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Electrification of Boilers in U.S. Manufacturing

(Revision 1.0)

M. Jibran S. Zuberi[1], Ali Hasanbeigi[2], William R. Morrow[1]

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November 2021

Executive Summary

Decarbonization of the industrial heat demand through electrification where low/no-carbon electricity is used can contribute significantly to global greenhouse gas (GHG) reduction. In U.S. manufacturing, thermal processes account for approximately 75% of the total final energy demand, of which nearly 17% was consumed by conventional industrial boilers for steam generation in 2018 (this does not include boilers for combined heat and power – CHP). Steam is generally used in industry to regulate temperatures and pressures in industrial processes, dry products, strip impurities from process fluids, etc. Although all kinds of energy sources such as fossil fuels, renewables, nuclear, and electricity can generate steam, fossil fuels'-fired boilers are dominant in U.S. manufacturing. Electric boilers, which are a mature technology, have a small market share for steam generation in the global and U.S. industry (approximately 2% in U.S. manufacturing) due to several techno-economic reasons.

This study aims to: a) examine the boiler energy demand in the U.S. industrial sectors both at the national- and state-level, b) quantify the potential opportunity to electrify the U.S. industrial boiler systems at the national- and state-level, and c) identify the barriers and drivers for the wide-scale application of electric boilers and provide insights for proposals to overcome the barriers. This work employs a bottom-up approach to investigate the sector-level and state-level techno-economic potentials of deploying electric boilers for steam generation in U.S. manufacturing up to 2050.

The results show that the electrification of industrial boilers in all the U.S. industrial sectors, except for the iron and steel sector, can initially lead to an increase in annual CO_2 emissions by around 43 $MtCO_2$ compared to the 2018 baseline. However, boiler electrification is projected to result in over 195 $MtCO_2$ per year reduction in CO_2 emissions in 2050, as shown in Figure ES.1. This significant decrease in CO_2 emissions in the future is projected as the consequence of the higher adoption of renewable electricity or grid decarbonization between 2018 and 2050.

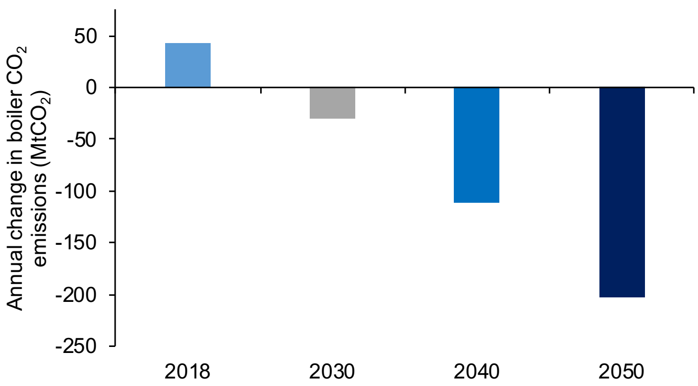

Figure ES - 1. Potential change in boilers' annual CO_2 emissions after electrification in U.S. manufacturing in 2018-2050 (This is the technical potential assuming 100% adoption rate).

The change in annual CO_2 emissions at the level of each sector is presented in Figure ES.2. The CO_2 emissions from industrial boilers in the U.S. iron and steel manufacture are currently very high due to the combustion of CO_2-intensive by-product gaseous fuels (i.e. blast furnace gas and coke oven gas). The national-level weighted CO_2 intensity of the combustion boilers employed in the iron and steel industry is higher than the current electricity grid emission factor in the U.S. Hence the electrification of boilers in the iron and steel sector can already reduce emissions by around 13 $MtCO_2$ vs. the 2018 baseline. However, it should be noted that if the byproduct gases are not combusted in boilers onsite, these gases must still be dealt with in another way. Manufacturing plants can either integrate these byproduct fuels into their processes for direct heating, consequently replacing conventional fossil fuels or find other green markets for their potential use. These efforts may incur additional costs and are not investigated in this study. The existence of low or no-cost byproduct fuels in some industries (such as also in refineries and forest products) poses a great challenge to the electrification of byproduct fuel boilers.

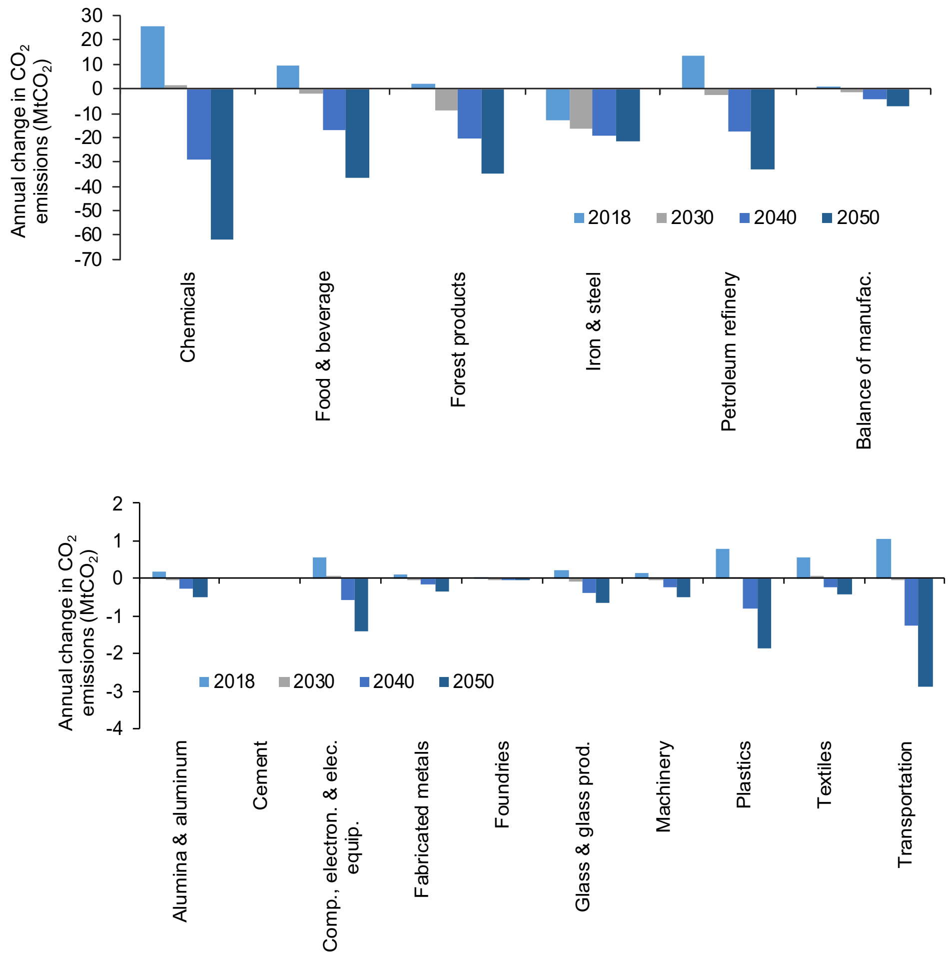

Figure ES - 2. Potential change in boilers' annual CO_2 emissions after electrification in different U.S. industrial sectors in 2018-2050 (This is the technical potential assuming 100% adoption rate).

Boiler electrification cost curves are developed to estimate the marginal costs and the technical potential for energy savings and CO_2 emissions reduction as a result of industrial boiler electrification. The technical potential energy savings by electrifying industrial boilers are estimated at 445 PJ per year of final energy or 21% of the U.S. industrial boiler energy demand in 2018. Moreover, if fully implemented, electric boilers can reduce the boiler onsite energy demand by 16-29% in different U.S. industrial sectors.

Figure ES.3 presents the CO_2 abatement costs for boiler electrification in different sectors in 2050 and shows the costs ranging between 67 and 185 \$/tCO_2-saved. Since the boiler emission factors in iron and steel plants are very high currently due to the wide-scale combustion of byproduct fuels for steam generation, switching to boilers operated on renewable electricity can mitigate large quantities of CO_2 emissions even in the near term. Hence the CO_2 abatement costs for the U.S. iron and steel sector are relatively the lowest in the manufacturing sectors.

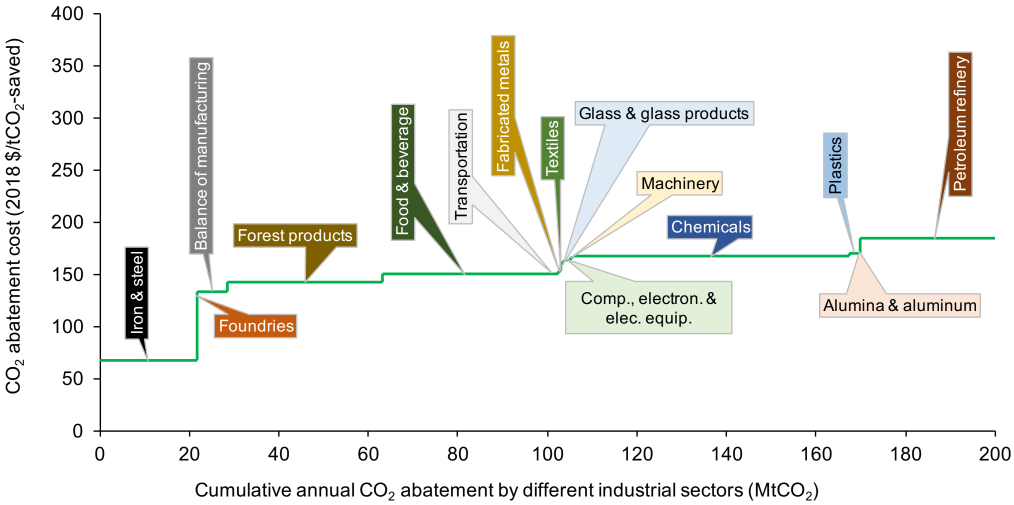

Figure ES - 3. CO_2 abatement cost curve for boiler electrification in U.S. manufacturing in 2050.

Figure ES.3 also shows that industrial boiler electrification incurs additional costs in each sector and none of the industrial sectors have CO_2 abatement costs falling below the horizontal axis (which would have otherwise represented cost savings). In other words, although there may be individual cost-effective opportunities for electrifying boilers in specific industrial sites, the overall abatement costs are above 100 \$/tCO_2-saved in almost all sectors. The major reason for the costs of boiler electrification to be high is the disparity between the electricity and fuel prices in the U.S. industry (e.g. the weighted average electricity price in the U.S. industry is almost 4 times higher than the average price of natural gas per unit of energy in 2018). Other factors including sectoral boiler efficiencies, boiler size distribution, energy mix, and fuel prices also affect the costs of boiler electrification in each industrial sector.

Since industry structure and energy infrastructure are different in each state, the state-level analysis presents more granularity. While the techno-economic trends and rankings are similar as in the national-level cost curves, the differences in costs of boiler electrification among the states are substantial. For example, the cost of CO_2 abatement in chemical plants in Texas is nearly 2.7 times lower than those in California. This contrast comes from the large differences in energy prices in the two states (e.g. industrial electricity and natural gas prices in Texas are approximately 2.5 and 2 times lower than that in California). Therefore, it can be concluded that CO_2 abatement costs are generally lower in states where energy prices are also low, hence possessing greater opportunities for earlier replacement of combustion boilers with electric boilers.

Furthermore, the electricity generation mix and the corresponding grid emission factor in a state dictate the CO_2 abatement potential. For example, electrification of industrial boilers in some states (e.g. California, Washington, New York, Oregon) may already result in CO_2 emissions reduction vs. 2018 since the grid emission factors in these states are lower than the most sectoral boiler emission factors. However, the corresponding CO_2 abatement costs are high in the current scenario given our fuel and electricity cost assumptions. A more substantial decrease in the electricity prices or increase in fossil fuel prices as the result of a carbon price scheme can make the electrification of industrial boilers much more economical. Alternatively, in the first phase of industrial boiler electrification, hybrid electric-gas boilers may be used for steam generation since these systems allow choosing between electric heating and fossil-fuel heating depending on electricity rates during a day.

Several challenges need to be overcome for the wider adoption of electric boilers and various stakeholders can work together to address them. Industrial companies can partner with academia, national labs, think tanks, among other stakeholders, to further enhance the electrification of industrial boilers. Companies can also develop business cases for the electrification of industrial boilers by mapping out their energy and non-energy benefits. This study shows financial barriers are the most important. Governments can act by incentivizing the deployment of electric boilers through tax credits or grants. Utilities can partner with industry and government to support research, development, and demonstration activities. Utilities must also ensure that the grid infrastructure will be ready to deliver uninterrupted electricity to electrified industrial boilers. Suppliers of electric boilers can engage with industrial plants to learn about their electrification needs. They can also provide information to companies, governments, and utilities about relevant technologies that are currently available and those under development.

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1 Introduction

The Paris Agreement sets out a global framework to mitigate climate change by restricting the increase in global average temperature well below 2°C and preferably to 1.5°C compared to pre-industrial levels. To contribute to the objectives of the historic agreement, countries are legally bound to submit comprehensive national climate action plans and increase their efforts and support actions to reduce greenhouse gas (GHG) emissions. Many countries see decarbonization of electricity generation and electrification of energy end-uses as a key approach for achieving net-zero emissions by 2050. For example, there has been quite some discussion in China to utilize renewable power in electric heating to displace coal- and gas-fired boilers in different Chinese economic sectors (Wang and Li, 2020; Pu et al., 2019; Zhang et al., 2016). The focus of end-use electrification has mostly been on the transportation and building sectors so far and limited opportunities have been explored in the industrial sector. The industrial sector accounts for approximately 25% of the energy use and GHG emissions in the U.S. (US DOE/EIA, 2021). The energy demand in the U.S. industrial sector is largely dominated (approx. 83% in 2018) by fossil fuels (US DOE/EIA, 2021).

Process heat demand is one end-use that is approximately one-fifth of the global energy demand and typically represents two-thirds of the total final energy demand in the manufacturing industry (Hasanbeigi et al., 2021). Hence decarbonization of industrial heat demand through electrification could contribute significantly to climate change mitigation efforts. In the U.S. manufacturing industry, thermal processes account for approximately 75% of the total final energy demand, of which nearly 17% (or 13% of the total final energy) is consumed by conventional industrial boilers for steam generation (excluding combined heat and power – CHP plants) in 2018 (US DOE/EIA, 2021; Energetics, 2019). Steam is generally used in industry to regulate temperatures and pressures in industrial processes, dry products, separate impurities from process fluids, etc. However, the equipment that uses steam varies substantially among industrial processes and sites. Typically, electrification of industrial boilers will require changes only in the boiler room i.e. replacing the existing combustion boilers with electrified boilers. In other words, substantial changes may not be required to end-use processes and equipment.

Although all kinds of energy sources such as fossil fuels, renewables, nuclear, and electricity can generate heat and steam, combustion boilers using fossil fuels and biomass are dominant in global and U.S. manufacturing (see Section 2.1). Water-tube boilers and fire-tube boilers are the most common types of combustion boilers deployed in the industry sector (IEA-ETSAP, 2013). Electric boilers, which are a mature technology and possess a high technology readiness level – TRL i.e. 7-9 (Schüwer and Schneider, 2018; Wiertzema et al., 2018), have a small market share for heat and steam generation in U.S. manufacturing due to several techno-economic reasons (US DOE/EIA, 2021) (refer to Section 4). Given the high efficiency of electric boilers (see later in this section) and anticipating a large contribution of replacing conventional boilers with electric boilers to decarbonize industry, the scope of this study is defined to highlight the different aspects of boiler electrification in U.S. manufacturing.

Electric boilers use electricity to heat water and generate steam. A thermostat is used to control the flow of electric current and the in-turn heating. The most common types of electric boilers are electric resistance boilers and electrode boilers (TNO, 2019). In electric resistance boilers, an electric-powered resistive element transfers heat to the water, raising its temperature to the desired level. In electrode boilers, the electric current passes directly through the water to boil the water. Electric resistance boilers typically possess lower thermal capacities (i.e. up to 5 MW_e). On the contrary, electrode boilers have capacities generally ranging between 3 MW_e and 70 MW_e. Electric (resistance/electrode) boilers can generate superheated steam with temperatures of up to 350°C and pressures of over 70 bars (TNO, 2019).

Compared to fossil fuel combustion boilers with an efficiency of 70-80%, electric boilers are also very efficient (i.e. 95-99% efficiency) with only minimal radiation losses from the exposed boiler surfaces (Madeddu et al., 2020). In addition, electric boilers possess many non-energy benefits such as lower criteria air pollution (depending on electricity grid fuel mix), lower permitting hurdles, and faster ramp-up times compared to combustion boilers (Rightor et al., 2020). Other types of electric boilers include infrared and induction boilers, but these are the least common in the industry sector and are only used for specialized applications (TNO, 2019).

The majority of the previous studies (such as Hasanbeigi et al. 2021, Bühler et al. 2019a-b.Wei et al. 2019, Schüwer & Schneider 2018, Heinen et al. 2018, Wiertzema et al. 2018 and Steinberg et al. 2017) generally offer a high-level analysis without quantifying the electrification potentials at the level of individual sectors and states. Moreover, the costs associated with a large-scale application of electric boilers in different industrial settings are not well established, hence calling for an in-depth investigation while considering sectoral and regional differences. This study aims to fill these literature gaps by :

a) examining the boiler energy demand in the U.S. industrial sectors and states,
b) quantifying the potential opportunity to electrify the U.S. industrial boiler systems at the national and state levels, and
c) identifying the barriers and drivers to the wide-scale application of electric boilers and proposals to overcome the barriers.

More precisely, this study employs a bottom-up approach to investigate the sector-level and state-level techno-enviro-economic potentials of deploying electric boilers for heat and steam generation in U.S. manufacturing in different timeframes (i.e. up to 2050). Moreover, this study reviews the major technical, financial, and policy barriers that hinder the large-scale deployment of electric boilers in the manufacturing industry and offers recommendations for key stakeholders. This study provides novel insights that should inform technology leaders', policymakers', and executives' decisions about electrification of the current and future U.S. industrial boiler systems.

2 Energy Use and CO_2 Emissions in Industrial Boilers

2.1. Sectoral and State-level Boiler Energy Demand

The U.S. industrial boiler systems, excluding CHP plants, accounted for nearly 13% of the total energy demand in 2018[1]. Figure 1 presents the share of energy demand by industrial boilers as a proportion of total fuel demand in the fifteen U.S. manufacturing sectors. The estimates in the figure are based on EIA's 2018 Manufacturing Energy Consumption Survey (US DOE/EIA, 2021) and 2014 Manufacturing Energy and Carbon Footprints (Energetics, 2019). Since the energy and carbon footprints for 2018 are not yet published, it is assumed that the ratio of a sector's boiler energy demand to the corresponding fuel demand in 2014 is also valid in 2018.

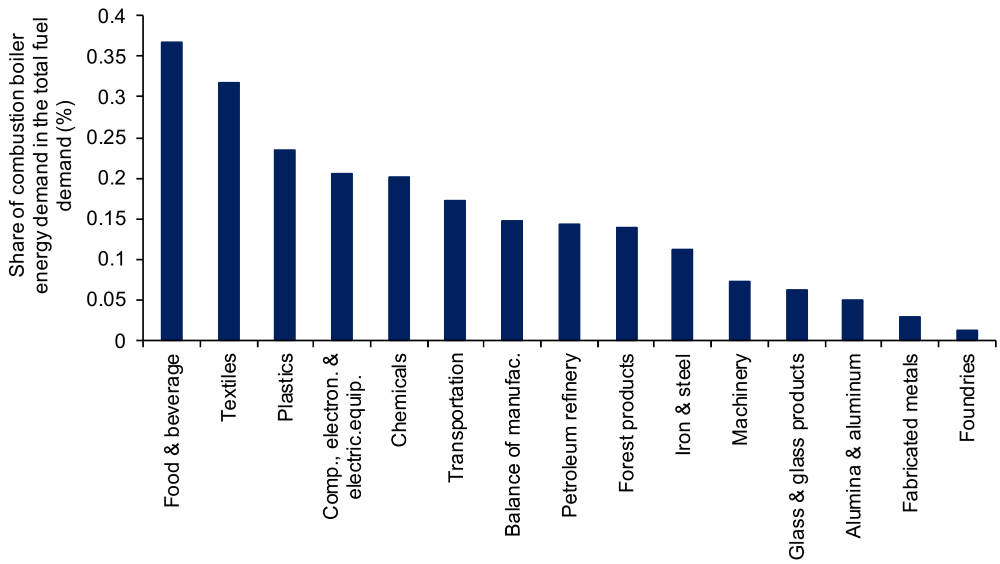


Figure 1. Sector-specific conventional boilers' annual energy demand as a proportion of total fuel demand in 2018 (Data source: Energetics, 2019).

1 Since electrifying CHP boilers to generate heat and power is somewhat irrational, this work does not consider energy demand by CHP boilers in the analysis.

Figure 2 presents the distribution of absolute boiler energy demand in the U.S. industrial sectors. The top five industrial sectors that consume over 90% of the boiler energy demand are ranked as follows: chemicals, petroleum refining, food and beverage, forest products including pulp and paper, and iron and steel (US DOE/EIA, 2021; Energetics, 2019).

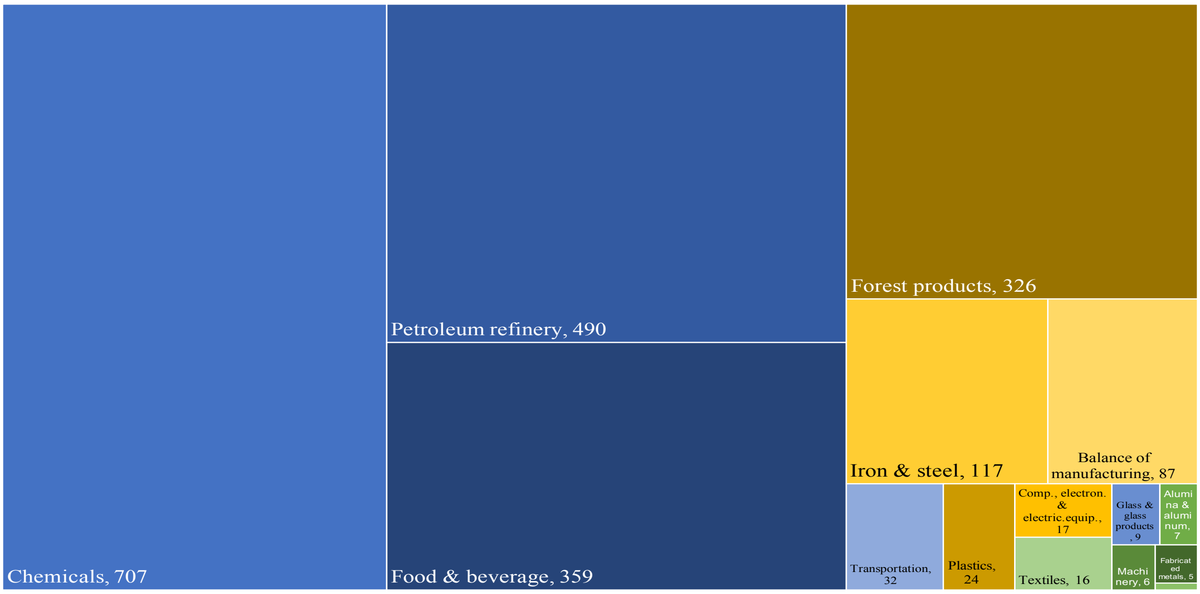


Figure 2. Sector-specific energy demand (in PJ) by the U.S. industrial conventional boilers in 2018 (Data sources: U.S. DOE/EIA, 2021; Energetics, 2019).

The sectoral energy demand by the industrial boilers in 2018 can be disaggregated further into state-level demand based on the detailed information on manufacturing energy use by end-use type at the level of U.S. counties published by McMillan and Narwade (2018). Figure 3 shows the breakdown of the U.S. boiler energy demand by industrial sectors and states. Texas, Louisiana, California, Illinois, and Ohio are the top five states that consume approximately 40% of the total energy demand by U.S. industrial boilers. This is mainly because most of the petroleum refining and chemicals production is concentrated in these five states.

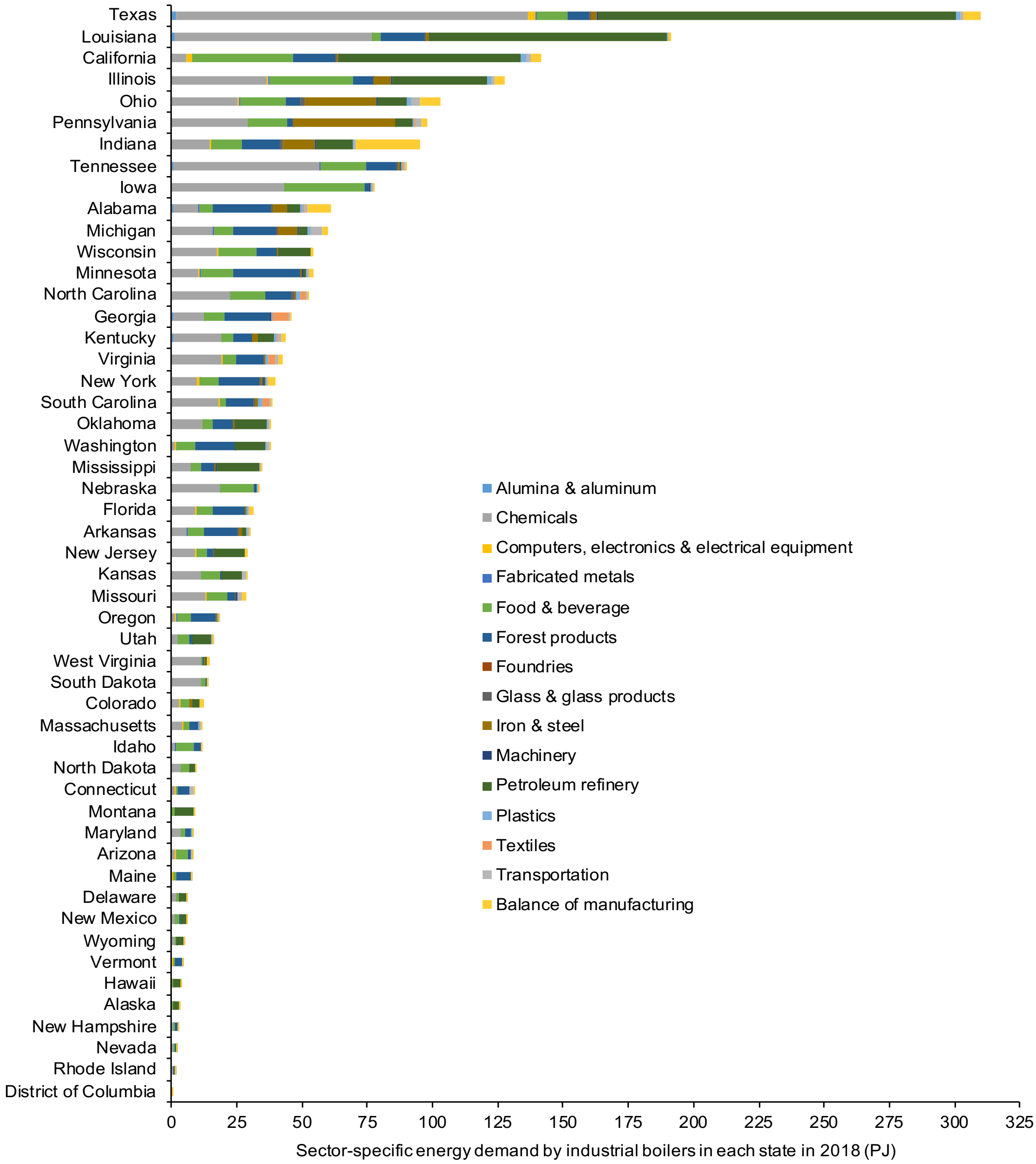


Figure 3. Sector-specific annual energy demand by industrial boilers in each U.S. state in 2018 (Adapted based on: U.S. DOE/EIA, 2021; Energetics, 2019; McMillan and Narwade, 2018).

Figure 4 classifies the sectoral energy demand by the industrial boilers in 2018 by energy carrier. It must be noted that the MECS datasets do not allocate fuels like wood, biomass, petroleum coke, byproduct fuels, etc. (categorized as “other” fuels in the figure) to energy end uses due to reasons best known to the surveyors and data compilers. Instead, a coarse breakdown of “other” fuels is published at the sectoral level. However, a significant amount of these “other” fuels are consumed in industrial boilers. Starting from 2006, EIA publishes Manufacturing Energy and Carbon Footprints (Energetics, 2019) after the release of every quadrennial MECS dataset. One of the value additions of the footprints is the allocation of “other” fuels to energy end uses based on expert judgments and suggestions. Despite the allocation, “other” fuels breakdown is also not made publicly available by Energetics (2019). Hence it is not possible to provide precise distribution of “other” fuels used in U.S. industrial boilers. However, rough estimations are made in this study based on the sectoral breakdown of these fuels given by MECS 2018 to calculate the weighted emission factors and prices of “other” fuels (see Figure 8 and the discussion around it later in Section 2.2).

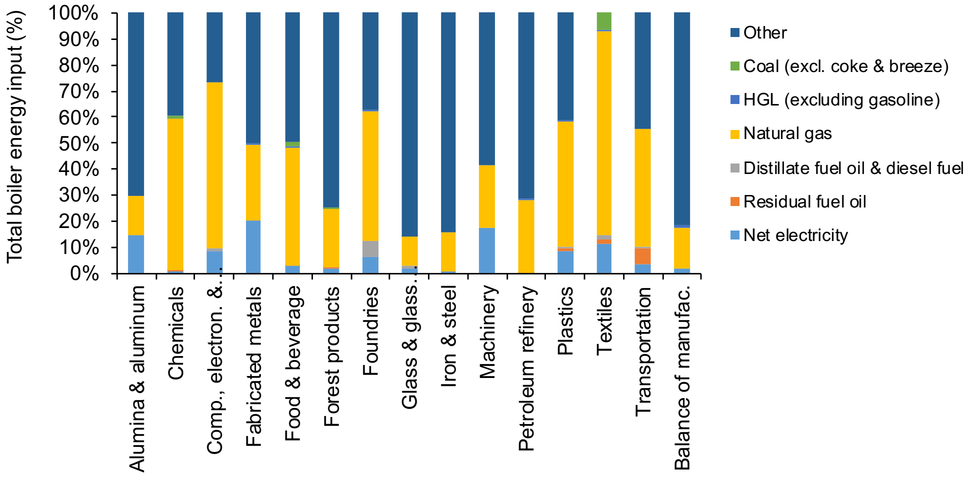


Figure 4. Industrial boilers’ annual energy demand breakdown by type of fuel in the U.S. in 2018 (Adapted based on: U.S. DOE/EIA, 2021; Energetics, 2019).

As mentioned earlier, the latest energy and carbon footprints use 2014 MECS data. This study used these footprints to estimate the total boiler energy demand by the industrial sectors in 2018 as shown in Figure 2. This study subtracts the sum of different boiler fuels (including natural gas, distillate fuel oil, residual fuel oil, hydrocarbon gas liquids - HGL, coal, and electricity) given in 2018 MECS from the total boiler energy demand in Figure 2 (refer to the earlier discussion in this section). The difference is assumed as the share of “other” fuels in the sectoral boiler energy demand and is presented in relative terms in Figure 4.

