and electricity that are in turn used in the BLD and PA sub-modules (OIAF 2006).

Figure 1. Energy Flows in the NEMS/IDM



Source: OIAF 2006

While the NEMS/IDM representation advances the representation of energy end-uses significantly beyond MECS, the fact that the indirect conversion operation take place outside the end-use module, the full integration of alternative energy use paths cannot be fully appreciated,. For example, looking at the end-use representations reported in OIAF 2006, it appears that engine driven refrigeration is considered in food products but the options of thermally activated refrigeration technologies or heat recovery from the engine are not available. While today the use of these technologies is small, this might not be the case in the future.

Energy End-Uses versus Service Demands

This tendency to equate service demands with end-uses is evident in most of the models reviewed by the author. For example, end-uses such as steam, electric motors, and lighting are all frequently viewed as service demands. This conflating of service demand and end-use can be problematic. In addition, a single end-use such as lighting may actually include more than one service demand – ambient and task, while steam is not a service demand at all, but an “energy carrier” that can be used to satisfy multiple service demands such as: shaft drive (thought the use of a turbine); drying or space heating (through the use of a heat exchanger); refrigeration (though an absorption chiller); and chemical reactions (through direct injection). So it is important to develop a good representation of the actual energy service demands, if we are to understand the technology choices that are available to manufacturing currently and in the future to satisfy these service demands. This understanding is particularly important if we are to better understand how service demands could evolve in the future, and how various energy sources can be used to meet these service demands. Concepts such as on-site power generation and CHP, while complicating this world view, also open up new opportunities for more efficient satisfaction of manufacturing service demands.

Some service demands may not necessarily require the direct application of significant amounts of energy at all. For example, fastening through welding of metals or plastics can be accomplished through various energy technologies – electric arc, gas flame, induction and ultrasonic – that fuse the material together. In addition, heat can be used to join the pieces through soldering or brazing in which a material with a lower melting temperature is used to bond two pieces together. However, there are also low-energy fastening strategies, including adhesives, solvents (for welding plastics), and mechanical fasteners (e.g. screws, bolts and rivets) that can all be used as well. They all satisfy the service demand for attaching two or more piece of materials together, but in very different ways. While direct application of energy is perhaps not always used, an "exergy service[3]" or work was used whether in the electricity or fuel required for the welding, the chemical processes required to manufacturer the adhesive, or the manufacturing of the metal fasteners.

Exergy Service Demands

This last example points out an additional problem that exists with analysis in manufacturing, which is the reality that manufacturing and the broader industrial sector as well is both a producer and consumer of products and intermediaries that are in turn used by other parts of the sector to produce other products with each firm adding value as the material is transformed, a challenge that the other economic sector do not have to face to the same degree. This duality of both being a producer and consumer also poses challenges to economic analysis in tracking the value added at the intermediate industries along the way toward the production of the final good. Similarly, energy is used in this intermediate production of goods, adding to the embodied energy content or energy value-added of the final product. Thus for the above example of fastening, the embodied energy of the adhesive or the bolt should be consider in comparison to the direct application of energy for say welding.

Ayers and Warr (2004) argue for tracking this embodied energy of products to better understand the relationship between energy use and economic activity. In their work they argue that what should be tracked is not energy consumption since all energy is not created equal, but the consumed potential to do work—referred to as exergy.[4] Ayer and Warr introduce the concept of "exergy service," which they define as the potential to do work. They assert that by using exergy services rather than energy consumption as the independent variable in a production function, the function can explain the unaccounted total economic output from considering labor and capital inputs – the so called "Solow residual."[5] While the tracking of embedded energy is beyond the

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[3] Exergy is a thermodynamic concept of the maximum potential work that a system can do – maximum potential energy. Ayers and Warr (2004) suggest that the exergy service is the work delivered to a system that meets a service demand or embodied in a product produced and subsequently consumed in meeting a service demand.

[4] In thermodynamics, exergy is defined as is the maximum work done by the system during a transformation which brings it into equilibrium with the reservoir (see http://en.wikipedia.org/wiki/Exergy).

[5] The Solow residual, named after Nobel Lauriat Robert M. Solow, represents the part of economic growth that cannot be explained through capital accumulation (see http://en.wikipedia.org/wiki/Solow_residual).

scope of this paper, it represents an important concept that warrants greater exploration to better understand how energy is embedded in our economy, particularly for the manufacturing sector.

