Industry Energy Futures: Challenges and Opportunities for the U.S. Industrial Sector in a Carbon-Constrained Future

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ABSTRACT

The U.S. Department of Energy (DOE) is assessing strategies to reduce dependence on fossil fuels and to reduce anthropogenic CO_2 emissions. Analysis reveals that it will be necessary for industry to address more than energy intensity alone; for example, reductions in the carbon intensity of materials, use of low/no carbon feedstocks, the efficient use of materials, and the development of new materials and processes will be required. Since the U.S. industrial base is diverse, from extractive operations like mining to energy intensive subsectors including chemicals, refining, pulp & paper, iron & steel, glass and cement, substantive reductions in the industrial sector will be particularly difficult. This paper will outline the changes necessary to achieve future CO_2 emissions reduction targets, and will present a strategy and vision for industry to achieve those targets within the context of a revitalized manufacturing sector.

Context

Instability in the US and world energy markets have a profound effect on U.S. industries. Within the past 36 months oil costs reached all-time highs of $147/bbl, in a matter of months collapsed to nearly $30/bbl, and climbed back above $100/bbl at the beginning of 2011. Spurred on by a global financial crisis, decreased demand for goods and services has compounded the effect on US manufacturing. The effects are broad reaching, from increased unemployment rates to fluctuations in the markets for commodities and even recyclables.

This economic vulnerability has arisen as the world faces an extraordinary global environmental problem. There is an overwhelming consensus amongst scientists that anthropogenic contributions of green house gases (GHGs) are adversely affecting climate, and countries are faced with the need to control GHG emissions. The Leaders of the Major Economies Forum on Energy and Climate (MEF)[1] consider climate change to be one of the greatest challenges of our time and have recognized "the scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2 degrees C." In the US, projections of GHG emissions by the DOE's Annual Energy Outlook (AEO) of 2011[2], total annual CO_2 emissions are projected to increase from 6.2 gigatons in 2008 to 6.8 gigatons in 2030, a 9.7% increase; approaches are needed that will reverse that trend. The stabilization of atmospheric greenhouse gases (GHG) concentrations will require approaches that address both energy and non-energy related emissions from all corners of the economy – the electric generation, transportation, buildings, and industrial sectors. This paper uses a simple scenario analysis to address the scope of the challenge within the industrial subsector.

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1 http://www.majoreconomiesforum.org/

2 *"The Annual Energy Outlook 2011 (AEO2011) Reference Case,"* Energy Information Administration: Washington, DC. http://www.eia.doe.gov/forecasts/aeo/

US Industry in 2010

The U.S. industrial base is comprised of many operations that convert raw materials into finished products, and accounts for one-third of the US energy consumption and associated carbon [1]emissions. In addition, industry has a structure and characteristics that pose unique challenges. For example, the industrial base is diverse, with about two-thirds of the end-use energy consumed by the energy intensive subsectors including chemicals, refining, pulp & paper, iron & steel, glass, aluminum, metal-casting and cement.2 It also includes a wide array of manufacturing operations that convert raw materials into finished products - from the foods we eat to the infrastructure that surrounds us. The implications are significant: Manufacturing contributes more to the US economy than any other sector; in 2009 it accounted for 11% of GDP and directly employed 12 million people,[3] supplied 57% of US exports,[4] and produced nearly 20% of the world's output.[5]

The energy requirements that drive this economic engine are significant: about 30 quads/year or primary energy, accounting for about 34% of natural gas use, 26% of electricity use, and 23% of oil use in 2010. Industrial energy use results in significant emissions: approximately 28 percent of all the U.S. energy-related CO_2 emissions. Direct emissions from industry are considerable (about approximately 0.9 Gt), resulting from about 20 quads of non-electric energy use. In addition to the energy-related emissions, there are process-related industrial emissions of a range of GHGs (tracked in CO_2 equivalents). About five quads of the total industry energy consumption is non-fuel use of coal, oil and natural gas (e.g. petroleum coke for steelmaking and natural gas for petrochemical feedstocks).

While efficiency improvements have reduced energy intensity, over time energy use and emissions tend to trend upwards due to growth of the US economy. The stable and steady deployment of energy-efficient industrial technologies is necessary to reduce the rate of energy consumption, but is insufficient to achieve required emissions reductions. Decarbonizing US industry will require aggressive gains in efficiency, switching to low-carbon/ no-carbon fuels and feedstocks, as well as a decarbonized source of electricity. In order to meet national aspirations of energy and emissions reductions, US industry must attain and improve state-of-the-art process efficiencies, and develop transformational industrial and manufacturing operations for next generation materials and infrastructure.