It is evident from Figure 4 that natural gas and “other” fuels account for the highest share in the total energy demand by the U.S. industrial boilers i.e. 40% and 58% respectively. The high share of “other” fuels in the energy demand is because petroleum refinery, forest products and, iron and steel sectors combust large quantities of byproduct fuels such as refinery waste gas (also called still gas), biomass (wood chips and black liquor), and blast furnace/coke oven gases respectively for steam generation. Although the share of electricity in aluminum, machinery, and fabricated metal sectors has increased substantially in the last few years, the weighted share of electricity in overall U.S. manufacturing is very small i.e. approximately 2% only. This shows that the current adoption of electric boilers in the major U.S. manufacturing sectors is very limited.

In addition, the 2014 Energy and Carbon Footprints also estimate the sector-specific energy losses from the U.S. industrial boilers. This information is used to determine weighted average efficiencies of combustion boilers in each industrial sector as presented in Figure 5.[2] The figure suggests that boilers in aluminum and plastics manufacture possess the highest efficiencies i.e. 83% followed by chemicals and transportation sectors i.e. 82%. The balance of manufacturing (or other manufacturing sectors) has the lowest boiler efficiencies of approximately 70%. Moreover, due to the lack of information, it is also assumed that the sector-specific boiler energy mix (in Figure 4) and boiler efficiencies (in Figure 5) are the same in each state.

2 Boiler efficiency does not only depend on the type of technology (e.g. fire-tube or water-tube and/or whether or not an economizer is present) but also varies by type of fuel combustion. The weighted average sectoral boiler efficiencies in Figure 5 are reflecting on all these aspects.

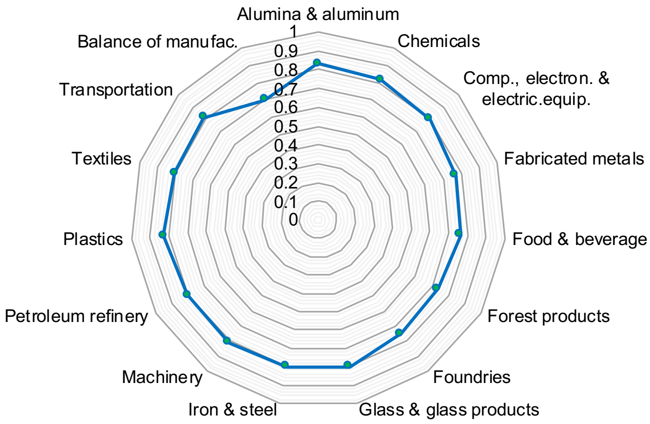


Figure 5. Sector-specific combustion boilers' efficiencies in U.S. manufacturing in 2018 (Adapted based on: Energetics, 2019).

EIA's Annual Energy Outlook (US DOE/EIA, 2019a) provides projections of U.S. industrial energy markets through 2050 under different scenarios. The outlook's reference scenario projected the change in energy demand in the U.S. industrial sectors in 2050 compared to the levels in the base year 2018. Since it is anticipated that process heat and steam systems will still be dominant in the industrial end uses in the future, this study makes a simplifying assumption that boiler energy demand in each industrial sector will also grow or shrink to the same corresponding rate as projected by the outlook through 2050 while maintaining the constant industry structure.

Figures 6 and 7 present the projected boiler energy demand in U.S. manufacturing and its sub-sectors in the future years until 2050 respectively. Similarly, state-level demand projections are made based on the assumption that the share of each state in the total boiler energy demand (refer to Figure 3) will remain the same. As shown in Figure 7, among the top five sectors, industrial boiler energy demand is expected to grow in chemicals, forest products, and food and beverage sectors, while the growth in petroleum refining and iron and steel sectors may remain rather stagnant. These projections are critical to estimate the industrial energy demand reduction and decarbonization potentials in the long term (see later in Section 3).

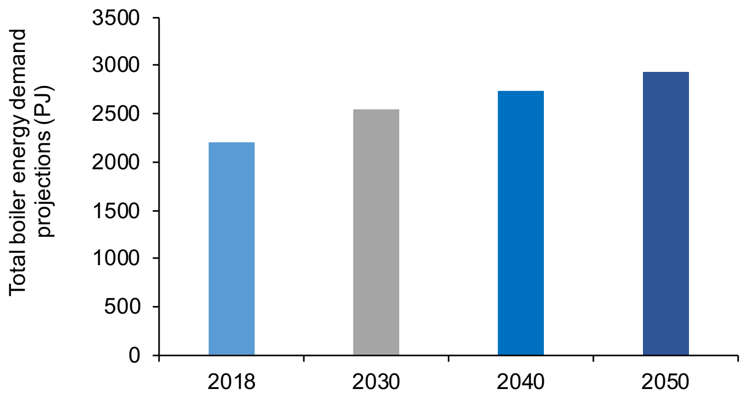


Figure 6. Boilers' annual energy demand projections in U.S. manufacturing up to 2050 (Adapted based on: U.S. DOE/EIA, 2021; Energetics, 2019; U.S. DOE/EIA, 2019a).

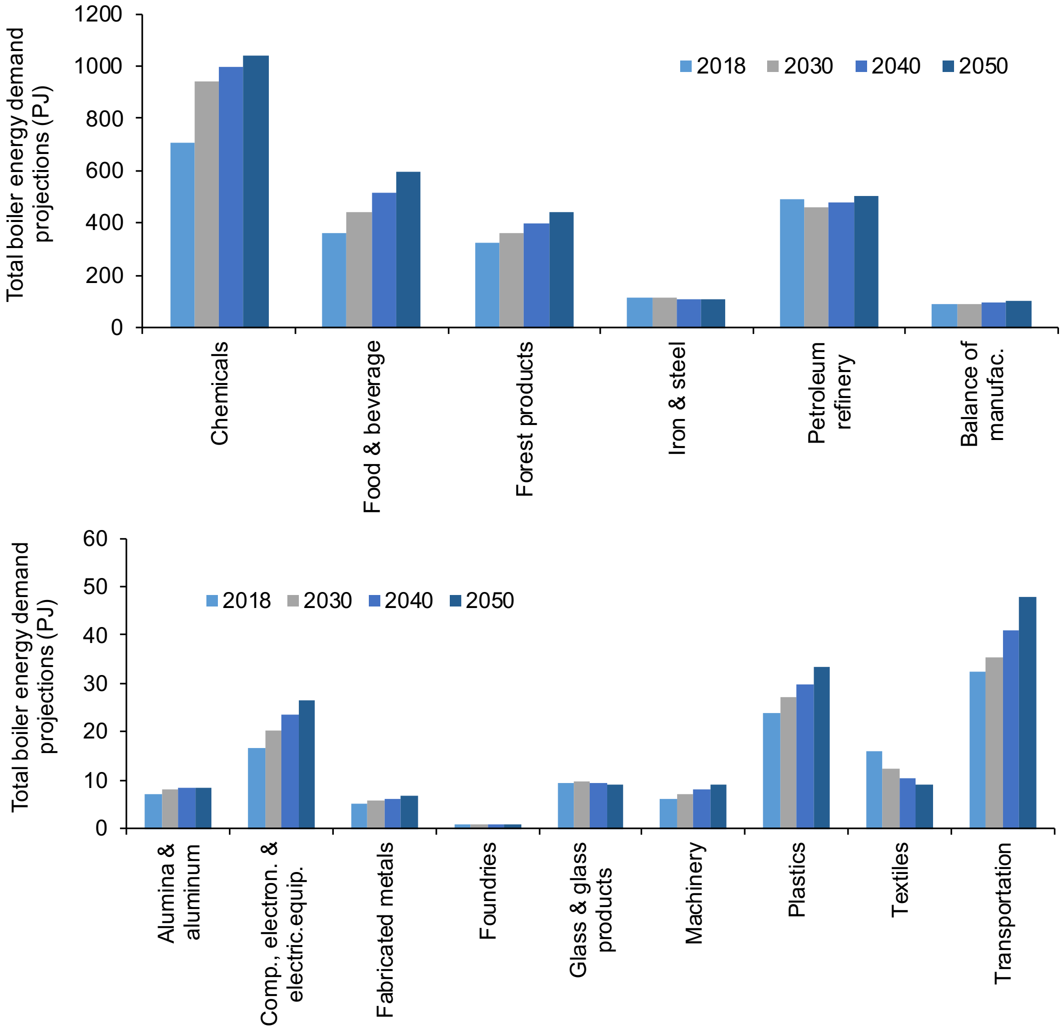


Figure 7. Boilers' annual energy demand projections in the top-six energy-intensive (top) and the remaining (bottom) U.S. industrial sectors up to 2050 (Adapted based on: U.S. DOE/EIA, 2021; Energetics, 2019; U.S. DOE/EIA, 2019a).

2.2. CO_2 Emissions in Industrial Boilers and Electricity Generation

Combustion-related CO_2 emissions from the U.S. industry contributed to approximately 15% (833.2 $MtCO_2$) of the total CO_2 emissions in the U.S. (5,424.9 $MtCO_2$) in 2018 while the share of emissions as a result of non-energy use of fuels including chemical feedstock was nearly 3% (i.e. 134.6 $MtCO_2$) (U.S. EPA, 2020). Sector- and state-level CO_2 emissions as a result of fuel combustion in industrial boilers can be estimated as the product of energy demand (refer to Figures 2 and 3) and the corresponding emission factors. Boiler-related emission factors for each industrial sector depend on its energy mix. Table 1 presents the fuel-specific emission factors. Due to the lack of detailed information on the type of "other" fuels used for combustion in boilers in each sector, the emission factor for "other" fuels is calculated based on the industry-wide contribution of some common fuels in this category such as petroleum coke, waste gases, and, waste materials, etc. (as given in U.S. DOE/EIA, 2021; refer to Figure 8). However, for petroleum refining, forest products, and iron and steel sectors, more weight is given to certain byproduct fuels (see Figure 8) to estimate the corresponding emission factors of"other" fuels, as also shown in Table 1. Based on these emission factors and the boiler energy breakdown in Figure 4, the weighted average emission factors for each sector are determined and presented in Figure 9.

Table 1. Fuel-specific emission factors used in this study (Source: U.S. EPA, 2012)[3] .

Energy carrier	Emission factor (kgCO_2/GJ)
Natural gas	50.3
Distillate fuel oil	70.1
Residual fuel oil	71.2
Coal	89.7
Hydrocarbon gas liquids	59.6
"Other" fuels	
for refining [1]	72.4
for forest products [2]	88.9
for iron and steel [3]	233.6
for the rest of the sectors [4]	73.1

[1] *These include waste/still gas, petroleum coke, and miscellaneous fuels.*

[2] *These include black liquor, biomass fuels, waste oils/tars, waste materials, and miscellaneous fuels.*

[3] *These include blast furnace and coke oven gases, and miscellaneous fuels.*

[4] *These include petroleum coke, biomass fuels, waste oils/tars, waste materials, and miscellaneous fuels* .

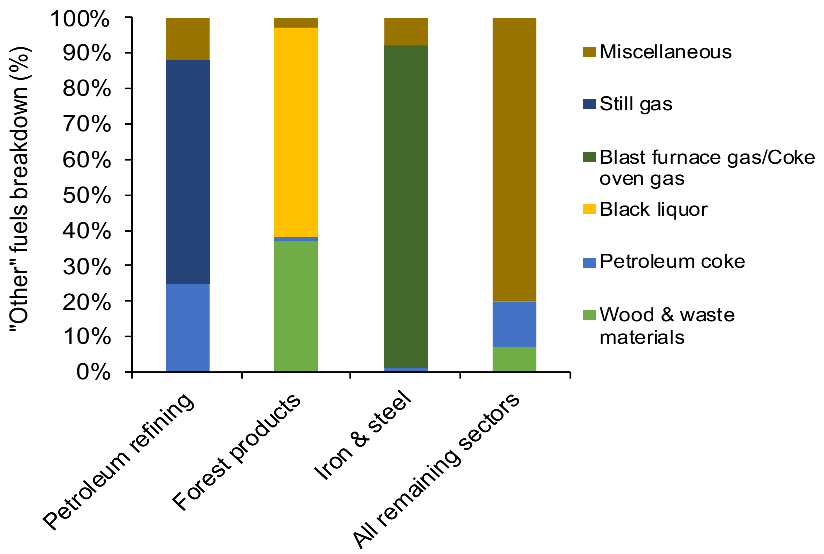


Figure 8. Assumed distribution of "other" fuels used in the U.S. industrial combustion boilers (in tCO_2/GJ) (Adapted based on: U.S. DOE/EIA, 2021).

3 The emission factors for blast furnace gas, coke oven gas, still gas, black liquor, petroleum coke, wood, waste materials, and miscellaneous fuels are taken as 260.0, 44.4, 63.2, 89.8, 97.1, 88.9, 70.1, and 70.1 kgCO_2/GJ respectively.

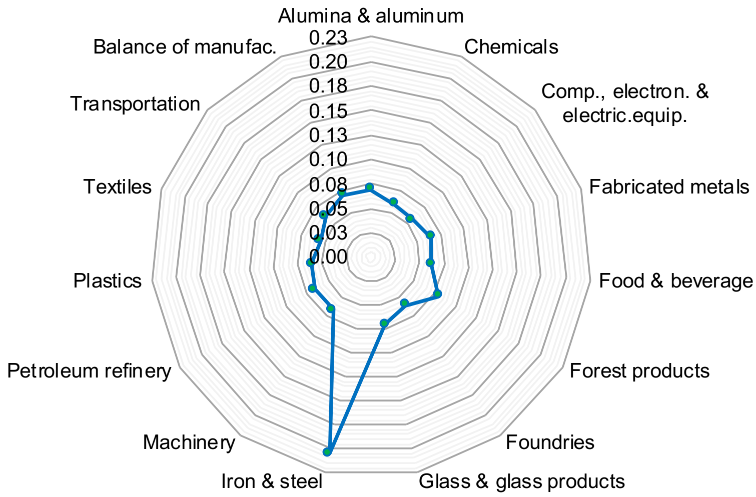


Figure 9. Boiler-related weighted emission factors for different industrial sectors (in tCO_2/GJ) (Adapted based on: U.S. EPA, 2012; U.S. DOE/EIA, 2021; Energetics, 2019).

Due to the large share of natural gas in the energy mix of different industrial sectors, the sectoral weighted emission factors are similar to the factor of natural gas. However, the weighted factors of iron and steel, forest products, and petroleum refining sectors are the major exceptions. This is due to the dominant share of "other" fuels in their energy mix. The type of "other" fuels also varies across these three sectors (refer to Figure 8). The emissions from the iron and steel sector are the highest because it consumes large quantities of blast furnace gas which is a fossil-fuel derived gaseous fuel and has very high CO_2 intensity. Similarly, the weighted emission factor representative for the manufacture of forest products is high because of the sector's large-scale consumption of solid biomass fuels including wood chips and black liquor which emit higher levels of CO_2 than natural gas if combusted.[4] Finally, since petroleum refining consumes large quantities of waste (still) gas which has a slightly higher CO_2 intensity than natural gas, the sector's weighted emission factor was also found to be on a higher side.

After establishing the emission factors, sector- and state-specific CO_2 emissions from industrial fossil fuel-fired boilers can be estimated[5]. Figure 10 presents the distribution of boiler-related CO_2 emissions in the U.S. industrial sectors.[6] The emissions are found to be approximately 18% of the total combustion-related CO_2 emissions in the U.S. industry. The top five energy-intensive sectors also account for over 90% of the total boiler-related CO_2 emissions.

4 Since the carbon-neutrality of biomass fuels is debated due to the concerns about origin of biomass feedstock supply, its sustainable aspects, and whether the associated air-quality impacts from biomass utilization are tolerable, this study does not consider biomass fuels as carbon-neutral.

5 It must be noted that due to a lack of detailed information on the type of industrial plants and processes in a sector in each state, the sectoral emission factors estimated for each state possess uncertainty. However, in the case of iron and steel, the states that manufacture primary steel are known. Hence only for these states, blast furnace and coke oven gases' CO_2 intensities are considered in estimating the emission factors for iron and steel manufacture.

6 The boiler-related CO_2 emissions in different industrial sectors exclude indirect emissions due to electricity use in boilers.

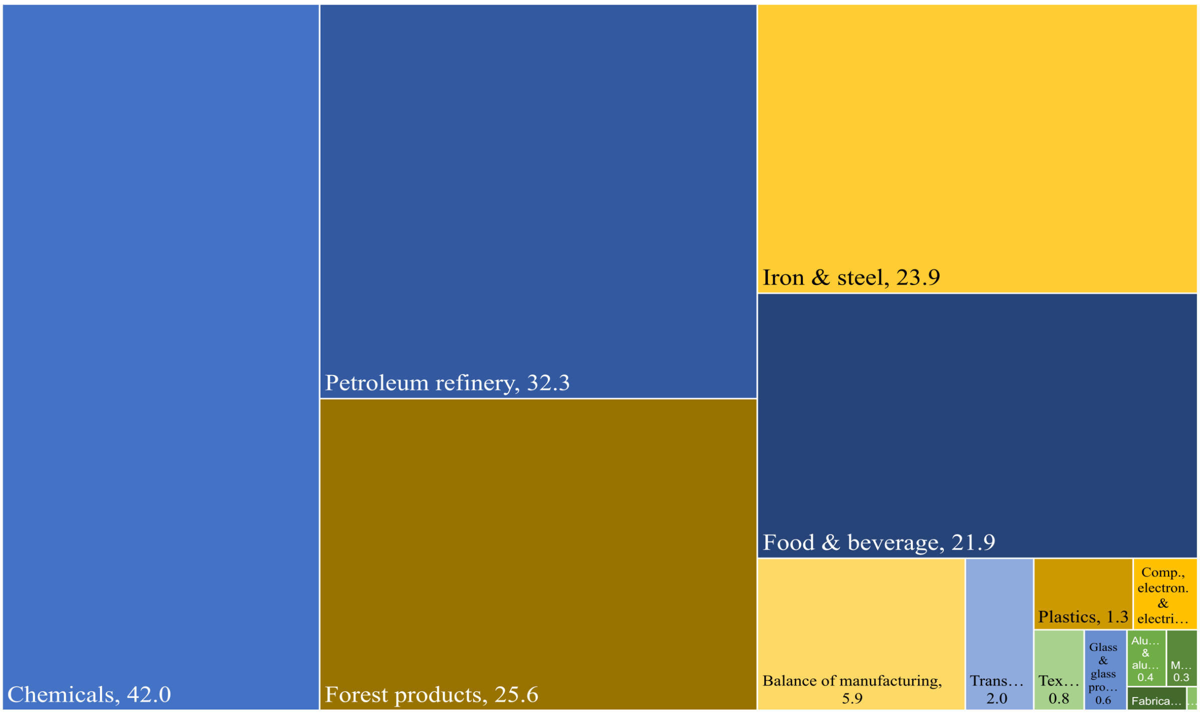


Figure 10. Sector-specific annual CO_2 emissions (in $MtCO_2$) by the U.S. industrial boilers in 2018 (Adapted based on: U.S. EPA, 2012; U.S. DOE/EIA, 2021; Energetics, 2019).

As briefly discussed earlier, the climate impact of electrification of industrial boilers (and of any end-use process in general) cannot be significant and, in some cases, can be negative if the electricity generation remains CO_2-intensive. It is essential to decarbonize the electricity grid via low-carbon energy sources and is a prerequisite for reducing the CO_2 intensity of industrial heating. Table 2 presents the net electricity generation and the corresponding CO_2 emissions in different states of the U.S. in 2018. Based on this information, the current electricity grid emission factors for each state are estimated and shown in the same table.

Table 2. State-level net electricity generation, grid emissions, and grid emission factors in 2018 (Data source: EIA SEDS, 2019).

State	Net electricity generation (TWh)	Electricity grid emissions ($MtCO_2$)	Electricity grid emission factor ($kgCO_2/kWh$)
Alabama	145	54	0.37
Alaska	6	3	0.43
Arizona	112	47	0.42
Arkansas	68	37	0.54
California	195	34	0.17
Colorado	55	34	0.62
Connecticut	39	8	0.21
Delaware	6	3	0.42
District of Columbia	0	0	0.00
Florida	244	101	0.41
Georgia	129	52	0.40
Hawaii	10	6	0.65
Idaho	18	1	0.07
Illinois	188	67	0.36
Indiana	113	90	0.79
Iowa	63	29	0.46
Kansas	52	23	0.45
Kentucky	79	67	0.85
Louisiana	102	34	0.33
Maine	11	1	0.10
Maryland	44	16	0.37
Massachusetts	27	8	0.28
Michigan	116	59	0.51
Minnesota	62	27	0.43
Mississippi	63	26	0.41
Missouri	85	66	0.77
Montana	28	15	0.54
Nebraska	37	24	0.64
Nevada	40	14	0.35
New Hampshire	17	2	0.12
New Jersey	75	17	0.23
New Mexico	33	18	0.56
New York	133	25	0.18
North Carolina	134	48	0.36
North Dakota	43	30	0.71
Ohio	126	78	0.61
Oklahoma	86	33	0.38
Oregon	64	8	0.13
Pennsylvania	215	75	0.35
Rhode Island	8	3	0.38
South Carolina	99	29	0.29
South Dakota	13	3	0.23
Tennessee	82	26	0.32
Texas	477	202	0.42
Utah	39	29	0.73
Vermont	2	0	0.00
Virginia	96	31	0.32
Washington	117	10	0.09
West Virginia	67	61	0.91
Wisconsin	66	40	0.61
Wyoming	46	41	0.88
United States	4,178	1754	0.42

It is evident from Table 2 that the current electricity grid emission factors in almost all the states, with a few exceptions, are higher than the boiler fuel-related CO_2 emission factors in different sectors (refer to Figure 9). In other words, electrification of steam generation will result in additional CO_2 emissions with the current grid in most states. However, since the U.S. is committed to the Paris accord and many states have specific electricity grid decarbonization targets already in place, industries have a great opportunity to meet their decarbonization goals by exploiting the potential for electrification of industrial processes (including steam generation) while using increased levels of potential renewable electricity.

More specifically, the optimism about the significant electricity grid decarbonization comes from the fact that many states have established targets to achieve net-zero emissions from their electricity generation by 2050 or earlier. For example, California's Renewables Portfolio Standard established in 2002 aims to have 100% clean electricity generation by 2045. Washington D.C. and New York also have a requirement of 100% renewable electricity generation by 2032 and 2040 respectively (NCSL, 2021). Similarly, Louisiana, Michigan, Connecticut, New Jersey, Illinois, and many other states have set goals to reach 100% carbon-free electricity by 2050 (S&P Global Platts, 2020). Although a few states are lacking specific targets for the decarbonization of their electricity grids, they may also establish similar targets soon.

Given these specific targets in different states, this study assumes the rates of electricity grid decarbonization in the future as shown in Figure 11. For example, if a state has a 100% carbon-free electricity target by 2045 (as in California), the electricity grid is assumed to be decarbonized in the future at rates represented by the light-blue dashed line in Figure11. Besides, there is a general perception that the rates of achieving specific energy and CO_2 reduction targets are initially slow (although the number of measures could be higher – low hanging fruits) and pick up over time (due to the implementation of high-impact measures that typically require years of planning). The rates are typically fast towards the end of the targeted period (Zuberi et al., 2020). Since the 100% carbon-free electricity generation targets in several states were established over 15 years ago (e.g. in California, Colorado, Washington, etc.) and with the cost of renewable electricity generation being quite competitive and still decreasing, it can be assumed that the phase with the slow adoption rates of renewable technologies has passed. Hence this study assumes a linear trend, as shown in Figure 11, to achieve the aforementioned targets.

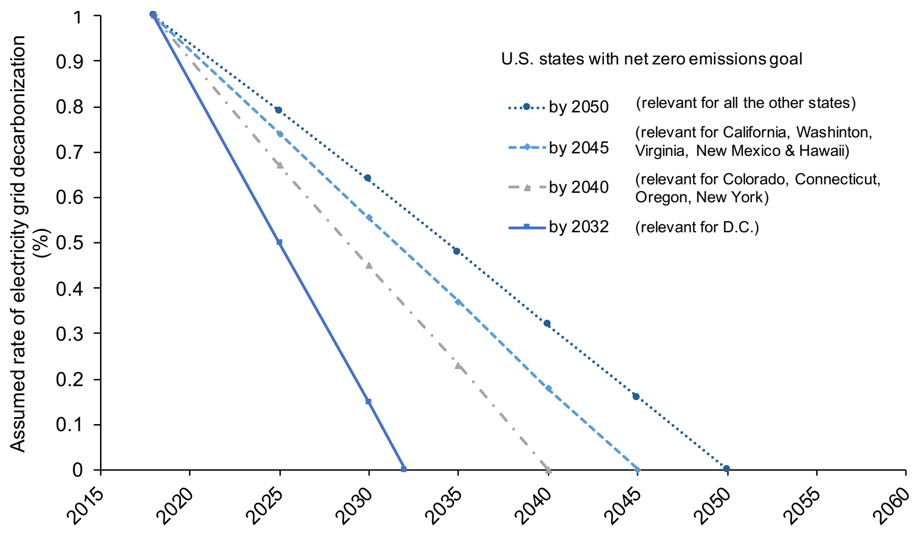


Figure 11. The assumed rates of electricity grid decarbonization in the U.S. up to 2050.

2.3. Industrial Boiler Capacities

Schoeneberger et al. (2021) estimate that the U.S. boiler population consists of approximately 38,500 units with a total cumulative capacity of 490 GW input. As per their estimates, the total industrial boiler capacity has increased by approximately 6% in recent years compared to the level in 2005 (EEA, 2005; Schoeneberger et al., 2021). Nearly half of the total number of boilers are less than 3 MW capacity however, these small boilers account for only 5% of the total capacity. Furthermore, boiler capacity is concentrated in five industries (i.e. chemicals, paper, food and beverage, petroleum refining, and primary metals), which represent approximately 75% of total boiler capacity. More than half of the boiler capacity in many industrial sectors is fired with natural gas, although certain industries such as petroleum refining, forest products, and metals have large shares of boiler capacity that are fired with byproduct fuels (refer to Figure 8).

For comparison with the EEA analysis in 2005 (EEA, 2005),Schoeneberger et al. (2021) have broadly classified industrial sectors into the following six: chemicals, paper, food, refining, primary metals, and “other” sectors. Using their results, this study assumes that the boiler capacity distribution of a) primary metals are representative for aluminum, foundries, and iron and steel manufacture, and b) paper sector for forest products manufacture. Similarly, the capacity breakdown of “other” sectors is relevant for all the rest of the individual sectors classified in this study. Figure 12 presents the adapted industrial boiler capacity distribution considered for both the national and state-level analyses. Based on the capacity distribution, industrial boiler energy demand and the corresponding CO_2 emissions are further disaggregated and presented in Table 3.

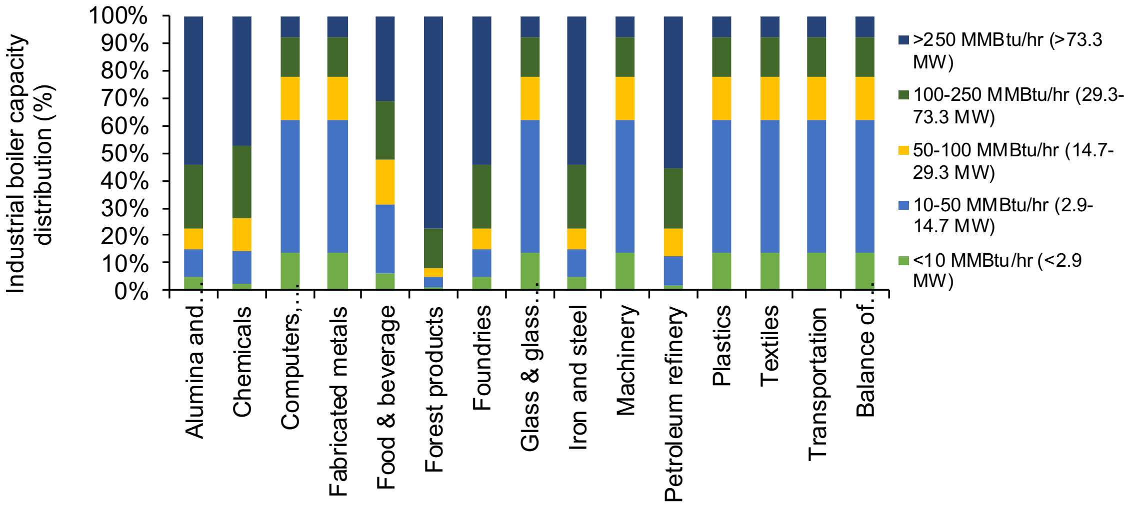
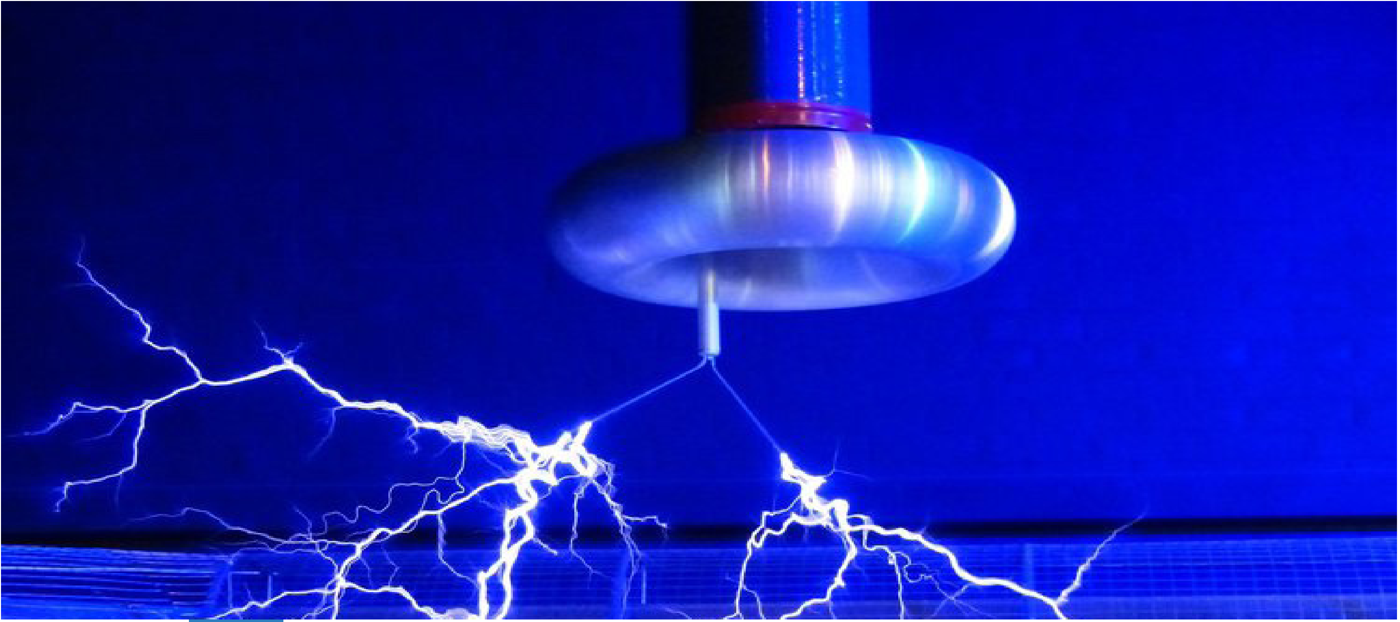


Figure 12. Boiler capacity distribution in the U.S. industrial sectors in 2018 (Adapted based on: Schoeneberger et al. 2021).

