Electrification of buildings and industry in the United States

Drivers, barriers, prospects, and policy approaches

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Executive Summary

Grid-connected electrification of energy end uses in U.S. buildings and industry is expected to continue to increase gradually under existing policies. This report reviews the possible benefits and barriers to greater electrification in these market sectors, the technical and economic potential for electrification, and policy and programmatic approaches for regions that want to encourage a more rapid transition to beneficial electrification. We do not evaluate the case for electrification directly. Rather, we illustrate the benefits of electrifying, discuss some of the drawbacks, and review policies, programs, and regulations that may promote or hinder electrification.

In buildings, electrification involves substituting electric technologies for combustion-fueled technologies for end uses where other fuels are being used — most notably, space heating and water heating. In industry, electrification means powering a wide range of industrial processes by electricity rather than combustion fuels.

Promising energy system benefits of electrification include greater flexibility for managing electric loads, opportunities to provide additional ancillary services[1] to the grid, and valuable synergies with electric vehicles, demand response, and distributed generation and energy storage. In addition, electrification may foster economic development, boost balance of trade, improve air quality, reduce fuel price risks, reduce consumers' costs in some applications, and improve product quality in some industrial processes and quality of some energy services in buildings.

For both the buildings and industry sectors, the ultimate barriers to electrification are economic, not technical. Fuel prices and differences in the capital costs of equipment are the chief determinants of the relative economics of electric compared to non-electric technologies.

In buildings, electric alternatives exist for all major energy end uses. Space heating with electric heat pumps is economically viable in a wide variety of buildings today. Electrification of end uses generally is *relatively* cost-effective in new (versus existing) buildings, in residential (versus commercial) buildings, in settings where a single heat pump can replace the need for the capital cost of an air conditioning unit as well as a space heating unit, and in areas with milder winters. However, electrification may in some cases be cost-effective for any building type in any location.

Many of the essential technological elements for industrial electrification exist, but much greater diversity of processes and high levels of process integration make solutions more complex. Electrification of process heating can be relatively cost-effective where product quality and manufacturing productivity is improved (e.g., using induction heating for metal processing), or when

[1] "Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system." https://www.ferc.gov/market-oversight/guide/glossary.asp. Examples include load following and reactive power-voltage regulation.

electricity costs are low relative to combustion fuel energy costs. Cost-effective electrification of process heating is generally more challenging at very high temperatures (e.g., cement manufacturing), where processes are highly integrated, and where combined heat and power is extensively utilized.

Many policies, programs, and regulations affect the prospects for electrification. These include government-sponsored research, development, and demonstration of electric technologies; electricity rate design; demand response program and electricity market design; financial incentives for adoption of these technologies; energy savings targets; building energy codes and appliance and equipment standards; educational and outreach efforts; energy planning processes; and air quality regulations. Emerging approaches that hold particular promise include charging lower prices for off-peak electricity usage (time-varying rates) and rewarding the grid services that newly-electrified end uses would offer (electricity market designs that reward flexibility).

The report offers several use cases and case studies of electrification in buildings and industry: air source heat pumps for space heating, zero net energy buildings, electric water heaters and demand response, electric arc furnaces, and electric boilers. Finally, the report suggests several areas for further research to better understand and advance beneficial electrification.

1. Introduction

1.1 Purpose and scope

This report reviews the prospects for grid-connected electrification of energy end uses in buildings[2] and industry in the United States.[3] While electrification may be desirable for a number of reasons, currently both past trends and future projections show gradual movement toward electrification of additional end uses in these sectors in the country overall.

We focus on electrification of end uses where direct use of other fuels currently has substantial market share. Some end uses, such as lighting, space cooling, and refrigeration, are already dominated by electric technologies.[4]

The remainder of Section 1 defines electrification, identifies the potential benefits and barriers of electrification, and reviews the principal factors that will likely most influence the rate of electrification in the near future. Section 2 examines current and projected trends in electrification in buildings and industry. It also provides a high-level assessment of the literature on technical and economic potential for electrifying end-uses in buildings and industry. Section 3 describes potential policy approaches to encourage beneficial electrification. Section 4 provides use cases and case studies of successful, or potentially successful, electrification for specific end uses or subsectors. Section 5 concludes with key findings and additional research needed.