Levers Affecting Industry Energy Use and GHG Emissions

Energy and commodities have a strong impact on the industrial sector, and affects the ability of U.S. industry to compete in a world market. An approach to industry and manufacturing is required that rethinks the valuations of materials and processing, and their resultant impact on the environment. Traditionally, industry has sought efficiency improvements through advances in energy efficiency. While reductions in energy intensity are an important driver, improvements in carbon intensity and use intensity can drive innovation, such as new business opportunities in climate-friendly technologies and products. Sustainable manufacturing methods that address a cradle-to-cradle approach to products more accurately reflect the true

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[3] *Gross-Domestic-Product-(GDP)-by-Industry Data*. http://www.bea.gov/industry/gdpbyind_data.htm

[4] "*The Facts About Modern Manufacturing* 2009," The Manufacturing Institute: Washington, DC. http://www.nist.gov/mep/upload/FINAL_NAM_REPORT_PAGES.pdf

[5] *GDP and its breakdown at current prices in US Dollars*. cited 2010. http://unstats.un.org/unsd/snaama/dnlList.asp

lifecycle energy and GHG emissions; and, substituting or developing new materials that provide the same or greater service with reduced energy and emissions are more cost effective. **Error! Reference source not found.** Table 1 categorizes example opportunities by principal driver.

Table 1 - Improvement Levers in the Industrial Sector

Use Intensity	Energy Intensity	Carbon Intensity
Primary and non-destructive recycling	Process efficiency	Feedstock substitution
Reuse and remanufacturing	Electrotechnologies	Green electrification
Materials substitution	Combined heat & power	Green chemistry
By-products	Process integration	Renewable distributed generation
Behavioral change	Waste heat recovery	Carbon capture & sequestration
Product-service systems	Supply chain integration	Biomass based fuels

There have been a number of studies of U.S. industry, but most have focused on only a fractional intensity aspect of industry, such as energy intensity (see Figure 1 for some example studies). Several studies have evaluated the potential for both cost-effective energy efficiency improvements; as well as opportunities to advance current state-of-the-art technology towards practical energy minimums.

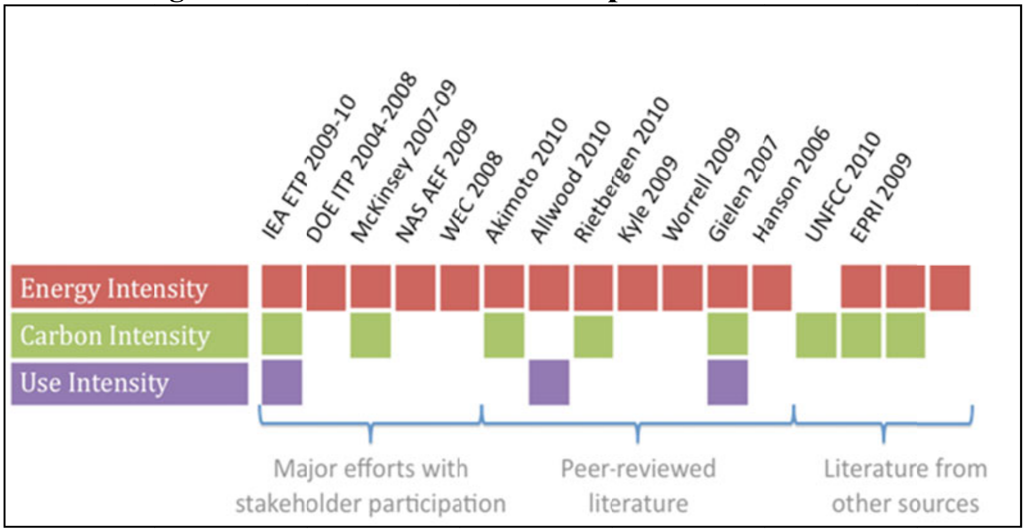
For example, McKinsey estimates that the industrial sector can reduce energy use by 18% by 2020 with existing technologies and NPV-positive investments (i.e., energy cost savings resulting from technologies financed with loans would yield positive cash flow).[6] On a primary energy basis, this study estimated 2.1 Quads in cost-effective available savings in 2020 from energy support systems including steam, motors, and buildings and an additional 0.9 Quads available through increased industrial combined heat and power (CHP) adoption; available savings from specific industrial processes were estimated to be additional 2.9 Quads. The National Academies has also surveyed a range of studies, which estimated the savings potential from deployment of existing and emerging technologies to be around 4.9 to 7.7 quads by 2020, inclusive of the potential for CHP.[7]

Because industry is so large and so diverse, scenario analyses can help to map the opportunity space analysis, and highlight how key drivers including carbon and use intensity can provide a roadmap to the transform industry. Improvements cross-cutting energy systems (e.g. compressed air, process heat, steam systems, motor drives) and industry specific process improvements – especially in the energy intensive industries – have the potential to significantly reduce CO2 emissions from U.S. industry. Below we review these systems, and assess the scale of energy-related GHG reduction potential in the U.S. by considering a range of scenarios in which strong efficiency and fuel switching is applied against a "business as usual" baseline.