Table 3. Annual energy demand and CO_2 emissions breakdown by industrial boiler capacity in 2018 (Data sources: Schoeneberger et al. 2021; U.S. EPA, 2012; U.S. DOE/EIA, 2021; Energetics, 2019)

Industrial sector	Energy demand breakdown (in PJ)					CO_2 emissions breakdown (in $ktCO_2$)				
	<2.9 MW	2.9-14.7 MW	14.7-29.3 MW	29.3-73.3 MW	>73.3 MW	<2.9 MW	2.9-14.7 MW	14.7-29.3 MW	29.3-73.3 MW	>73.3 MW
Alumina & aluminum	0.3	0.6	0.4	1.4	3.3	20	43	31	97	229
Chemicals	18.9	80.7	84.3	187.0	330.3	1,130	4,835	5,053	11,205	19,791
Comp., electron.	2.1	7.3	2.4	2.3	1.1	119	418	135	129	64
Fabricated metals	0.2	0.4	0.3	1.0	2.2	13	27	19	62	145
Food & beverage	20.7	89.0	55.9	76.2	107.2	1,298	5,576	3,506	4,776	6,715
Forest products	3.1	11.6	10.4	47.1	247.0	252	927	831	3,773	19,771
Foundries	0.0	0.1	0.1	0.2	0.4	2	5	4	11	26
Glass & glass prod.	1.3	4.4	1.4	1.4	0.7	89	312	100	96	48
Iron & steel	5.5	11.9	8.5	27.0	63.4	1,137	2,444	1,735	5,541	13,006
Machinery	0.7	2.4	0.8	0.8	0.4	46	162	52	50	25
Petroleum refinery	8.9	51.0	48.7	107.7	272.6	588	3,372	3,224	7,127	18,036
Plastics	3.0	10.6	3.4	3.3	1.6	183	643	207	199	99
Textiles	1.9	6.8	2.2	2.1	1.0	105	369	118	114	57
Transportation	4.3	15.2	4.9	4.7	2.3	269	943	303	291	145
Balance of manufac.	11.8	41.3	13.3	12.8	6.3	817	2,865	921	886	440
All manufacturing	82.8	333.3	236.9	474.9	1040.0	6,069	22,941	16,238	34,357	78,595

Note: The table excludes electricity demand and the corresponding indirect CO_2 emissions in boilers.



3 Electrification of the U.S. Industrial Boilers

3.1 Impact of Boiler Electrification on Energy Demand and CO_2 Emissions

Using the weighted average efficiencies of combustion boilers (refer to Figure 5), sectoral useful energy demand (defined as the energy output of an energy conversion equipment; calculated as the product of combustion boilers' energy demand and boiler efficiencies) can be determined. The efficiency of an electric boiler is assumed 99%, which is used to estimate the potential electricity consumption in electric boilers. Figures 13 and 14 show the comparison of current onsite energy demand in combustion boilers, and potential electricity use in electric boilers in U.S. manufacturing and its sub-sectors in 2018, respectively. The comparison shows that electric boilers can reduce the boiler onsite energy demand by 16-29% in different U.S. industrial sectors in 2018.

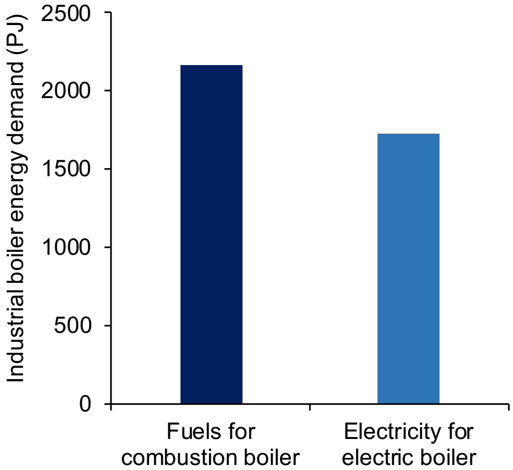


Figure 13. Estimated annual energy demand in combustion and electric boilers in the U.S. manufacturing in 2018.

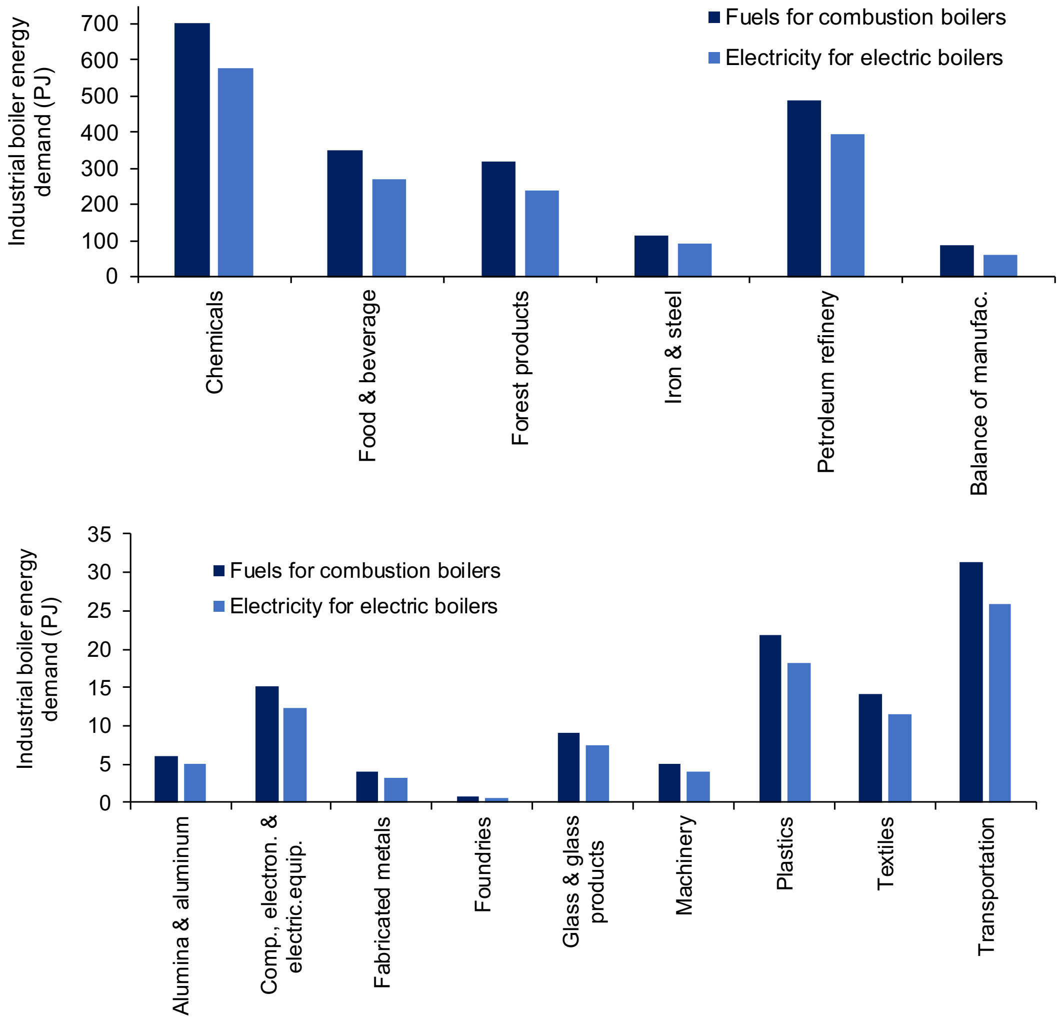


Figure 14. Estimated annual energy demand in combustion and electric boilers in the top-six energy-intensive (top) and the remaining (bottom) U.S. industrial sectors in 2018.

Figures 15 and 16 show that electrification could significantly reduce boiler energy demand for steam generation in U.S. manufacturing and its sub-sectors during the period 2018-2050 respectively (negative values in the figure represent energy savings). Approximately 445 PJ of annual onsite energy demand in the overall U.S. manufacturing can be saved if the existing fossil fuel-fired boiler capacity is electrified vs. 2018. This is equal to nearly 21% of the total energy demand in the U.S. industrial combustion boilers. Since the boiler energy demand is projected to increase in the future (refer to Figure 7), the annual savings potential is estimated at 595 PJ in 2050 as also shown in Figure 15. It must be noted that the change in energy demand (Figure 16) and CO_2 emissions (see later) estimated for each U.S. industrial sector are the technical potentials assuming an adoption rate of 100%. However, the actual adoption of electric boilers in U.S. manufacturing will be gradual and over time.

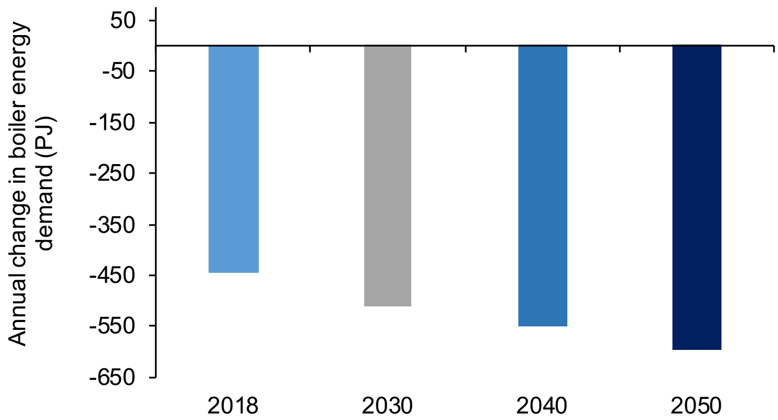


Figure 15. Potential change in boiler's annual energy demand in U.S. manufacturing after electrification in 2018-2050.

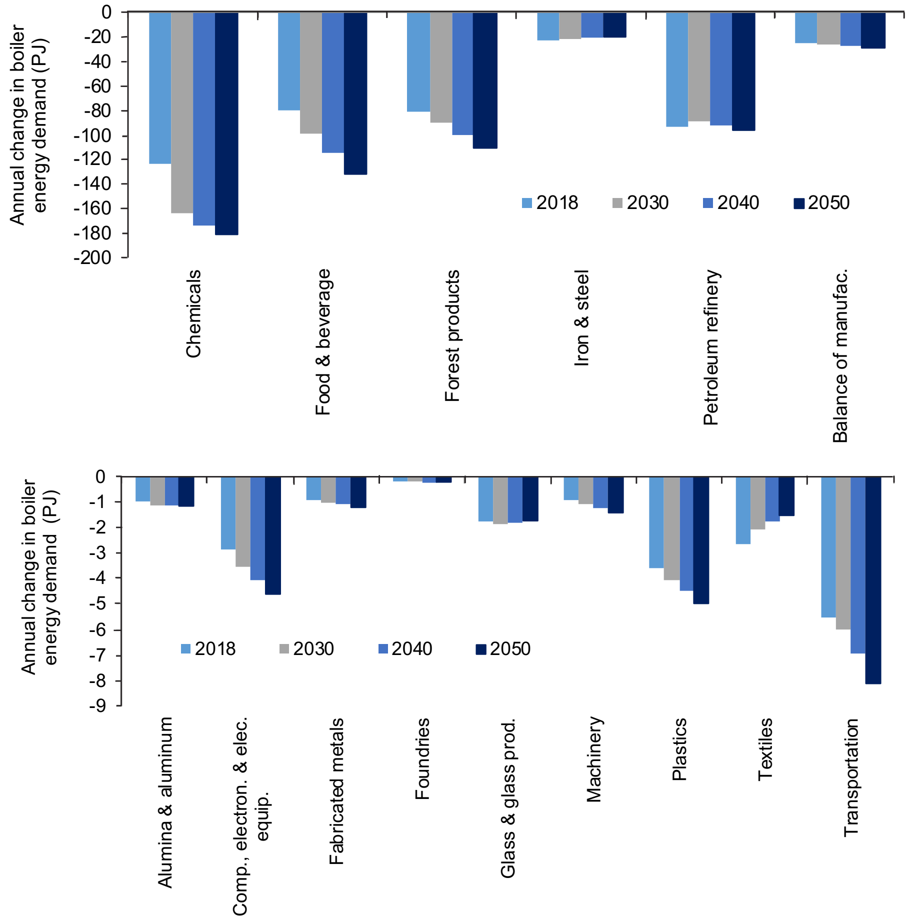


Figure 16. Potential change in boiler's annual energy demand after electrification in the top six (top) and the remaining (bottom) U.S. industrial sectors in 2018-2050.

As mentioned earlier, the electrification of combustion boilers in all the U.S. industrial sectors, except for the iron and steel sector, could initially lead to an increase in annual CO_2 emissions by around 43 $MtCO_2$ vs. 2018 using the current average U.S. grid emission factor assuming all boilers were electrified immediately. However, boiler electrification is projected to result in over 200 $MtCO_2$ per year reduction in CO_2 emissions in 2050, as shown in Figure 17. This significant decrease in CO_2 emissions in the future is projected as the consequence of the higher adoption of renewable electricity or grid decarbonization between 2018 and 2050.

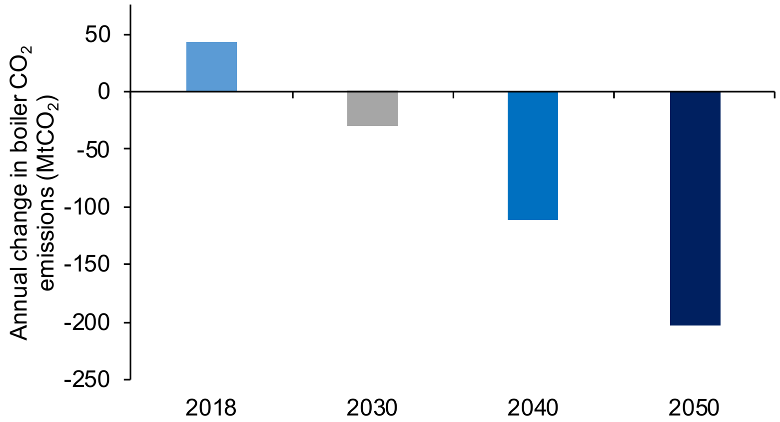


Figure 17. Potential change in boiler's annual CO_2 emissions after electrification in different U.S. industrial sectors in 2018-2050 (This is the technical potential assuming 100% adoption rate).

Figure 18 presents the potential change in boiler CO_2 emissions in different U.S. industrial sectors in the period 2018-2050. The CO_2 emissions from industrial boilers in the U.S. iron and steel manufacture are currently very high due to the combustion of CO_2-intensive by-product gaseous fuels (i.e. blast furnace and coke oven gases). The weighted CO_2 intensity of the combustion boilers employed in the iron and steel industry (refer to Figure 9) is higher than the current electricity grid emission factor in the U.S. Hence the electrification of boilers in the iron and steel sector can already reduce emissions by around 13 $MtCO_2$ vs. 2018.

However, it should be noted that if the byproduct gases are not combusted in boilers onsite, these gases must still be dealt with in some other way. Manufacturing plants can either integrate these byproduct fuels into their processes for direct heating, consequently replacing conventional fossil fuels, or find other green markets for their potential use. These efforts may incur additional costs and are not investigated in this study. Therefore, the existence of low or no-cost byproduct fuels in some industries (such as also in refineries and forest products) poses a great challenge to the electrification of byproduct fuel boilers (see further details in Section 4.3).

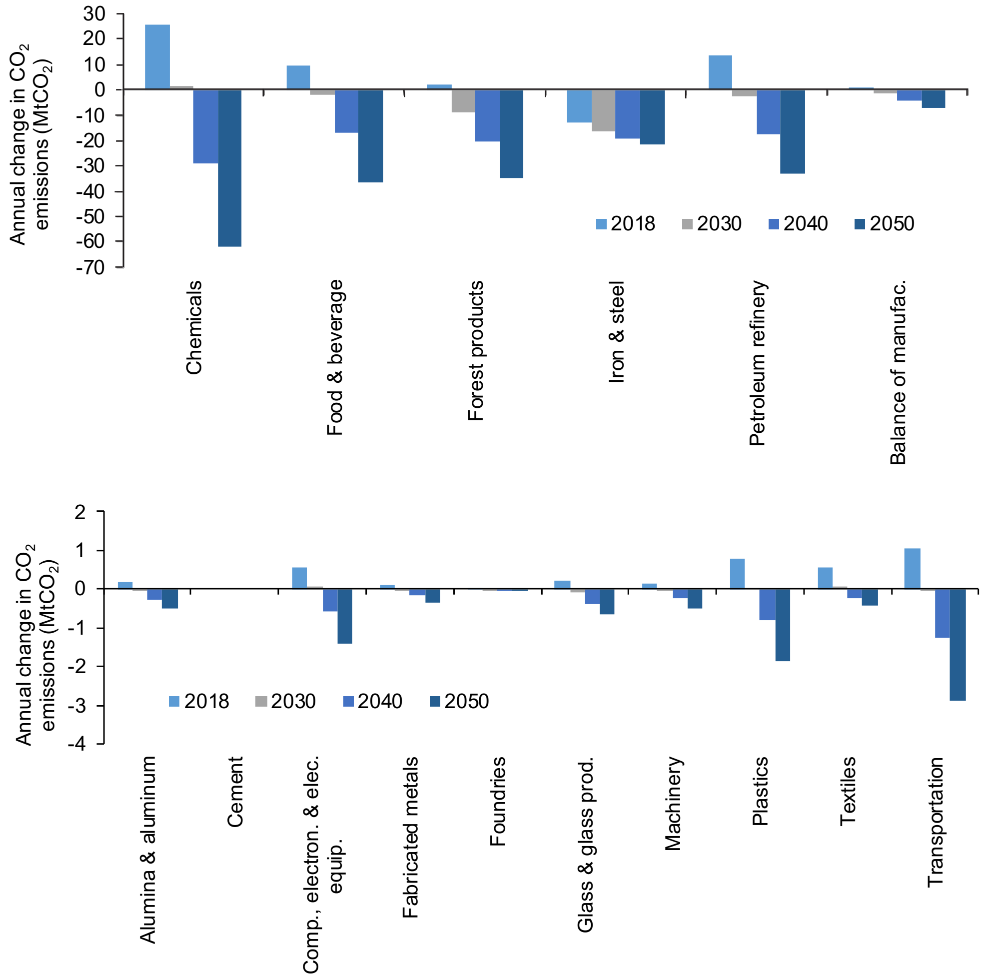


Figure 18. Potential change in boiler's annual CO_2 emissions after electrification in different U.S. industrial sectors in 2018-2050 (This is the technical potential assuming 100% adoption rate).

3.2 Economic Assessment for Industrial Boiler Electrification

A conservation supply curve (also called the energy efficiency cost curve or abatement cost curve) is an analytical tool commonly used to present the techno-economic perspectives of energy and/or CO_2 reduction. The curve shows the marginal costs of energy efficiency and CO_2 abatement measures as a function of the potential energy and/or CO_2 reduction. In this study, conservation supply curves are developed to estimate the marginal costs and the technical potential for energy and CO_2 savings due to boiler electrification in the U.S. industrial sectors. The method to build supply curves is described in detail in Appendix A. To estimate the marginal costs of electrification of industrial boilers, capital investment, and operations and maintenance (O&M) costs are acquired from literature (Jadun et al., 2017; Panos and Kannan, 2016; TNO, 2019) and adjusted for U.S. manufacturing where necessary, refer to Appendix B. The key component of boiler electrification costs is energy prices in the U.S. industry. Typically, more than half of the boiler lifetime costs are energy costs. Sector- and state-specific prices of different fuels and electricity in constant 2018 dollars are projected for the study period 2018-2050 based on the national statistics (U.S. DOE/EIA, 2019a; U.S. DOE/EIA, 2019b), see Appendix C. A real discount rate of 10% from the private perspective is assumed for the economic analysis (Zuberi et al., 2017) and the technical lifetime of electric boilers is assumed as 20 years (Bühler et al., 2019b)

The boiler electrification cost curve in Figure 19 shows the costs of conserved energy due to electrification of boilers in different U.S. industrial sectors as a function of their corresponding sector-wide potential energy savings in 2018. The height of each industrial sector on the vertical axis displays the sectoral costs (in 2018 $/GJ-saved) while the width of each sector on the horizontal axis shows the technical energy saving potential (in PJ). The figure shows that the technical potential energy savings by electrifying industrial boilers are approximately 445 PJ per year vs. 2018. The figure also shows that industrial boiler electrification incurs additional costs in each sector and none of the U.S. industrial sectors have energy conservation costs falling below the horizontal axis (which would have otherwise represented cost savings). In other words, although there may be individual cost-effective opportunities for electrifying boilers in specific industrial sites, the overall costs are not economical (higher than zero) in all industrial sectors. The major reason for the costs of conserved energy to be high is the disparity between the electricity and fuel prices in the U.S. industry. For example, the average electricity price in the U.S. industry (i.e. 19.3 $/GJ) is almost 4 times higher than the average price of natural gas (i.e. 4.6 $/GJ) in 2018 (refer to Table C.1 in Appendix C).

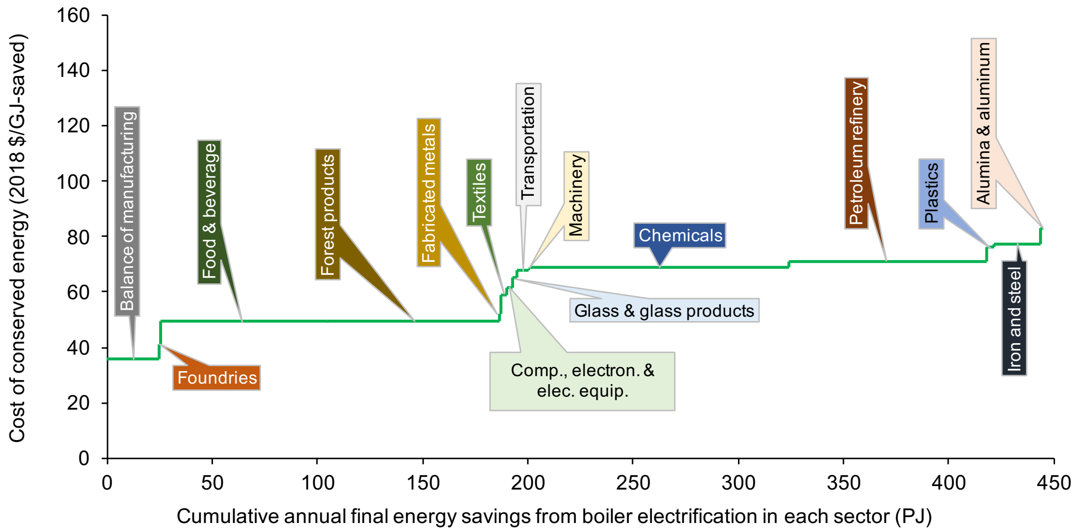


Figure 19. Boiler electrification cost curve for U.S. manufacturing in 2018.

Multiple factors including sectoral boiler efficiencies, boiler size distribution, energy mix, and fuel prices affect the costs of boiler energy conservation. Although the difference in electricity and fossil fuel prices is the primary reason why the boiler electrification costs are high in general, the role of these price differences in ranking the U.S. industrial sectors based on costs of conserved energy is rather small. Sector-specific boiler efficiency is found to be the most influential factor in ranking the industrial sectors. Since the balance of manufacturing (or other manufacturing sectors) possess the lowest boiler efficiencies among all the industrial sectors (i.e. around 70% on average, refer to Figure 5), replacing combustion boilers with high-efficiency electric boilers in these small industries will result in large energy savings. Hence, the energy conservation costs in these sectors are relatively the most economical. However, boiler electrification is the most expensive in aluminum and plastics manufacture partly due to high boiler efficiency levels (consequently low energy savings).

Among the five most energy-intensive sectors, costs of boiler energy conservation are lower in food and beverage and forest products manufacture compared to the petroleum refining, chemicals, and iron and steel sectors (see Figure 19). Although boiler efficiencies are playing a pivotal role in the rankings of these five sectors, other relevant factors have also contributed significantly to the costs. More than half of the boiler capacity in the petroleum refining, chemicals, and iron and steel sectors consists of large boilers i.e. greater than 70 MW (refer to Figure 12). Since large electric boilers are relatively cheaper per kW than small electric boilers (refer to Figure B.1), the specific investments (dollars per unit of energy conserved) to replace large boilers in refining, chemicals, and iron and steel sectors are lower than the specific capital required for smaller boiler replacements in forest products and food and beverage sectors. However, since approximately 90% of the electric boiler lifetime costs are electricity costs (and only 10% is related to the capital and other O&M costs), the effect of low specific investments is largely offset by the high electricity prices.

Moreover, in petroleum refining, forest products, and iron and steel sectors, the fuel prices are low due to the high share of inexpensive byproduct fuels available on site for combustion. Consequently, switching to electric boilers will increase the energy costs substantially in these three sectors. High energy costs could be a limiting factor for adopting electrified technologies in general in the industrial sectors (see Section 4.1).

Industrial boiler energy demand and combustion fuel prices are projected to grow in the future (refer to Figures 6 and C.2 respectively). However, the electricity prices are expected to slightly decrease in the future. All these projections will impact the costs of boiler energy conservation. Figure 20 presents the industrial boiler electrification cost curve in 2050 (the curves for years 2030 and 2040 are presented in Appendix D). The figure shows that while the potential energy savings in 2050 could increase to almost 595 PJ per year, the costs may moderately decrease i.e. from 36-83 $/GJ-saved in 2018 to 31-74 $/GJ-saved in 2050. The moderate decrease in costs of conserved energy is because electricity prices are expected to come down in the future but as per the projections, they may still be higher on an equal unit energy basis than combustion fuels in 2050 (refer to Figure C.1 in Appendix C).

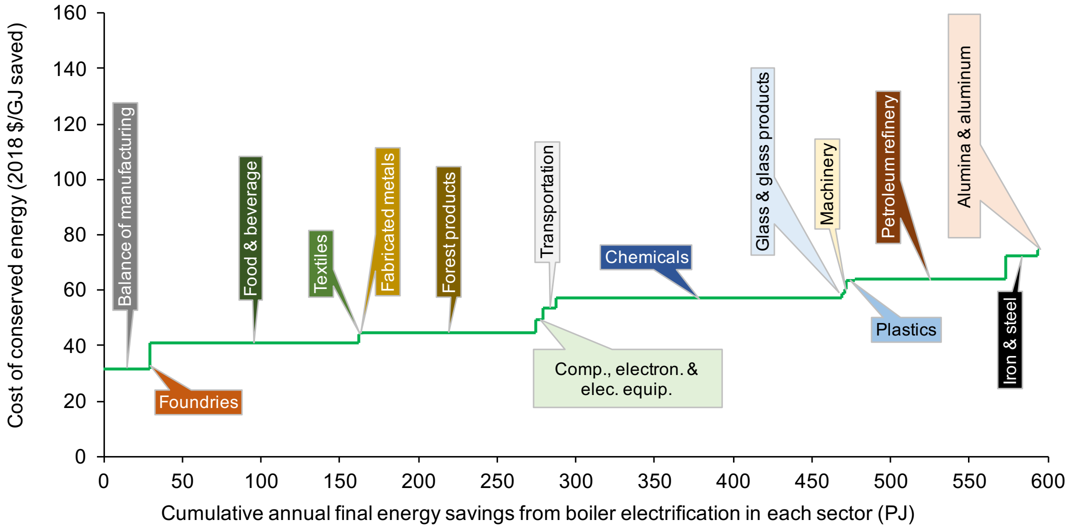


Figure 20. Boiler electrification cost curve for U.S. manufacturing in 2050.

As presented in Table 2, the current average U.S. electricity grid emission factor is higher than the weighted emission factors of industrial boiler fuels. Hence the electrification of combustion boilers in the manufacturing industry, except for the iron and steel sector (refer to the discussion around Figure 18 in the previous section), can initially increase the annual CO_2 emissions by around 43 $MtCO_2$ per year vs. 2018 assuming a 100% adoption rate. However, given the fact that electricity grids will be further decarbonized and potentially fully decarbonized in 2050 (refer to Figure 11), industrial boilers'-specific CO_2 abatement is projected to be over 200 $MtCO_2$ per year in 2050 (reaching net-zero emissions in 2050).

As shown in Figure 21, the CO_2 abatement costs in different sectors range between 67 and 185 $/tCO_2$. Since the weighted average boiler emission factor for the iron and steel sector is very high due to the combustion of blast furnace and coke oven gases for steam generation (see Figure 9), switching to boilers operated on renewable electricity can mitigate large quantities of CO_2 emissions. Hence the CO_2 abatement costs are the most economical in the U.S. iron and steel sector compared to other sectors.

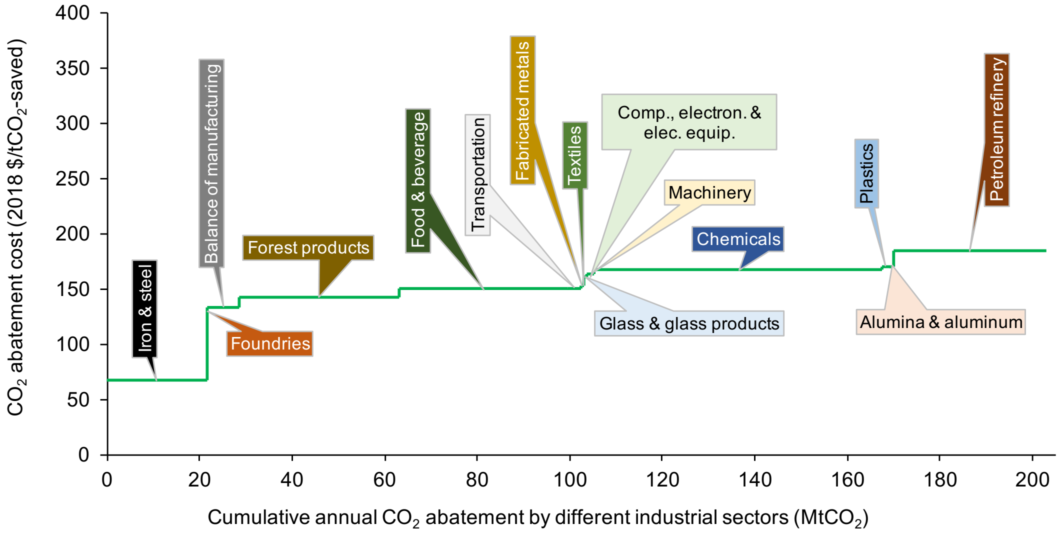


Figure 21. CO_2 abatement cost curve for boiler electrification in U.S. manufacturing in 2050.

It should be noted that the future cost results are quite sensitive to fuel and electricity price projections. Although the state-level analysis presents different levels of CO_2 abatement costs due to different energy prices in different states, a hypothetical scenario has been created to assess the electricity price sensitivity. Figure 22 shows that the CO_2 abatement costs can be reduced significantly (i.e. 2-8 times for different sectors) if today's U.S. average electricity price is halved in 2050 compared to the projected electricity price in the same year. Despite reducing the electricity price by half, the CO_2 abatement costs do not fall below zero (costs less than zero represent cost savings, refer to the methodology in Appendix A).

