Initial Assessment of ISO 50001 Efficiency Improvements in Energy and Carbon Intensive Industrial Subsectors

Douglas L. Nelson, Clemson University

ABSTRACT

Efficient energy usage is essential to reducing greenhouse gas emissions across all sectors. ISO 50001: Energy Management Systems has been established as a method to achieving improved energy efficiency in facilities regardless of sector, with 10% minimum savings projected across sectors. The impact of efficiency in energy and carbon intensive subsectors (chemicals, petroleum, steel, and cement) is of particular importance as a significant fraction of consumption and emissions relate to these subsectors. However, the impact of ISO 50001 implementation on the industrial sector and these intensive subsectors has not yet been quantified. Using currently available case studies on ISO 50001 adoption, this study provides an initial understanding of the average savings realized by these energy and carbon intensive subsectors and discusses the statistical significance of each subsector's data. It was found that a 10% baseline minimum average energy savings was generally an overestimate, with some average energy savings from ISO 50001 less than 5% from the baseline year. While these reductions remain significant economic and energy savings relative to industrial status-quo, they are below the energy saving needed to mitigate an additional 2°C global warming by 2050. Additionally, as ISO 50001 is a relatively new (since 2013) standard for strategic energy management, it is unclear whether the savings reported have a selection bias. It is recommended that more case studies be conducted to form a complete understanding of the impact of ISO 50001 on energy and carbon efficiency as part of an economically viable strategy to mitigate climate change.

Introduction

The industrial sector accounts for almost 40% of annual global energy consumption and 30% of annual global greenhouse gas (GHG) emissions (IEA 2020). Within the industrial sector, energy-intensive sectors account for 50% of the industrial sector's energy consumption and 80% of its CO2 emissions (IEA 2020; Shukla et al. 2019; Ritchie 2019), where energy-intensive sectors are defined as the food, pulp and paper, basic chemicals and refining, iron and steel, nonferrous metals, and nonmetallic minerals industries. As a result of their large impact on the world's resources, targeted improvement of energy efficiency technology and practices in these sectors has the potential to greatly reduce global energy consumption and GHG emissions (Rissman et al. 2020). However, achieving significant improvement in industrial sector energy efficiency has historically proven more difficult than in other sectors due to the unique nature of each facility's energy consumption and GHG emissions when compared to the largely similar needs of other sectors.

ISO 50001 is an international standard for energy management systems created by the International Organization for Standardization (ISO) (ISO 2011). Energy management systems (EnMS) are combinations of software, business structures, and people that work together as a system to manage and continually improve a facility's energy efficiency (Aman et al. 2013; ISO

2011). ISO 50001's uptake widely varies from country to country, with Germany leading the world in adoption numbers and the US having only a couple hundred certified sites (ISO 2020). Across the globe, many organizations that have adopted an ISO 50001 EnMS realize initial annual energy consumption savings of 10% or more, with many achieving savings as high as 40% in one year (CEM 2020). However, many of the facilities found in these studies are from the service sector, comprising government buildings, public schools, office buildings, or warehouses (Better Buildings 2020; CEM 2020). While the impact of ISO 50001 on this sector is notable, it is also desirable to understand its impact on the industrial sector due to industry's significant impact on global energy consumption and GHG emissions.

To date, a broad study on the effects of ISO 50001 in specific sectors, particularly the energy-intensive industrial sector, has not been conducted. In fact, some important studies on ISO 50001's uptake and its effects on energy consumption and climate change mitigation have used average energy savings values from sources comprised solely of commercial sector facilities as being representative of both commercial and industrial sector facilities (McKane et al 2017). Until an accurate summary of ISO 50001 EnMS in energy-intensive industries is produced, models such as the ISO 50001 Impact Estimator Tool (IET 50001) cannot be adequately utilized to predict ISO 50001's total potential impact on world energy consumption and climate change mitigation (Aghajanzadeh et al 2016). This study seeks to combine all currently available case studies on ISO 50001 adoption in energy-intensive industries to form a starting comparison of average energy savings for these sectors. An average minimum energy savings of 10% is often provided for an ISO 50001 EnMS (CEM 2020), so this baseline value was compared to the average savings of each energy-intensive sector.