[6] "*Unlocking Energy Efficiency in the U.S. Economy*," McKinsey & Company, July 2009 http://www.mckinsey.com/clientservice/electricpowernaturalgas/downloads/us_energy_efficiency_full_report.pdf

[7] *"Real Prospects for Energy Efficiency in the United States,"* The National Academies, 2009.

Figure 1 - Studies of Industrial Improvement Potential



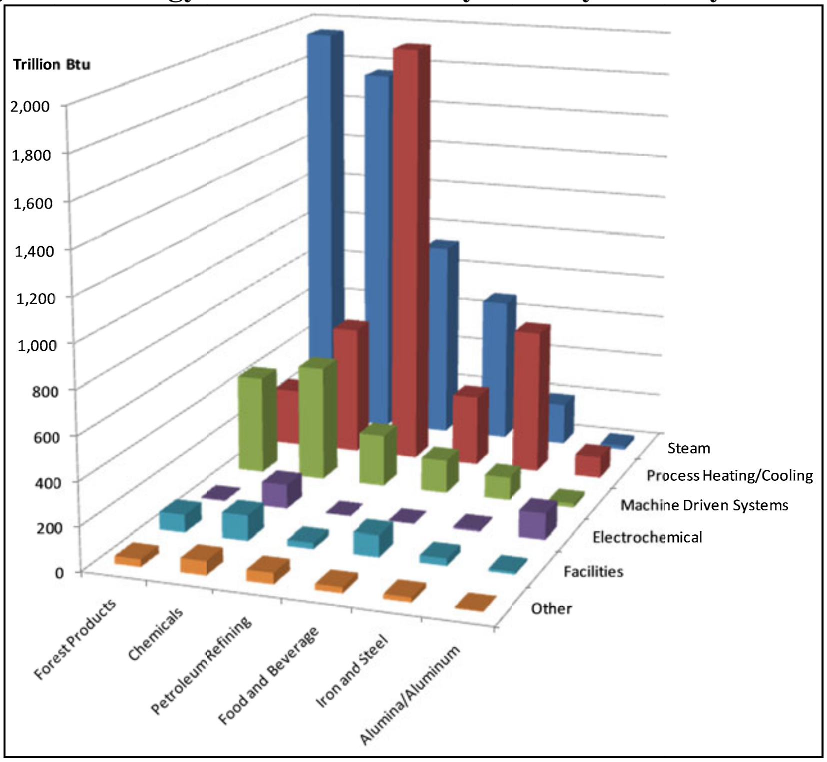
Improvements of Industrial Energy Delivery Systems

Industry can be thought of as a system at a number of levels. Primary industry involves the conversion of natural resources into primary products; these raw materials and commodities feed the light and heavy industries of the manufacturing sector. The heavy industries in particular can be energy intensive, and in addition to producing products often produce by-products of the manufacturing processes including waste heat and waste materials.

Within industry, energy is consumed in several key systems. For example, steam is produced in boilers and available for process use and cogeneration (combined heat and power) purposes. Direct process heat – generated in furnaces, ovens, kilns, and similar equipment – is used for melting and smelting, curing and drying, and other processes. Electricity is used to drive pumps, fans, compressors, and materials handling equipment. Energy is also used for space heating and lighting. Recovery systems are employed to utilize waste heat for beneficial uses such as material preheating or steam generation. Figure 2 shows the cross-cutting nature of key energy delivery systems for several energy-intensive manufacturing sectors.

Improvements in industrial energy efficiency and associated GHG reductions focus on process energy use at the manufacturing site, as well as onsite generation of energy (principally cogeneration). Best practices and deployment of commercially available, state-of-the-art manufacturing technologies to improve efficiency are the fastest routes to improved industrial efficiencies. There are a number of industrial subsystems that are used across a range of industries; for example, steam systems are widely used in petroleum refining, chemicals, food & beverage and forest products industries. There is significant headroom to improve the efficiency of existing processes and subsystems, such as through the use of high-efficiency motor systems, recovery of heat from thermal systems, etc.

Figure 2 - Energy Use of Industrial Systems by Industry Subsector



Many cost-effective energy efficient technologies have not been widely adopted due to barriers that include insufficient access to industry-specific energy efficiency expertise and workforce, slow capital stock turnover and uncertainty of energy prices, which deter corporate energy efficiency investments. Additional efficiency investments could become cost-competitive through energy RD&D. Key systems include:

Process heating. Process heating is the most energy consuming use of process energy; approximately 5,000 Trillion Btus of mostly fossil fuels, 380 Trillion Btus of electricity and 3,200 Trillion Btus of steam are used.8 Common process heating systems include equipment such as furnaces, ovens, heat exchangers, digesters, evaporators, kilns, dryers and melters. This equipment is utilized for a variety of processes, including separation and reactor preheating, evaporation, curing, drying, agglomeration and sintering, forming, smelting, and other specialized heating processes. Energy losses in these systems may include radiation and convection losses; insulation losses; wall, door, or opening losses; or cooling losses. Losses also occur through flue or exhaust gases.