The analysis in Figure 22 concludes that decreasing electricity prices alone will not solve the problem and fossil fuel prices must be raised to a level closer to the price of electricity to make industrial boiler electrification economically competitive. Any form of a carbon tax scheme that results in higher fossil fuel prices could make the electrification of boilers substantially more cost-effective. However, we have not assumed any form of a carbon tax for fossil fuels in this study. Furthermore, this work only studies the effect of change in industrial energy demand and prices. To forecast change in all the relevant parameters such as boiler energy mixes, efficiencies, prices of electric boilers, etc. in the future, much more information is required which is currently unavailable, hence not done. In addition, the application of electric boilers possesses several co-benefits including the elimination of combustion-related pollutants, lower space requirements, less frequent maintenance, etc., however, techno-economic quantification of these co-benefits is outside the scope of this work.

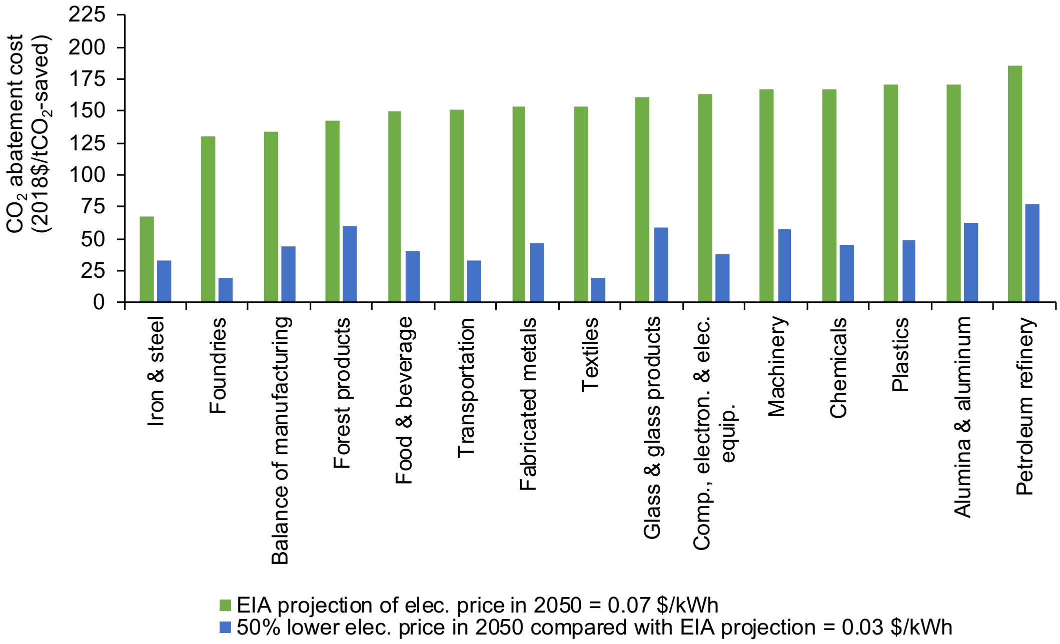


Figure 22. Comparison of the CO_2 abatement costs for boiler electrification in U.S. manufacturing under different electricity price scenarios in 2050.

3.3 State-level Analysis for Industrial Boiler Electrification

Following the methodology outlined in Appendices A-C and using the assumptions discussed in Section 2, potential boiler energy and CO_2 savings and costs of energy conservation and CO_2 abatement can be estimated for each industrial sector in each state. Since industry structure and energy infrastructure are different in each state, the state-level analysis presents more granularity. Table 4 presents the potential energy savings due to the electrification of combustion boilers and the associated costs in the five most energy-intensive industrial sectors in each state (see Appendices E and F for the state-specific results of all the industrial sectors).

Similarly, Table 5 presents the potential CO_2 abatement (due to simultaneous electrification of combustion boilers and electricity grid decarbonization) and the associated costs in the state-specific five most energy-intensive industrial sectors in 2050 (refer to Appendices G and H for the state-specific results of all the industrial sectors). Since the electricity grids in all the states are assumed to be completely decarbonized in 2050, the CO_2 abatement potentials in Table 5 are independent of the effect of electricity grid emissions (grid emissions are zero in 2050). However, before the electricity grid is completely decarbonized, the electricity generation mix and the corresponding grid emission factor in a state dictates the CO_2 abatement potential. For example, electrification of industrial boilers in some states (such as California, Washington, New York, Oregon, etc.) may result in CO_2 emissions reduction in the near term already (see Appendix G) since the grid emission factors in these states are lower than the most sectoral boiler emission factors (refer to Figure 9 and Table 2). However, the CO_2 abatement costs in these sectors are very high in the current scenario (see Appendix H).

Table 4. Sectoral potential for industrial boilers' annual energy savings and costs of electrification in each state in 2018.

State	Potential energy savings by electrifying industrial boilers in 2018 (PJ)					Cost of boiler electrification in 2018 (2018 $/GJ)				
	Chemicals	*Food & beverage*	*Forest products*	*Refinery*	*Iron & steel*	*Chemicals*	*Food & beverage*	*Forest products*	*Refinery*	*Iron & steel*
Alabama	1.71	1.14	5.66	1.00	1.08	59	42	42	61	52
Alaska	0.00	0.10	0.00	0.50	0.00	198	142	131	188	175
Arizona	0.20	0.90	0.30	0.00	0.00	61	44	45	n.a.	52
Arkansas	0.98	1.41	3.22	0.29	0.29	46	33	37	53	38
California	0.94	8.57	4.11	13.37	0.12	144	104	98	141	125
Colorado	0.53	0.77	0.02	0.52	0.15	76	54	53	77	66
Connecticut	0.23	0.19	1.06	0.00	0.01	154	110	103	n.a.	134
Delaware	0.34	0.22	0.01	0.54	0.00	68	50	56	76	53
District of Columbia	0.01	0.00	0.00	0.00	0.00	102	71	n.a.	n.a.	n.a.
Florida	1.56	1.36	3.13	0.02	0.05	74	53	54	77	63
Georgia	2.04	1.73	4.32	0.00	0.04	58	41	42	61	50
Hawaii	0.00	0.12	0.00	0.52	0.00	260	193	189	269	n.a.
Idaho	0.20	1.59	0.69	0.00	0.00	66	47	46	n.a.	58
Illinois	6.35	7.21	1.89	6.98	1.29	66	47	49	68	81
Indiana	4.97	3.27	0.61	1.25	7.44	72	51	53	74	88
Iowa	7.43	6.88	0.34	0.03	0.05	62	45	46	66	53
Kansas	1.92	1.60	0.16	1.44	0.00	80	57	57	79	70
Kentucky	3.22	0.92	1.82	1.20	0.39	55	38	40	57	47
Louisiana	13.17	0.72	4.21	17.47	0.29	53	37	38	55	47
Maine	0.05	0.25	1.41	0.00	0.00	87	63	65	n.a.	72
Maryland	0.56	0.45	0.51	0.00	0.00	75	55	57	n.a.	62
Massachusetts	0.68	0.53	0.80	0.00	0.00	156	113	110	n.a.	133
Michigan	2.69	1.63	4.30	0.65	1.48	69	49	50	73	84
Minnesota	3.04	3.24	1.88	2.32	0.07	78	55	54	78	68
Mississippi	1.23	0.85	1.28	3.14	0.17	56	40	42	60	48
Missouri	2.28	1.72	0.69	0.00	0.04	68	49	51	n.a.	57
Montana	0.00	0.25	0.07	1.30	0.00	42	30	35	49	35
Nebraska	3.23	2.83	0.10	0.00	0.06	80	57	57	n.a.	70
Nevada	0.08	0.10	0.22	0.01	0.00	57	41	42	61	n.a.
New Hampshire	0.08	0.09	0.26	0.00	0.00	139	101	99	n.a.	118
New Jersey	1.60	0.87	0.58	2.19	0.04	102	73	73	105	86
New Mexico	0.20	0.31	0.25	0.40	0.00	59	41	42	60	n.a.
New York	1.66	1.60	3.89	0.12	0.10	48	35	40	56	38
North Carolina	3.85	2.98	2.55	0.00	0.14	57	41	43	n.a.	48
North Dakota	0.56	0.77	0.03	0.45	0.00	89	63	60	86	80
Ohio	4.41	3.86	1.41	2.15	5.30	66	48	50	71	83
Oklahoma	2.08	0.77	2.02	2.43	0.05	55	39	39	55	50
Oregon	0.20	1.12	2.42	0.00	0.12	55	39	41	n.a.	48
Pennsylvania	2.53	2.53	3.68	2.69	2.42	57	42	46	66	81
Rhode Island	0.10	0.05	0.02	0.00	0.00	163	118	115	n.a.	138
South Carolina	3.05	0.58	2.54	0.00	0.25	58	41	42	n.a.	50
South Dakota	1.98	0.35	0.05	0.00	0.00	81	57	56	n.a.	71
Tennessee	9.77	3.85	3.00	0.09	0.13	53	38	39	56	45
Texas	23.51	2.65	2.08	26.29	0.38	54	38	39	56	48
Utah	0.36	0.92	0.29	1.38	0.06	55	39	41	58	47
Vermont	0.03	0.20	0.66	0.00	0.00	119	85	80	n.a.	105
Virginia	3.32	1.07	2.65	0.00	0.10	68	48	49	n.a.	59
Washington	0.19	1.64	3.79	2.18	0.03	34	24	30	42	27
West Virginia	1.91	0.11	0.12	0.14	0.04	67	47	47	66	60
Wisconsin	1.79	2.85	6.40	0.18	0.11	74	53	52	75	64
Wyoming	0.23	0.09	0.00	0.55	0.00	70	49	48	70	62
United States	123.06	79.82	81.48	93.79	22.29	69	49	49	71	78

Table 5. Sectoral potential for CO_2 abatement and costs of industrial boiler electrification in each state in 2050.

State	Potential CO_2 abatement by electrifying industrial boilers in 2050 ($ktCO_2$)					Cost of CO_2 abatement in 2050 (2018 $/$tCO_2$)				
	Chemicals	*Food & beverage*	*Forest products*	*Refinery*	*Iron & steel*	*Chemicals*	*Food & beverage*	*Forest products*	*Refinery*	*Iron & steel*
Alabama	861	515	2,407	356	282	125	110	109	143	124
Alaska	2	47	1	176	0	574	515	426	553	597
Arizona	101	410	127	0	1	113	102	110	n.a.	103
Arkansas	495	639	1,369	104	76	112	104	117	150	95
California	472	3,886	1,747	4,737	33	407	366	316	409	412
Colorado	265	348	10	185	40	155	138	135	175	153
Connecticut	115	84	453	0	3	418	373	313	n.a.	432
Delaware	171	99	2	192	0	141	133	153	185	115
District of Columbia	3	1	0	0	0	274	235	n.a.	n.a.	n.a.
Florida	783	619	1,334	7	12	171	154	152	195	165
Georgia	1,027	786	1,838	1	12	134	118	116	152	133
Hawaii	1	52	0	185	0	690	651	593	765	n.a.
Idaho	99	722	293	0	0	137	120	117	n.a.	137
Illinois	3,193	3,268	805	2,471	1,510	151	137	135	171	57
Indiana	2,501	1,484	258	443	8,699	165	149	145	185	62
Iowa	3,740	3,120	144	9	14	123	113	115	148	113
Kansas	965	725	68	510	1	172	155	148	184	169
Kentucky	1,619	419	775	426	102	112	99	102	131	109
Louisiana	6,624	327	1,792	6,186	75	147	130	123	162	149
Maine	26	113	601	0	0	223	203	193	n.a.	213
Maryland	280	203	217	0	0	167	154	157	n.a.	150
Massachusetts	341	242	340	0	1	418	378	330	n.a.	417
Michigan	1,351	738	1,829	230	1,726	158	144	138	183	60
Minnesota	1,530	1,471	801	822	17	164	148	138	180	160
Mississippi	619	385	544	1,112	45	113	102	106	137	105
Missouri	1,147	781	295	0	10	129	120	126	n.a.	112
Montana	1	113	28	461	0	63	58	82	101	46
Nebraska	1,626	1,286	44	0	16	173	155	148	n.a.	173
Nevada	42	46	95	4	0	107	95	103	134	n.a.
New Hampshire	39	41	109	0	0	371	336	300	n.a.	367
New Jersey	803	393	245	775	9	292	263	235	309	290
New Mexico	99	139	106	143	0	121	105	106	136	n.a.
New York	836	727	1,656	42	26	128	117	127	159	113
North Carolina	1,938	1,350	1,084	0	37	127	114	119	n.a.	118
North Dakota	280	351	14	158	0	202	178	159	203	211
Ohio	2,220	1,748	599	763	6,193	149	136	136	177	59
Oklahoma	1,044	350	858	859	13	159	139	128	165	167
Oregon	100	509	1,029	0	33	147	130	128	n.a.	144
Pennsylvania	1,274	1,147	1,567	953	2,825	154	141	147	191	65
Rhode Island	50	25	8	0	1	436	396	346	n.a.	435
South Carolina	1,536	262	1,079	0	67	133	117	117	n.a.	130
South Dakota	998	160	23	0	0	171	154	144	n.a.	169
Tennessee	4,914	1,748	1,275	31	35	106	94	100	129	99
Texas	11,829	1,200	887	9,312	101	151	133	126	164	153
Utah	180	417	125	489	15	100	90	100	128	90
Vermont	17	89	280	0	0	324	286	240	n.a.	340
Virginia	1,671	486	1,128	0	25	160	142	136	n.a.	160
Washington	96	745	1,614	773	9	74	68	89	112	55
West Virginia	962	50	52	50	11	164	141	132	170	171
Wisconsin	903	1,294	2,723	63	28	174	157	145	190	171
Wyoming	117	41	0	193	0	148	129	123	161	152
United States	61,905	36,199	34,675	33,219	21,582	167	150	143	185	67

Furthermore, while the techno-economic trends and rankings in Tables 4 and 5 are similar as in the national-level cost curves (see Section 3.2), the differences in costs of energy conservation and CO_2 abatement among the states are substantial. For example, as shown in Figure 23, the CO_2 abatement costs in chemical plants in Texas are nearly 2.7 times lower than those in California. This contrast comes from the large differences in energy prices in the two states (e.g. industrial electricity and natural gas prices in Texas are 2.5 and 2 times lower than those in California respectively, refer to Table C.1).

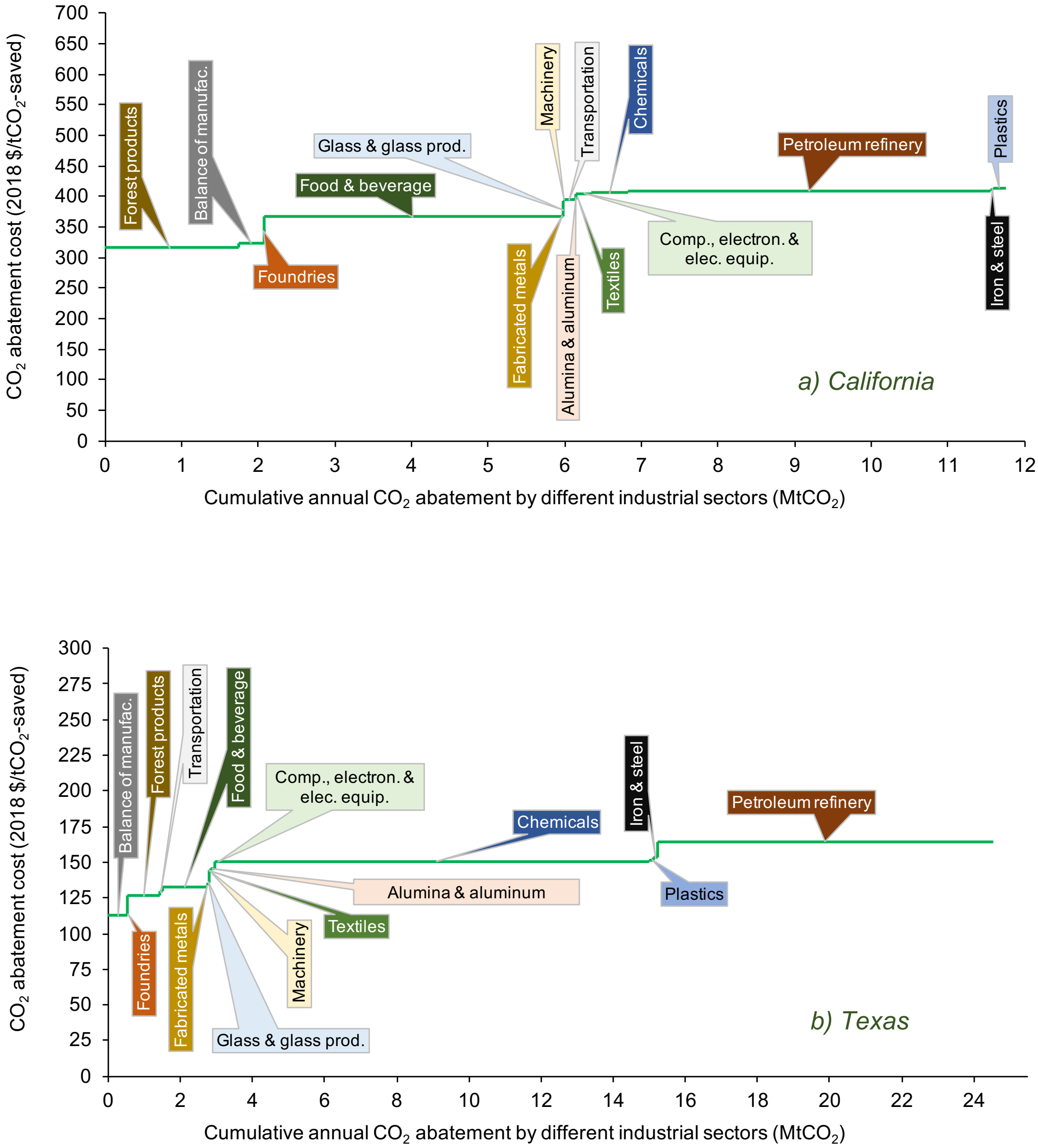


Figure 23. CO_2 abatement cost curve for industrial boiler electrification in a) California and b) Texas in 2050.

Figure 24 presents the CO_2 abatement cost curve for the top 20 industrialized states (by CO_2 emissions) showing potential CO_2 emissions reduction due to boiler electrification and their associated costs in 2050. The CO_2 abatement potential in these states is estimated at 165 $MtCO_2$ per year in 2050 which is approximately 81% of the total potential in all states (refer to Figure 21). Needless to say, due to the high energy prices in California, industrial boiler electrification in the state is found to be the most expensive among all the top 20 states. Figure 24 also presents that the overall CO_2 abatement costs can be reduced by 2-8 times in different states if today's state-specific average electricity prices are halved in 2050 compared to the projected electricity prices in the same year. Despite decreasing the electricity prices to half, the CO_2 abatement costs do not appear to be less than zero in any state which would have otherwise represented cost savings. It should be noted that the state rankings also change with the change in electricity prices (refer to Figure 24). Since the projected weighted average combustion fuel prices (reference price scenarios) are different for each state, change in energy costs due to industrial boiler electrification in different states does not occur at the same level.

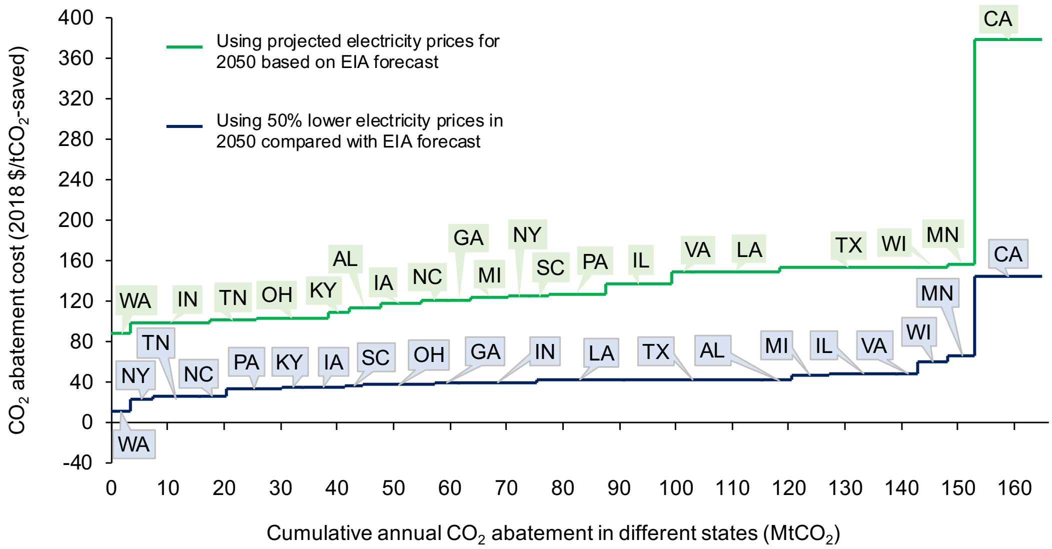


Figure 24. CO_2 abatement cost curve for industrial boiler electrification in the U.S. top 20 industrialized states in 2050.

Finally, although the results show that electrification of boilers may contribute significantly to the overall clean energy transition in U.S. manufacturing, the associated costs are high given the fuel and electricity cost assumptions in this study. A more substantial decrease in the electricity prices or increase in fossil fuel price as the result of a carbon price scheme can make industrial boiler electrification much more cost-effective. Alternatively, in the first phase of boiler electrification, hybrid electric-gas boilers may be used for industrial steam generation. These systems allow choosing between electric heating and fossil heating depending on the prices of electricity. Since electricity prices may fall due to large quantities of renewable electricity coming online and increasing energy demand, there may be times during the day when electricity is available at a rate lower than natural gas. For example, there are hours of the day when surplus renewable electricity is exported from California to its neighboring states, and the California Independent System Operator (ISO) pays off-takers a maximum of 25 $/MWh for this electricity (Deason et al., 2018). Finally, the results show that there is a large potential for energy and GHG emissions reduction associated with a high level of electric boiler adoption across industries, but to realize these benefits the cost disparity between electricity and fossil fuels (especially natural gas) needs to be addressed via coordinated effort (see Section 5 for proposed action plans).

4

Challenges and Barriers to the Electrification of Industrial Boilers

4.1 Financial Barriers

At present, electric boilers are approximately 40% cheaper than combustion boilers and are more energy-efficient (Jadun et al., 2017). However, the impact of high efficiency and low investments can be largely offset by the higher regional electricity prices compared to fossil fuels (e.g. the average electricity price in the U.S. was nearly four times higher than natural gas per unit of energy in 2018). Since approximately 90% of the electric boiler lifetime costs are electricity costs (see Section 3.2), the economic viability of boiler electrification heavily depends on the difference between the costs of energy to run electric and combustion boilers. High electricity prices may negatively influence the adoption decision of a manufacturing plant (Deason et al., 2018).

Electricity is more expensive than combustion fuels because it is commonly produced from these conventional fuels in thermal power plants at low efficiencies (Roelofsen et al., 2020). To electrify industrial steam generation (or any thermal process in general), the price of electricity must be brought down significantly to make it comparable with combustion fuels especially natural gas. Low average electricity prices can be realized by the decreasing costs of electricity generated from renewable sources and the increase of these sources in the power generation portfolio (Roelofsen et al., 2020). Low electricity prices, and/or a sustainable carbon price on combustion of fossil fuels may cause the electrification of industrial boilers to be financially attractive. Also, a hybrid electric-gas boiler system can be beneficial and the operation of an electric boiler can be sequenced when inexpensive off-peak carbon-free electricity is available (Hasanbeigi et al., 2021).

Although the electrification of industrial boilers may not require changes in core manufacturing processes, energy losses during the steam distribution and condensate return may offset the efficiency gains that electric boilers provide (Hasanbeigi et al., 2021). Hence a system-wide approach must be applied to reduce energy losses (e.g. through leak repairs, condensate recovery, etc.) and improve the overall efficiency of an industrial steam system. The application of supplementary energy efficiency measures will incur additional investments which can be justified given the corresponding energy and non-energy benefits.

Finally, electrification of thermal processes including industrial boiler systems also faces internal competition to acquire capital investments. Industrial enterprises often need to balance several considerations that include capital investments across locations, growth in product manufacture, environmental regulations, technology substitution, and safety (Rightor et al., 2020). Hence, the threshold for acquiring capital funding can be high, thus resulting in a delay in the application of electrification projects, including those that are technologically mature, easy to implement, and economically attractive.

4.2 Existing Boiler Stock

Based on boiler sales in the U.S. industry, EEA (2005) suggested that approximately half of the boiler stock in early 2000 was at least 40 years old and only 7% of the capacity was less than 10 years old. Given that the analysis was done over fifteen years ago and there are increasing regulations to mitigate climate change, it can be assumed that part of the old boiler capacity may have been replaced with new standard fossil fuel-fired boilers since then (fossil-derived fuels still dominate the industrial boiler energy demand, refer to Figure 4). Hence the relatively new boiler stock (from the perspective of service lifetime which could be up to more than 50 years) can be a major challenge in expediting the wide-scale application of electric boilers. On the other hand, the remaining half of the existing boiler stock might be close to the end of its technical lifetime. Since industrial equipment including combustion boilers can be operated longer than its technical lifetime with regular and high-cost maintenance, buying an electric boiler could be economically more sensible in some cases, when a company replaces an expired combustion boiler or builds a new facility (McKinsey & Company, 2020).

The U.S. EPA outlines an advanced method to monitor costs and energy savings in case of equipment replacement. According to the method, the cost difference between the electric and the standard boiler (typically natural gas-fired) should be added to the remaining present value of the existing boiler which is to be replaced. Similarly, the boiler energy savings during and after the remaining lifetime of the existing old boiler must be calculated as the difference between the energy demand of electric and old boilers, and electric and standard boilers, respectively. Zuberi and Patel (2017). performed a case study to test the EPA metrics and demonstrated that it could be profitable to replace old equipment with a more energy-efficient one before the end of the technical lifetime of existing equipment. This could also be true for the existing boiler capacity in U.S. manufacturing, however, this hypothesis is hard to prove due to the lack of sufficient data on the age of the current boiler stock. Under normal circumstances and without policy interventions, it may take decades for electric boilers to penetrate across all sectors in the U.S. manufacturing industry.

4.3 Existence of Low/no-cost Byproduct Fuels in Some Industries

Another major aspect that is usually not discussed in the literature is the existence of low/no-cost byproduct fuels in some industries which are typically combusted in industrial boilers for steam generation. For example, there is a large share of biomass waste products, such as wood chips and black liquor, used in the boiler energy mix in forest products manufacture.

Considering that these waste fuels have no price[7], will incur costs of disposal (i.e. landfill and transport costs) if not utilized on-site, and the discussion on whether replacing the bio-based byproduct fuels with electricity is advantageous from the overall GHG emissions perspective, the adoption of electric boilers as a replacement of byproduct fuel-fired boilers could be challenging (Rightor et al., 2020). Similarly, the switch to electric boilers from combustion boilers fired by byproduct hydrocarbon fuels such as waste or still gas in petroleum refining and chemicals manufacture, and blast furnace gas and coke oven gas in the iron and steel sector, adds further to the overall complexity.

However, the industrial boilers that use waste products for heat and/or steam generation may not be fully optimized and generally operate at low efficiencies because industrial plants often consider these processes as a way of reducing waste materials (Rightor et al., 2020). In such cases, electric boilers may possess a large potential advantage of improving the overall system efficiency.

4.4 Electricity Grid and Delivery Infrastructure

Transitioning to an electrified process from a direct combustion process, as in the case of boiler electrification, will significantly increase companies' electricity demand and affect load profiles. This will ultimately result in companies' increased reliance on their electric utilities and local utility providers to meet the additional electricity demand. As discussed, CO_2 emissions reduction targets through electrification of the industrial thermal processes cannot be achieved if electricity generation remains CO_2-intensive. Hence, companies that electrify their thermal processes will seek to purchase renewable electricity to meet the additional demand. Although it may be possible for some companies to find renewable resources to generate electricity on-site or at a nearby location, many industrial plants may be located far from these resources (Hasanbeigi et al., 2021). Therefore, an upgrade of the existing infrastructure and an increase in transmission and distribution capacity to link renewables to the electricity grid and end-users will most likely be required.

As shown in Table 2, the U.S. net electricity generation was almost 15,000 PJ (or 4178 TWh) in 2018 while at the end of 2020, the country's generation capacity was estimated at approximately 1.1 TW (U.S. DOE/EIA, 2021b). Switching to electric boilers will need an additional 1735 PJ (or 480 TWh) of electricity (refer to Figure 13). Managing the additional electric load can be very challenging for electric utilities. Utilities will have to steer the impact on their grid operation and consider quick dispatch of electricity to industrial plants that operate in batch mode or otherwise possess variable demand (Hasanbeigi et al., 2021). Therefore, companies must work closely with electricity suppliers to ensure grid reliability. In addition, converting existing combustion boilers to electric (especially large capacity boilers) may need an upgrade to the electricity service feed for industries. This upgrade could be expensive and may discourage the large-scale application of electric boilers in industrial facilities (Deason et al., 2018). Also, utilities may not be able to expand electricity grids due to a lack of space and/or other constraints.

7 The U.S. Internal Review Service (IRS) recognize black liquor as an alternative fuel and the U.S. paper mills get tax credit for burning this byproduct on-site (Booth and Leuenberger, 2018).

5 Action Plan and Policy Implications

5.1 Technology Research, Development, Demonstration, and Deployment

While industrial electric boilers are commercially available, further advancement of industrial electric boilers, especially for large boilers, depends on further investment in research, development, demonstration, and deployment (RDD&D). Optimal electrification strategies are influenced by various variables, including sector, location, and processes. Several RDD&D activities are listed below.

Industrial companies can partner with academia, national labs, think tanks, among other stakeholders, to further enhance the electrification of industrial boilers. Industrial companies can also develop business cases for the electrification of industrial boilers by mapping out their energy and non-energy benefits.

Governments can act by incentivizing the deployment of industrial boiler electrification. They can also help make advancements by using the excellent capacity at the U.S. DOE national labs. Moreover, they can provide tax credits or grants to financially incentivize large industrial boiler electrification pilots and demonstrations.

Utilities can partner with industry and government to support RDD&D activities for industrial boiler electrification. They can also collaborate with industry and research institutes to evaluate the grid implication of industrial electrification in their area of service and nationality.

Suppliers of electric boilers can collaborate with industry, academia, national labs, think tanks, service and engineering firms, and other stakeholders to scale the electrification of industrial boilers. Moreover, they can enhance business cases for industrial boiler electrification by including both energy and non-energy benefits. They can also collaborate with the industry to demonstrate new electric boiler technologies and disseminate the results.

5.2. Economics of Electrification

Energy cost per unit of production is often higher for the electric boilers compared to the conventional natural gas- or coal-fired boilers in the U.S. Moreover, energy cost is only a small portion of the total manufacturing cost for most industrial sectors, except for several industries, including the cement and steel industries, to which, energy accounts for 30-40% of the total manufacturing cost. In sectors where energy cost is only a small portion of the total production cost, a small or even moderate increase in energy cost per unit of product, resulting from the electrification of boilers, will have a minimal impact on the price of the final product. Therefore, it will have a minimal impact on the price that final consumers will pay for the product or the products that are made from those materials.