Estimation of Service Demands

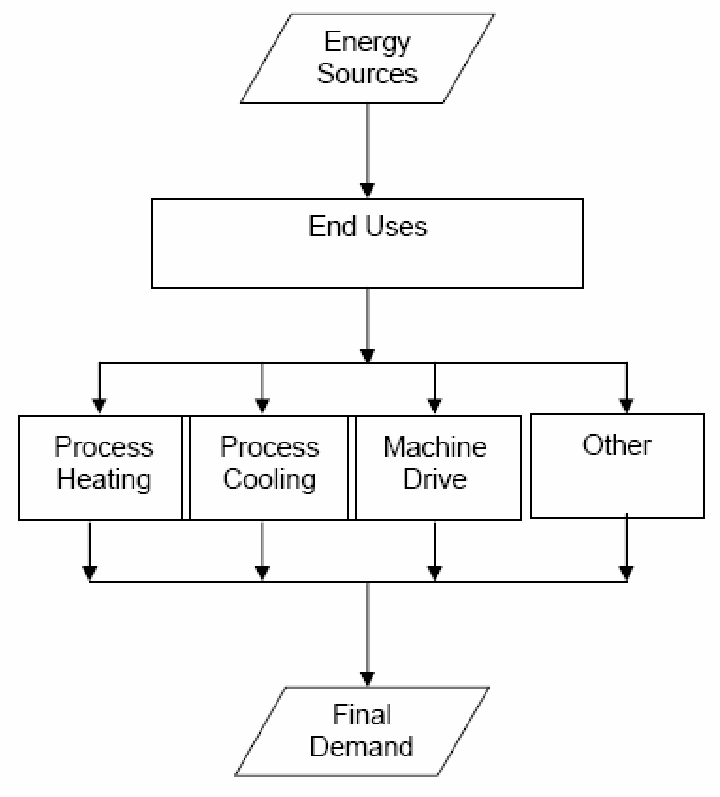
While data to estimate key energy service demands is not directly collected by any data source, a reasonable estimate can be made drawing upon various collected data sources and the application of informed, engineering judgment. While clearly some potential for estimation error exists in the estimation process, using collected energy end-use data as a proxy for service demands may result in an even greater distortion of energy choice options, and creates unnecessary rigidity in energy models that restricts possible future energy resource options. The literature discusses the problem of "shifting baselines," and the fact that energy use or service demands are not static, but constantly evolving in response to changes in technology and markets (see Laitner and Brown 2005, Shipley and Elliott 2006). It is important to maintain this longer-term perspective if we are to provide useful insights into possible futures.

Characterizing Delivered Exergy Services in Food Products Manufacturing

The NEMS/IDM characterization of industrial energy use represents a good starting point to develop an alternative representation of energy flows in manufacturing that better captures the actual end-use service demands, and reflects the broad range of options for satisfying these through various energy paths. The NEMS/IDM has begun this process building upon the MECS data, and using addition data source and analysis to create a more robust representation. In this exercise we build upon the end-use estimates in the NEMS/IDM, combining them with additional data sources and engineering judgment, allowing for the estimation energy service demands in manufacturing.

As a proof of concept, we will use the food products manufacturing industry (NAICS 311), which is a significant energy consumer but somewhat less complex than say more process focused industries such as chemicals or primary metals. For food products manufacturing, NEMS/IDM groups energy end uses into four major energy using processes: lighting, drive power, refrigeration and heating (see Figure 2 and Table 2). The service demands will of course vary by manufacturing sector, but a similar approach would be used for all sectors.

Figure 2. Energy Use Flows in the NEMS/IDM for Food Manufacturing (NAICS 311)



Source: OIAF 2006

Table 2. 2002 Energy End Uses for Food Manufacturing as Represented in the NEMS/IDM

Energy Carriers	Buildings				Process and Assembly				
	Lighting	HVAC	Facility Support	Onsite Transport	Direct Heat	Refrigeration	Machine Drive	Other	Total
Total	17.26	74.76	8.63	6.07	662.51	77.40	150.43	5.68	1,002.75
Steam		15.94			427.68				443.62
Electricity	17.26	18.34	3.24	1.07	8.75	66.91	133.81	1.31	250.69
Fuels									-
Natural gas		40.48	4.98	0.26	213.40	8.31	13.56	4.37	285.36
Residual					3.94				3.94
Distillate			0.26	3.18	0.87	2.19	3.06		9.56
LPG			0.15	1.56	1.75				3.46
Coal					6.12				6.12
Other									
Note: This table was complied from the data presented in tables B1 and B10 of OIAF (2006).									

The next step in estimating the energy service demands is to define what these key service demands are. Based on a review of information on the food products industry (Okos et al. 1998), it appears that there are four key service demands exist in the food products industry: lighting, drive power (other than that required for refrigeration), refrigeration and heating (in this case including both space condition and process related – e.g., cooking, baking and drying). The flow of electricity going to lighting and the flow of fuels and steam going to heating are fairly clear. Parsing the balance of electricity becomes the challenge.

The task is to estimate the distribution of this electricity going to various end-uses. The majority of end-use electricity goes to electric motors. The estimation of delivered drive power builds upon this NEMS/IDM data. Building upon these end-use estimates, combined with the Xenergy (1998) data together with Nadel et. al (2002), using engineering judgment to apportion the end-use energy to various services. Table 3 presents the author's apportionment of the electricity end-use data, compared with Xenergy's (1998) reported distribution.

Table 3. ACEEE's Estimates of Electric Motor Energy Use for NEMS/IDM Energy Uses in Food Manufacturing (NAICS 311) in TBtu

Electric Motor Application	**End Uses**								**Xenergy Distribution (2)**
	Buildings			**Process and Assembly**				Total & Distribution	
	HVAC (1)	Facility Support	Onsite Transport	Direct Heat	Refrigeration	Machine Drive	Other		
Total	15.59	3.24			66.91	133.81	1.12	220.66	
Pump	6.42					30.11		16.6%	16.4%
Fan	5.50					12.04		8.0%	7.5%
Compressed Air						16.73		7.6%	7.7%
Refrigeration	2.75				63.56			30.1%	29.4%
Materials Handling						13.38		6.1%	6.1%
Materials Processing						57.54		26.1%	26.1%
Other								5.7%	6.8%
Notes:	(1) assumes 85% of HVAC electricity use is for electric motors.								
	(2) distribution of motor energy use as reported in Xenergy 1998, Table1-17.								