Steam systems. Steam systems encompass steam production on manufacturing sites from conventional boilers (1,700 Trillion Btu8) or cogeneration systems (2,200 Trillion Btu8), as well as off-site steam production (900 Trillion Btu8); then the distribution of steam throughout the plant, and use of steam (for process heating systems, etc.). Common pieces of end-use equipment that utilize steam include heat exchangers, turbines, fractionating towers, strippers, and chemical reaction vessels. Industrial boiler efficiency can be improved by innovations such as high-intensity heat transfer; high-efficiency, low-emission burners; smart control systems; efficient preheating; flame radiation; and other enhancements.

Motor systems. Motor-driven equipment used throughout manufacturing currently accounts for over 1,750 Trillion Btu of electric energy[8] use, as well as an additional 250 Trillion Btu of mostly fossil fuel and 380 Trillion Btu of steam use.8 In many cases, the efficiency of motor use can be enhanced by upgrading the motor (e.g., variable speed drives, high efficiency motor) or through rewinding. Efficiency of common motor systems, such as pumps, fans, compressed air, and material handling systems can be enhanced through system optimization.

Combined Heat & Power (CHP). CHP has potential applications for any industry that has both electrical and thermal requirements. CHP's inherent higher efficiency and elimination of transmission and distribution losses from the central station generator result in reduced primary energy use and lower GHG emissions. Overall efficiencies of 70% or higher are achievable through generation of electricity (0.5 Trillion Btu generated onsite) and useful thermal energy (2.2 Trillion Btu generated onsite) from a single fuel source (natural gas, coal, oil, and alternative fuels) for direct process applications, or indirect use to produce steam, hot water, hot air for drying, refrigeration, or chilled water for process cooling. CHP generally consists of a prime mover, a generator, a heat recovery system, and electrical interconnection equipment configured into an integrated system.

CHP systems include reciprocating engines, combustion or gas turbines, steam turbines, microturbines, and fuel cells. Waste heat CHP systems are bottoming cycles in which energy recovered from the hot exhaust is converted to electricity through a Rankine power cycle. Steam is most often used Rankine cycles, but the lower temperatures often found in heat recovery applications allow other working fluids such as hydrocarbons (organic Rankine cycle or ORC) to be used as well. Steam cycles have a proven history in industrial applications to generate power from operations with hot exhaust gases such as coke oven batteries and cement kilns. ORCs are commonly used to generate power in geothermal power plants, and have been increasingly used in lower temperature industrial heat recovery.

CHP is already an important resource for the U.S. – there is 85 GW of CHP capacity at over 3,600 industrial and commercial facilities which represents approximately eight percent of current U.S. generating capacity and over 12 percent of total MWh generated annually.[Error! Bookmark not defined.] CHP can be utilized in a variety of applications that have significant, and coincident, power and thermal loads. Eighty-eight percent of existing CHP capacity is found in industrial applications, providing power and steam to energy intensive industries such as chemicals, paper, refining, food processing, and metals manufacturing. Countries such as Denmark and the Netherlands have a much higher percentage of their total power supplied by CHP (50 and 30 percent respectively) than the U.S. The potential exists in the U.S. to more than double existing CHP capacity, increasing CHP's contribution to 20% of total generation by 2030.**Error! Bookmark not defined.**

[8] http://www1.eere.energy.gov/industry/pdfs/mfg_footprint.pdf

Energy Intensity Improvements – The Potential and Limits of Efficiency for Existing Industries

DOE has commissioned a number of studies ("bandwidth studies") that have examined the potential for energy efficiency in specific manufacturing industries. These studies assessed opportunities from both adoption of state-of-the-art technology and best operating practices, and to some extent the potential from advanced technologies yet to be completely developed.

The analyses performed in these bottoms-up, technical studies show the potential improvements for a variety of industrial subsectors. Table 2 shows average industry energy use, the potential energy use if existing state-of the-art technologies were deployed, and the practical and theoretical thermodynamic limits of energy use in those subsectors.

Table 2 - Average, State-of-the-Art, and Potential Improvements for Major Industrial Subsectors

INDUSTRIAL SUBSECTOR	AVERAGE 2008[a]:		ENERGY USE, QUADS/YEAR (%EFFICIENCY IMPROVEMENT OVER 2008 AVERAGE)		
	TOTAL ENERGY	ENERGY INTENSITY	STATE OF THE ART (SOTA)	PRACTICAL MINIMUM[b]	THEORETICAL MINIMUM[b]
	QUADS	(MBTU/$)	QUADS (%)	QUADS (%)	QUADS (%)
chemicals[9]	6.9	30	5.7 (18)	2.0 (71%)	0.82 (88%)
pulp & paper[10]	2.2	14	1.6 (26)	1.3 (39%)	1.2 (43%)
petrol refining[11]	3.9	18	2.8 (30)	2.4 (38%)	1.1 (71%)
iron & steel[12]	1.5	20	1.2 (22)	1.1 (39%)	0.71 (53%)
aluminum[13]	0.4	13	0.34 (12)	0.11 (72%)	0.06 (84%)
glass[14]	0.2	9	0.14 (34)	0.01 (52%)	0.01 (61%)
cement	0.4	54	0.30 (30)[c]	N/A	N/A

[a]AEO[15]; [b]DOE Industrial Technology Program Bandwidth Studies[9,10,11,12,13,14]; [c]IEA data[16]; N/A: not available.