Energy prices can vary significantly from state to state and even county to county within the U.S. The results of the cost per unit of production comparisons are highly sensitive to the unit price of energy (fuel and electricity). Additionally, renewable electricity prices are anticipated to continue to decline and may decline faster than predicted, giving electric boilers a more competitive edge compared to conventional fossil-fuel-based boilers.

Natural gas and other fossil fuel prices may rise higher than we have projected, especially if a particular type of carbon pricing policy is introduced in the U.S. Yet, we have not included such considerations in our natural gas and coal price projections – we directly used projections from EIA's Annual Energy Outlook 2019.

5.3. Industry Capacity Building

Due to a lack of familiarity, industrial consumers may be risk-averse to and avoid new technologies altogether. Subsequently, electric boilers must compete with familiar fuel-fired boilers that have been used for decades and are already well understood. Companies and industrial facility operators need more information about the availability, applicability, and integration of electric boilers with existing systems. Employees and contractors may require training on electric boilers, especially on installation, operation, and maintenance.

Industrial companies can seek information about available electric boilers. They can participate in technical assistance programs. They can engage with the industrial facility's electric utility to learn about electricity rates and whether additional infrastructure for connection is required. They can also learn about where boiler electrification has occurred, then disseminate information or case studies about its challenges and successes.

Governments can support demonstrations and deployments of electric boilers that have already been developed. Moreover, they can offer or support technical assistance programs for boiler electrification. They can create or support an industrial boiler electrification information dissemination platform, which would include the development and dissemination of case studies. They can also conduct or support research and analysis on the economic development potential of boiler electrification. Government can also support grants that create fellowships to provide dedicated staffing support to industries to help their boiler electrification efforts.

Utilities can evaluate the substantial demand response potential (including its financial impacts) that the advancement of industrial boiler electrification can provide to utilities. They can also provide information to industrial customers about the utility side implications of boiler electrification and potential economic gains from demand response if applicable to each industrial plant. Moreover, they can provide information about their electricity rates and market structures and provide information about required connection upgrades.

Suppliers of electric boilers can engage with industrial companies to learn about their electrification needs. They can provide information about available technologies and those under development to industrial companies, governments, and utilities.

5.4. Other Stakeholders' Capacity Building

Utilities, policymakers, and the financial community may not be aware of the benefits of industrial electric boilers, or of companies' or facilities' interest in pursuing it as a way to reduce their energy use and emissions. Those outside the industrial sector also require additional information about electric boilers and the benefits that they can deliver. A better understanding of industrial electric boilers' capabilities and the need for additional investment and support can improve policy and investment decisions.

In addition to understanding industrial electric boilers, more education will be needed about the implications of increased electrification for electricity demand and the electric grid. Presently, there is interest in electrifying vehicles, buildings, and industrial facilities, using renewable electricity to reduce the emissions from these applications. This increased demand across sectors will require an additional supply of renewable electricity, as well as an electric transmission and distribution system that can adequately manage the increased volume of electric energy.

Industrial companies can educate their peers about the benefits of electric boilers. They can also inform policymakers about their interest in industrial electrification and the benefits that could be realized by adopting electric boilers, including industrial decarbonization. Additionally, they can educate utilities, policymakers, and the public, about the increased demand for renewable electricity as a result of an increase in electrification. Furthermore, they can educate financial institutions and potential investors about the benefits of electric boilers.

Governments can educate the public about the benefits that could be realized by adopting electric boilers, including decarbonization, air quality and health, and economic development opportunities. Utilities can educate policymakers and the public about the increased demand for renewable electricity, energy storage, and demand response, transmission system expansion needs, distribution system hardening, and grid modernization as a result of an increase in electrification of boilers.

Suppliers of electric boilers can educate policymakers and the industry about their technologies and the benefits that could be realized by adopting electric boilers, including industrial decarbonization. They can also educate financial institutions and potential investors about their products and the advantages of electric boilers.

5.5. Policy Development

To increase the deployment of electric boilers in the industrial sector, a wide range of policy options could be pursued. Industrial companies can collaborate with policymakers to discuss their interest in the electrification of boilers and the benefits that could be realized. They can also engage with utilities about electrification needs and viable solutions.

Governments can adopt policies to support the demonstration and deployment of electric boilers that are market-ready. Moreover, they can adopt tax policies that encourage investment in electric boilers; policies that price carbon emissions at a level that supports electrified technologies; adopt electricity rate designs that encourage electrification, and adopt renewable portfolio requirements for thermal energy.

Utilities can adopt electricity rate designs that encourage the electrification of boilers. Additionally, they can support policies that permit more on-site generation, storage, and microgrid deployment, to help address reliability concerns and to mitigate costs to all ratepayers of increased industrial load.

5.6. Workforce Development

In addition to company knowledge, employees and contractors at industrial facilities may require training on electric boilers and their installation, integration, operation, and maintenance. The industrial sectors, governments, and utilities can work together with trade groups and educational institutions to ensure that current and future workers are prepared to meet the new demands of an increasingly electrified industrial sector.

Industrial companies can provide training for employees and contractors on electric boilers. They can engage with trade groups, educational institutions, and utilities to discuss education and training needs and develop application programs.

Governments can offer or support education and training programs for those that will install, operate, and maintain electric boilers. Utilities can engage with the industrial sector, trade groups, and education institutions to discuss education and training needs and develop appropriate programs. Suppliers of electric boilers can provide training on their technologies.

Figure 25 provides a summary of the aforementioned action plans which different stakeholders could take to facilitate the electrification of the industrial boiler systems.

	Industry	Government	Utilities	Suppliers
RDD&D	• Develop business cases, increase efficiency, reduce energy intensity.	• Incentivize development and demonstrations of tech. • Use excellent capacity at US DOE national labs. • Provide tax credits and grants for pilots.	• Incentivize development and demonstrations • Partner with stakeholders to support RD&D • Collaborate with stakeholders to evaluate grid implications.	• Work with stakeholders to enhance business cases, and develop, scale, pilot and demonstrate electrification efforts.
Economics	• Conduct techno-economic analyses. • Conduct life cycle costing. • Include non-energy benefits	• Provide financial incentives for adoption of electrification technologies	• Provide rates that incentivize electrification	• Join government sponsored R&D to lower technology cost
Industrial Education	• Seek information on electrification technologies. • Participate in technical assistance programs. • Learn about electric rates and infrastructure requirements.	• Offer or support technical assistance programs. • Create or support an information dissemination platform. • Conduct research and analysis on product quality, and process-level. Develop process designs, equipment costs.	• Evaluate demand response potential for utilities. • Educate industrial customers about utility side implications of electrification and economic gains from demand response. • Provide insight on electric rates and market structures. • Provide insight on required connection upgrades.	• Engage industry to learn electrification needs. • Educate industry, government and utilities on available technologies and those in development. • Disseminate information or case studies on challenges and successes where electrification of boilers have occurred.
Other Stakeholders' Education	• Inform relevant stakeholders about electrification interest and benefits. • Educate stakeholders about the increased demand for renewable electricity.	• Educate the public about the benefits of industrial boiler electrification.	• Educate policymakers and the public about the increased demand for renewable electricity, energy storage, demand response, transmission system expansion, distribution system hardening, and grid modernization.	• Educate policy makers and public about electric boilers and the benefits • Educate financial institutions and potential investors about products and the advantages of electrification.
Policy Development	• Collaborate with policymakers on interest in the electrification of boilers and benefits. • Engage utilities about electrification needs and solutions.	• Adopt tax policies that encourage investment. • Adopt electricity rate designs and renewable portfolio requirements. • Adopt policies that price carbon emissions; and support demonstration and deployment of technologies.	• Adopt electricity rate designs that enable electrification. • Support policies that permit more on-site generation, and storage and microgrid deployment.	• Communicate clearly with policy makers on the needs for wider adoption of technologies
Workforce Development	• Provide training for employees and contractors. • Engage with trade groups, educational institutions, and utilities to discuss education and training needs and develop applicable programs.	• Offer or support education and training programs for installing, operating, and maintaining industrial boiler electrification.	• Engage industrial sector, trade groups, and education institutions, to discuss education and training needs, and develop applicable programs.	• Provide training on technologies or equipment. • Engage with trade groups, educational institutions, and utilities, to discuss education and training needs, and develop applicable programs.

Figure 25. Action plan and policy implications to promote the wide-scale application of electric boilers in the manufacturing sector.

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Appendices

Appendix A. Methodology - Potential and Costs of Boiler Electrification

Using the weighted average efficiencies of combustion boilers, sectoral useful energy demand (defined as the energy output of an energy conversion equipment; calculated as the product of combustion boilers' energy demand and boiler efficiencies) can be determined. The efficiency of an electric boiler is assumed 99%, which is used to estimate the potential electricity consumption in electric boilers. Potential energy savings *ES* due to the electrification of industrial boilers can be estimated by the following equation:

$$ES_{i,s} = E_{comb,i,s} - E_{elec,i,s} \quad \text{(A.1)}$$

Where;
$E_{comb,i,s}$ = Energy demand by combustion boilers in a sector *i* in a state s, refer to Figure 3
$E_{elec,i,s}$ = Electricity demand by electric boilers in a sector *i* in a state s, estimated by Equation A.2

$$E_{elec,i,s} = \left(\frac{E_{comb,i,s} \times \eta_{comb,i,s}}{\eta_{elec,i,s}}\right) \quad \text{(A.2)}$$

Where;
$\eta_{comb,i,s}$ = Weighted efficiency of combustion boilers in a sector *i* in a state s, refer to Figure 5
$\eta_{elec,i,s}$ = Electric boiler efficiency in a sector *i* in a state s assumed as 99%

Similarly, potential CO_2 abatement *CA* due to the electrification of industrial boilers and simultaneous electricity grid decarbonization can be estimated by the following equation:

$$CA_{i,s} = (E_{comb,i,s} \times f_{comb,i,s}) - (E_{elec,i,s} \times f_{egrid,s}) \quad \text{(A.3)}$$

Where;
$f_{comb,i,s}$ = Weighted emission factor of combustion boilers in a sector *i* in a state s, refer to Figure 9
$f_{egrid,s}$ = Electricity grid emission factor in a state s, refer to Table 2

A conservation supply curve is an analytical tool, commonly used to present the techno-economic perspectives of energy and/or CO_2 conservation. The curve shows the marginal costs of climate mitigation measures as a function of the potential energy and/or CO_2 conservation. In this study, conservation supply curves are developed to estimate the specific costs of energy conservation due to boiler electrification C_{elec} and the technical potential for energy savings *ES* and CO_2 abatement *CA* in state-specific industrial sectors. The specific costs are calculated using the following equations.

Costs of conserved energy:

$$C_{elec,i,s} = \frac{\alpha . I_{i,s} + O\&M_{i,s} - B_{i,s}}{\mathrm{ES}_{i,s}} \tag{A.4}$$

Costs of CO_2 abatement:

$$C_{elec,i,s} = \frac{\alpha . I_{i,s} + O\&M_{i,s} - B_{i,s}}{\mathrm{CA}_{i,s}} \tag{A.5}$$

Where;

$I_{i,s}$ = Capital investment costs of electric boilers in a sector *i* in a state *s*

$O\&M_{i,s}$ = Annual operations and maintenance costs of electric boilers in a sector *i* in a state *s*

$B_{i,s}$ = Annual cost benefits in a sector *i* in a state *s*, calculated by Equation A.6

α = Capital recovery factor or annuity factor, calculated by Equation A.7

$$B_{i,s} = \left(E_{comb,i,s} \times P_{comb,i,s}\right) - \left(E_{elec,i,s} \times P_{elec,i,s}\right) \tag{A.6}$$

Where;

$P_{comb,i,s}$ = Weighted average price of combustion fuels in a sector *i* in a state *s*

$P_{elec,i,s}$ = Electricity price in a sector *i* in a state *s*

$$\alpha = \frac{(1+r)^L \times r}{(1+r)^L - 1} \tag{A.7}$$

Where;

r = real discount rate, taken as 10% from the private perspective

L = Lifetime of electric boilers assumed as 20 years

When plotting the boiler electrification cost curve, industrial sectors are arranged in ascending order by conservation costs and displayed against their annual cumulative potential energy or CO_2 savings. The height of each industrial sector on the vertical axes displays the sector-specific costs of boiler electrification while the width of each sector on the horizontal axes shows the annual energy or CO_2 savings. Finally, since annual benefits in Equations A.4 and A.5 are presented as negative values as a consequence of energy cost savings, all sectors that fall below zero on the horizontal axis will be considered cost-effective.

Appendix B. Methodology - Electric Boiler Investment and O&M Costs

The capital investment costs of an electric boiler are nearly 40% less than that of an equivalent natural gas boiler (Jadun et al., 2017). The capital costs of electric boilers are estimated based on international literature (Jadun et al., 2017; Panos and Kannan, 2016; Soini et al., 2017; TNO, 2019), and range between 13 and 44 $/GJ depending on the size of the boiler. The range of capital costs includes equipment and installation costs and are presented after adjustments to correct for the regional differences in material and labor costs and exchange rates where necessary. Moreover, in case the grid connection capacity is insufficient, costs for the connection capacity expansion can be substantial and may vary from a few thousand dollars for low voltage grids to several million dollars to connect to the electricity transmission grid (TNO, 2019). Since these costs are very site-specific, hence not considered in this study.

After establishing the range of capital costs of industrial electric boilers, this study assumes that the maximum and the minimum costs of the range are representative for boilers of capacities <2.9 MW and >73 MW respectively. Based on experience, it is further assumed that the specific investment costs for boiler capacities between 2.9 and 73 MW follow power-law as shown in Figure B.1. The annual operations and maintenance (O&M) costs of electric boilers are assumed to be 1% of the total investment costs (based on TNO 2018 and Panos and Kannan 2015) and are presented in Figure B.2.

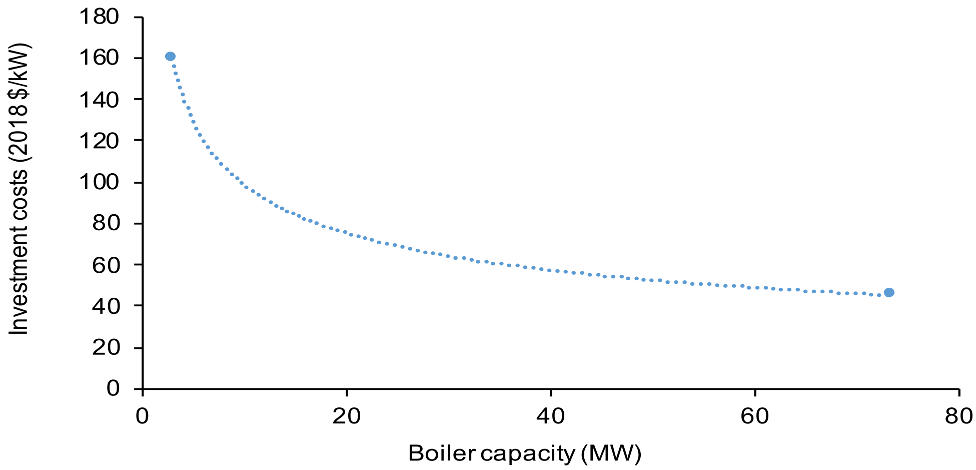

Figure B - 1. Investment costs of an electric boiler as a function of its size.

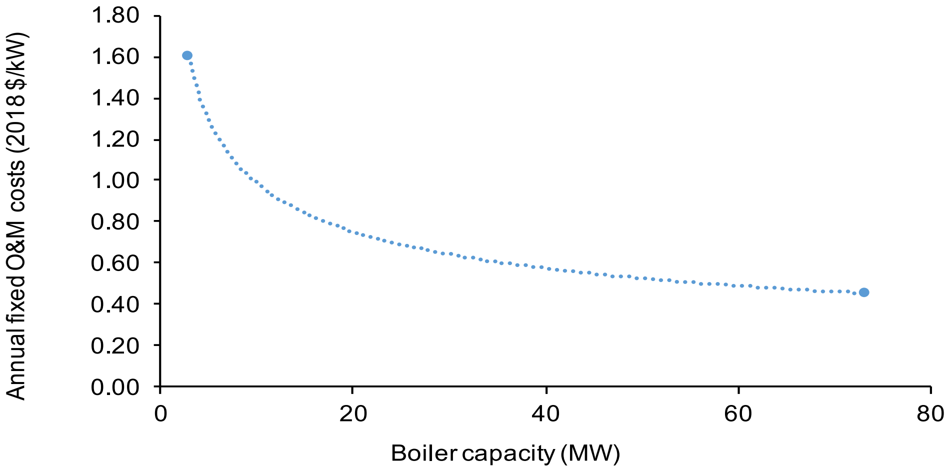

Figure B - 2. Operations and maintenance costs of an electric boiler as a function of its size.

Appendix C. Methodology - Current and Projected Industrial Energy Prices

The national- and state-level prices of different energy carriers for the industry sector in 2018 are acquired from the EIA's State Energy Data System (EIA SEDS, 2019) and presented in Table C.1. Due to the lack of data on the type of "other" fuels used for combustion in boilers in each sector and state, the prices for "other" fuels are calculated based on the U.S. industry-wide contribution of some common fuels in this category such as petroleum coke, waste oils/gases, and waste materials, etc. However, for petroleum refining, forest products, and iron and steel sectors, more weight is given to certain byproduct fuels (refer to Figure 8) based on the information given in MECS (2018) to estimate the corresponding prices of "other" fuels in these sectors, as presented in Table C.1.

Besides, EIA's Annual Energy Outlook (2019) forecasts industry-specific energy prices until 2050 for different U.S. geographical regions under their reference case scenario. Based on the future price development as presented in Table C.2, this study projects the future energy prices for the industry located in different states (refer to Figure C.1 for the average prices at the national level). Based on these energy price projections and the sectoral boiler energy mix shown in Figure 4, the weighted average future energy prices for combustion boilers in each U.S. industrial sector are determined and presented in Figure C.2.

Table C - 1. Industrial energy prices in different U.S. regions and states (Adapted based on EIA SEDS, 2019).

Region/State	Energy prices (2018 $/GJ)									
	Net electricity	*Residual fuel oil*	*Diesel*	*Natural gas*	*LPG - NGL*	*Coal*	*Other (for all other sectors)*	*Other (for refining)*	*Other (for forest prod.)*	*Other (for iron & steel)*
New England										
Connecticut	38.25	12.66	17.29	6.03	18.38	0.00	3.03	1.19	1.10	3.09
Maine	25.89	12.57	17.15	8.46	18.24	5.23	3.03	1.19	1.10	3.09
Massachusetts	41.36	12.65	17.27	9.48	18.36	5.43	3.01	1.19	0.99	3.09
New Hampshire	37.28	11.91	16.26	9.01	17.28	0.00	2.93	1.19	0.57	3.09
Rhode Island	42.75	12.75	17.39	9.63	18.49	0.00	2.94	1.19	0.64	3.09
Vermont	29.60	12.62	17.23	4.17	18.32	0.00	3.05	1.19	1.18	3.09
Mid-Atlantic										
New Jersey	27.97	0.00	15.40	7.32	25.43	0.00	2.78	0.72	1.01	2.63
New York	16.72	9.72	16.43	7.18	17.08	4.25	3.06	1.32	0.89	3.22
Pennsylvania	18.99	9.42	15.30	7.92	23.77	3.85	2.75	0.72	0.89	0.00
East North Central										
Illinois	18.88	10.56	16.49	5.11	9.15	2.92	2.96	1.19	0.72	0.00
Indiana	20.51	10.63	16.37	5.53	13.54	4.20	3.06	1.32	0.90	0.00
Michigan	19.72	10.54	16.83	5.41	13.41	4.42	2.77	0.71	0.98	0.00
Ohio	19.48	10.51	16.79	5.90	20.63	4.00	2.73	0.72	0.76	0.00
Wisconsin	20.37	10.44	16.67	4.70	13.29	3.68	3.03	1.19	1.10	3.09
West North Central										
Iowa	17.93	10.54	16.83	4.80	9.75	2.05	2.88	0.99	0.84	2.90
Kansas	21.10	10.59	16.91	4.00	13.48	2.24	2.89	1.19	0.38	3.09
Minnesota	20.92	10.63	17.71	4.35	13.53	2.50	3.03	1.19	1.09	3.09
Missouri	20.05	10.36	16.55	6.03	13.18	2.09	3.06	1.32	0.90	3.22
Nebraska	21.11	0.00	16.75	4.01	13.35	1.46	2.91	1.19	0.47	3.09
North Dakota	22.17	0.00	16.67	2.88	13.29	1.18	2.97	1.19	0.79	3.09
South Dakota	21.59	0.00	16.59	4.46	13.22	2.09	3.04	1.19	1.17	3.09
South Atlantic										
Delaware	22.08	0.00	14.44	9.15	16.43	0.00	2.90	1.19	0.43	3.09
District of Columbia	23.04	0.00	15.28	0.00	17.38	0.00	3.02	1.19	1.05	3.09
Florida	21.30	9.66	16.79	5.89	15.71	4.31	3.01	1.19	0.97	3.09
Georgia	16.68	9.47	16.47	4.27	15.41	3.86	2.99	1.11	1.09	3.01
Maryland	22.85	9.91	15.31	7.72	17.41	2.34	3.03	1.19	1.08	3.09
North Carolina	17.59	9.54	16.59	5.69	15.52	3.37	3.03	1.19	1.10	3.09
South Carolina	16.95	9.66	16.79	4.55	15.71	3.55	3.10	1.32	1.10	3.22
Virginia	19.05	9.59	16.67	4.55	15.60	3.69	3.03	1.19	1.09	3.09
West Virginia	17.77	9.66	16.79	3.07	25.60	4.44	3.01	1.19	0.98	3.09
East South Central										
Alabama	16.71	10.34	17.04	3.90	10.87	3.72	3.03	1.19	1.10	3.09
Kentucky	15.78	10.54	16.83	3.97	11.13	3.24	3.09	1.32	1.06	3.22
Mississippi	16.67	10.63	17.53	4.75	11.18	0.00	3.03	1.19	1.09	3.09
Tennessee	15.79	10.63	16.98	4.50	13.54	3.00	3.03	1.19	1.07	3.09
West South Central										
Arkansas	15.67	0.00	17.45	6.34	11.14	2.94	3.03	1.19	1.09	3.09
Louisiana	14.87	10.04	17.16	3.28	10.46	5.12	2.92	0.99	1.03	2.90
Oklahoma	14.84	10.39	16.59	2.45	13.22	3.31	2.99	1.19	0.89	3.09
Texas	14.98	11.01	17.41	3.16	11.05	4.08	2.89	0.99	0.87	2.90
Pacific										
Alaska	47.51	11.13	19.58	5.66	16.52	5.20	2.99	1.19	0.87	3.09
California	36.66	10.84	18.02	6.53	22.45	3.35	3.02	1.19	1.04	3.09
Hawaii	72.51	11.09	17.47	22.28	17.18	0.00	3.05	1.19	1.19	3.09
Oregon	16.29	10.66	16.80	4.45	16.52	3.18	3.03	1.19	1.07	3.09
Washington	13.10	10.77	18.94	6.26	17.59	5.58	3.09	1.32	1.06	3.22
Mountain										
Arizona	18.19	0.00	17.74	5.45	17.44	2.73	3.05	1.19	1.20	3.09
Colorado	20.75	0.00	17.03	4.67	15.22	2.55	3.05	1.19	1.20	3.09
Idaho	17.98	9.39	18.84	3.62	15.68	2.22	3.03	1.19	1.09	3.09
Montana	14.43	0.00	16.55	5.83	14.80	2.15	2.99	1.19	0.88	3.09
Nevada	16.96	0.00	17.95	4.89	17.65	3.07	3.04	1.19	1.17	3.09
New Mexico	16.24	0.00	17.23	3.40	10.99	2.59	3.01	1.19	0.97	3.09
Utah	16.39	9.39	17.53	4.82	15.67	2.21	3.01	1.19	1.01	3.09
Wyoming	18.63	0.00	17.21	3.49	15.38	2.23	3.04	1.19	1.17	3.09
United States	19.30	10.59	17.06	4.60	11.40	3.35	3.02	1.19	1.05	0.27

Table C - 2. Projected industrial energy price indices for different U.S. geographic regions (Data source: U.S. DOE/EIA, 2019).

Region	Net electricity			Natural gas		
	2030	2040	2050	2030	2040	2050
United States	0.95	0.95	0.96	1.18	1.29	1.48
New England	0.98	0.97	0.97	0.97	1.05	1.19
Mid-Atlantic	0.99	1.01	1.04	1.07	1.15	1.28
East North Central	0.95	0.92	0.92	1.15	1.24	1.39
West North Central	0.89	0.89	0.86	1.20	1.31	1.50
South Atlantic	0.95	0.94	0.93	1.14	1.22	1.37
East South Central	0.87	0.87	0.88	1.18	1.28	1.44
West South Central	1.02	1.04	1.07	1.24	1.38	1.58
Pacific	1.04	1.06	1.04	1.17	1.29	1.48
Mountain	0.82	0.84	0.86	1.21	1.32	1.53
Region	Hydrocarbon gas liquids			Distillate fuel oil		
	2030	2040	2050	2030	2040	2050
United States	1.27	1.37	1.38	1.04	1.12	1.12
New England	1.27	1.37	1.38	1.12	1.21	1.21
Mid-Atlantic	1.27	1.37	1.38	1.06	1.15	1.14
East North Central	1.27	1.37	1.38	0.91	0.99	0.99
West North Central	1.27	1.37	1.38	0.90	0.98	0.98
South Atlantic	1.27	1.37	1.38	1.12	1.21	1.21
East South Central	1.27	1.37	1.38	1.08	1.17	1.16
West South Central	1.27	1.37	1.38	1.09	1.17	1.17
Pacific	1.27	1.37	1.38	1.07	1.15	1.15
Mountain	1.27	1.37	1.38	1.12	1.21	1.20
Region	Residual fuel oil			Coal		
	2030	2040	2050	2030	2040	2050
United States	1.73	1.91	1.96	1.07	1.08	1.10
New England	1.48	1.65	1.70	1.10	1.16	1.23
Mid-Atlantic	1.44	1.60	1.65	1.07	1.09	1.10
East North Central	2.03	2.30	2.38	1.05	1.06	1.07
West North Central	1.80	2.03	2.09	1.03	1.05	1.06
South Atlantic	1.67	1.84	1.89	1.10	1.15	1.20
East South Central	1.86	2.03	2.09	1.08	1.09	1.14
West South Central	1.86	2.04	2.09	1.09	1.11	1.11
Pacific	1.01	1.13	1.16	1.01	1.00	1.01
Mountain	1.98	2.21	2.28	1.01	1.01	1.02

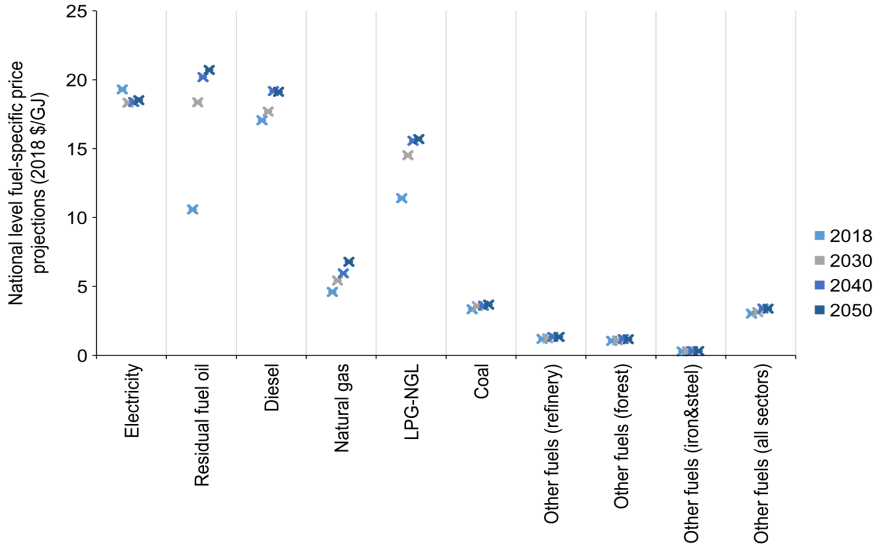

Figure C - 1. Projected prices of different energy carriers in the U.S. industry.

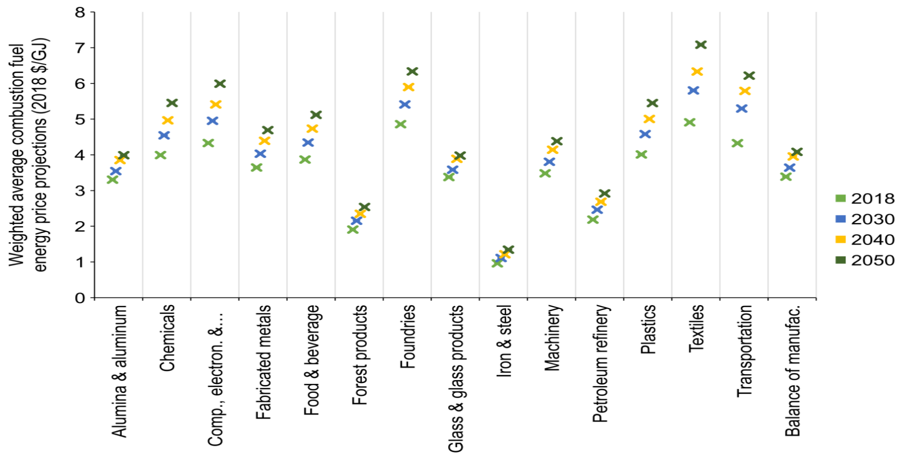

Figure C - 2. Weighted average energy prices' projections in the U.S. industrial sectors.

Appendix D. Additional Results - National-level Cost Curves for Years 2030 and 2040

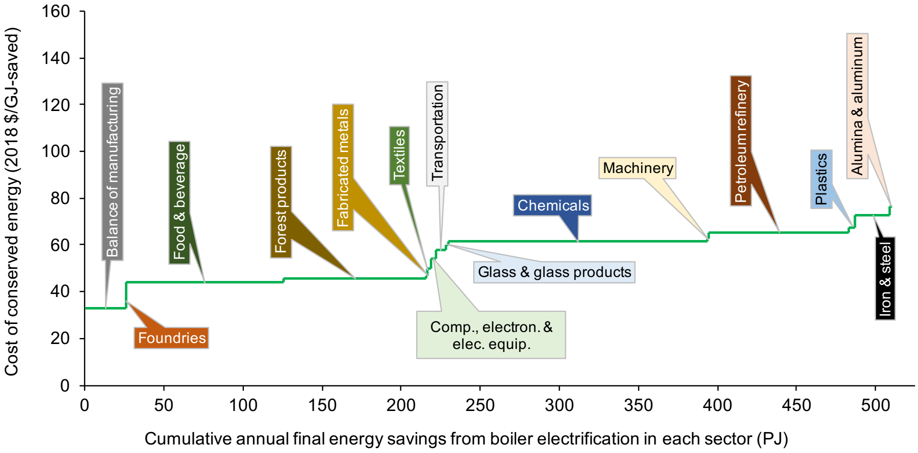

Figure D - 1. Industrial boiler electrification cost curve for 2030.