1.2 Definition of electrification and qualifications

Electrification is the process through which end uses such as heating and cooling appliances that are currently directly powered by solid, liquid, or gaseous fossil fuels (e.g., natural gas or fuel oil) are powered by electricity instead.[5] Examples in buildings are gas-powered furnaces and domestic water heaters or boilers that are replaced with heat pumps[6] or heat pump water heaters[7] powered by electricity. There are also hybrid-heat residential and commercial heating systems that can automatically switch fuels (e.g., between natural gas and electricity) depending on their relative prices.[8]

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[2] We cover both residential and commercial buildings, including buildings at industrial sites.

[3] While transportation is outside the scope of this report, we briefly discuss transportation electrification where it is relevant to electrification of buildings and industry.

[4] We do not consider whether non-electric technologies may develop to threaten the predominance of electricity in these end uses.

[5] According to EPRI, "expanding end-use applications of electricity … involves replacing less efficient fossil-fueled end-use technologies (existing or planned) with more efficient electric end-use technologies." (EPRI 2009). This definition is not meant to cover the historic trend of extending electricity service to non-electrified or undeveloped areas. Note also that this definition of electrification is also distinct from increasing electricity demands from existing end uses that are already powered by electricity such as data centers, indoor agriculture, and air conditioning units.

[6] See Section 4.1 for more on heat pump technologies for space heating.

[7] See Section 4.2 for more on heat pump technologies for water heating.

[8] See, for example, Bryant Hybrid Heat systems (https://www.bryant.com/bryant/en/us/before-you-buy/sy stem-types/).

For buildings, additional considerations for qualifying fuel switching as electrification include the following:

- Some end uses currently use both natural gas and electricity. For example, a gas clothes dryer uses electricity to run the tumbler motor. Electrification in this case entails conversion to an all-electric dryer with electricity providing heating energy as well as the energy to run the motor.
- Some end uses in the building sector can be partially electrified, such as solar thermal water heaters which need a source of backup heating — commonly electric resistance heating.

For industry, additional considerations apply:

- As a large user of energy with large facilities, industry may consider more flexible arrangements for the provision of energy services. For example, industrial users of steam systems may choose a hybrid gas-electric boiler, with the electric mode deployed when electricity rates are low (or gas prices are high) as an electrification measure.[9]
- Industrial processes powered by electricity may need auxiliary heating systems. For example, in glass furnaces, typical glass feedstock formulations become conductive at temperatures above 700°C (Orfeuil 1987). Above this point, the feedstock will conduct electricity and this "resistive load" can achieve molten glass heating. But an auxiliary source of heat is still needed to heat the glass feedstock, and combustion-fired heating systems can still be the most economical for this.
- Other indirect pathways enable electricity to replace industrial fuel demand — in particular, hydrogen as an energy carrier[10] or feedstock (see Section 2.2.3.2). Hydrogen can be produced in multiple ways and used in multiple applications: as a transportation fuel, as a heating fuel, for energy storage, for electricity generation, and as an industrial feedstock. Hydrogen can be integrated across multiple energy sectors, increase energy system flexibility, improve system resilience, and reduce environmental impacts.[11]

1.3 Benefits of electrification

In this section we review a number of the benefits potentially attendant to electrification. We also call out some of the drawbacks of electrification. We do not attempt to evaluate the overall case for electrification, either in general or in specific situations; such an analysis is beyond the scope of this report.

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[9] See the hybrid gas-electric boiler case study in Section 4 of this report.

[10] ISO 13600 defines energy carriers as a "substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes." https://www.iso.org/obp/ui/#iso:std:iso:13600:ed-1:v1:en, accessed October 16, 2017.

[11] We do not highlight indirect electrification of buildings with hydrogen as an energy carrier since there are more economic direct electrification opportunities and existing technologies on the market for electrifying building heating.