Methodology

The case studies employed for this analysis were gathered from the Clean Energy Ministerial's (CEM) publications library (CEM 2020). The CEM's Energy Management Working Group (EMWG) works to "accelerate ISO 50001 adoption around the globe" and provides case studies detailing the energy savings achieved by ISO 50001 implementation in various facilities from both the industrial and service sectors (CEM 2020). A total of 64 case studies were available for energy-intensive sectors: chemicals and refining (21), nonmetallic minerals (simplified to cement) (15), food and beverage (14), iron and steel (7), nonferrous metals (simplified to aluminum) (4), and pulp and paper (3), the full data for which can be found in the Appendix. In each case study, the energy savings obtained are generally given as the percent reduction of actual energy consumed over the length of the study period in reference to a baselines year, typically the year immediately preceding the study period; because of this, values for the continual savings incurred each year of the study period cannot be obtained. Despite the differing time intervals of each case study, each savings value is normalized against a continual baseline energy consumption for each facility, making them comparable across differing study intervals. To provide a more meaningful metric than the simple average of each sector's energy savings, a weighted average was obtained by summing the product of each site's energy savings percentage and annual energy consumption before ISO 50001 and then averaging that value against the sum of each site's annual energy consumption (again, before ISO 50001 adoption). A median and standard deviation savings values are also provided for each sector's energy savings. The results of this study are summarized in Table 1 below.

Table 1. Data for energy-intensive sector case studies

Sector (# of Sites)	Avg. Energy Savings	Weighted Avg. Energy Savings	Median Energy Savings	Std. Deviation
Chemicals and Refining (21)	4.5%	5.0%	4.0%	2.7%
Cement (14)	5.0%	4.6%	5.0%	2.3%
Food and Beverage (14)	14.7%	6.2%	8.6%	12.5%
Iron & Steel (7)	6.8%	3.4%	6.2%	3.7%
Aluminum (4)	6.9%	7.2%	5.7%	5.0%
Pulp & Paper (3)	14.3%	21.7%	15.2%	8.2%

Case studies from the CEM on ISO 50001 implementation in energy-intensive subsectors. *Source*: CEM, "Publications", 2020.

Results and Discussion

From the data provided by these case studies, it is clear that most facilities in most sectors are underperforming the desired (and claimed) minimum average energy savings. Several statistical conclusions can also be drawn from the data given, namely the effects of a facility's size on its energy savings and the uniformity of results in each sample. In each sample, if the weighted average and average savings differ by 0.5% or more, this is considered significant in determining the effects of the size of a facility on its success in energy efficiency improvement. Additionally, a difference of 1.0% or greater between the average savings and median savings is considered representative of significant outliers in the data sample. A standard deviation of 5.0% or greater is taken as significant deviation from uniformity (and thus consistency and confidence in the data set). Due to the relatively small amount of case studies obtained (67), a general statement about ISO 50001 in any of these sectors is not possible from the current study; rather, these results offer a first look into the potential effects of energy efficiency savings from ISO 50001 in energy-intensive industries. Each sector is discussed in detail below.

Chemicals and Refining

The chemicals and refining sector had the highest number of case studies (21), suggesting the most confidence in its data. However, this sector encompasses a wide range of industrial facilities producing very different products, and so a further breakdown is desirable, provided in Table 2 below. This breakdown divides the chemicals and refining sector into petroleum refining, fertilizer production, and basic petrochemicals with the total for the chemicals and refining sector given at the top. For fertilizer plants, the weighted average savings of 3.7% when compared to an average savings of 5.0% suggest that larger fertilizer facilities tended to incur lower savings than smaller sites. The opposite is true for petrochemical plants with a weighted average of 4.6% and an average savings of 3.5%. The only sector with a significant outlier was the fertilizer sector with an average savings of 5.0% and a median savings of 3.8%; this deviation is attributed to the MOPCO, Egypt site that achieved 11.7% energy savings with ISO 50001. Disregarding this facility, the average and median savings for fertilizers drop to 3.6% and 3.8%, respectively. For all three chemical sectors, a minimum average savings of 10% was not statistically likely.