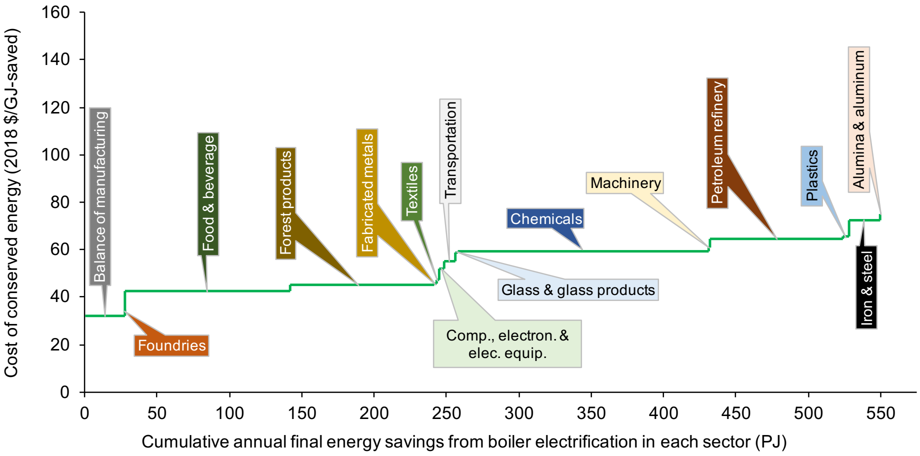

Figure D - 2. Industrial boiler electrification cost curve for 2040.

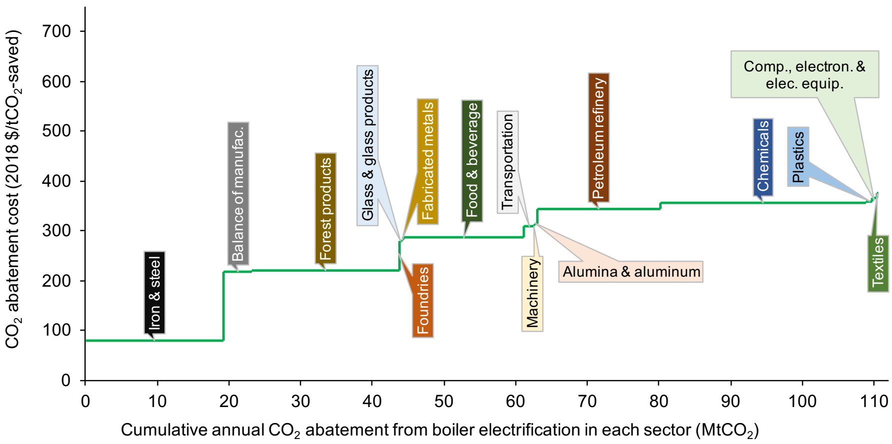

Figure D - 3. Industrial boiler electrification CO_2 abatement cost curve for 2040.

Appendix E. Additional Results - State-level Results for Years 2018 to 2050 – Potential Energy Savings

Table E - 1. Sectoral potential for energy savings after industrial boiler electrification in each state in 2018.

State	Potential energy savings in the base year 2018 (PJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	0.05	1.71	0.03	0.01	1.14	5.66	0.01	0.06	1.08	0.00	1.00	0.15	0.06	0.16	2.73
Alaska	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.01
Arizona	0.00	0.20	0.13	0.01	0.90	0.30	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.05	0.05
Arkansas	0.03	0.98	0.02	0.02	1.41	3.22	0.00	0.06	0.29	0.01	0.29	0.07	0.00	0.04	0.11
California	0.00	0.94	0.41	0.05	8.57	4.11	0.00	0.02	0.12	0.02	13.37	0.31	0.05	0.29	1.15
Colorado	0.00	0.53	0.06	0.01	0.77	0.02	0.00	0.00	0.15	0.00	0.52	0.05	0.00	0.01	0.44
Connecticut	0.00	0.23	0.03	0.01	0.19	1.06	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.30	0.14
Delaware	0.00	0.34	0.00	0.00	0.22	0.01	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.01
District of Columbia	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Florida	0.03	1.56	0.04	0.02	1.36	3.13	0.00	0.02	0.05	0.01	0.02	0.04	0.01	0.08	0.51
Georgia	0.07	2.04	0.04	0.01	1.73	4.32	0.00	0.00	0.04	0.01	0.00	0.11	0.99	0.10	0.30
Hawaii	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.00	0.00
Idaho	0.00	0.20	0.06	0.01	1.59	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Illinois	0.02	6.35	0.07	0.06	7.21	1.89	0.01	0.01	1.29	0.09	6.98	0.19	0.01	0.22	1.13
Indiana	0.05	4.97	0.05	0.04	3.27	0.61	0.02	0.00	7.44	0.04	1.25	0.14	0.00	0.46	0.61
Iowa	0.03	7.43	0.02	0.02	6.88	0.34	0.00	0.00	0.05	0.05	0.03	0.08	0.00	0.04	0.21
Kansas	0.00	1.92	0.02	0.01	1.60	0.16	0.00	0.02	0.00	0.02	1.44	0.05	0.00	0.23	0.10
Kentucky	0.07	3.22	0.03	0.01	0.92	1.82	0.01	0.05	0.39	0.01	1.20	0.14	0.06	0.20	0.49
Louisiana	0.13	13.17	0.00	0.01	0.72	4.21	0.00	0.06	0.29	0.00	17.47	0.02	0.00	0.03	0.34
Maine	0.00	0.05	0.02	0.00	0.25	1.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.02
Maryland	0.00	0.56	0.01	0.00	0.45	0.51	0.00	0.01	0.00	0.00	0.00	0.04	0.01	0.01	0.05
Massachusetts	0.00	0.68	0.10	0.02	0.53	0.80	0.00	0.01	0.00	0.01	0.00	0.04	0.02	0.11	0.19
Michigan	0.01	2.69	0.04	0.05	1.63	4.30	0.03	0.01	1.48	0.06	0.65	0.15	0.00	0.75	0.69
Minnesota	0.00	3.04	0.09	0.03	3.24	1.88	0.01	0.00	0.07	0.03	2.32	0.03	0.00	0.04	0.26
Mississippi	0.00	1.23	0.02	0.02	0.85	1.28	0.00	0.00	0.17	0.01	3.14	0.03	0.01	0.06	0.06
Missouri	0.01	2.28	0.03	0.05	1.72	0.69	0.00	0.12	0.04	0.03	0.00	0.05	0.00	0.21	0.52
Montana	0.00	0.00	0.00	0.00	0.25	0.07	0.00	0.00	0.00	0.00	1.30	0.00	0.00	0.00	0.00
Nebraska	0.00	3.23	0.01	0.01	2.83	0.10	0.00	0.00	0.06	0.10	0.00	0.02	0.00	0.02	0.03
Nevada	0.00	0.08	0.00	0.00	0.10	0.22	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.08
New Hampshire	0.00	0.08	0.02	0.01	0.09	0.26	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.03
New Jersey	0.00	1.60	0.03	0.01	0.87	0.58	0.00	0.12	0.04	0.01	2.19	0.05	0.00	0.01	0.29
New Mexico	0.00	0.20	0.04	0.00	0.31	0.25	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.02

New York	0.03	1.66	0.18	0.03	1.60	3.89	0.00	0.14	0.10	0.07	0.12	0.10	0.00	0.09	0.80
North Carolina	0.01	3.85	0.06	0.01	2.98	2.55	0.00	0.16	0.14	0.02	0.00	0.21	0.42	0.08	0.14
North Dakota	0.00	0.56	0.00	0.00	0.77	0.03	0.00	0.00	0.00	0.01	0.45	0.00	0.00	0.01	0.14
Ohio	0.01	4.41	0.08	0.10	3.86	1.41	0.02	0.25	5.30	0.06	2.15	0.24	0.01	0.56	2.32
Oklahoma	0.00	2.08	0.01	0.01	0.77	2.02	0.00	0.00	0.05	0.02	2.43	0.08	0.00	0.04	0.09
Oregon	0.00	0.20	0.15	0.01	1.12	2.42	0.01	0.01	0.12	0.00	0.00	0.08	0.00	0.02	0.14
Pennsylvania	0.02	2.53	0.07	0.04	2.53	3.68	0.01	0.18	2.42	0.03	2.69	0.07	0.00	0.18	7.01
Rhode Island	0.00	0.10	0.00	0.01	0.05	0.02	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.05
South Carolina	0.04	3.05	0.09	0.01	0.58	2.54	0.00	0.14	0.25	0.02	0.00	0.19	0.44	0.10	0.16
South Dakota	0.00	1.98	0.01	0.00	0.35	0.05	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.07
Tennessee	0.06	9.77	0.05	0.03	3.85	3.00	0.01	0.06	0.13	0.02	0.09	0.12	0.03	0.17	0.16
Texas	0.21	23.51	0.47	0.08	2.65	2.08	0.00	0.12	0.38	0.06	26.29	0.24	0.04	0.20	1.92
Utah	0.00	0.36	0.08	0.00	0.92	0.29	0.00	0.00	0.06	0.00	1.38	0.01	0.00	0.06	0.10
Vermont	0.00	0.03	0.04	0.00	0.20	0.66	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Virginia	0.04	3.32	0.05	0.02	1.07	2.65	0.00	0.00	0.10	0.01	0.00	0.20	0.45	0.17	0.47
Washington	0.02	0.19	0.05	0.00	1.64	3.79	0.00	0.01	0.03	0.00	2.18	0.06	0.00	0.21	0.10
West Virginia	0.00	1.91	0.01	0.02	0.11	0.12	0.00	0.06	0.04	0.00	0.14	0.01	0.00	0.01	0.25
Wisconsin	0.01	1.79	0.06	0.05	2.85	6.40	0.01	0.00	0.11	0.07	0.18	0.11	0.01	0.08	0.50
Wyoming	0.00	0.23	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00
United States	0.96	123.06	2.87	0.91	79.82	81.48	0.19	1.76	22.29	0.93	93.79	3.58	2.65	5.50	25.04

Table E - 2. Sectoral potential for energy savings after industrial boiler electrification in each state in 2030.

State	Potential energy savings in 2030 (PJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	0.06	2.28	0.03	0.01	1.41	6.27	0.01	0.07	1.07	0.00	0.95	0.17	0.05	0.18	2.87
Alaska	0.00	0.01	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.01
Arizona	0.00	0.27	0.16	0.01	1.12	0.33	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.06	0.05
Arkansas	0.03	1.31	0.02	0.02	1.75	3.57	0.00	0.06	0.29	0.02	0.28	0.09	0.00	0.04	0.11
California	0.01	1.25	0.51	0.05	10.62	4.55	0.00	0.02	0.12	0.02	12.60	0.35	0.04	0.32	1.21
Colorado	0.00	0.70	0.07	0.01	0.95	0.03	0.00	0.00	0.15	0.00	0.49	0.06	0.00	0.01	0.46
Connecticut	0.00	0.30	0.04	0.01	0.23	1.18	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.32	0.14
Delaware	0.00	0.45	0.00	0.00	0.27	0.01	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.01
District of Columbia	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Florida	0.04	2.07	0.05	0.02	1.69	3.47	0.00	0.02	0.05	0.01	0.02	0.05	0.01	0.09	0.54
Georgia	0.08	2.72	0.05	0.01	2.15	4.79	0.00	0.00	0.04	0.02	0.00	0.12	0.76	0.11	0.32
Hawaii	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.00	0.00	0.00
Idaho	0.00	0.26	0.07	0.01	1.97	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Illinois	0.02	8.44	0.09	0.06	8.93	2.10	0.01	0.01	1.25	0.10	6.57	0.22	0.00	0.24	1.18
Indiana	0.05	6.61	0.06	0.05	4.05	0.67	0.02	0.00	7.20	0.04	1.18	0.16	0.00	0.50	0.64
Iowa	0.03	9.88	0.03	0.02	8.52	0.37	0.00	0.00	0.05	0.06	0.02	0.10	0.00	0.04	0.23
Kansas	0.00	2.55	0.02	0.01	1.98	0.18	0.00	0.02	0.00	0.02	1.36	0.06	0.00	0.25	0.10
Kentucky	0.08	4.28	0.03	0.01	1.15	2.02	0.01	0.05	0.38	0.01	1.13	0.16	0.04	0.22	0.51
Louisiana	0.15	17.51	0.00	0.02	0.89	4.67	0.00	0.06	0.28	0.00	16.46	0.02	0.00	0.03	0.36
Maine	0.00	0.07	0.02	0.00	0.31	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.02
Maryland	0.00	0.74	0.02	0.00	0.55	0.57	0.00	0.01	0.00	0.01	0.00	0.04	0.01	0.01	0.05
Massachusetts	0.00	0.90	0.12	0.02	0.66	0.89	0.00	0.01	0.00	0.01	0.00	0.04	0.02	0.12	0.20
Michigan	0.01	3.57	0.05	0.06	2.02	4.76	0.03	0.01	1.43	0.06	0.61	0.18	0.00	0.81	0.72
Minnesota	0.00	4.04	0.12	0.04	4.02	2.09	0.01	0.00	0.07	0.03	2.19	0.04	0.00	0.05	0.28
Mississippi	0.00	1.64	0.02	0.02	1.05	1.42	0.00	0.00	0.17	0.01	2.96	0.03	0.01	0.06	0.06
Missouri	0.01	3.03	0.03	0.06	2.13	0.77	0.00	0.12	0.04	0.03	0.00	0.05	0.00	0.23	0.54
Montana	0.00	0.00	0.00	0.00	0.31	0.07	0.00	0.00	0.00	0.00	1.23	0.00	0.00	0.00	0.00
Nebraska	0.00	4.30	0.01	0.01	3.51	0.11	0.00	0.00	0.06	0.11	0.00	0.02	0.00	0.02	0.03
Nevada	0.00	0.11	0.01	0.00	0.13	0.25	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.09
New Hampshire	0.00	0.10	0.02	0.02	0.11	0.28	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.04
New Jersey	0.00	2.12	0.04	0.01	1.07	0.64	0.00	0.13	0.04	0.01	2.06	0.05	0.00	0.01	0.30
New Mexico	0.00	0.26	0.04	0.00	0.38	0.28	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00	0.02
New York	0.03	2.21	0.22	0.03	1.99	4.31	0.00	0.14	0.10	0.08	0.11	0.11	0.00	0.10	0.84
North Carolina	0.01	5.12	0.07	0.01	3.69	2.82	0.00	0.17	0.14	0.03	0.00	0.24	0.32	0.09	0.15
North Dakota	0.00	0.74	0.00	0.00	0.96	0.04	0.00	0.00	0.00	0.01	0.42	0.00	0.00	0.01	0.15
Ohio	0.02	5.87	0.10	0.11	4.78	1.56	0.02	0.27	5.13	0.07	2.03	0.27	0.01	0.61	2.44
Oklahoma	0.00	2.76	0.01	0.01	0.96	2.23	0.00	0.00	0.05	0.02	2.29	0.09	0.00	0.04	0.09

Oregon	0.00	0.27	0.18	0.01	1.39	2.68	0.01	0.01	0.12	0.00	0.00	0.09	0.00	0.02	0.15
Pennsylvania	0.02	3.37	0.09	0.04	3.13	4.08	0.01	0.19	2.34	0.04	2.54	0.09	0.00	0.19	7.37
Rhode Island	0.00	0.13	0.00	0.01	0.07	0.02	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.06
South Carolina	0.04	4.06	0.11	0.01	0.71	2.81	0.00	0.15	0.25	0.02	0.00	0.22	0.34	0.11	0.17
South Dakota	0.00	2.64	0.01	0.00	0.44	0.06	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.08
Tennessee	0.07	12.99	0.06	0.03	4.77	3.32	0.01	0.06	0.13	0.02	0.08	0.13	0.02	0.18	0.16
Texas	0.24	31.26	0.58	0.08	3.28	2.31	0.00	0.12	0.38	0.07	24.78	0.27	0.03	0.22	2.02
Utah	0.00	0.48	0.09	0.00	1.14	0.33	0.00	0.00	0.06	0.00	1.30	0.02	0.00	0.07	0.11
Vermont	0.00	0.05	0.05	0.00	0.24	0.73	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Virginia	0.04	4.42	0.06	0.02	1.33	2.94	0.00	0.00	0.10	0.01	0.00	0.23	0.35	0.18	0.49
Washington	0.02	0.25	0.07	0.00	2.03	4.20	0.00	0.01	0.03	0.00	2.06	0.07	0.00	0.22	0.10
West Virginia	0.01	2.54	0.01	0.02	0.14	0.14	0.00	0.06	0.04	0.00	0.13	0.01	0.00	0.02	0.27
Wisconsin	0.01	2.39	0.07	0.06	3.53	7.09	0.01	0.00	0.10	0.08	0.17	0.12	0.00	0.09	0.53
Wyoming	0.00	0.31	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.00
United States	1.09	163.62	3.51	1.00	98.89	90.31	0.19	1.85	21.68	1.06	88.39	4.07	2.04	5.99	26.33

Table E - 3. Sectoral potential for energy savings after industrial boiler electrification in each state in 2040.

State	Potential energy savings in 2040 (PJ)														
	Alumina & aluminum	*Chemicals*	*Comp., electron. & elec.*	*Fabricated metals*	*Food & beverage*	*Forest products*	*Foundries*	*Glass & glass prod.*	*Iron & steel*	*Machinery*	*Petroleum refinery*	*Plastics*	*Textiles*	*Transport.*	*Balance of manufac.*
Alabama	0.06	2.41	0.04	0.01	1.63	6.93	0.01	0.06	1.04	0.01	0.98	0.19	0.04	0.21	3.01
Alaska	0.00	0.01	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.00	0.00	0.01
Arizona	0.00	0.28	0.19	0.01	1.29	0.37	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.06	0.05
Arkansas	0.03	1.39	0.02	0.03	2.02	3.95	0.00	0.06	0.28	0.02	0.29	0.09	0.00	0.05	0.12
California	0.01	1.32	0.59	0.06	12.26	5.03	0.00	0.02	0.12	0.02	13.07	0.38	0.03	0.37	1.27
Colorado	0.00	0.74	0.08	0.01	1.10	0.03	0.00	0.00	0.15	0.00	0.51	0.06	0.00	0.01	0.49
Connecticut	0.00	0.32	0.04	0.01	0.27	1.31	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.38	0.15
Delaware	0.00	0.48	0.01	0.00	0.31	0.01	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.01
District of Columbia	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Florida	0.04	2.19	0.06	0.03	1.95	3.84	0.00	0.02	0.05	0.01	0.02	0.05	0.01	0.10	0.56
Georgia	0.08	2.88	0.05	0.01	2.48	5.30	0.00	0.00	0.04	0.02	0.00	0.13	0.64	0.13	0.34
Hawaii	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.00
Idaho	0.00	0.28	0.08	0.01	2.28	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Illinois	0.02	8.95	0.10	0.07	10.31	2.32	0.01	0.01	1.21	0.11	6.82	0.24	0.00	0.28	1.24
Indiana	0.05	7.01	0.07	0.05	4.68	0.74	0.02	0.00	6.99	0.05	1.22	0.18	0.00	0.58	0.67
Iowa	0.03	10.48	0.03	0.03	9.84	0.41	0.00	0.00	0.05	0.06	0.03	0.11	0.00	0.05	0.24
Kansas	0.00	2.70	0.03	0.01	2.29	0.20	0.00	0.02	0.00	0.03	1.41	0.06	0.00	0.29	0.11
Kentucky	0.08	4.54	0.04	0.01	1.32	2.23	0.01	0.05	0.37	0.01	1.18	0.18	0.04	0.25	0.54
Louisiana	0.16	18.56	0.00	0.02	1.03	5.16	0.00	0.06	0.28	0.00	17.07	0.02	0.00	0.04	0.38
Maine	0.00	0.07	0.02	0.00	0.36	1.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.02
Maryland	0.00	0.78	0.02	0.00	0.64	0.63	0.00	0.01	0.00	0.01	0.00	0.05	0.01	0.02	0.06
Massachusetts	0.00	0.96	0.14	0.02	0.76	0.98	0.00	0.01	0.00	0.01	0.00	0.05	0.01	0.14	0.21
Michigan	0.01	3.79	0.06	0.06	2.33	5.27	0.03	0.01	1.39	0.07	0.64	0.19	0.00	0.94	0.76
Minnesota	0.00	4.29	0.13	0.04	4.64	2.31	0.01	0.00	0.06	0.03	2.27	0.04	0.00	0.05	0.29
Mississippi	0.00	1.73	0.02	0.02	1.21	1.57	0.00	0.00	0.16	0.01	3.07	0.03	0.01	0.08	0.06
Missouri	0.01	3.21	0.04	0.06	2.46	0.85	0.00	0.12	0.04	0.03	0.00	0.06	0.00	0.27	0.57
Montana	0.00	0.00	0.00	0.00	0.36	0.08	0.00	0.00	0.00	0.00	1.27	0.00	0.00	0.00	0.00
Nebraska	0.00	4.56	0.01	0.01	4.06	0.13	0.00	0.00	0.06	0.13	0.00	0.02	0.00	0.02	0.03
Nevada	0.00	0.12	0.01	0.00	0.15	0.27	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.09
New Hampshire	0.00	0.11	0.02	0.02	0.13	0.31	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.04
New Jersey	0.00	2.25	0.05	0.01	1.24	0.71	0.00	0.12	0.03	0.01	2.14	0.06	0.00	0.01	0.32
New Mexico	0.00	0.28	0.05	0.00	0.44	0.30	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.02
New York	0.03	2.34	0.25	0.03	2.29	4.77	0.00	0.14	0.10	0.09	0.12	0.12	0.00	0.12	0.88
North Carolina	0.01	5.43	0.09	0.01	4.26	3.12	0.00	0.16	0.13	0.03	0.00	0.27	0.27	0.10	0.16
North Dakota	0.00	0.78	0.00	0.00	1.11	0.04	0.00	0.00	0.00	0.01	0.44	0.00	0.00	0.01	0.16
Ohio	0.02	6.22	0.12	0.11	5.52	1.73	0.03	0.26	4.98	0.08	2.10	0.30	0.00	0.71	2.56
Oklahoma	0.00	2.92	0.01	0.01	1.10	2.47	0.00	0.00	0.05	0.03	2.37	0.10	0.00	0.05	0.10

Oregon	0.00	0.28	0.21	0.01	1.61	2.96	0.01	0.01	0.12	0.00	0.00	0.10	0.00	0.02	0.15
Pennsylvania	0.02	3.57	0.10	0.04	3.62	4.51	0.01	0.18	2.27	0.05	2.63	0.09	0.00	0.22	7.73
Rhode Island	0.00	0.14	0.01	0.01	0.08	0.02	0.00	0.01	0.00	0.00	0.00	0.05	0.00	0.00	0.06
South Carolina	0.04	4.30	0.12	0.02	0.83	3.11	0.00	0.14	0.24	0.02	0.00	0.24	0.29	0.13	0.17
South Dakota	0.00	2.80	0.01	0.00	0.50	0.06	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.08
Tennessee	0.07	13.77	0.06	0.04	5.51	3.67	0.01	0.06	0.13	0.02	0.08	0.15	0.02	0.21	0.17
Texas	0.25	33.14	0.67	0.09	3.79	2.56	0.01	0.12	0.37	0.08	25.69	0.30	0.03	0.25	2.12
Utah	0.00	0.51	0.11	0.00	1.32	0.36	0.00	0.00	0.05	0.00	1.35	0.02	0.00	0.08	0.12
Vermont	0.00	0.05	0.06	0.00	0.28	0.81	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Virginia	0.04	4.68	0.06	0.02	1.53	3.25	0.00	0.00	0.09	0.01	0.00	0.25	0.29	0.21	0.52
Washington	0.02	0.27	0.08	0.00	2.35	4.65	0.00	0.01	0.03	0.00	2.13	0.08	0.00	0.26	0.11
West Virginia	0.01	2.69	0.01	0.02	0.16	0.15	0.00	0.06	0.04	0.00	0.14	0.01	0.00	0.02	0.28
Wisconsin	0.01	2.53	0.08	0.06	4.08	7.84	0.01	0.00	0.10	0.10	0.17	0.13	0.00	0.10	0.55
Wyoming	0.00	0.33	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00
United States	1.13	173.44	4.06	1.08	114.20	99.90	0.19	1.79	21.06	1.21	91.66	4.48	1.72	6.94	27.59

Table E - 4. Sectoral potential for energy savings after industrial boiler electrification in each state in 2050.

State	Potential energy savings in 2050 (PJ)														
	Alumina & aluminum	*Chemicals*	*Comp., electron. & elec.*	*Fabricated metals*	*Food & beverage*	*Forest products*	*Foundries*	*Glass & glass prod.*	*Iron & steel*	*Machinery*	*Petroleum refinery*	*Plastics*	*Textiles*	*Transport.*	*Balance of manufac.*
Alabama	0.06	2.52	0.04	0.01	1.88	7.67	0.01	0.06	0.99	0.01	1.03	0.21	0.04	0.24	3.20
Alaska	0.00	0.01	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.01
Arizona	0.00	0.29	0.21	0.01	1.50	0.40	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.08	0.05
Arkansas	0.03	1.45	0.02	0.03	2.33	4.37	0.00	0.06	0.27	0.02	0.30	0.10	0.00	0.06	0.13
California	0.01	1.38	0.67	0.06	14.18	5.57	0.00	0.02	0.11	0.02	13.73	0.43	0.03	0.43	1.35
Colorado	0.00	0.78	0.09	0.01	1.27	0.03	0.00	0.00	0.14	0.00	0.54	0.07	0.00	0.01	0.52
Connecticut	0.00	0.34	0.05	0.02	0.31	1.44	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.44	0.16
Delaware	0.00	0.50	0.01	0.00	0.36	0.01	0.00	0.00	0.00	0.00	0.56	0.01	0.00	0.01	0.01
District of Columbia	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Florida	0.04	2.29	0.07	0.03	2.26	4.25	0.00	0.02	0.04	0.02	0.02	0.06	0.01	0.12	0.60
Georgia	0.08	3.01	0.06	0.01	2.87	5.86	0.00	0.00	0.04	0.02	0.00	0.15	0.55	0.15	0.36
Hawaii	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00
Idaho	0.00	0.29	0.09	0.01	2.63	0.94	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
Illinois	0.02	9.35	0.12	0.07	11.93	2.57	0.01	0.01	1.16	0.13	7.16	0.27	0.00	0.33	1.32
Indiana	0.05	7.33	0.08	0.05	5.42	0.82	0.02	0.00	6.70	0.06	1.28	0.20	0.00	0.68	0.72
Iowa	0.03	10.95	0.04	0.03	11.39	0.46	0.00	0.00	0.05	0.07	0.03	0.12	0.00	0.06	0.25
Kansas	0.00	2.83	0.03	0.01	2.65	0.22	0.00	0.02	0.00	0.03	1.48	0.07	0.00	0.34	0.12
Kentucky	0.08	4.74	0.05	0.01	1.53	2.47	0.01	0.05	0.36	0.01	1.24	0.20	0.03	0.30	0.57
Louisiana	0.16	19.40	0.01	0.02	1.20	5.71	0.00	0.06	0.26	0.01	17.94	0.02	0.00	0.05	0.40
Maine	0.00	0.08	0.03	0.00	0.41	1.92	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.05	0.02
Maryland	0.00	0.82	0.02	0.00	0.74	0.69	0.00	0.01	0.00	0.01	0.00	0.05	0.01	0.02	0.06
Massachusetts	0.00	1.00	0.16	0.02	0.88	1.09	0.00	0.01	0.00	0.01	0.00	0.05	0.01	0.17	0.22
Michigan	0.01	3.96	0.06	0.06	2.69	5.83	0.03	0.01	1.33	0.08	0.67	0.22	0.00	1.10	0.81
Minnesota	0.00	4.48	0.15	0.04	5.37	2.55	0.01	0.00	0.06	0.04	2.38	0.05	0.00	0.06	0.31
Mississippi	0.00	1.81	0.03	0.02	1.40	1.73	0.00	0.00	0.16	0.01	3.22	0.04	0.01	0.09	0.07
Missouri	0.01	3.36	0.04	0.07	2.85	0.94	0.00	0.12	0.03	0.04	0.00	0.07	0.00	0.32	0.61
Montana	0.00	0.00	0.00	0.00	0.41	0.09	0.00	0.00	0.00	0.00	1.34	0.00	0.00	0.00	0.00
Nebraska	0.00	4.76	0.01	0.01	4.69	0.14	0.00	0.00	0.06	0.15	0.00	0.03	0.00	0.03	0.03
Nevada	0.00	0.12	0.01	0.00	0.17	0.30	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.10
New Hampshire	0.00	0.11	0.03	0.02	0.15	0.35	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.04
New Jersey	0.00	2.35	0.05	0.01	1.43	0.78	0.00	0.12	0.03	0.01	2.25	0.07	0.00	0.02	0.34
New Mexico	0.00	0.29	0.06	0.00	0.51	0.34	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.02
New York	0.03	2.45	0.29	0.04	2.65	5.28	0.00	0.13	0.09	0.10	0.12	0.14	0.00	0.13	0.94
North Carolina	0.01	5.68	0.10	0.02	4.93	3.46	0.00	0.15	0.13	0.03	0.00	0.30	0.23	0.12	0.17
North Dakota	0.00	0.82	0.00	0.00	1.28	0.04	0.00	0.00	0.00	0.01	0.46	0.00	0.00	0.02	0.17
Ohio	0.02	6.50	0.14	0.12	6.38	1.91	0.02	0.25	4.77	0.10	2.21	0.33	0.00	0.83	2.73
Oklahoma	0.00	3.06	0.01	0.01	1.28	2.74	0.00	0.00	0.05	0.03	2.49	0.11	0.00	0.06	0.10

Oregon	0.00	0.29	0.24	0.01	1.86	3.28	0.01	0.01	0.11	0.00	0.00	0.11	0.00	0.03	0.16
Pennsylvania	0.02	3.73	0.12	0.05	4.19	5.00	0.01	0.17	2.17	0.05	2.76	0.10	0.00	0.26	8.23
Rhode Island	0.00	0.15	0.01	0.01	0.09	0.02	0.00	0.01	0.00	0.00	0.00	0.05	0.00	0.00	0.06
South Carolina	0.04	4.50	0.14	0.02	0.95	3.44	0.00	0.14	0.23	0.03	0.00	0.27	0.25	0.15	0.18
South Dakota	0.00	2.92	0.01	0.00	0.58	0.07	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.08
Tennessee	0.07	14.39	0.07	0.04	6.38	4.07	0.01	0.06	0.12	0.02	0.09	0.16	0.01	0.25	0.18
Texas	0.25	34.65	0.76	0.10	4.38	2.83	0.00	0.12	0.35	0.09	27.00	0.33	0.02	0.29	2.25
Utah	0.00	0.53	0.12	0.00	1.52	0.40	0.00	0.00	0.05	0.00	1.42	0.02	0.00	0.09	0.12
Vermont	0.00	0.05	0.07	0.00	0.32	0.89	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Virginia	0.04	4.89	0.07	0.02	1.77	3.60	0.00	0.00	0.09	0.02	0.00	0.28	0.25	0.25	0.55
Washington	0.03	0.28	0.09	0.00	2.72	5.15	0.00	0.01	0.03	0.00	2.24	0.09	0.00	0.30	0.12
West Virginia	0.01	2.82	0.01	0.02	0.18	0.17	0.00	0.06	0.04	0.00	0.15	0.01	0.00	0.02	0.30
Wisconsin	0.01	2.64	0.09	0.07	4.72	8.68	0.01	0.00	0.10	0.11	0.18	0.15	0.00	0.12	0.59
Wyoming	0.00	0.34	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00
United States	1.15	181.32	4.62	1.17	132.12	110.56	0.19	1.73	20.16	1.38	96.32	4.99	1.48	8.11	29.37

Appendix F. Additional Results - State-level Results for Years 2018 to 2050 – Costs of Conserved Energy

Table F - 1. Sectoral costs of conserved energy as a result of boiler electrification in each state in 2018.