1.3.1 Energy system benefits

Grid support and ancillary services. A future grid system with more electrified end uses, coupled with greater control and automation of end-use operation, can provide grid operators and utilities with greater control over load shapes and aggregated end uses. Third-party aggregators can provide these services as well. This control of aggregated load shapes offers the potential to provide a range of grid support and ancillary services and opportunities for end-users to lower costs. These include real-time control for grid balancing services (Weiss et al. 2017), load-following demand response, and regulation demand response (Alstone et al. 2017).[12]

Flexibility for integration of variable energy resources. Electric loads in many cases can provide value by providing greater grid flexibility (Weiss et al. 2017), especially when integrating greater amounts of variable renewable energy resources such as wind, solar, and run of the river hydroelectricity. Electric loads from newly electrified end uses (e.g., space heating converted from combustion fuels) and from new equipment for existing electrified end uses (e.g., lighting and refrigerators) can be treated as "smart loads" if they are equipped with appropriate control and monitoring capabilities enabled by grid modernization. Electrified end uses in the residential sector such as electric water heaters (Dennis 2015) and industrial applications (e.g., water pumping, wood processing) can facilitate greater load-responsive flexibility via demand response and demand shifting (Alstone 2017). For solar photovoltaic (PV) systems, an increasing issue is the reduced value for marginal units and the potential for overproduction of solar power (Mills and Wiser, 2015),[13] relative to load, as penetration levels of these systems increase. Shifting electricity demand to match up with the solar peak would provide better utilization of resources and could reduce the system peak demands that occur later in the day. Similarly, the availability of flexible end-use loads can avoid curtailment of variable energy resources (e.g., wind power), as is the case today in Minnesota through electric vehicle charging programs.[14] Electrification expands the volume of electricity use that could be shifted to make better use of these resources.[15] Well-controlled flexible electric loads can mitigate future electricity grid stressors such as the need for rapid down-ramping or up-ramping and potentially higher peak loads from extreme weather events.

Electric vehicles and storage. Electrified buildings and industrial end uses provide synergistic opportunities for electric vehicles (EVs) and distributed storage. For example, a microgrid for a future corporate building campus could feature onsite solar PV, flexible loads such as electrified water

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[12] From Alstone et al. 2017, "Load-following DR resources are those capable of responding within five minutes of being dispatched, and enable load to participate in both the real-time energy and spinning reserves markets. Regulation DR resources must be capable of responding within four seconds, and enable load to participate in regulation markets."
[13] This reference also describes several options for mitigating the decline in value of solar PV and wind at high penetration such as increased geographic diversity, low cost storage, and real-time pricing and technological diversity. We note also the countervailing trend that increased adoption of time-varying pricing will reduce the value of solar PV systems for offsetting host customers' utility bills (Darghouth et al. 2016).
[14] See, for example, https://nawindpower.com/wind-powered-electric-vehicle-program-continues-minnesota.
[15] While outside the scope of this report, transportation electrification, with right-time charging and discharging, will make important contributions here. See for example, Schwartz et. al. (2017), Chapter 5.1.4.

heating, pre-cooling of buildings[16], and employee-parked electric vehicles providing flexible charging and/or discharging, all networked in a way that would minimize grid purchases of electricity – especially during high-demand time periods – and grid-based demand charges.

1.3.2 Non-energy and indirect system benefits

Economic development. Electrification enables the broad use of a variety of domestic resources and potential expansion of domestic production and supply chains for electric appliances, emerging battery manufacturing, new and upgraded distribution system equipment, and related supply chains. Potential indirect economic development benefits relate to the associated build-out of the electricity grid (e.g., transmission lines). Conversely, aggressive electrification policies could lead to higher costs of energy service and this could act as a counterbalance to economic development.

Balance of trade for fuels. Increasing use of domestic renewable energy resources for U.S. electricity production to meet higher demand driven by electrification may enable more export of coal, coke, and natural gas. There also is potential for growing export markets for end-use equipment for expanded electrified uses.

Energy security. Increasing the use of local resources such as domestic fossil fuels, hydropower, wind, solar, and battery storage – all to meet greater demand due to electrification – can reduce dependence on imported liquid fuels and improve energy security through greater decentralization.

Air quality. Electrically powered end uses do not rely on combustion of fuels onsite, eliminating emissions at the point of customer usage compared to end uses that require onsite combustion of natural gas, heating oil, and other fuels. On the other hand, electrification may increase emissions from power plants. Upstream emissions from electricity generation can be lowered by installing energy-efficient electric equipment or by using a greater fraction of clean electricity sources. Thus, increased electrification can lead to better air quality, including lower levels of criteria pollutants,[17] and improved public health outcomes. This may be particularly beneficial for industrial sites, which are often concentrated in urban areas with disadvantaged communities and a disproportionately large air pollution load from multiple sources including industrial sources, trucking, and residential combustion (Bell et al. 2012). Air quality can be a severe health problem in these areas (Nadeau et al. 2010).