By applying the potentials from the range of bottoms-up studies to baseline projections to 2030 and 2050 of industrial energy use, it is possible to assess the scale of energy-related GHG reduction potential in the U.S. manufacturing sector through scenario analyses. Additional scenarios superimpose fuel switching in addition to efficiency improvements to assess scale of the impact from the different GHG abatement levers. Baseline industry data comes directly from the Energy Information Agency (EIA) Annual Energy Outlook (AEO). The AEO breaks up the industry data into 11 subsectors (Refining, Food, Paper, Bulk Chemicals, Glass, Cement, Iron & Steel, Aluminum, Metal Based Durables, Other Manufacturing, and Non-Manufacturing). The

9 "*Chemical Bandwidth Study*," 2006, U.S. Department of Energy, Washington, DC.
10 "*Pulp and Paper Industry Energy Bandwidth Study*," 2006, U.S. Department of Energy, Washington, DC.
11 "*Energy Bandwidth for Petroleum Refining Processes*," 2006, U.S. Department of Energy, Washington, DC.
12 "*Steel Industry Energy Bandwidth Study*," 2006, U.S. Department of Energy, Washington, DC.
13 "*U.S. Energy Requirements for Aluminum Production*," 2007, U.S. Department of Energy, Washington, DC.
14 "*Industrial Glass Bandwidth Analysis*," 2006, U.S. Department of Energy, Washington, DC.
15 *An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook*. 2009, Energy Information Administration: Washington, DC.
16 *Tracking Industrial Energy Efficiency and CO_2 Emissions*. 2007, International Energy Agency: Paris.

AEO data only goes out to 2035, so the data is linearly extrapolated from 2035 to 2050. Table 3 shows the heuristic reasoning developed to make scenario projections for the efficiency improvements to in 2030 and 2050.

In addition to projecting energy consumption for each industry subsector, the AEO reports the fuel mix for each industry subsector. By using the AEO as a "business as usual" baseline (reference case), energy efficiency measures are first applied to each subsector; then fuel mix changes are applied within each subsector. It is also possible to assess the impact and effects of additional industrial combined heat and power (CHP) by performing a broader scenario analysis by including projections for electric generation (not shown here).

The two efficiency cases (Low Case Efficiency and High Case Efficiency) are both more aggressive than the AEO reference case. The Low Case Efficiency scenario (see Figure 3) assumes that all current state-of-the-art (SOTA) will be deployed by 2030, and that by 2050 all subsectors will achieve either 2030 Maximum Efficiency levels, or 75% of the Practical Minimum (see Table 2), whichever is better. The High Case Efficiency scenario (Figure 4) assumes that by 2030 all subsectors will average 20% greater efficiency than current SOTA, or 50% of the Practical Minimum, whichever is better; by 2050, the Maximum Efficiency scenario assumes all subsectors will average 25% greater efficiency than current SOTA, or 75% of the Theoretical Minimum, whichever is better. For those subsectors where DOE has not performed detailed technical analyses, data from IEA[16] adapted.

Table 3 - Heuristic Decisions for "Low" & "High" Efficiency Scenario Projections

	2030		**2050**	
SCENARIO:	**Low Case Efficiency** Scenario 2030	**High Case Efficiency** Scenario 2030	**Low Case Efficiency** Scenario 2050	**High Case Efficiency** Scenario 2050
SCENARIO RULE:	*Equal to 2010 State-of-the-Art (SOTA)*	*20% Better than 2010 SOTA or 50% of Practical Min.*	*Equal to 2030 Max. or 75% of Practical Min.*	*25% Better than 2010 SOTA or 75% of Theoretical Min.*
INDUSTRIAL SUBSECTOR	**% Eff. Increase**	**% Eff. Increase** (**higher value** used)	**% Eff. Increase** (**higher value** used)	**% Eff. Increase** (**higher value** used)
chemicals	**18%**	21% or **35%**	35% or **53%**	23% or **66%**
pulp & paper	**26%**	**31%** or 19%	**31%** or 29%	**33%** or 32%
petro. refining	**30%**	**36%** or 19%	**36%** or 29%	38% or **53%**
iron & steel	**22%**	**27%** or 19%	27% or **29%**	28% or **40%**
aluminum	**12%**	15% or **36%**	36% or **54%**	15% or **63%**
glass	**34%**	**40%** or 26%	**40%** or 39%	43% or **46%**
cement	**30%** c	**36%** or N/A	**36%** or N/A	**38%** or N/A
food manuf.	**15%** c	**18%** or N/A	**18%** or N/A	**19%** or N/A
metal durables	**15%** c	**18%** or N/A	**18%** or N/A	**19%** or N/A
other manuf.	**15%** c	**18%** or N/A	**18%** or N/A	**19%** or N/A
non-manuf.	**15%** c	**18%** or N/A	**18%** or N/A	**19%** or N/A

cIEA data

The low and high efficiency cases present the bounds of an example, aggressive scenario in which only the energy intensity lever is utilized, resulting in a range of 34 to 40% potential CO_2 emissions reductions. In order to achieve higher levels of practical emissions reductions, fuel switching is added to the scenario. Figure 5 shows the significance of switching to low carbon energy supplies for industry. In the efficiency only scenarios, fuel use is assumed at the EIA projections.