Table 2. Breakdown for the Chemicals and Refining Sector

Subsector (# of Sites)	Avg. Energy Savings	Weighted Avg. Energy Savings	Median Energy Savings	Std. Deviation
Chemicals and Refining Total (21)	4.5%	5.0%	4.0%	2.7%
Refining (9)	4.8%	5.2%	5.0%	2.8%
Fertilizers (6)	5.0%	3.7%	3.8%	3.7%
Petrochemicals (6)	3.5%	4.6%	3.4%	1.4%

Breakdown for the Chemicals and Refining Sector into Refining, Fertilizers, and Petrochemicals.

Cement

The cement sector had 15 case studies available. While this is fewer than the amount of case studies available for the chemicals and refining sector, the cement case studies do not require a breakdown and thus this sector's data can be analyzed with higher confidence. Adding to this confidence is the lack of any statistical deviation in the cement sector's data, as its average and weighted average savings are 5.0% and 4.6% respectively. In addition to this, the cement case studies contained no significant outliers or nonuniformity with a median of 5.0% and standard deviation of 2.3%. Thus for this sample an average of 5.0% or less in savings under ISO 50001 was typical, amounting to almost half of the projected average of 10% listed in other sources and providing a strong suggestion that a 10% minimum average savings may not be accurate for energy-intensive sectors.

Food and Beverage

The food and beverage sector produced 14 case studies for analysis, although confidence in the data from these studies is not as high as that for other sectors due to the large variance in products from different food and beverage factories when compared to that of basic chemicals or cement sites. This sector displayed one of the largest differences between its average and weighted average savings of 14.7% and 6.2%, respectively. This indicates a significant trend in the size of a site and its energy savings potentials for this sample of facilities. Additionally, the standard deviation for this group was 12.5%, indicating a great deal of deviation from the averages presented. The median savings of 8.6% was much smaller than the average savings, indicating the presence of higher savings outliers, such as Wyeth Nutrition, Ireland and Coca-Cola, Portugal with energy savings of 38.0% and 30.7%, respectively. It is important to note that while the average savings period length is slightly less than 3 years for all case studies observed, the length of both the Wyeth Nutrition and Coca-Cola case studies was 6 years in length, suggesting a significant amount of continual improvement with each additional year in these facilities. While the average savings of these sites suggests a value greater than the 10% minimum baseline, the weighted average does not suggest this baseline when plant size is considered.

Iron and Steel

The iron and steel sector had 7 case studies available for study, however it had to be split into two different groups in similar fashion to the chemicals sector due to the presence of both integrated steel mills and mini-mills in this sector. The breakdown of the iron and steel sector is presented below in Table 3. An obvious trend that presents itself is the drastic difference between the savings for integrated and mini-mills where integrated mills on average saved much less than mini-mills. Additionally, the weighted savings for integrated mills (3.9%) were statistically lower than its average savings (4.4%) while the opposite was true for the weighted average (11.2%) and average savings (9.8%) for mini-mills, indicating that it was easier for smaller integrated mills and larger mini-mills to save more energy relative to their size. This trend for mini-mills that appeared in the petrochemicals sector as well, is counterintuitive to what is expected for larger facilities in terms of relative energy savings. It is likely explainable by the small sample size present in both sectors and the study as a whole. No statistically significant deviation was notable in the median and standard deviation for both integrated and mini-mills. While integrated steel mills did not meet the 10% minimum energy savings baseline, the average and weighted average savings of mini-mills hugged this value.

Table 3. Breakdown for the Iron and Steel Sector

Subsector (# of Sites)	Avg. Energy Savings	Weighted Avg. Energy Savings	Median Energy Savings	Std. Deviation
Iron and Steel Total (7)	6.8%	3.4%	6.2%	3.7%
Integrated (4)	4.4%	3.9%	5.3%	2.3%
Mini-Mills (3)	9.8%	11.2%	9.1%	2.7%

Breakdown for the Iron and Steel Sector into Integrated and Mini-Mills.