State	Cost of electrification in the base year 2018 (2018 $/GJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	70	59	53	44	42	42	35	55	52	58	61	65	51	58	30
Alaska	n.a.	198	178	149	142	131	n.a.	183	175	192	188	217	175	197	103
Arizona	76	61	53	47	44	45	35	60	52	62	n.a.	68	51	64	33
Arkansas	62	46	39	36	33	37	26	49	38	50	53	52	36	50	26
California	173	144	129	109	104	98	90	137	125	142	141	158	125	144	77
Colorado	91	76	67	57	54	53	45	71	66	75	77	84	66	78	39
Connecticut	182	154	137	116	110	103	97	144	134	150	n.a.	168	135	152	81
Delaware	n.a.	68	57	55	50	56	n.a.	75	53	74	76	77	52	73	40
District of Columbia	n.a.	102	95	72	71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	99	n.a.	47
Florida	92	74	65	57	53	54	44	73	63	75	77	82	61	74	40
Georgia	70	58	52	43	41	42	34	55	50	58	61	64	49	57	30
Hawaii	n.a.	260	224	209	193	189	n.a.	279	n.a.	276	269	290	207	270	155
Idaho	n.a.	66	59	49	47	46	38	60	58	64	n.a.	72	58	65	33
Illinois	81	66	58	50	47	49	39	64	81	66	68	72	55	65	35
Indiana	88	72	63	55	51	53	43	70	88	72	74	79	60	71	38
Iowa	76	62	55	47	45	46	37	60	53	63	66	69	53	61	33
Kansas	94	80	72	60	57	57	48	74	70	78	79	88	70	78	41
Kentucky	65	55	49	41	38	40	31	51	47	54	57	60	47	53	28
Louisiana	62	53	48	39	37	38	30	48	47	51	55	58	45	51	26
Maine	n.a.	87	75	69	63	65	53	91	72	92	n.a.	97	68	88	50
Maryland	99	75	65	59	55	57	46	78	62	79	n.a.	84	60	76	43
Massachusetts	n.a.	156	138	121	113	110	99	155	133	159	n.a.	173	130	158	86
Michigan	86	69	61	53	49	50	41	68	84	70	73	76	57	68	37
Minnesota	92	78	69	58	55	54	46	72	68	76	78	85	67	76	40
Mississippi	69	56	50	43	40	42	32	54	48	57	60	62	48	55	30
Missouri	85	68	59	52	49	51	40	67	57	69	n.a.	75	56	68	37
Montana	56	42	36	33	30	35	23	n.a.	35	45	49	48	33	46	24
Nebraska	94	80	72	60	57	57	48	74	70	78	n.a.	88	71	82	41
Nevada	n.a.	57	50	43	41	42	33	55	n.a.	58	61	64	48	60	30
New Hampshire	174	139	122	108	101	99	88	139	118	142	n.a.	154	117	140	77
New Jersey	127	102	89	78	73	73	63	101	86	104	105	113	86	106	56
New Mexico	n.a.	59	53	43	41	42	34	53	n.a.	57	60	65	53	61	29

New York	66	48	41	39	35	40	27	53	38	53	56	54	35	49	28
North Carolina	73	57	50	44	41	43	33	57	48	59	n.a.	64	47	57	31
North Dakota	101	89	80	65	63	60	n.a.	79	80	84	86	97	81	90	44
Ohio	84	66	58	51	48	50	39	67	83	68	71	73	53	66	36
Oklahoma	62	55	50	40	39	39	32	48	50	52	55	60	50	53	26
Oregon	67	55	49	42	39	41	32	53	48	55	n.a.	61	47	54	29
Pennsylvania	79	57	48	46	42	46	33	63	81	63	66	64	42	59	34
Rhode Island	n.a.	163	143	126	118	115	103	161	138	165	n.a.	179	138	164	90
South Carolina	70	58	51	44	41	42	34	55	50	58	n.a.	64	49	57	30
South Dakota	95	81	72	60	57	56	49	n.a.	71	79	n.a.	89	71	83	41
Tennessee	65	53	47	40	38	39	30	51	45	53	56	58	44	52	27
Texas	62	54	48	40	38	39	31	49	48	52	56	59	47	52	27
Utah	n.a.	55	48	41	39	41	31	53	47	55	58	61	46	54	29
Vermont	n.a.	119	107	89	85	80	n.a.	109	105	115	n.a.	130	106	117	61
Virginia	82	68	61	51	48	49	40	64	59	67	n.a.	75	58	67	35
Washington	48	34	29	27	24	30	17	38	27	38	42	39	23	34	20
West Virginia	77	67	60	49	47	47	39	60	60	64	66	73	59	65	33
Wisconsin	89	74	66	56	53	52	44	70	64	73	75	81	63	73	38
Wyoming	n.a.	70	63	51	49	48	41	n.a.	62	67	70	77	62	72	35
United States	83	69	62	52	49	49	41	65	78	68	71	76	59	68	36

Table F - 2. Sectoral costs of conserved energy as a result of boiler electrification in each state in 2030.

State	Cost of electrification in 2030 (2018 $/GJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	56	46	40	34	32	35	25	44	39	46	50	50	37	41	24
Alaska	n.a.	203	182	153	145	136	n.a.	189	178	198	194	222	178	203	106
Arizona	55	41	35	32	29	34	21	44	33	44	n.a.	47	31	45	23
Arkansas	60	42	34	34	31	36	22	48	32	47	52	48	30	47	25
California	178	146	130	112	105	101	91	141	126	146	145	161	125	147	78
Colorado	68	54	47	41	38	41	30	53	46	55	59	60	45	57	29
Connecticut	176	149	133	112	107	100	93	139	130	145	n.a.	162	131	145	77
Delaware	n.a.	57	47	47	42	51	n.a.	67	43	65	68	65	41	63	36
District of Columbia	n.a.	96	88	67	66	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	93	n.a.	43
Florida	83	65	57	50	47	50	38	66	54	68	71	72	51	63	36
Georgia	62	51	45	38	36	38	28	49	43	51	55	56	41	48	26
Hawaii	n.a.	260	221	212	193	193	n.a.	287	n.a.	282	275	291	200	272	158
Idaho	n.a.	47	42	35	33	36	25	44	41	47	n.a.	52	39	43	24
Illinois	76	59	52	46	43	45	35	60	77	62	64	65	47	55	33
Indiana	83	64	56	50	46	49	39	66	83	67	69	71	50	60	36
Iowa	66	50	43	39	36	39	29	52	41	53	56	56	39	47	28
Kansas	82	67	59	51	48	50	40	65	56	67	68	73	55	62	35
Kentucky	51	41	36	31	29	33	22	40	35	42	46	46	33	37	21
Louisiana	61	51	45	38	36	37	28	47	44	50	54	56	42	46	26
Maine	n.a.	84	73	66	61	63	50	86	70	88	n.a.	93	66	82	47
Maryland	89	65	55	52	47	52	38	71	52	71	n.a.	73	49	64	38
Massachusetts	n.a.	152	134	117	110	107	95	150	129	153	n.a.	167	126	150	83
Michigan	81	62	54	49	45	47	37	64	80	65	68	69	48	58	35
Minnesota	80	64	56	49	46	47	38	63	54	65	67	71	52	60	35
Mississippi	55	42	36	33	30	34	23	43	34	44	49	47	33	38	23
Missouri	73	54	46	43	39	43	31	59	42	59	n.a.	60	40	51	31
Montana	39	25	20	21	18	26	11	n.a.	18	30	35	30	16	29	15
Nebraska	82	67	59	51	48	50	40	65	57	67	n.a.	74	57	70	35
Nevada	n.a.	39	33	30	27	32	19	40	n.a.	41	46	44	30	42	21
New Hampshire	168	135	119	104	98	97	84	133	114	137	n.a.	149	114	134	74
New Jersey	124	98	85	75	70	71	59	98	82	100	102	108	81	102	54
New Mexico	n.a.	42	37	31	29	32	22	39	n.a.	41	46	47	36	44	21
New York	63	45	37	36	32	39	25	51	35	50	54	51	31	44	27
North Carolina	65	49	42	38	35	39	27	51	40	52	n.a.	55	38	47	27
North Dakota	88	76	68	56	54	53	n.a.	69	67	73	74	83	68	78	38
Ohio	79	59	51	47	43	46	35	63	79	63	66	66	44	55	34
Oklahoma	61	54	49	39	37	39	31	47	48	51	55	58	47	48	26

Oregon	68	55	48	42	39	42	31	54	47	56	n.a.	61	45	54	29
Pennsylvania	76	53	45	43	39	45	30	61	80	60	64	60	37	54	32
Rhode Island	n.a.	158	139	122	114	112	99	155	134	159	n.a.	174	134	157	86
South Carolina	63	51	44	38	36	39	28	49	43	51	n.a.	56	41	48	26
South Dakota	83	67	59	51	48	48	40	n.a.	57	68	n.a.	74	56	70	36
Tennessee	51	40	34	30	28	32	21	40	32	41	46	44	30	35	21
Texas	62	52	46	39	36	38	29	48	45	51	55	57	43	46	26
Utah	n.a.	37	31	28	26	31	18	38	29	39	44	41	27	33	20
Vermont	n.a.	115	104	85	82	77	n.a.	104	102	110	n.a.	125	103	110	58
Virginia	74	60	53	45	43	45	34	58	51	60	n.a.	66	50	57	31
Washington	48	32	26	26	23	30	15	38	24	38	42	37	20	33	19
West Virginia	69	60	54	43	42	43	34	54	53	58	61	65	52	56	29
Wisconsin	84	67	59	51	48	49	40	66	56	68	70	74	54	63	36
Wyoming	n.a.	51	45	37	35	37	28	n.a.	45	50	54	56	44	53	25
United States	76	61	54	47	44	46	36	60	73	62	65	68	50	58	33

Table F - 3. Sectoral costs of conserved energy as a result of boiler electrification in each state in 2040.

State	Cost of electrification in 2040 (2018 $/GJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	54	44	38	33	31	34	23	42	37	44	49	48	35	39	23
Alaska	n.a.	205	184	155	147	138	n.a.	192	180	201	197	225	179	205	108
Arizona	55	40	33	31	29	34	20	43	32	44	n.a.	46	30	44	23
Arkansas	60	40	32	33	29	36	21	47	30	46	51	46	27	45	25
California	181	147	130	113	106	103	92	143	126	148	147	162	125	148	79
Colorado	68	54	46	41	38	42	29	53	45	55	60	60	44	57	28
Connecticut	172	145	130	109	104	99	90	136	126	142	n.a.	158	127	141	76
Delaware	n.a.	53	42	44	39	49	n.a.	65	38	62	66	61	36	59	34
District of Columbia	n.a.	94	87	65	65	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	92	n.a.	42
Florida	80	62	53	48	44	48	35	63	51	65	69	68	48	59	34
Georgia	60	48	42	36	34	37	26	46	41	49	54	53	38	45	25
Hawaii	n.a.	258	219	213	193	195	n.a.	291	n.a.	284	278	290	195	272	160
Idaho	n.a.	47	41	35	33	36	25	44	40	47	n.a.	51	39	42	24
Illinois	71	54	47	42	39	43	31	56	74	57	60	60	41	49	30
Indiana	78	59	51	46	43	46	34	62	80	63	65	65	45	54	33
Iowa	64	48	41	38	35	38	27	51	38	51	55	53	36	44	27
Kansas	80	64	57	49	46	49	38	63	54	65	67	71	53	59	34
Kentucky	50	40	35	30	28	32	21	38	33	40	45	43	31	34	20
Louisiana	60	50	44	37	35	38	28	47	43	50	55	55	40	45	25
Maine	n.a.	80	69	63	58	61	47	84	65	85	n.a.	89	61	78	45
Maryland	85	61	51	49	45	50	35	68	48	67	n.a.	69	44	60	36
Massachusetts	n.a.	147	129	114	106	104	92	146	124	149	n.a.	162	121	145	81
Michigan	76	57	49	45	41	44	33	60	77	61	64	63	42	52	32
Minnesota	78	62	54	47	44	46	36	62	52	63	66	68	50	57	33
Mississippi	53	40	34	31	29	33	21	41	32	43	47	44	31	35	22
Missouri	71	51	43	41	37	42	29	57	39	56	n.a.	57	36	48	30
Montana	38	24	18	20	17	26	10	n.a.	17	29	35	28	14	28	15
Nebraska	80	65	57	49	46	49	38	63	55	65	n.a.	72	55	68	34
Nevada	n.a.	38	31	29	27	32	18	40	n.a.	41	46	43	28	41	20
New Hampshire	164	130	114	101	95	95	81	130	110	133	n.a.	144	109	129	72
New Jersey	126	99	85	76	71	72	60	100	83	102	104	109	81	103	54
New Mexico	n.a.	42	36	31	29	33	21	39	n.a.	41	46	46	36	44	21
New York	64	44	37	36	32	39	24	51	34	50	54	50	30	43	26
North Carolina	62	46	39	36	33	38	25	49	37	50	n.a.	52	34	44	26
North Dakota	86	74	66	55	52	52	n.a.	68	65	72	73	81	66	76	37
Ohio	74	54	46	43	39	43	31	59	76	59	62	60	38	49	31
Oklahoma	61	54	48	39	37	39	30	47	47	51	55	58	46	47	26

Oregon	69	55	48	41	39	42	31	54	46	56	n.a.	61	44	54	29
Pennsylvania	77	53	44	43	39	45	30	61	82	60	65	60	36	53	32
Rhode Island	n.a.	153	134	118	111	110	95	152	129	155	n.a.	168	128	151	84
South Carolina	60	48	42	36	34	38	26	47	40	49	n.a.	53	38	44	25
South Dakota	81	64	56	49	46	48	38	n.a.	54	66	n.a.	72	53	68	35
Tennessee	49	37	32	29	26	31	19	38	30	40	45	41	28	33	20
Texas	61	51	45	38	36	39	28	48	44	51	55	56	42	45	26
Utah	n.a.	36	30	28	25	31	17	38	28	39	44	40	26	31	20
Vermont	n.a.	112	101	83	79	76	n.a.	101	99	108	n.a.	122	100	107	56
Virginia	71	57	50	43	40	43	32	55	49	58	n.a.	63	46	54	30
Washington	48	31	24	26	22	30	14	38	22	37	42	35	17	31	19
West Virginia	66	58	52	42	40	42	32	51	51	56	59	63	49	53	27
Wisconsin	78	62	54	48	44	46	36	62	52	64	66	68	49	56	34
Wyoming	n.a.	51	44	37	35	38	27	n.a.	44	50	54	56	44	53	25
United States	75	59	52	45	42	45	34	59	72	61	64	65	47	55	32

Table F - 4. Sectoral costs of conserved energy as a result of boiler electrification in each state in 2050.

State	Cost of electrification in 2050 (2018 $/GJ)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	55	43	37	33	30	34	23	43	35	44	49	47	33	38	23
Alaska	n.a.	196	175	149	141	133	n.a.	187	170	194	191	215	169	196	105
Arizona	57	39	31	31	28	35	19	45	29	44	n.a.	44	26	43	23
Arkansas	61	38	30	33	29	37	20	49	27	47	52	45	23	44	25
California	174	139	122	107	100	99	86	139	117	142	141	153	115	140	76
Colorado	70	53	45	41	38	42	29	55	44	56	60	60	42	57	29
Connecticut	172	143	127	108	102	98	88	135	123	141	n.a.	156	123	139	75
Delaware	n.a.	48	37	42	36	48	n.a.	64	33	60	64	56	29	55	33
District of Columbia	n.a.	94	87	65	64	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	92	n.a.	42
Florida	79	59	50	46	42	48	33	63	47	63	67	65	43	57	33
Georgia	59	46	40	35	32	37	25	46	38	48	53	51	35	42	24
Hawaii	n.a.	236	195	200	178	186	n.a.	281	n.a.	269	264	267	167	252	153
Idaho	n.a.	47	41	35	33	37	24	46	39	48	n.a.	51	37	42	24
Illinois	70	51	44	41	38	42	30	56	74	56	59	57	38	47	30
Indiana	77	56	48	45	41	46	33	61	81	61	64	63	41	52	33
Iowa	60	42	35	34	31	36	23	48	32	48	51	47	29	38	26
Kansas	76	59	51	46	42	46	34	60	48	61	64	65	46	54	33
Kentucky	50	38	33	29	27	32	20	39	31	40	45	42	29	33	20
Louisiana	63	50	44	38	36	39	28	49	43	51	56	55	40	46	26
Maine	n.a.	76	65	61	56	60	45	83	61	83	n.a.	85	55	74	45
Maryland	84	57	47	47	42	49	32	67	43	65	n.a.	65	39	56	35
Massachusetts	n.a.	143	125	112	104	104	89	146	119	148	n.a.	158	114	142	80
Michigan	75	54	46	44	39	43	31	60	77	60	63	60	38	50	32
Minnesota	74	56	48	44	40	43	32	58	45	59	62	62	43	52	31
Mississippi	53	39	32	31	28	33	20	42	30	42	47	43	28	34	22
Missouri	67	44	36	37	33	40	25	54	32	52	n.a.	50	28	42	28
Montana	39	22	15	19	16	26	8	n.a.	13	29	35	26	10	27	15
Nebraska	76	59	51	46	42	46	34	60	49	61	n.a.	66	48	63	32
Nevada	n.a.	36	30	29	26	32	18	41	n.a.	41	46	42	25	41	21
New Hampshire	163	127	110	99	92	94	78	130	105	131	n.a.	140	103	125	71
New Jersey	129	100	86	78	72	74	60	103	83	104	106	111	81	105	56
New Mexico	n.a.	41	36	31	29	33	21	40	n.a.	42	47	46	34	44	21
New York	66	44	36	36	32	40	24	52	32	51	55	50	28	43	27
North Carolina	61	43	36	35	31	37	23	48	34	48	n.a.	49	30	41	25
North Dakota	82	69	61	51	49	50	n.a.	65	60	68	70	76	60	71	35
Ohio	73	51	42	42	37	43	29	58	77	58	61	57	34	47	31
Oklahoma	63	54	49	40	38	40	30	49	48	53	57	59	46	48	27

Oregon	66	50	43	39	36	40	27	52	41	53	n.a.	56	39	49	27
Pennsylvania	79	53	43	44	39	46	29	63	85	61	66	60	34	53	33
Rhode Island	n.a.	149	130	116	108	109	93	152	124	154	n.a.	164	122	148	84
South Carolina	59	45	39	35	32	37	24	46	37	48	n.a.	50	35	42	24
South Dakota	77	59	50	46	42	45	34	n.a.	48	62	n.a.	66	47	62	33
Tennessee	50	36	30	28	26	31	18	39	28	40	44	40	25	32	20
Texas	64	52	45	39	36	40	28	50	44	52	57	56	41	46	27
Utah	n.a.	34	28	28	25	31	17	39	26	39	44	38	23	31	20
Vermont	n.a.	111	99	82	78	75	n.a.	101	97	107	n.a.	120	97	105	56
Virginia	70	55	48	42	39	43	30	55	46	57	n.a.	61	43	52	29
Washington	45	25	19	23	19	28	10	36	16	34	38	30	10	26	18
West Virginia	66	56	50	41	39	41	31	51	49	55	59	61	47	51	27
Wisconsin	78	60	52	47	43	46	35	62	49	63	65	66	46	54	33
Wyoming	n.a.	50	44	38	35	39	27	n.a.	43	51	55	56	42	53	26
United States	75	57	49	45	41	45	33	59	72	60	64	63	44	53	32

Appendix G. Additional Results - State-level Results for Years 2018 to 2050 – Potential CO_2 Abatement by Electrifying Industrial Boilers

Table G-1. Sectoral potential CO_2 abatement by electrifying industrial boilers in each state in 2018.

State	Potential CO_2 abatement in 2018 ($ktCO_2$)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	-6	-241	-4	0	-81	70	0	-4	388	0	-90	-22	-10	-21	-24
Alaska	0	-1	0	0	-13	0	0	0	0	0	-80	0	0	0	0
Arizona	0	-40	-26	-1	-104	-8	0	0	1	0	0	-3	-1	-10	-2
Arkansas	-10	-360	-5	-5	-328	-410	-1	-15	4	-4	-86	-30	-1	-14	-13
California	1	112	41	6	987	713	0	4	94	2	1,911	40	4	39	144
Colorado	-1	-243	-25	-2	-232	-4	0	0	-20	-1	-197	-25	0	-4	-76
Connecticut	1	17	2	1	16	157	0	2	8	1	0	1	0	27	14
Delaware	0	-68	-1	0	-25	0	0	0	0	0	-77	-1	0	-1	0
District of Columbia	0	2	0	0	1	0	0	0	0	0	0	0	0	0	4
Florida	-5	-303	-8	-2	-150	-67	0	-2	13	-1	-3	-9	-3	-14	-19
Georgia	-10	-375	-7	-1	-177	-63	0	0	13	-2	0	-21	-195	-17	-9
Hawaii	0	-1	0	0	-39	0	0	0	0	0	-219	0	0	0	-1
Idaho	0	49	13	1	334	176	0	0	0	0	0	1	0	1	1
Illinois	-1	-766	-9	-3	-411	47	-1	0	245	-6	-503	-25	-1	-24	2
Indiana	-33	-3,440	-30	-20	-1,528	-200	-9	-1	-1,750	-24	-730	-108	-2	-312	-179
Iowa	-7	-1,940	-6	-3	-1,085	-21	-1	0	10	-10	-5	-24	0	-10	-15
Kansas	0	-458	-4	-1	-226	-8	0	-2	1	-4	-256	-12	0	-52	-6
Kentucky	-55	-2,467	-20	-4	-482	-686	-7	-32	-232	-7	-784	-120	-43	-152	-161
Louisiana	-6	-1,169	0	0	-25	187	0	-1	126	0	-760	-2	0	-2	6
Maine	0	11	3	0	46	331	0	0	0	0	0	1	0	7	4
Maryland	0	-78	-2	0	-32	6	0	0	0	0	0	-6	-1	-2	0
Massachusetts	0	-17	-3	0	6	67	0	0	1	0	0	-1	-1	-1	9
Michigan	-4	-857	-12	-10	-325	-424	-5	-3	62	-15	-163	-53	-1	-228	-69
Minnesota	0	-675	-20	-4	-421	-72	-1	0	15	-4	-378	-8	-1	-9	-13
Mississippi	0	-229	-3	-2	-88	-20	0	0	50	-1	-410	-5	-3	-10	-2
Missouri	-7	-1,505	-16	-23	-765	-215	-2	-62	-16	-15	0	-34	-1	-138	-142
Montana	0	-1	0	0	-56	-8	0	0	0	0	-366	0	0	0	0
Nebraska	0	-1,603	-3	-2	-925	-21	0	0	-12	-42	0	-10	0	-10	-6
Nevada	0	-9	-1	0	-5	7	0	0	0	0	-1	-1	0	0	1
New Hampshire	0	14	3	3	15	55	0	3	1	2	0	1	0	3	5
New Jersey	0	67	1	0	52	72	0	12	23	1	161	2	0	1	24
New Mexico	0	-76	-13	0	-76	-35	0	0	0	0	-125	0	0	-1	-2
New York	5	171	15	3	166	637	0	21	72	10	15	11	0	11	93
North Carolina	-1	-486	-8	-1	-181	54	0	-8	53	-2	0	-29	-60	-9	0
North Dakota	0	-324	-1	0	-301	-9	0	0	0	-4	-218	-2	0	-6	-34
Ohio	-7	-2,022	-36	-29	-1,154	-261	-7	-88	-325	-25	-807	-118	-3	-249	-399
Oklahoma	0	-322	-1	-1	-63	7	0	0	17	-2	-250	-14	-1	-5	-1

New Mexico	0	-77	-13	0	-77	-35	0	0	0	0	-125	0	0	-1	-3
New York	5	166	15	3	161	637	0	20	7	9	15	11	0	10	90
North Carolina	-1	-497	-8	-1	-190	54	0	-9	-19	-2	0	-30	-60	-9	-1
North Dakota	0	-326	-1	0	-304	-9	0	0	0	-4	-218	-2	0	-6	-34
Ohio	-7	-2,035	-36	-29	-1,165	-261	-7	-90	3,060	-26	-807	-119	-3	-251	-408
Oklahoma	0	-328	-1	-1	-65	7	0	0	-8	-2	-250	-14	-1	-6	-2
Oregon	0	21	13	1	116	400	1	2	9	0	0	9	0	2	16
Pennsylvania	-1	-285	-8	-2	-131	117	0	-7	2,152	-2	-167	-9	0	-17	26
Rhode Island	0	-16	-1	-1	-5	0	0	-1	0	0	0	-6	0	0	-1
South Carolina	0	-112	-4	0	1	199	0	4	-14	0	0	-7	-27	-2	7
South Dakota	0	82	0	0	21	7	0	0	0	0	0	0	0	0	6
Tennessee	-2	-745	-4	-1	-100	162	0	0	-12	-1	-3	-9	-3	-11	3
Texas	-40	-4,976	-96	-9	-326	-62	-1	-15	-81	-9	-3,971	-55	-9	-39	-91
Utah	0	-218	-43	-1	-374	-81	0	0	-32	-1	-697	-9	0	-36	-26
Vermont	0	12	12	0	53	206	0	2	0	0	0	1	0	3	4
Virginia	-1	-255	-4	0	-28	143	0	0	-9	0	0	-16	-44	-11	10
Washington	7	43	11	1	317	924	0	2	6	1	532	15	0	50	18
West Virginia	-4	-1,617	-6	-11	-64	-52	0	-40	-32	0	-102	-8	-1	-12	-94
Wisconsin	-3	-805	-24	-16	-836	-1,132	-4	-1	-45	-28	-65	-51	-2	-36	-85
Wyoming	0	-188	0	0	-50	0	0	0	0	0	-375	0	0	0	-1
United States	-176	-25,415	-567	-106	-9,532	-2,184	-22	-218	12,887	-145	-13,736	-799	-574	-1,065	-1,119

Table G-2. Sectoral potential CO_2 abatement by electrifying industrial boilers in each state in 2030.

State	Potential CO_2 abatement in 2030 ($ktCO_2$)														
	Alumina & aluminum	*Chemicals*	*Comp., electron. & elec.*	*Fabricated metals*	*Food & beverage*	*Forest products*	*Foundries*	*Glass & glass prod.*	*Iron & steel*	*Machinery*	*Petroleum refinery*	*Plastics*	*Textiles*	*Transport.*	*Balance of manufac.*
Alabama	6	78	1	1	76	757	0	6	657	0	63	6	0	8	232
Alaska	0	0	0	0	2	0	0	0	0	0	10	0	0	0	0
Arizona	0	-1	-2	0	29	32	0	0	1	0	0	0	0	0	3
Arkansas	-2	-144	-2	-1	-86	112	0	-2	114	-1	-17	-10	0	-4	1
California	2	274	96	11	1,987	1,074	1	6	110	4	2,934	83	6	74	214
Colorado	0	-13	-2	0	16	2	0	0	81	0	10	-1	0	0	25
Connecticut	1	68	7	3	44	282	0	3	10	2	0	3	0	77	26
Delaware	0	-2	0	0	7	1	0	0	1	0	17	0	0	0	0
District of Columbia	0	3	0	0	1	0	0	0	0	0	0	0	0	0	4
Florida	2	-1	-1	1	49	345	0	1	26	0	1	0	0	1	34
Georgia	5	17	0	0	73	496	0	0	25	1	0	1	-18	2	21
Hawaii	0	0	0	0	-9	0	0	0	0	0	-39	0	0	0	0
Idaho	0	75	18	1	461	211	0	0	0	0	0	1	0	2	1
Illinois	2	394	3	5	564	270	1	1	395	8	513	12	0	15	104
Indiana	-16	-2,108	-17	-9	-808	-66	-4	-1	306	-12	-294	-56	-1	-153	-65
Iowa	0	-425	-1	0	-11	27	0	0	27	0	0	-4	0	-1	9
Kansas	0	-73	-1	0	18	14	0	1	2	0	14	-2	0	-4	5
Kentucky	-27	-1,569	-12	-2	-268	-259	-3	-14	5	-3	-332	-65	-16	-77	-64
Louisiana	20	1,176	0	1	70	660	0	8	189	0	1,585	2	0	3	35
Maine	0	18	4	0	68	412	0	0	0	0	0	1	0	10	4
Maryland	0	25	0	0	30	68	0	1	0	0	0	2	0	1	4
Massachusetts	0	97	11	2	71	148	0	2	2	1	0	5	1	15	23
Michigan	-1	-287	-4	-1	-56	237	-1	0	315	-2	-22	-15	0	-54	16
Minnesota	0	-73	-3	1	67	184	0	0	35	1	43	-1	0	0	15
Mississippi	0	8	0	1	35	145	0	0	97	0	120	0	0	1	4
Missouri	-3	-905	-9	-10	-394	-66	-1	-25	4	-7	0	-17	-1	-66	-49
Montana	0	0	0	0	-14	3	0	0	0	0	-69	0	0	0	0
Nebraska	0	-831	-2	-1	-383	-2	0	0	17	-16	0	-4	0	-4	-1
Nevada	0	6	0	0	9	33	0	0	0	0	1	1	0	0	8
New Hampshire	0	25	4	4	23	71	0	4	1	3	0	2	0	5	7
New Jersey	1	320	5	1	148	123	0	25	28	2	353	9	0	2	42
New Mexico	0	-16	-3	0	-5	17	0	0	0	0	-7	0	0	0	1
New York	10	521	45	7	395	1,061	0	39	90	21	28	29	0	25	155
North Carolina	1	222	2	1	224	357	0	17	87	2	0	12	3	5	13
North Dakota	0	-184	-1	0	-143	-2	0	0	0	-2	-79	-1	0	-3	-10
Ohio	-2	-993	-17	-9	-439	-9	-2	-23	791	-9	-235	-49	-1	-95	-57
Oklahoma	0	68	0	1	45	257	0	0	30	1	133	3	0	2	7

Oregon	0	62	37	2	274	662	1	4	23	1	0	23	0	5	27
Pennsylvania	2	172	3	3	205	544	0	20	2,427	3	214	5	0	12	646
Rhode Island	0	3	0	1	3	2	0	1	0	0	0	1	0	0	4
South Carolina	7	403	9	2	72	459	0	22	17	3	0	24	22	13	19
South Dakota	1	394	1	1	60	11	0	0	0	1	0	1	1	1	10
Tennessee	9	963	3	3	392	490	1	8	6	2	9	11	1	16	16
Texas	9	-392	-12	2	65	216	0	6	-13	2	681	-3	-1	0	111
Utah	0	-127	-24	0	-184	-21	0	0	-14	0	-259	-4	0	-17	-8
Vermont	0	16	15	0	66	228	0	2	0	0	0	1	0	3	4
Virginia	7	483	5	2	142	498	0	1	7	2	0	27	26	22	58
Washington	9	70	16	1	466	1,155	0	3	7	1	594	21	0	65	21
West Virginia	-2	-1,064	-4	-5	-37	-22	0	-19	-16	0	-45	-5	0	-6	-41
Wisconsin	-1	-391	-11	-5	-314	-3	-1	0	-18	-10	-18	-21	-1	-14	-12
Wyoming	0	-122	0	0	-29	0	0	0	0	0	-162	0	0	0	0
United States	43	-1,516	-63	30	2,197	8,647	3	98	16,372	32	2,689	-37	-71	23	1,491

Table G-3. Sectoral potential CO_2 abatement by electrifying industrial boilers in each state in 2040.