As mentioned earlier, drive power can be delivered by energy carriers other than electricity, such as fuel to operate an engine or steam to drive a turbine. Using the above motor estimates and the NEMS/IDM data (OIAF 2006), the delivered drive power – in other words the actual power delivered by the drive shaft of the motor or engine – is estimated for three primary end-uses for which drive power is significant: HVAC and support; process machine drive; and refrigeration. These estimates are presented in Table 4. These estimates make a number of assumptions:

- The HVAC drive power is exclusive of refrigeration, and is all provide by electric motors
- The fuel allocated for process machine drive is used to operate direct drive engines of about 35%
- Assumes an average efficiency for electric motors providing process machine drive is 85%.
- The fuel allocated for refrigeration is used to operate engine driven chillers with an operating efficiency of about 35%
- Assumes all of refrigeration electricity is all used to operate electric motors and electric motor efficiency is assumed to be 90%.

Table 4. Delivered Drive Power for Food Manufacturing

Energy Carriers	**Delivered Drive Power**					
	HVAC, support & other	Equivalent Machine Drive		Equivalent Drive Power Delivered to Refrigeration		**Total Drive Power**
Total	16.28	119.56		66.37		202.20
Steam						
Electricity	11.92	113.74	95.1%	62.692	94.5%	188.35
Fuels						
Natural gas		4.744705	4.0%	2.908	4.4%	7.65
Distillate		1.071385	0.9%	0.7653	1.2%	1.84

Table 5 takes the estimates developed to this point and combines them to estimates the exergy services delivered to the three primary service demand categories: lighting, drive power, refrigeration and heating. For purposes of this service demand estimate, process and facility services are not treated separately. The key assumption in this table is the efficiency with which the energy carrier delivers services. The estimated conversion efficiencies represent current, typical field-measured efficiencies from the literature (cites).

Observations on Food Manufacturing Service Demands

Several interesting observations emerge from looking at the results presented in the table. Looking in particular at the total energy carrier line, lighting (which is only serviced by electricity) provides a very small delivered exergy service, while heating accounts for most of the energy service provided. Interestingly refrigeration receives more exergy service than does drive power applications, in large part because of conversion efficiency of 250%. It is probably important to explain to non-technical readers that this efficiency reflects the assumption that all the refrigeration is delivered via a vapor compression cycle that “pumps” the heat. In engineering this is reported as the coefficient of performance (COP) that represents the multiplier effect of the Carnot cycle.[6] An alternative to vapor compression refrigeration would be a thermally activated technology like absorption refrigeration for which the COP is typically

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[6] For an further explanation see http://en.wikipedia.org/wiki/Refrigeration_cycle.

between 0.9 and 1.1. Direct combustion of fuel, steam or waste heat all represent the energy carriers that would be used to operate these technologies to deliver refrigeration services.

Table 5. Estimated Delivered Exergy Services for Food Manufacturing (NAICS 331)

	Energy Carrier Conversion Efficiency				**Delivered Exergy Service (TBtu)**			
Energy Carrier	**Lighting**	**Drive Power**	**Refrigeration**	**Heating**	**Lighting**	**Drive Power**	**Refrigeration**	**Heating**
Total					6.90 0.7%	131.48 13.6%	165.91 17.1%	663.52 68.6%
Steam				95%				421.44
Electricity	40%	100%	250%	95%	6.90	125.66	156.73	10.92
Fuels								
Natural gas		100%	250%	85%		4.74	7.27	220.03
Residual				85%				3.35
Distillate		100%	250%	85%		1.07	1.91	0.96
LPG				85%				1.61
Coal				85%				5.20

Linking Energy Sources and Service Demands

Once energy service demands are estimated, consideration of a full range of potential energy flows is now possible, linking available service demands to various energy resources available to the industry. How we represent energy flows within manufacturing is often constrained by current usage patterns, meaning that we frequently overlook some of the “non-conventional” options. Granted, some of these options are not used for legitimate technical or economic reasons. However, not including them in the representation of energy flows eliminates there consideration in the future as technology and markets change.

In creating this representation of energy flows, the goal is to track all the possible energy flows from the energy sources through to the service demands. When considering the various energy sources that may be available at a facility, it is important to look not just at the purchased energy sources – i.e., electricity and fuels such as natural gas, petroleum products, coal, or other fuels – but also on-site energy sources such as waste fuels and waste heat.

We apply a useful concept to link energy resources and service demands – “energy carriers.” This concept is analogous to the MARKAL construct of he same name. Energy carriers are important to creating the linkages between energy sources and service demands because energy carriers in most cases are the medium directly used to satisfy the service demand. It is also important to consider “energy carriers” that are produced, on-site either from purchased or on-site energy sources. Among the energy carriers that might be considered are:

- Electricity
- Fuels
- Steam and hot water
- Direct shaft horsepower
- Hot gasses
- Compressed air
- Chilled water

While energy carriers could easily become quite complex when the full range of technically possible energy carriers is considered, available data does not allow for reasonable quantification of this detailed a representation. If, however we restrict ourselves to current energy use patterns are used as the starting point, we can identify just a few key, significant energy carriers.