Aluminum

The aluminum industry only had 4 case studies available and thus only a small amount of confidence can be placed in the data obtained from these studies. The weighted average (7.2%) and average savings (6.9%) were not statistically divergent. However, the median savings (5.7%) were quite different from the average savings with a standard deviation of 5.0%, indicating the presence of at least one large outlier in the sample. This was taken to be Qingtonxia Al, China with a savings of 13.9%. Removing this outlier, the average savings and median savings become 4.6% and 4.4%, respectively. With or without this correction, the average and weighted average savings for this sample did not reach the 10% baseline.

Pulp and Paper

The pulp and paper sector contained the fewest case studies at 3, providing the least confidence in its data and the conclusions made from said data. Likewise, every statistical difference observable in the datasets for these case studies was found in the pulp and paper sector's results. The average savings (14.3%) differed greatly from the weighted average savings (21.7%) in the opposite direction from what would be expected (meaning the weighted average should be lower, but is much higher). Additionally, the median savings for pulp and paper were higher than the average savings, the only instance of this phenomenon in all of the case studies. The standard deviation was 8.2%, the second highest deviation of the sectors studied. With only

3 case studies, it is nearly impossible to both identify and remove an outlier to obtain meaningful results, and thus no real conclusions can be drawn about the effects of ISO 50001 and energy efficiency on this sector without a much larger study being conducted employing many more case studies. Of the 3 studies observed, two exceeded the 10% minimum baseline.

Conclusion

The 64 case studies analyzed in this report revealed that, for the sample taken from each energy-intensive sector, a 10% baseline minimum average savings was an inaccurate assumption for all but the food and beverage and pulp and paper sectors. However, with these sectors and with every energy-intensive sector studied in this report, there is not a large enough sample size to accurately characterize the effects of energy efficiency through ISO 50001 on the energy-intensive portion of the industrial sector. If the currently assumed minimum 10% average savings (CEM 2020) cannot be applied to energy-intensive sectors as suggested here, then energy efficiency improvements will contribute to a much smaller portion of the world's energy sustainability goals. A proper study containing hundreds of case studies from industrial countries that have already widely adopted ISO 50001 EnMS must be conducted to gain a more accurate understanding of the role that this standard and energy efficiency technology will play in achieving a net-zero carbon society. Such a study would be made significantly easier through the increased sharing and dissemination of knowledge in the global industrial sector regarding successful methods and strategies for reducing energy consumption and GHG emissions (Whitlock et al. 2020). At the moment, most facilities (whether adopting ISO 50001 or not) are not required to disclose information regarding their sustainability improvements that could potentially aid the rest of the industry. As a result, such a comprehensive study is not possible with the current amount of data available, and so the dissemination of energy efficiency improvements in industry, particularly through ISO 50001, should be encouraged and explored going forward.

Appendix

Table 4. Chemicals and Refining Sector Case Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
ADNOC, UAE	6.00%	3	56868.80	947813.40	315937.80
LG Chem Daesan, South Korea	4.88%	1	1971.36	40396.78	40396.78
ZRCC, China	1.71%	4	2451.34	143353.17	35838.29
XLX, China	4.00%	5	6250.07	156251.78	31250.36
PT CAP, Indonesia	1.36%	2	731.56	53791.06	26895.53
Lutianhua Co., China	1.03%	4	932.79	90562.37	22640.59
Hubei Group,	6.13%	3	3306.37	53937.54	17979.18

China					
PT PG, Indonesia	3.16%	1	486.11	15383.37	15383.37
ENAP, Chile	4.20%	3	1600.14	38098.65	12699.55
Pupuk Kaltim, Indonesia	3.76%	2.5	821.05	21836.56	8734.62
YPF SA CILP, Argentina	6.20%	4	1627.92	26256.71	6564.18
PTT Branch 6, Thailand	1.89%	4	445.21	23556.27	5889.07
CNPC, China	7.42%	3	693.56	9347.20	3115.73
MOPCO, Egypt	11.70%	4	1453.26	12420.99	3105.25
SIDPEC, Egypt	2.80%	1.5	95.03	3393.85	2262.57
MOC, Thailand	2.27%	3	109.73	4833.85	1611.28
PT NSI, Indonesia	4.00%	2	79.37	1984.15	992.08
OLDELVAL, Argentina	9.50%	1	89.58	942.91	942.91
CJ Pasuruan, Indonesia	4.99%	3	132.29	2651.11	883.70
PTT Branch 12, Thailand	1.85%	4	60.76	3284.30	821.08
ONWJ, Indonesia	5.00%	2	0.91	18.25	9.13