Figure 3 - Emissions Reductions with Low Case Efficiency: 34% Reduction by 2050

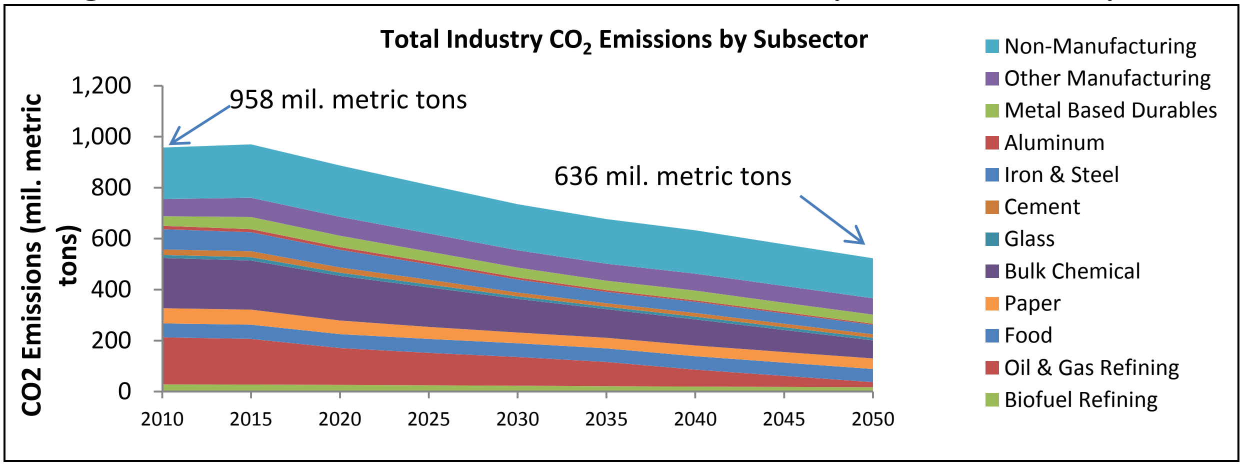


Figure 4 - Emission Reduction with High Case Efficiency: 40% Reduction by 2050

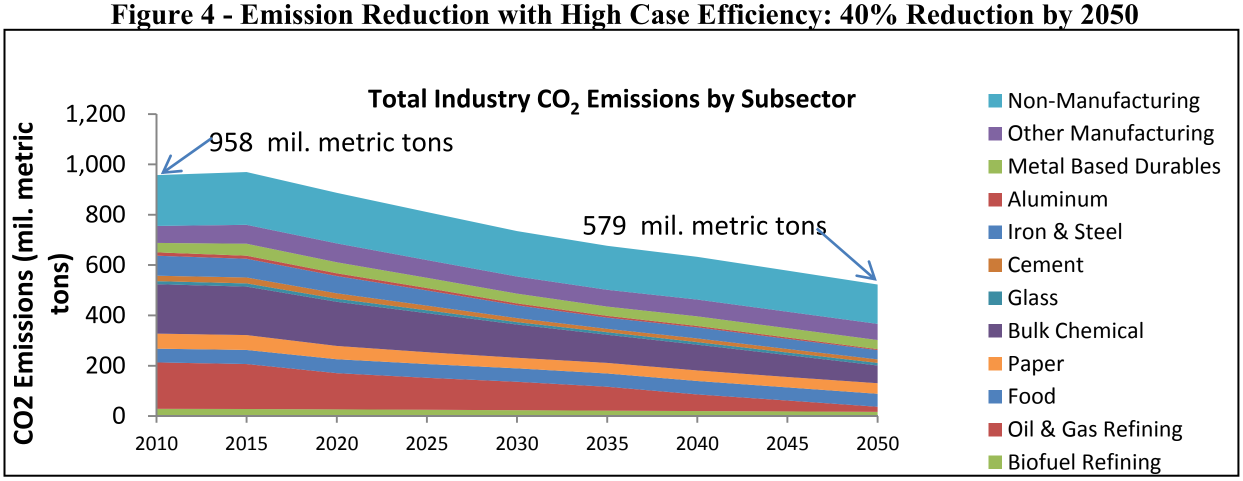


Figure 5 - Emission Reduction with High Case Efficiency + Fuel Switching: 61% Reduction by 2050