Energy Flows in Food Products Manufacturing

For our example of food products manufacturing, the list can be reduced to three: electricity, fuels and steam/hot-water. In addition, the direct shaft horsepower could apply, though its current implementation is *de minimis*. Obviously, the fuels category is actually composed of several different fuels that each may be restricted to only certain applications, but for simplicity of graphical representation they will be represented in aggregate even though in an actual model implementation they would be represented individually (Figure 3).

Figure 3. Representation of Energy Flows and Service Demands in Food Products Manufacturing (NAICS 311)

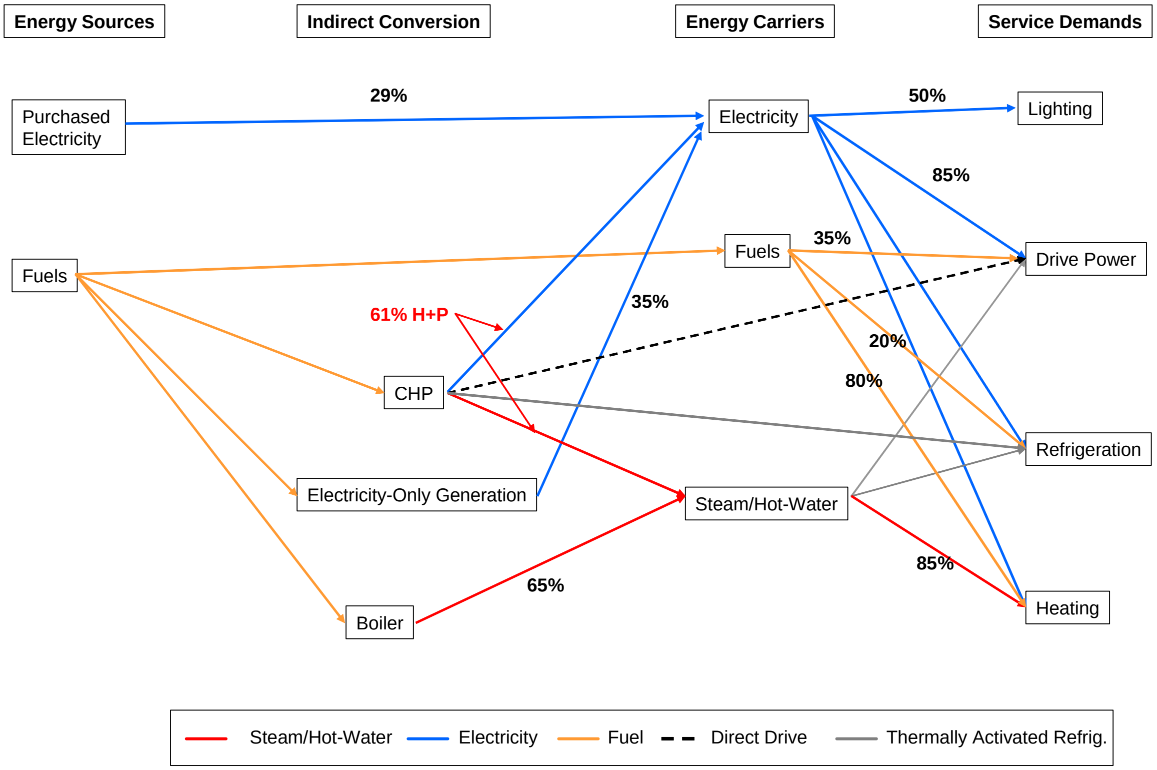


Figure 3 also reflects another important concept – "indirect conversion." Indirect conversion processes convert one energy carrier, usually a fuel, into another carrier. In the food industry representation we have three indirect conversion processes that consume fuels and produce other energy carriers: boiler producing steam and/or hot water; electricity-only generation that produces electricity; and combined heat and power (CHP) that produces a range of out-puts including electricity, direct shaft drive power, refrigeration through a thermally activated cooling technology such as direct fired absorption refrigeration, and steam and/or hot water. This concept of indirect conversion is taken from the NEMS/IDM (OIAF 2006) (see Figure 1), though it is implemented in a less integrated fashion than is proposed here. What this representation offers is an expansion of the various technology implementations that could be used to satisfy the different service demands.

Hierarchical Technology Choice Representation

Expanding upon the previous representation of energy flows, let us focus in upon the drive power and refrigeration service demands. In each case, a set of energy carrier and technology choices are presented as we move from energy resources (the left side of Figure 3) to the service demands (right side). These technology and resource choice decisions can be represented as a series of discrete choices in a decision tree format as is presented in Elliott and Wroblewski 2001 for motor decision making. While this representation was developed as an engineering decision tree representation, it bears a striking similarity to the hierarchical representation of investment choices seen in economic models such as AMIGA (Laitner and Hanson 2006), and could be implemented as a series of nested constant elasticity of substitution (CES) production functions. We will now look at these two service demands in detail.