State	Potential CO_2 abatement in 2040 ($ktCO_2$)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	17	457	6	2	269	1,506	1	15	880	1	202	38	6	42	483
Alaska	0	1	0	0	22	0	0	0	0	0	89	0	0	0	1
Arizona	0	48	27	2	196	75	0	0	2	0	0	3	0	12	7
Arkansas	6	163	2	3	229	680	0	10	205	3	40	12	0	7	15
California	2	402	156	15	3,038	1,452	1	8	123	6	4,032	127	8	117	279
Colorado	2	255	25	2	304	9	0	0	158	1	176	23	0	4	117
Connecticut	2	111	13	4	74	409	0	5	12	3	0	4	0	134	36
Delaware	0	82	1	0	48	1	0	1	1	0	100	1	0	1	1
District of Columbia	0	3	0	0	1	0	0	0	0	0	0	0	0	0	4
Florida	9	377	9	4	299	793	0	4	37	3	4	10	1	19	86
Georgia	20	505	8	2	385	1,105	0	1	35	4	0	26	85	24	52
Hawaii	0	0	0	0	28	0	0	0	0	0	106	0	0	0	1
Idaho	0	87	22	2	582	249	0	0	0	0	0	2	0	2	1
Illinois	5	1,749	17	12	1,753	513	2	2	518	25	1,441	52	0	59	203
Indiana	4	89	0	2	182	80	1	0	2,031	3	58	3	0	15	47
Iowa	7	1,579	4	4	1,356	80	0	0	42	12	4	17	0	9	33
Kansas	0	427	4	2	327	39	0	3	3	5	250	10	0	50	16
Kentucky	3	-51	-1	0	29	207	0	3	204	0	31	-2	-1	1	31
Louisiana	45	3,819	1	3	183	1,174	0	15	241	1	3,765	5	0	9	64
Maine	0	22	6	0	89	499	0	0	0	0	0	2	0	13	5
Maryland	1	148	3	0	106	136	0	2	0	1	0	9	1	3	9
Massachusetts	0	216	27	4	146	235	0	3	2	2	0	12	2	35	37
Michigan	3	500	6	8	290	957	3	2	527	12	98	28	0	137	99
Minnesota	1	699	19	6	681	464	1	1	51	7	414	8	0	9	43
Mississippi	1	303	3	4	188	326	0	0	136	2	591	6	1	14	10
Missouri	1	74	0	3	114	97	0	10	22	2	0	2	0	10	43
Montana	0	0	0	0	41	14	0	0	0	0	184	0	0	0	1
Nebraska	0	344	1	1	340	19	0	0	41	14	0	2	0	2	3
Nevada	0	23	1	0	25	61	0	0	0	0	3	2	0	1	15
New Hampshire	0	32	6	5	31	89	0	4	1	3	0	3	0	6	8
New Jersey	1	557	10	1	257	179	1	35	33	3	552	16	0	4	60
New Mexico	0	59	9	0	80	71	0	0	0	0	89	0	0	1	3
New York	15	806	77	10	635	1,496	0	51	103	33	40	46	0	41	212
North Carolina	2	1,052	14	3	719	687	0	38	115	7	0	57	40	21	26
North Dakota	0	37	0	0	71	5	0	0	0	1	34	0	0	1	14
Ohio	3	545	8	12	510	266	2	37	1,724	10	241	29	0	71	278
Oklahoma	0	540	2	2	179	530	0	1	41	6	478	20	0	10	15

Oregon	0	96	64	3	440	929	2	5	34	1	0	37	0	8	37
Pennsylvania	6	700	17	8	614	1,009	1	42	2,654	10	564	20	0	46	1,253
Rhode Island	0	25	1	2	13	5	0	2	0	0	0	9	0	0	9
South Carolina	13	949	24	3	154	741	0	36	43	5	0	58	51	31	30
South Dakota	2	686	2	1	104	17	0	0	0	2	0	1	1	3	15
Tennessee	20	2,861	12	7	982	847	1	15	21	5	19	33	3	47	29
Texas	58	5,450	95	15	556	520	1	25	46	15	4,784	54	3	44	309
Utah	0	19	3	0	74	45	0	0	1	0	98	1	0	4	9
Vermont	0	17	18	0	77	253	0	2	0	1	0	1	0	4	4
Virginia	15	1,246	15	5	337	867	0	1	20	4	0	72	64	59	102
Washington	10	86	22	1	609	1,400	0	3	8	1	696	27	0	86	25
West Virginia	0	-104	-1	0	0	12	0	2	-2	0	1	0	0	0	12
Wisconsin	1	224	6	6	378	1,229	1	1	6	12	21	13	0	11	59
Wyoming	0	-9	0	0	1	0	0	0	0	0	8	0	0	0	0
United States	268	28,804	577	174	16,913	20,448	26	375	19,226	236	17,199	813	218	1,243	4,048

Table G-4. Sectoral potential CO_2 abatement by electrifying industrial boilers in each state in 2050.

State	Potential CO_2 abatement in 2050 ($ktCO_2$)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	28	869	13	3	521	2,407	1	23	1,073	2	356	78	10	86	769
Alaska	0	2	0	0	47	1	0	0	0	0	176	0	0	0	2
Arizona	0	101	65	3	414	127	0	0	2	0	0	7	1	27	13
Arkansas	14	500	8	8	646	1,369	1	21	287	7	104	39	0	21	30
California	2	476	202	18	3,927	1,747	1	8	124	8	4,737	160	7	155	326
Colorado	2	267	28	2	352	10	0	0	152	1	185	26	0	5	124
Connecticut	2	116	15	5	85	453	0	5	12	3	0	5	0	157	39
Delaware	0	172	2	0	100	2	0	1	1	0	192	2	0	2	2
District of Columbia	0	3	0	0	1	0	0	0	0	0	0	0	0	0	4
Florida	17	790	20	8	625	1,334	0	7	47	6	7	22	2	42	145
Georgia	36	1,036	18	4	794	1,838	0	2	44	8	1	56	159	53	86
Hawaii	0	1	0	0	53	0	0	0	0	0	185	0	0	0	1
Idaho	0	100	28	2	729	293	0	0	0	0	0	2	0	3	1
Illinois	8	3,221	35	21	3,303	805	3	3	625	47	2,471	102	1	118	318
Indiana	24	2,523	23	16	1,499	258	5	1	3,604	21	443	75	1	243	173
Iowa	15	3,772	11	8	3,153	144	1	1	55	26	9	44	0	22	61
Kansas	0	973	10	4	732	68	1	6	4	11	510	25	0	123	28
Kentucky	36	1,633	14	3	424	775	4	19	386	5	426	76	9	106	137
Louisiana	71	6,681	2	5	331	1,792	0	22	286	2	6,186	9	1	16	97
Maine	0	26	8	0	115	601	0	0	0	0	0	2	0	17	6
Maryland	1	282	7	1	205	217	0	3	0	3	0	19	1	6	14
Massachusetts	0	344	48	6	244	340	0	4	3	4	0	20	3	60	53
Michigan	6	1,363	20	19	746	1,829	7	4	715	31	230	81	0	394	194
Minnesota	1	1,544	46	12	1,487	801	2	1	66	14	822	18	0	22	75
Mississippi	2	624	8	7	389	544	0	0	170	4	1,112	14	2	31	16
Missouri	5	1,157	13	19	789	295	1	43	38	14	0	25	0	113	146
Montana	0	1	0	0	114	28	0	0	0	0	461	0	0	1	1
Nebraska	0	1,640	3	3	1,299	44	0	0	63	53	0	10	0	10	8
Nevada	0	42	2	0	47	95	0	0	0	0	4	4	0	1	23
New Hampshire	0	39	8	6	41	109	0	5	1	4	0	3	0	9	10
New Jersey	2	810	16	2	397	245	1	44	36	4	775	24	0	6	81
New Mexico	0	100	17	0	141	106	0	0	0	0	143	1	0	2	5
New York	15	843	88	11	734	1,656	0	50	99	38	42	52	0	48	226
North Carolina	4	1,955	29	5	1,364	1,084	0	58	139	13	0	112	67	43	41
North Dakota	0	282	1	0	355	14	0	0	0	4	158	2	0	5	40
Ohio	7	2,240	42	36	1,767	599	6	94	2,566	35	763	125	1	295	655
Oklahoma	1	1,053	4	4	354	858	0	2	51	11	859	42	1	20	25

Oregon	0	100	73	3	509	1,029	2	5	33	1	0	41	0	9	39
Pennsylvania	10	1,274	35	14	1,147	1,567	2	64	2,825	19	953	39	0	92	1,948
Rhode Island	0	50	2	4	25	8	0	4	1	1	0	19	0	1	15
South Carolina	20	1,536	43	5	262	1,079	0	50	67	9	0	100	71	55	44
South Dakota	2	998	3	1	160	23	0	0	0	3	0	2	2	4	20
Tennessee	31	4,914	22	11	1,748	1,275	2	21	35	9	31	60	4	88	43
Texas	110	11,829	231	29	1,200	887	1	43	101	32	9,312	124	6	103	534
Utah	0	180	37	1	417	125	0	0	15	1	489	7	0	32	29
Vermont	0	17	20	0	89	280	0	2	0	1	0	1	0	5	4
Virginia	19	1,671	22	7	486	1,128	0	2	25	6	0	103	73	87	130
Washington	11	96	26	1	745	1,614	0	3	9	2	773	32	0	107	27
West Virginia	2	962	4	7	50	52	0	21	11	0	50	5	0	8	70
Wisconsin	3	903	28	20	1,294	2,723	4	1	28	40	63	55	1	43	139
Wyoming	0	117	0	0	41	0	0	0	0	0	193	0	0	0	0
United States	503	61,905	1,395	340	36,199	34,675	47	636	21,582	500	33,219	1,856	427	2,876	6,954

Appendix H. Additional Results - State-level Results for Years 2018 to 2050 – CO_2 Abatement costs

Table H - 1. Sectoral CO_2 abatement costs of industrial boiler electrification in each state in 2018.

State	CO_2 abatement costs in 2018 (2018 \$/tCO_2)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	n.a.	n.a.	n.a.	n.a.	n.a.	3,430	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Alaska	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Arizona	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Arkansas	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
California	953	1,241	1,331	883	922	567	900	831	1,517	960	987	1,244	1,548	1,115	632
Colorado	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Connecticut	1,365	2,089	2,381	1,259	1,351	702	1,343	1,137	3,030	1,391	n.a.	2,076	3,283	1,759	814
Delaware	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
District of Columbia	n.a.	300	313	248	260	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	344	n.a.	200
Florida	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Georgia	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Hawaii	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Idaho	n.a.	267	273	220	226	181	204	212	290	235	n.a.	268	288	248	176
Illinois	n.a.	n.a.	n.a.	n.a.	n.a.	1,976	n.a.	n.a.	92	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Indiana	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	238	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Iowa	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Kansas	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Kentucky	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Louisiana	n.a.	n.a.	n.a.	n.a.	n.a.	848	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1,847
Maine	n.a.	406	406	349	346	277	319	359	421	380	n.a.	415	400	386	289
Maryland	n.a.	n.a.	n.a.	n.a.	n.a.	4,763	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Massachusetts	n.a.	n.a.	n.a.	7,537	X	1,307	X	4,367	n.a.	X	n.a.	n.a.	n.a.	n.a.	1,845
Michigan	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	120	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Minnesota	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mississippi	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Missouri	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Montana	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nebraska	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nevada	n.a.	n.a.	n.a.	n.a.	n.a.	1,261	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,884
New Hampshire	683	769	786	627	637	465	611	622	835	675	n.a.	777	836	722	499
New Jersey	1,352	2,622	3,418	1,184	1,294	578	1,276	1,058	6,636	1,376	1,428	2,610	9,275	2,044	686
New Mexico	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

New York	405	482	498	345	347	245	303	350	561	396	433	495	538	433	249
North Carolina	n.a.	n.a.	n.a.	n.a.	n.a.	2,034	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
North Dakota	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ohio	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	144	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oklahoma	n.a.	n.a.	n.a.	n.a.	n.a.	X	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oregon	402	537	579	364	381	246	347	343	673	406	n.a.	540	680	465	250
Pennsylvania	n.a.	n.a.	n.a.	n.a.	n.a.	1,455	n.a.	n.a.	91	n.a.	n.a.	n.a.	n.a.	n.a.	9,271
Rhode Island	n.a.	n.a.	n.a.	n.a.	n.a.	X	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
South Carolina	8,148	n.a.	n.a.	4,450	X	541	n.a.	1,968	n.a.	X	n.a.	n.a.	n.a.	n.a.	706
South Dakota	980	1,943	2,523	883	977	441	956	n.a.	4,585	1,013	n.a.	1,926	6,068	1,523	502
Tennessee	n.a.	n.a.	n.a.	n.a.	n.a.	725	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1,237
Texas	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Utah	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Vermont	n.a.	349	355	304	310	254	n.a.	296	368	318	n.a.	349	370	329	257
Virginia	n.a.	n.a.	n.a.	n.a.	n.a.	904	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1,603
Washington	155	149	143	131	127	122	98	142	146	149	171	155	126	141	110
West Virginia	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Wisconsin	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Wyoming	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
United States	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	134	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Note: "X" represents a very large and unrealistic value for the sector and the state.

Table H - 2. Sectoral CO_2 abatement costs of industrial boiler electrification in each state in 2030.

State	CO_2 abatement costs in 2030 (2018 \$/tCO_2)														
	Alumina & aluminum	*Chemicals*	*Comp., electron. & elec.*	*Fabricated metals*	*Food & beverage*	*Forest products*	*Foundries*	*Glass & glass prod.*	*Iron & steel*	*Machinery*	*Petroleum refinery*	*Plastics*	*Textiles*	*Transport.*	*Balance of manufac.*
Alabama	656	1,467	2,119	568	628	288	571	492	6,377	677	753	1,439	X	933	304
Alaska	n.a.	n.a.	n.a.	6,750	9,800	1,517	n.a.	4,354	n.a.	9,797	9,139	n.a.	n.a.	n.a.	2,073
Arizona	1,337	n.a.	n.a.	1,019	1,258	353	1,176	807	n.a.	1,417	n.a.	n.a.	n.a.	8,568	398
Arkansas	n.a.	n.a.	n.a.	n.a.	n.a.	1,166	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	7,596
California	603	677	691	562	571	429	547	554	731	600	622	682	723	640	454
Colorado	2,571	n.a.	n.a.	1,912	2,810	465	3,302	1,263	n.a.	2,961	2,995	n.a.	n.a.	n.a.	564
Connecticut	585	674	695	554	569	421	547	535	737	587	n.a.	674	742	620	443
Delaware	n.a.	n.a.	n.a.	1,460	1,750	521	n.a.	1,223	n.a.	2,014	2,084	n.a.	n.a.	9,722	616
District of Columbia	n.a.	280	293	229	241	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	324	n.a.	182
Florida	1,804	n.a.	n.a.	1,458	1,774	502	1,813	1,140	n.a.	1,916	1,991	n.a.	n.a.	6,680	598
Georgia	1,149	X	n.a.	958	1,140	370	1,108	760	n.a.	1,221	1,323	X	n.a.	2,893	414
Hawaii	n.a.	n.a.	n.a.	n.a.	n.a.	9,811	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Idaho	n.a.	169	169	142	144	129	120	141	176	155	n.a.	169	170	146	115
Illinois	762	1,347	1,686	660	708	352	670	603	74	770	816	1,342	3,368	963	392
Indiana	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	118	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Iowa	n.a.	n.a.	n.a.	X	n.a.	539	n.a.	2,651	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	751
Kansas	5,670	n.a.	n.a.	3,720	7,779	606	X	1,984	n.a.	7,708	6,626	n.a.	n.a.	n.a.	786
Kentucky	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Louisiana	494	789	919	445	475	265	431	399	1,227	506	566	784	1,278	598	272
Maine	n.a.	323	321	285	281	240	256	294	328	309	n.a.	329	309	301	241
Maryland	1,044	2,123	2,971	865	932	431	874	800	9,074	1,044	n.a.	2,119	X	1,468	491
Massachusetts	n.a.	1,449	1,556	1,015	1,053	640	1,025	965	1,788	1,115	n.a.	1,456	1,806	1,277	720
Michigan	n.a.	n.a.	n.a.	n.a.	n.a.	937	n.a.	n.a.	87	n.a.	n.a.	n.a.	n.a.	n.a.	1,878
Minnesota	3,023	n.a.	n.a.	2,281	3,344	529	4,123	1,501	n.a.	3,486	3,385	n.a.	n.a.	n.a.	683
Mississippi	1,044	X	n.a.	842	1,000	330	922	685	n.a.	1,095	1,199	X	n.a.	2,542	367
Missouri	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Montana	n.a.	n.a.	n.a.	n.a.	n.a.	719	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2,162
Nebraska	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nevada	n.a.	733	842	387	408	237	334	367	n.a.	462	529	748	1,349	637	235
New Hampshire	524	566	571	484	488	388	463	485	593	518	n.a.	571	589	531	402
New Jersey	569	661	677	511	522	366	489	509	741	563	597	671	741	636	392
New Mexico	n.a.	n.a.	n.a.	n.a.	n.a.	527	n.a.	X	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	729
New York	202	193	185	172	166	157	138	187	185	194	216	199	165	180	147
North Carolina	676	1,225	1,549	570	611	311	546	526	2,805	681	n.a.	1,225	3,549	885	331
North Dakota	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ohio	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	94	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oklahoma	817	2,476	4,641	731	843	337	810	590	n.a.	869	944	2,367	n.a.	1,388	357

Oregon	217	236	237	197	199	168	175	198	249	215	n.a.	239	240	219	159
Pennsylvania	705	1,049	1,203	577	595	335	533	571	77	692	758	1,071	1,816	839	368
Rhode Island	n.a.	7,088	X	2,261	2,550	968	2,607	1,920	n.a.	2,670	n.a.	6,872	n.a.	4,428	1,186
South Carolina	385	510	547	343	356	237	314	326	636	387	n.a.	512	632	423	233
South Dakota	378	447	462	343	351	249	324	n.a.	506	376	n.a.	454	506	430	260
Tennessee	380	533	587	328	341	216	289	314	724	381	434	535	724	405	212
Texas	1,706	n.a.	n.a.	1,381	1,832	410	1,952	964	n.a.	1,906	2,005	n.a.	n.a.	X	475
Utah	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Vermont	n.a.	337	344	292	298	246	n.a.	284	357	306	n.a.	336	359	311	245
Virginia	423	550	588	382	396	263	359	363	673	426	n.a.	552	669	467	266
Washington	132	116	107	108	101	109	74	122	105	125	145	122	86	112	95
West Virginia	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Wisconsin	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Wyoming	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
United States	1,921	n.a.	n.a.	1,548	1,976	477	2,097	1,143	96	2,090	2,150	n.a.	n.a.	X	579

Note: "X" represents a very large and unrealistic value for the sector and the state.

Table H - 3. Sectoral CO_2 abatement costs of industrial boiler electrification in each state in 2040.

State	CO_2 abatement costs in 2040 (2018 \$/tCO_2)														
	Alumina & aluminum	*Chemicals*	*Comp., electron. & elec.*	*Fabricated metals*	*Food & beverage*	*Forest products*	*Foundries*	*Glass & glass prod.*	*Iron & steel*	*Machinery*	*Petroleum refinery*	*Plastics*	*Textiles*	*Transport.*	*Balance of manufac.*
Alabama	208	235	239	187	189	157	159	185	253	207	239	236	240	195	143
Alaska	n.a.	1,275	1,337	987	1,020	685	n.a.	938	1,463	1,052	1,077	1,277	1,472	1,177	750
Arizona	231	241	233	195	192	167	150	207	250	224	n.a.	250	232	246	154
Arkansas	332	350	339	270	264	211	207	290	371	316	363	369	341	354	206
California	462	490	492	431	433	356	410	433	508	457	476	494	498	471	367
Colorado	155	157	153	140	139	132	117	145	159	153	173	161	153	161	120
Connecticut	394	425	429	374	379	315	360	369	443	393	n.a.	425	442	397	319
Delaware	n.a.	315	294	274	263	240	n.a.	307	298	315	349	332	279	328	230
District of Columbia	n.a.	275	288	224	236	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	320	n.a.	177
Florida	332	365	368	294	294	235	258	298	390	326	361	371	369	326	229
Georgia	243	279	285	218	221	178	189	215	306	242	277	281	291	240	165
Hawaii	n.a.	1,375	1,349	1,201	1,180	894	n.a.	1,269	n.a.	1,313	1,340	1,415	1,333	1,352	1,014
Idaho	n.a.	151	150	130	130	122	107	130	156	141	n.a.	151	148	129	107
Illinois	265	280	281	235	234	194	207	241	64	259	284	284	274	237	190
Indiana	1,267	6,012	n.a.	1,041	1,186	430	1,160	885	80	1,306	1,366	5,582	n.a.	2,367	501
Iowa	294	323	326	257	257	199	222	263	344	288	320	328	328	271	199
Kansas	354	415	430	322	329	248	300	316	461	353	379	417	454	354	244
Kentucky	1,445	n.a.	n.a.	1,116	1,483	344	1,493	797	n.a.	1,601	1,731	n.a.	n.a.	n.a.	376
Louisiana	216	246	253	199	201	165	174	194	268	217	248	247	253	209	153
Maine	n.a.	266	260	241	236	213	211	253	263	262	n.a.	271	244	248	209
Maryland	327	328	320	280	274	232	238	299	328	315	n.a.	337	306	301	230
Massachusetts	n.a.	658	666	559	561	435	533	560	695	599	n.a.	665	674	615	459
Michigan	385	439	451	337	338	242	302	340	70	378	416	445	455	365	254
Minnesota	336	385	395	303	307	229	277	301	422	334	362	388	410	330	233
Mississippi	216	234	232	188	189	159	151	193	243	212	246	236	236	192	146
Missouri	977	2,536	4,803	788	859	372	793	721	n.a.	980	n.a.	2,494	n.a.	1,444	422
Montana	209	202	184	159	151	148	96	n.a.	197	196	243	218	171	215	123
Nebraska	603	891	997	538	570	334	530	500	1,271	609	n.a.	899	1,356	791	349
Nevada	n.a.	192	185	158	156	143	119	167	n.a.	180	212	199	183	197	126
New Hampshire	433	450	448	398	398	337	374	406	459	426	n.a.	454	451	424	342
New Jersey	384	403	400	347	347	285	320	357	418	377	403	410	409	401	291
New Mexico	n.a.	198	200	158	161	142	132	155	n.a.	174	204	202	213	197	121
New York	146	130	122	123	117	125	95	138	118	139	157	135	104	123	112
North Carolina	233	242	239	201	199	173	165	210	248	226	n.a.	247	229	214	161
North Dakota	856	1,661	2,114	776	859	404	n.a.	671	3,592	888	934	1,645	4,543	1,319	443
Ohio	506	634	673	428	434	282	385	430	72	497	543	643	741	505	299
Oklahoma	239	295	309	225	234	182	208	211	335	244	275	293	330	244	166

Oregon	157	160	158	142	141	134	122	147	162	155	n.a.	163	154	151	122
Pennsylvania	282	271	259	236	228	202	194	259	70	269	302	280	233	254	199
Rhode Island	n.a.	842	859	685	696	511	662	679	912	739	n.a.	848	909	775	544
South Carolina	200	217	218	179	179	158	151	180	228	198	n.a.	219	215	190	142
South Dakota	246	262	262	224	225	188	202	n.a.	274	243	n.a.	268	268	262	185
Tennessee	172	180	178	150	149	136	118	155	184	169	198	183	169	148	120
Texas	260	311	323	239	245	190	213	229	350	262	298	311	336	255	177
Utah	n.a.	934	1,176	423	449	248	358	398	2,259	518	602	931	2,969	615	242
Vermont	n.a.	329	334	284	290	241	n.a.	276	347	298	n.a.	327	348	301	238
Virginia	201	215	215	183	184	162	160	185	224	200	n.a.	217	213	193	150
Washington	115	96	86	93	85	100	59	108	83	108	127	101	65	93	84
West Virginia	X	n.a.	n.a.	4,922	X	540	n.a.	1,948	n.a.	X	X	n.a.	n.a.	n.a.	662
Wisconsin	520	697	758	461	479	295	441	441	890	521	561	698	889	555	314
Wyoming	n.a.	n.a.	n.a.	2,185	3,764	448	5,280	n.a.	n.a.	3,835	3,787	n.a.	n.a.	n.a.	528
United States	314	357	365	282	286	220	254	280	79	311	344	360	376	308	217

Note: "X" represents a very large and unrealistic value for the sector and the state.

Table H - 4. Sectoral CO_2 abatement costs of industrial boiler electrification in each state in 2050.

State	CO_2 abatement costs in 2050 (2018 $/t$CO_2$)														
	Alumina & aluminum	Chemicals	Comp., electron. & elec.	Fabricated metals	Food & beverage	Forest products	Foundries	Glass & glass prod.	Iron & steel	Machinery	Petroleum refinery	Plastics	Textiles	Transport.	Balance of manufac.
Alabama	126	125	123	112	110	109	91	117	124	123	143	127	114	107	96
Alaska	n.a.	574	578	511	515	426	n.a.	509	597	536	553	578	586	554	442
Arizona	129	113	103	107	102	110	76	122	103	122	n.a.	119	91	122	97
Arkansas	140	112	99	113	104	117	78	134	95	130	150	121	80	125	107
California	399	407	403	368	366	316	343	377	412	392	409	412	399	395	323
Colorado	159	155	149	141	138	135	116	150	153	155	175	160	145	161	123
Connecticut	393	418	420	370	373	313	353	369	432	390	n.a.	419	429	391	318
Delaware	n.a.	141	123	144	133	153	n.a.	174	115	165	185	151	101	156	140
District of Columbia	n.a.	274	287	223	235	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	319	n.a.	176
Florida	181	171	165	159	154	152	132	171	165	175	195	176	150	160	141
Georgia	134	134	131	120	118	116	98	125	133	132	152	136	122	120	103
Hawaii	n.a.	690	646	685	651	593	n.a.	765	n.a.	745	765	719	582	710	648
Idaho	n.a.	137	134	121	120	117	97	125	137	133	n.a.	138	129	118	103
Illinois	161	151	146	142	137	135	119	152	57	155	171	154	131	131	127
Indiana	176	165	159	155	149	145	131	167	62	170	185	168	141	146	139
Iowa	138	123	117	118	113	115	93	131	113	132	148	127	101	108	108
Kansas	174	172	169	157	155	148	137	164	169	170	184	174	161	153	137
Kentucky	114	112	109	101	99	102	79	106	109	112	131	114	100	94	87
Louisiana	143	147	146	131	130	123	111	133	149	142	162	149	138	128	111
Maine	n.a.	223	214	210	203	193	178	227	213	230	n.a.	229	192	210	189
Maryland	192	167	155	162	154	157	129	183	150	181	n.a.	174	134	159	150
Massachusetts	n.a.	418	413	384	378	330	355	397	417	409	n.a.	425	397	400	339
Michigan	171	158	152	150	144	138	125	163	60	165	183	162	133	140	135
Minnesota	169	164	160	151	148	138	129	159	160	164	180	167	149	146	133
Mississippi	122	113	107	105	102	106	79	114	105	117	137	115	99	97	93
Missouri	153	129	119	127	120	126	98	146	112	144	n.a.	134	98	117	119
Montana	89	63	51	66	58	82	33	n.a.	46	81	101	70	35	75	64
Nebraska	173	173	169	157	155	148	137	164	173	170	n.a.	178	168	177	137
Nevada	n.a.	107	98	99	95	103	70	111	n.a.	113	134	112	89	115	89
New Hampshire	374	371	364	340	336	300	313	354	367	364	n.a.	376	357	354	302
New Jersey	296	292	284	267	263	235	241	281	290	288	309	298	281	296	237
New Mexico	n.a.	121	118	106	105	106	85	109	n.a.	116	136	124	118	124	89
New York	150	128	118	125	117	127	94	143	113	141	159	134	97	122	115
North Carolina	139	127	120	119	114	119	91	131	118	133	n.a.	131	104	116	106
North Dakota	188	202	203	176	178	159	n.a.	176	211	188	203	205	210	201	150
Ohio	167	149	141	143	136	136	115	159	59	159	177	153	118	132	131
Oklahoma	145	159	162	137	139	128	122	134	167	146	165	159	161	137	113

Oregon	150	147	142	133	130	128	109	141	144	146	n.a.	150	134	139	116
Pennsylvania	181	154	142	150	141	147	118	173	65	170	191	161	118	150	140
Rhode Island	n.a.	436	430	399	396	346	371	413	435	426	n.a.	442	424	417	354
South Carolina	135	133	129	119	117	117	97	126	130	132	n.a.	135	120	119	103
South Dakota	175	171	166	156	154	144	135	n.a.	169	170	n.a.	177	162	176	138
Tennessee	113	106	101	97	94	100	73	106	99	109	129	108	88	89	85
Texas	146	151	150	134	133	126	114	135	153	144	164	152	143	129	113
Utah	n.a.	100	93	95	90	100	66	106	90	108	128	103	79	86	85
Vermont	n.a.	324	328	281	286	240	n.a.	276	340	297	n.a.	323	339	296	237
Virginia	160	160	158	144	142	136	122	149	160	157	n.a.	163	150	146	124
Washington	102	74	61	77	68	89	41	97	55	93	112	80	36	74	74
West Virginia	150	164	165	140	141	132	123	139	171	151	170	164	162	145	115
Wisconsin	178	174	171	160	157	145	139	168	171	174	190	177	159	153	141
Wyoming	n.a.	148	145	129	129	123	108	n.a.	152	140	161	151	147	150	109
United States	171	167	163	153	150	143	130	161	67	166	185	170	153	151	134

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Acronyms and Abbreviations

AEO	Annual Energy Outlook
AMO	Advanced Manufacturing Office
CHP	Combined Heat & Power
CO_2	Carbon Dioxide
DOE	Department of Energy
EEA	Energy and Environmental Analysis, Inc.
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse Gases
IEA	International Energy Agency
ISO	California Independent System Operator
LPG-NGL	Liquefied Petroleum Gas – Natural Gas Liquids
MECS	Manufacturing Energy Consumption Survey
O&M	Operations & Maintenance Costs
RDD&D	Research, Development, Demonstration, and Deployment
SEDS	State Energy Data System
TRL	Technology Readiness Level