Greenhouse gas reductions. The electrification of fossil-fuel supplied end uses coupled with low-carbon electricity supply sources has been highlighted as an important pathway to decarbonize the energy system (Williams et al. 2012, Wei et al. 2013). Electrification, combined with a shift towards low and zero carbon electric generating technologies, reduces both GHGs and criteria air pollutant

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[16] Pre-cooling of buildings refers to shifting the operation of cooling equipment to earlier in the day to make use of more favorable electricity rates and relying on the thermal inertia of the building to provide adequate building comfort in subsequent hours.

[17] Criteria pollutants include carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide.

emissions. The electrification pathway to decarbonization, while technically possible, needs to be evaluated versus other pathways in terms of costs to customers, utilities, and overall societal costs.

Resilience and potential reduction of fuel price risk. To the extent that energy end uses move away from combustion of fossil fuels with volatile prices, fuel price risk may be reduced. Further reductions in fuel price risk can be realized through the expanded use of zero marginal cost electricity resources.[18] To the degree that oil and gas imports are reduced, electrification can improve the country's resilience to price shocks for these fuels.[19]

In the residential sector, as electric storage becomes increasingly affordable, the combination of electrified heating, solar PV, and electric storage can offer a long-term hedge against rising fossil fuel prices as well as greater resilience to power outages. Conversely, increased reliance on the electricity grid without an increase in distributed generation sources and/or microgrids could leave customers solely reliant on the electricity grid more vulnerable to power outages.

Another form of resilience is robustness to extreme weather. In addition to weather-hardening existing industrial production and distribution resources, electrification of end uses coupled with more renewable energy supplies could reduce the dependence on geographically-concentrated oil refining and gas processing. Electrified end uses can rely on geographically dispersed grid resources or distributed generation.

Today, over 45% of total U.S. petroleum refining capacity and 51% of total U.S. natural gas processing plant capacity[20] are located along the Gulf Coast and are highly vulnerable to hurricane-induced damage and storm surges. Reduced dependence on natural gas for heating applications in buildings and industry could reduce the dependence on concentrated natural gas processing.

Process improvements in industry (e.g., quality, process controllability). Electricity offers better process control and potentially yields higher quality products in some applications. The DOE Advanced Manufacturing Office recently highlighted the enhanced productivity potential of electrotechnologies in industrial process heating applications (Thekdi et al, 2017) from improved process speed, improved product quality, manufacturing flexibility, and cleaner processing (less polluting emissions). For example, a recent report (Vairamohan 2014) details the non-energy benefits of induction heating:[21]

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[18] The declining prices of zero marginal cost renewable electricity resources are discussed in the following report: https://energy.gov/eere/downloads/revolutionnow-2016-update.

[19] See "Annual Energy Outlook 2017 with projections to 2050" (https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf) for historical and projected U.S. net energy trade. The Annual Energy Outlook 2018 will be released by EIA in February 2018.

[20] See https://www.eia.gov/special/gulf_of_mexico/.

[21] Induction heating is an electrotechnology that relies on the electromagnetic induction effect for process heating. When a conducting object is placed in a time-varying magnetic field (typically generated by a high frequency alternating current in an induction coil), induced eddy-currents in the object will heat the object from localized electric resistance-heating. Induction heating is a non-contact process (the object is placed within the induction coils) and can only heat materials with high electrical conductivity (such as aluminum, copper, and gold).

higher yield, faster startup, better product quality, flexibility in starting material, automatic operation, compact installation, better working environment (see Table 1). These “form-value” benefits are broadly applicable to many electrified heating applications in industry. Induction heating and melting applications include gears, shafts, valve parts service hardening, tempering (spring steel, chain links), and annealing (aluminum and steel strip).