Drive Power Technology Choice Options

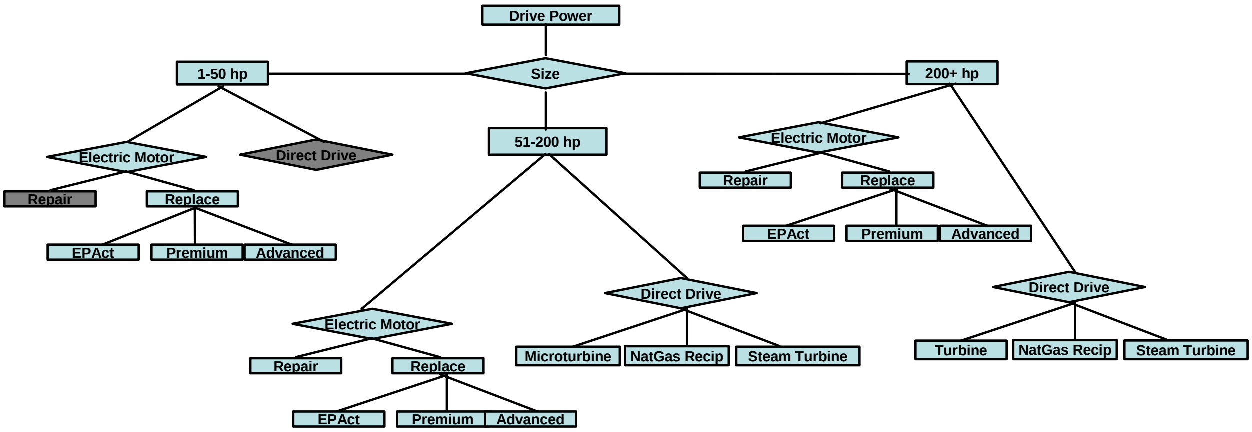
In many ways drive power represents the best understood but also most complex of the service demands. Over the past twenty years, significant efforts has been focused on characterization of available technologies and how these industrial users make technology decisions (see Freedman, et al. 1996, Xenergy 1998, Nadel et al. 2001, and OIAF 2006). Most of the analysis has been focused on electric motor technologies that can be used to satisfy this service demand, in large part because electric motors represent the dominate technology used to satisfy this service demand and account for over half of all electricity consumption economy-wide, and over two-thirds of all electricity consumption in the manufacturing sector (Nadel et al. 2001). Based on a review of the electric-motor literature, and analysis of the market and technologies by the author and others, the it can be persuasively argued that the electric motor end-use market can be separated into three size bins that can then be used to represent the technologies choices available to satisfy the drive power service demand.

- *1-50 hp* – this size range represents the majority of the motors, though in general not of the energy use. These smaller motors are ubiquitous being used for almost every imaginable application distributed widely throughout manufacturing facilities. Because of their relatively high cost of repair they are more likely to be replaced on failure than are larger motors (see Nadel et al. 2001).
- *51-200 hp* – these represent the workhorses of industrial motors driving large stationary machines such as fans, pumps and compressors. Most manufacturing facilities will have numerous motors in this size so are likely to swap out a repaired or new replacement motor from inventory when these motors fail. Both these and the 1-50 hp motors are covered by the EPAct motor rule (see Nadel et al. 2001 for a detailed discussion). In most cases, these motors will be repaired unless there is some economic or technical reason not to.
- *Above 200 hp* – these are the largest size category representing in many cases the largest concentrated electrical loads at most manufacturing facilities. These are used to drive large compressor, fans, pumps or processing equipment. Most of these motors are engineered for their particular application. While they are not covered by EPAct, they are in general of a high efficiency level at least equivalent to NEMA Energy Efficient because of their high duty cycle and large energy use. Because of their cost, spare motors are seldom kept on site, and are usually repaired.

While electric motors are the predominate, current technology choice to satisfy the drive power service demand (refrigeration service demand as will be discussed next), to implement the enhanced service demand representation set forth in the previous section, we also need to expand the technology choice opportunities to include direct-drive technology options. The reasons for electric motors predominance lie in electric motors convenience, low first-cost and ease of procurement and operation. However, various engine technologies are proven and commercially available to satisfy most of these applications.

These Thus, building upon technology choice representation for electric motor decision-making in Elliott and Wroblewski 2001, we can expand the representation to reflect the available technology choices to satisfy motor drive service demand as is shown in Figure 4.

Figure 4. Representation of Drive Power Technology Choices



To develop these CES production functions requires a set of technology characterization. Because electric motors are manufactured to strict performance standards (see Nadel et al. 2001), and market data is fairly readily available (see Nadel et al. 2001 and Motor Master 2005), we can characterize the operational characteristics of motors fairly easily. We can similarly characterize engines for each size category using a new report prepared for EIA (Discovery Insights 2006). The parameters used to characterize the equipment categories were:

- Average Operating Efficiency (electric or combustion) (%)
- Installed Capital Cost ($/hp)
- Non-energy operating cost ($/hp/yr)
- Average operating hours (hrs/yr)
- Average operating load (%)
- Motor life (yrs)

Five different technologies were characterized for each size category and for three points in time – 2005, 2015 and 2030:

- *Installed base electric motor* – this represents the performance of the existing, operating base in time. The efficiency of this category converges to the EPAct level in 2030 under the assumptions that EPAct became the default minimum for new motors in 2000, and the vast majority of the motor stock will have turned over in 30 years.

- *EPAct Motor* – this motor is the minimum efficiency motor specified in the Energy Policy Act of 1992 (see Nadel et al. 2001 for a discussion). This efficiency level equates to the NEMA "Energy Efficiency" specification in NEMA MG-1 for motor of 1-200 hp. Because EPAct does not apply above 200 hp, the NEMA specification is used for these motors.