All case studies for the Chemicals and Refining Sector

Table 5. Cement Case Sector Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
Star Cement, UAE	5.87%	0.17	121.84	2075.66	12453.98
Linqu Cement, China	1.97%	1	205.85	10449.46	10449.46
Shree Cement, India	4.60%	1	464.49	10097.67	10097.67
Shanshui Huixian, China	3.70%	2	688.19	18599.84	9299.92
Sungshin Danyang, South Korea	2.20%	3	594.97	27043.96	9014.65
JK Cement Mangrol, India	8.20%	1	604.56	7372.73	7372.73
CEMEX Phillipines	3.00%	3	374.94	12498.03	4166.01

Arabian Cement, Egypt	8.00%	3	994.15	12426.90	4142.30
Shanshui Shandong, China	5.70%	1	171.49	3008.66	3008.66
Shanshui Anqiu, China	7.53%	5	605.09	8035.70	1607.14
Dalmia Trichiralli, India	6.50%	1	81.89	1259.86	1259.86
JK Cement Durg, India	7.20%	1.33	106.99	1486.00	1117.29
Shanshui Zaozhuang, China	1.00%	3	29.63	2962.86	987.62
St. Mary's Cement, Canada	4.98%	1	32.50	652.54	652.54
Dalmia Ariyalur, India	4.90%	3	36.30	740.90	246.97

All case studies for the Cement Sector.

Table 6. Food and Beverage Case Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
Jing Brand, China	3.50%	3	311.51	8900.18	2966.73
PT Pineapple, Indonesia	5.77%	2	209.97	3639.07	1819.53
Mastellone, Argentina	1.00%	3	51.28	5127.67	1709.22
Indofood, Indonesia	10.70%	3	146.63	1370.41	456.80
Tipperary Creamery, Ireland	5.80%	2	41.80	720.67	360.33
Dairygold, Ireland	10.50%	3	58.35	555.69	185.23
Wyeth Nutrition, Ireland	38.00%	6	416.37	1095.72	182.62
AVOD, Oman	25.83%	1	41.48	160.59	160.59
Southseas OF, China	28.90%	7	290.24	1004.30	143.47
Coca-Cola Portugal	30.70%	6	163.50	532.57	88.76
BAMBI, Serbia	4.51%	2	7.63	169.18	84.59
PT AIO,	6.60%	3	13.65	206.80	68.93

Indonesia					
Astarta-Kiyev, Ukraine	27.00%	4	27.11	100.40	25.10
EPPEN, China	6.60%	2	0.52	7.88	3.94

All case studies for the Food and Beverage Sector.

Table 7. Iron and Steel Sector Case Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
PJSC MMK, Russia	5.00%	4	8107.22	162144.45	40536.11
CAP Acero, Chile	1.00%	2.5	698.32	69832.33	27932.93
EZDK, Egypt	5.60%	2	1261.60	22528.61	11264.31
AM Dofasco, Canada	6.16%	3	1632.49	26501.52	8833.84
SCP Vasind, India	12.82%	3	134.78	1051.36	350.45
SCP Tarapur, India	9.11%	3	40.02	439.31	146.44
AD Makstil, Macedonia	7.54%	2	11.11	147.38	73.69

All case studies for the Iron and Steel Sector.

Table 8. Aluminum Sector Case Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
Hindalco, India	6.89%	4	3572.59	51851.75	12962.94
BALCO, India	4.42%	3	458.69	10377.55	3459.18
Qingtonxia Al, China	13.89%	4	1065.73	7672.66	1918.17
Vedanta Smelter, India	2.35%	2	0.05	2.28	1.14

All case studies for the Aluminum Sector.