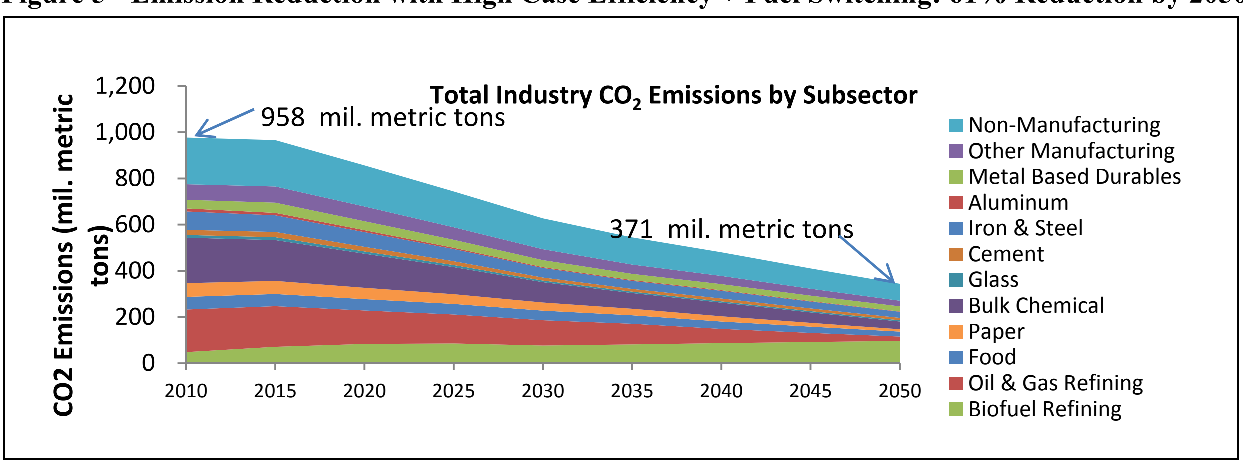


Figure 6 shows the relative proportions of fuels projected in EIA's Annual Energy Outlook). In the fuel switching scenario (Figure 7), the shift to lower carbon intensive fuels boosts the emissions reduction of the high efficiency case from 40% to 61% from current emissions levels.

Figure 6 - EIA Fuel Mix Projection for Industry

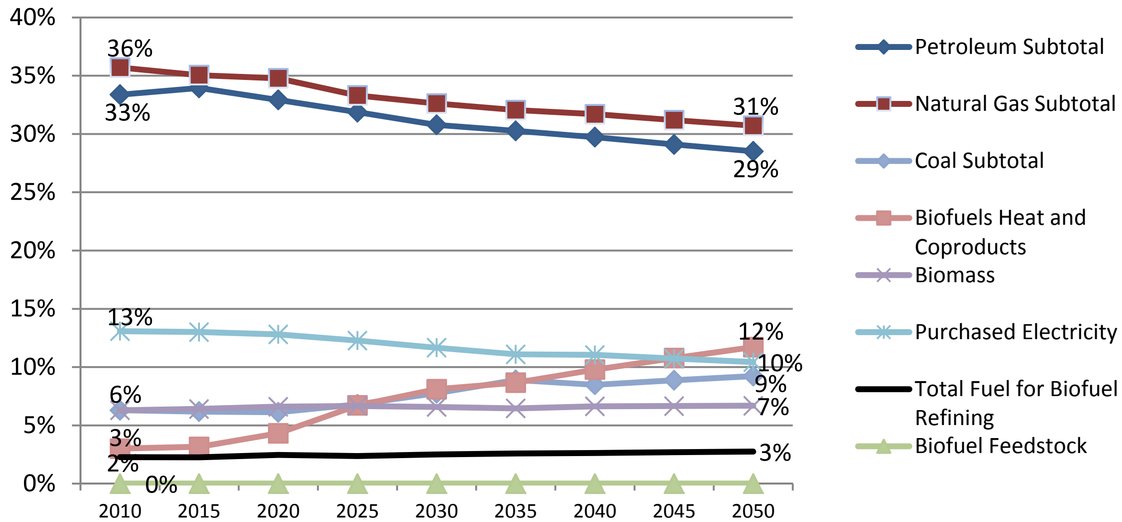
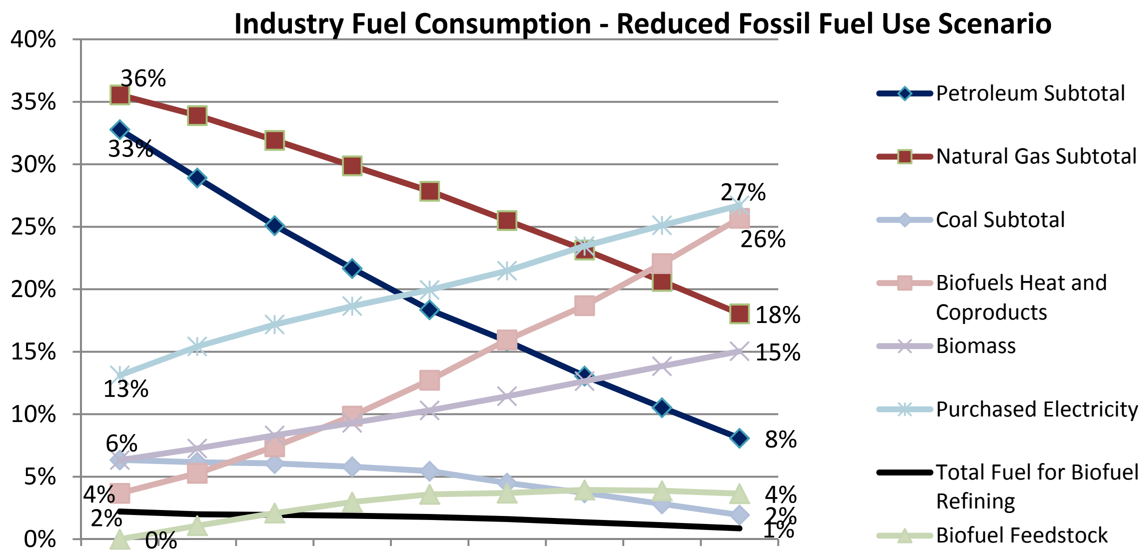