- *NEMA Premium Motor* – These are motors that meet the NEMA efficiency specification, and have been labeled as such since 2001. Unlike EPAct, NEMA Premium covers all three-phase low and medium-voltage motors.

- *Advanced Electric Motor* – The advanced motor is a construct that has evolved from ACEEE work on emerging technologies (see Martin et al. 2000 and Sachs et al. 2004). As a result of profiling individual emerging motor technologies over the past decade, the author has noted that while understanding the adoption path for any individual technology is difficult if not impossible, the technologies that succeed in the market appear to have a certain characteristics. This category represents the author's judgment of what performance characteristics of the next successful electric motor will look like (These assumption will be explored in greater depth in a forthcoming paper).

- *Direct Drive* – For each electric motor size category, corresponding engine technologies also exist. Based on Discovery Insights (2006), it appears unlikely that any engine technology will be competitive for general drive power applications in the below 50 hp size category. This judgment stems from the view that these applications are generally of the dispersed nature of smaller motors within manufacturing facilities and the cost of providing non-electric energy carrier infrastructure, it is assumed that direct drive technologies do not significantly participate in this market and can be ignored for this size category. Depending upon future however, technologies such as small, efficient steam turbines might become more available that would allow them to compete with electric motors in this category. In the larger categories, existing commercial products already are available and the infrastructure challenges are less daunting. Three direct technologies are suggested for category: turbine, reciprocating engine and steam turbine.

Note that several additional simplifying assumptions are made in this representation. First, for the 1-50 hp size, it is assumed that failed motors should be replaced on an economic basis, so the "repair" option is not assumed to be available. Obviously, it is unlikely direct drive will compete for all applications because of operating and logistical considerations, so the assumption is made that direct drive competes for half of the 51-200 hp size load and 75% of the 200+ hp load. Since the literature suggests that industrial motors are seldom retrofitted before failure (Nadel et al. 2001 and Optimal et al. 2003), it is assumed that only failed motors and motor purchases for new applications are the only load available for consideration.

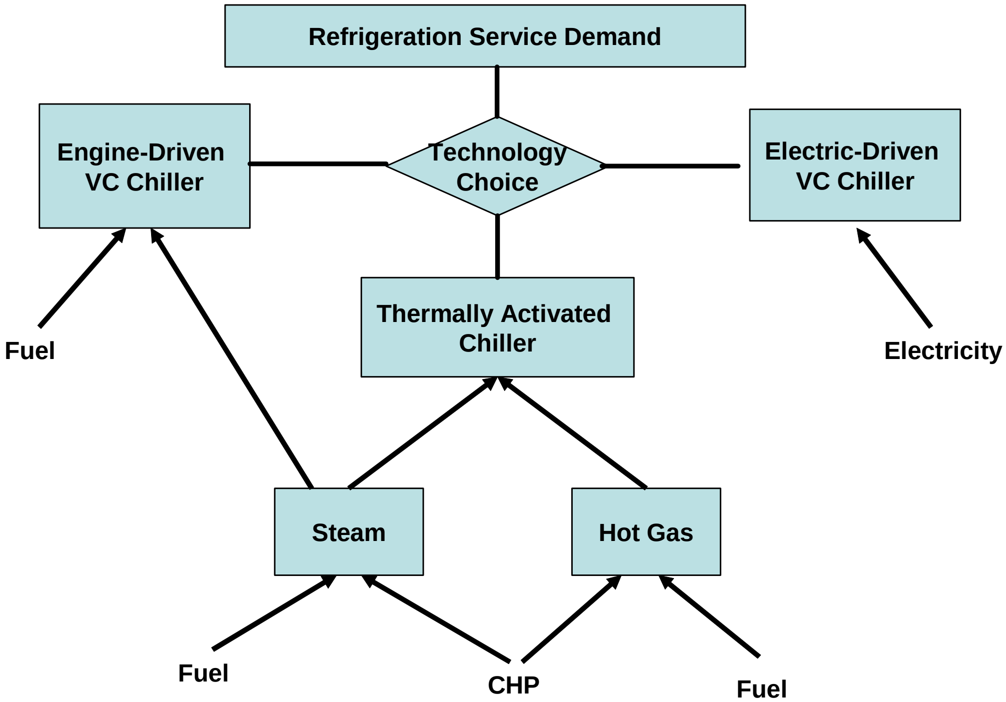
Refrigeration Technology Choice Options

The technology choices for the refrigeration service demand can be represented in a similar manner (Figure 5). Here the technology-choice topology is less complex with three options competing to satisfy the service demand:

- *Electrically-driven vapor-compression refrigeration* – this technology choice is the dominant refrigeration used for almost all application currently. It makes use of an electric motor driving a Carnot refrigeration cycle. The type of compressor driven by the electric motor and the working fluid used in the system can vary, but the fundamental thermodynamic principles and system component configuration remain the same. The Carnot system is a so-called "heat pump" in that it moves thermal energy from location to another reducing the temperature at the source and rising the temperature at the sink. Because the thermal energy is moved rather than generated, the efficiency of the cycle is greater than 100%. In other word, you get more cooling than is input to the system. This phenomenon is measure by the coefficient of performance (COP), which for most industrial vapor-compression refrigeration systems is about 2.5 (or 250%).