Table 9. Pulp and Paper Case Studies

Site Name, Country	Energy Savings	Savings Period [yr]	Total Savings [GBtu]	Calc. Total Cons. for Period before ISO 50001 [GBtu]	Calc. Avg. Annual Cons. before ISO 50001 [GBtu]
CMPC, Chile	22.00%	4	17060.64	77548.37	19387.09
PT IKPP Tangerang, Indonesia	15.20%	3	406.45	2674.04	891.35

Catalyst Paper Crofton, Canada	5.60%	3	0.37	6.54	2.18

All case studies for the Pulp and Paper Sector.

References

Aghajanzadeh, A., P. L. Therkelsen, P. Rao, and A. T. McKane. 2016. "Global Impact Estimation of ISO 50001 Energy Management System for Industrial and Service Sectors." Lawrence Berkeley National Laboratory. eta-publications.lbl.gov/sites/default/files/lbnl-1006337_0.pdf

Aman, S., Y. Simmhan, and V. K. Prasanna. 2013. "Energy Management Systems: State of the Art and Emerging Trends." *IEEE Communications* 51: 114-119. ieeexplore.ieee.org/document/6400447

Better Buildings. 2020. "Energy Management Case Studies." US Department of Energy. betterbuildingssolutioncenter.energy.gov/iso-50001/resources/case-studies

CEM. 2020. "Energy Management and ISO 50001." Clean Energy Ministerial. www.cleanenergyministerial.org/initiative-clean-energy-ministerial/energy-management-and-iso-50001

CEM. 2020. "Energy Management Working Group." Clean Energy Ministerial. www.cleanenergyministerial.org/initiative-clean-energy-ministerial/energy-management-working-group

CEM. 2020. "Publications. Clean Energy Ministerial." www.cleanenergyministerial.org/publication-cem

IEA. 2020. "Global CO2 Emissions by Sector, 2018." International Energy Agency, Paris. www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018

IEA. 2020. "Tracking Industry 2020." International Energy Agency, Paris. www.iea.org/reports/tracking-industry-2020

IEA. 2020. "World Sankey Diagram – Final Consumption." International Energy Agency, Paris. www.iea.org/sankey/#?c=World&s=Final%20consumption

ISO. 2011. "ISO 50001:2011 Energy management systems – Requirements with guidance for use." International Organization for Standardization. www.iso.org/standard/51297.html

ISO. 2020. "The ISO Survey." International Organization for Standardization. www.iso.org/the-iso-survey.html

McKane, A., P. Therkelsen, A. Scodel, P. Rao, A. Aghajanzadeh, S. Hirzel, R. Zhang, R. Prem, A. Fossa, A. Lazarevska, M. Matteini, B. Schreck, F. Allard, N. Alcántar, K. Steyn, E.

Hürdoğan, T. Björkman, and J. O'Sullivan. 2017. "Predicting the quantifiable impacts of ISO 50001 on climate change mitigation." *Energy Policy* 107: 278-288. www.sciencedirect.com/science/article/pii/S0301421517302744?via%3Dihub

Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley. "Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems." Intergovernmental Panel on Climate Change. www.ipcc.ch/srccl/chapter/summary-for-policymakers/

Ritchie, H. 2019. "Food production is responsible for one-quarter of the world's greenhouse gas emissions." Our World in Data. ourworldindata.org/food-ghg-emissions

Rissman, J., C. Bataille, E. Masanet, N. Aden, W. R. Morrow III, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S. A. Miller, J. Roy, P. Fennell, B. Cremmins, T. K. Blank, D. Hone, E. D. Williams, E. S. Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielsen, H. Lu, T. Lorber, J. Dinkel, J. Helseth. 2020. "Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070." *Applied Energy* 266: 114848. www.sciencedirect.com/science/article/pii/S0306261920303603?via%3Dihub

Whitlock, A., N. Elliott, E. Rightor. 2020. "Transforming Industry: Paths to Industrial Decarbonization in the United States." American Council for an Energy-Efficient Economy. www.aceee.org/research-report/IE2001