Figure 7 - Example Scenario of Fuel Switching to Lower Carbon Intensive Fuels



Moving Beyond State-of-the-Art – The Promise of Next Generation Industry

The reduction of energy use and carbon emissions by advancements in energy intensive processes cut across many manufacturing sectors. Specific technology applications can generate large energy-saving benefits across a variety of industries. Examples of technologies with the potential to drive industry towards practical minimum energy use include:

- *Reactions and separations.* New technologies with improved energy intensity and process intensification capabilities that yield dramatic energy and cost savings to a wide range of industries such as oil refining, food processing and chemical production.
- *High-temperature processing.* Improvements for producing metals and non-metallic materials that include deployment of lower-energy or non-thermal alternatives to conventional high-temperature processing technologies.
- *Waste heat minimization and recovery.* Technology advances in ultra-efficient steam production, high performance furnaces and broadly applicable waste-heat recovery that contribute to sustainability, reduced water usage and a lower carbon footprint for U.S. industry.
- *Sustainable manufacturing.* Technologies that enable the manufacture of components with multiple market applications and new manufacturing options that reduce process steps or parts count, thereby reducing energy intensity through the manufacturing value chain.

Scenario analyses identify the importance of efficiency in the near term, but also reveal the limitation of an efficiency-only approach with respect to deep emissions reductions. Fuel switching has great potential to provide low carbon energy to industry in the form lower (natural gas), and low/no carbon feedstocks and fuels. Other scenarios (for example the International Energy Agency's Blue Scenario) place a strong dependency on carbon capture and storage (CCS) technologies. However, in order to achieve transformational improvements, U.S. manufacturers will need to develop next generation manufacturing processes to provide critical energy and environmental improvements. Achieving super-efficient processing will require the reduction and/or integration of process steps, development of alternative low-energy pathways, and development of entirely new processes and unit operations. Approaches include:

- *Smart manufacturing systems.* Intensified use of manufacturing intelligence speeds time to market and enables dynamic demand response while improving energy and environmental performance. An example goal is a significant reduction in commercialization cycles.
- *Advanced forming & fabrication technology.* Allows for parts/product manufacture in near final form with minimal materials and energy use. An example goal is complete material utilization with reduced energy use.
- *Non-thermal-based chemical conversion processes.* Allows for dramatically lower energy use by replacing thermal processes. Examples include electron beam curing of composites. An example goal is substantially lower energy use than equivalent thermal chemical conversion.
- *High-performance separations, including membrane & hybrid reaction-separations.* Allows for dramatically lower energy use. New technologies with improved energy intensity and process intensification capabilities can yield dramatic energy and cost savings to a wide range of industries such as oil refining, food processing and chemical production. An example goal is significant energy reduction compared with conventional, high-temperature separations.

- *Nanoscale manufacturing & processing.* Enable the next generation of materials production via low energy pathways. An example goal is high performance materials with increased functionality produced via low energy-intensity manufacturing.
- *Single/minimal stage conversion pathways for energy-intensive materials.* Allows for dramatically lower energy use. An example goal is significant reduction in the embedded energy of finished part over current levels.
- *New production systems, such as innovative bioprocessing techniques that mimic the low-emission, low-temperature fabrication of living systems.* Synthetic organic chemistry and synthetic biology are new fields of research that offer opportunities for the bio-products industry to move in a direction that can help the deliver renewable solutions. The replacement of traditional processing routes used in areas such as chemical catalysis and polymer manufacturing can enable dramatically lower energy usage and carbon emissions. An example goal is the reduction of fossil-based feedstocks for production of chemicals and materials.