- *Engine-driven vapor-compression refrigeration* –this technology choice replaces the electric motor with an engine that converts an energy carrier such as steam or fuel into drive power that drives the compressor in the system. COP is the same with the only difference being the prime-mover.
- *Thermally Activated Refrigeration* – Thermally activated cooling technologies apply fundamentally different physical principles to produce refrigeration using heat input rather than drive power to drive the refrigeration cycle. The predominate technology is absorption cooling is that the working fluid is transformed into a liquid by being absorbed into another liquid rather than being mechanically compressed. Absorption refrigeration actually predates vapor-compression refrigeration, but fell out of favor for reasons of cost and material limitations. Over the past quarter century significant advances have been made in cost and materials making it a viable technology. Because of the different thermodynamic cycle the COP for industrial system is about 1.0, meaning one unit of cooling for every unit of energy input. In this case the energy input is largely heat rather than drive power however, which can frequently be produce with lower exergy than electricity. Thermal input can be in the form of steam, hot exhaust gasses from another process, or from a dedicated fuel burner.

Figure 5. Representation of Refrigeration Technology Choices



Implications of this Alternative Representation

By implementing this alternate representation of industrial energy use, breaking the energy flow down into service demands, energy carriers and energy sources, and incorporating indirect conversion allows the exploration of different energy technology scenarios. Two observations flow from examining this alternative representation of energy flows in Food Products:

1. The overall energy efficiency (i.e., primary or second-law) for different energy sources may produce surprising results, with direct use of fuel being more efficient than using purchased electricity. For example, to prove drive power from purchased electricity may only yield an efficiency of 25% while providing the same drive power using an internal combustion engine burning fuel could yield and efficiency closer to 35%. In reality, some service demands will have to be met with a particular energy carrier (i.e., there are applications that will require electricity, steam or hot water for which switching energy carrier is not technically feasible), but for at least a significant subset of the service demands a real technical choice may exist.

2. The potential to satisfy multiple service demands with a CHP system would offer significant efficiency opportunities. The challenge with CHP is to allocate the cost and efficiency to the different energy streams going to meet the service demands. Most industrial firms have allocated the costs of producing steam from an independent boiler to the thermal output from the CHP system (cite), with the balance of energy and costs being allocated to the power (e.g., electricity). This approach makes logical economic sense for an industrial consumer if we assume that they will "need" steam and the only way to produce it is to operate a boiler, so the electricity (which can be readily purchased from an external party) should only reflect the incremental costs. However from the perspective of incorporating it endogenously into an energy model it may be preferable to take an electric-centric perspective. This approach may be more appropriate because from a value perspective, electricity as an energy carrier is equivalent whether generated or purchased, and presence of available thermal energy (e.g., steam) may affect the choices of using it to satisfy a non-heating service demand (e.g., refrigeration or drive power).

While only a few of these energy flow paths currently are significant in the installed base, as has been noted in the examples of the drive power and refrigeration service demands, the technologies needed to enable many of these alternative paths are currently mature and available. While it is unlikely that any of these technologies will take over the servicing of these service demands wholesale in the immediate future, over the course of the next 25 years we could certainly envision scenarios in which shifts could occur that would result in these technologies taking over a significant share from the incumbent technology.

Examples of Technology and Energy Resources Alternatives in Food Products

[Various options for satisfying drive power and refrigeration service demands are explored, and the energy implications of various technology choices examples are contrasted.]

Extension of Service Demand Representations to other Market Sectors

[The application of this exergy service demand representation to other market sectors, in particular integrated building systems, is discussed.]

The Impacts of Market and Technology Evolution on Future Industrial Service Demand

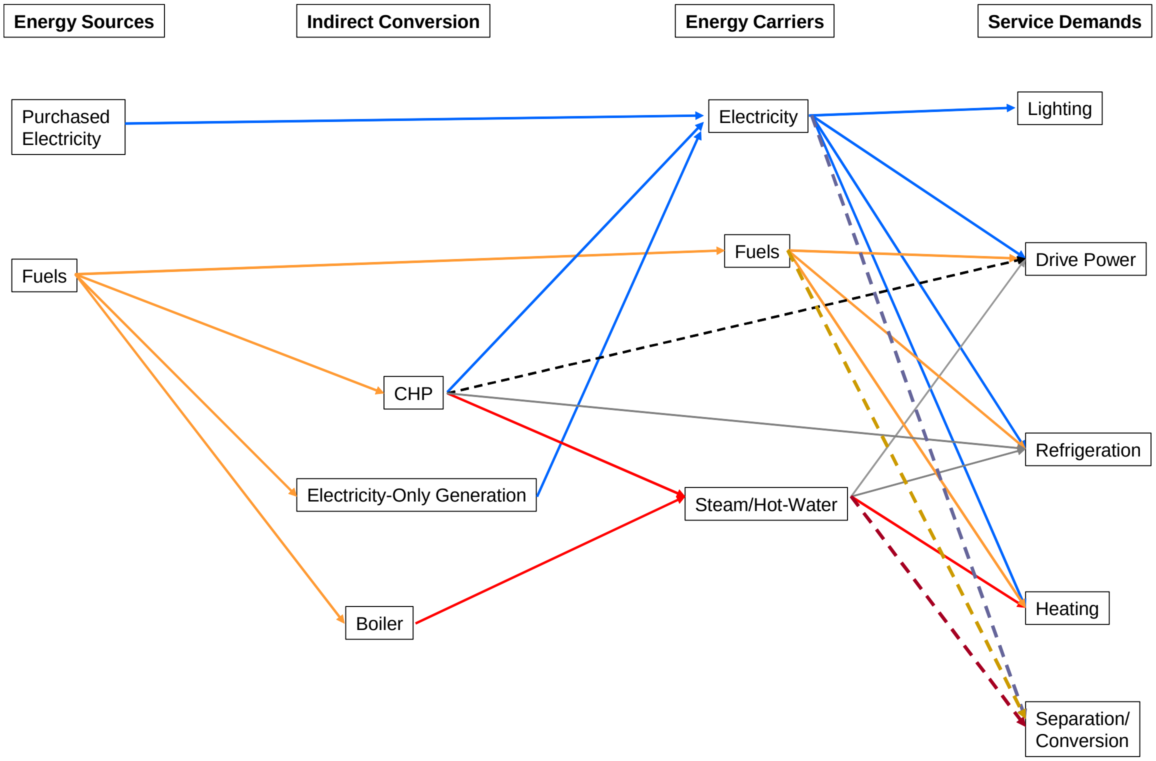
While many models treat energy service demands are not static, in reality they are very dynamic. Looking back, we see changes in markets and technology can result in the fundamental shifts in the processes we use and the products we produce (see Interlab 2000, Laitner and Brown 2005, Shipley and Elliott 2006). These changes have resulted in changes in the relative size of energy service demands, changes in energy resources that satisfy them, or the introduction of wholly new service demands. The emergence and transformative power of computer controls and sensors over the past quarter century is an example of how processes can change, and the emergence of silicon semiconductor technology an example of new products that were not envisioned as recently as 35 years ago.

Some of these changes have products widespread changes. One important example has been the shift from steam to electricity as the energy carrier that is used to satisfy many of many service demands. This change has been (implicitly or explicitly) modeled as an autonomous electrification trend in many models (Ross et al 1993, Bluestein 2005, Honeycutt 2006). The assumption has frequently been made that this trend is likely to continue into the future. While there may be justification for this assumption, there are other scenarios that could just as readily play out. The assumption of an electrification trend in part results from an inadequate representation of energy flows in manufacturing, limiting the estimates of the potential for CHP and various thermally activated technologies. While these technologies are not currently widely use, there are no technical reasons they could not be implemented, and refinements to these technologies and the emergence of other, unforeseen technologies could accelerate a reversal of this trend. As has been noted in the CHP literature (e.g., Elliott et al, 2003 and Brooks 2006), many of the barriers to expanded industrial adoption of CHP are regulatory or market, rather than technical or economic.

Possible Structural Changes in Food Products Manufacturing and the Range of Impacts on Service Demands

To explore these issues we will consider a future scenario for food products manufacturing in which we shift from processing of food products to actual synthesis of food products from building blocks. Laitner and Brown (2005) hint at this with their discussion of synthesis of products using ink-jet printing technology – more formally selective laser sintering. Applying this concept to an industrial application for food products manufacturing, we could see this industry transformed into an industry that produces building blocks from various agricultural feed stocks – amino acids, simple sugars and fats – and then reassembles them to produce food products, not unlike what has been proposed by some science fiction writers. Under this model, new separation and conversion processes, not unlike those in the organic chemicals industry, would become important to food product creating new process energy service demands not envisioned by today's industry. Thus the energy flow model for the industry could change as is suggested in Figure 6. While these technologies are not currently in wide commercial use, they do exist today and could be deployed on a significant scale in timeframes frequently seen in modeling exercises – e.g., 25-50 years. While this exercise is not intended to predict the future, it is useful to consider what range of scenarios could occur and how they might effect both energy consumption but also how energy is used and what options might exists for satisfying these energy service demands.

Figure 6. Possible Future Energy Flow Representation for Food Manufacturing



Conclusions and Need for Further Work

A robust representation of energy service demands is important to better representation of energy use in manufacturing. Existing end-use focused representations unnecessarily restrict technology choices, and tend to lock in existing industrial practices. By restricting technology choices, modelers lock the economy onto energy paths that can miss opportunities for reduced energy use and carbon reductions.

This assessment also reveals the relative importance of various service demands and allows for better targeting of key technology research opportunities. A robust characterization allows for the development of a representation of energy flows that allows the exploration of a wider range of technology choices to satisfy these service demands. One key area that the energy flow representation proposed in this paper offers is the exploration of integration of a broad range fuel switching choices into energy models. Perhaps most importantly, the efficiency opportunities that result from the application of combined heat and power (CHP or cogeneration) to satisfy a broad array of service demands.

Further Research

The representation for service demands in food products manufacturing presented here can certainly stand further refinements. By identifying the key service demands and technologies that can be used to satisfy them, research can be focused on developing better representations for these technologies and providing greater richness in the technology options that are available. These characterizations need to be regularly updated to capture changes resulting from market conditions and technology evolution.

Representations for other industries should also be developed. These representations will require the development of additional technology characterizations. In addition, the impacts of the expanded range of potential technology choices need to be explored so we can gain a better understanding of the range of energy and carbon reductions that can be achieved from existing and near-term emerging technologies. In addition, the exergy service demand concept suggested by Ayers should be explored further so that we can better understand the interactions between not just within industries.

Exploration of various future market and technology scenarios can contribute to better understanding what the future may hold for manufacturing energy use – both from a risk and opportunity perspective.

References