Table 1. Some non-energy benefits of induction heating (Source: Vairamohan 2014)

Benefit	Details
Higher yield and faster startup	Due to the absence of combustion sources, induction furnaces reduce oxidation losses that can be significant in the melting process.
Better product quality	Induction furnaces allow precise control, resulting in dependable and consistent quality. Exact control of power input ensures that the optimum temperature is maintained throughout processing. Medium frequency magnetic fields give a strong stirring effect, resulting in a homogeneous melt.
Flexibility	Induction furnaces require no molten metal as the starting batch. This facilitates repeated cold starting and frequent alloy changes.
Automatic operation	Precise automatic control of power reduces furnace operation manpower to that required only for charging, tapping, and metallurgical measurements.
Compact installation	High melting rates can be obtained from small induction furnaces. No space is required for fuel storage and handling.
Better working environment	Induction furnaces are much quieter than gas furnaces, arc furnaces, or cupolas. No combustion gas is presented and waste heat is minimized.

1.4 Barriers to electrification

Fuel and other operating costs. The operating economics of electrified end uses relative to direct use of combustion fuels is a critical factor for uptake of electric technologies. Where commercially available electric and non-electric alternatives exist for a given end use, relative fuel prices often explain adoption decisions. See, for example, the case study on electric boilers in Section 4 of this report. The price of natural gas has dropped recently, while the cost of electricity has been flat or rising, making the relative cost of energy more unfavorable for electricity.

Capital costs of fuel switching. Similarly, the relative cost of installing electric and direct fuel technologies plays a critical role. Capital costs arise in a few ways, some more obvious than others.

- Generally, in order to electrify, existing direct fuel equipment needs to be replaced with electrically powered alternatives. The relative upfront costs of electric and direct fuel equipment vary. If the change-out occurs before the end of the useful life of the existing direct fuel equipment, this effectively raises the cost of the replacement.

- Converting existing direct fuel equipment to electric may require an upgrade to a building's electricity service feed to power the new equipment. This one-time change can be expensive enough[22] to deter otherwise cost-effective electricity conversion.
- Converting industrial equipment powered by direct fuel combustion to electricity can trigger a variety of other changes in an integrated industrial process. Requirements to develop and design potentially industry-specific systems and manufacturing lines would be a high barrier for medium and smaller sized companies. There is currently relatively little publicly-supported research, development, and deployment support for industrial electrification in general — and industrial electrified heating in particular — to help defray these costs (Greenblatt et al. 2012). A common issue is the waste heat generated from fuel combustion. Many industrial processes take advantage of this waste heat to power other processes. Combined heat and power (CHP) systems are a fully developed example of this. Electrically powered heating would not generate nearly as much waste heat, requiring either purchase of energy previously supplied at no cost or broader redesign of the process. On the positive side, electrified heating can offer process control, throughput, and higher product quality that in some cases (Lovins 2011) can outweigh higher costs of energy and potentially higher capital costs.

Availability of electric processes in industry. Most industrial processes are not currently designed to use electricity and electrified alternatives are not currently available for many applications, e.g., high temperature processes such as cement manufacturing.

Heterogeneity of industrial sectors. The industrial sector has a diversity of sub-sectors and products and a variety of process heating modules and applications. This diversity presents a barrier for widespread electrification in terms of process design, development, and conversion costs. Each industry sub-sector and product can have its own process heating requirements and product specifications that require application-specific designs and performance requirements for electrified processing. This design and engineering challenge is an especially difficult barrier for electrifying processes that have a high degree of process integration.

Consumer acceptance, familiarity, and risk aversion. Electric equipment and appliances do not provide identical amenities to their direct-fuel counterparts, which may cause consumers to avoid them even if the economics are favorable. For example, some people prefer to cook with natural gas; others prefer the more even heat of electric stoves. While natural gas heat is faster and more controllable than traditional electric ranges, electric induction heating is faster than gas and just as controllable – though it requires different cooking habits and different cookware.[23] Speed of heat provision can be an issue in many applications, particularly in industry. Risk aversion and lack of

[22] To accommodate electric space heating, TRC (2016) estimates a cost of $4700 to upgrade the service for an existing single-family building, $35,000 for a low-rise multifamily building, and $5800 for a small or medium office. The office upgrades do not require upgrades to the electrical panel, which is the most expensive item in the residential upgrades.
[23] See, for example, http://www.nytimes.com/2010/04/07/dining/07induction.html.

familiarity with new technologies can also be an issue, especially in industry. Electrification may introduce financial and operational risk to company business processes (Greenblatt et al. 2012). This is even more pronounced in low margin, commodity type industries such as glass, cement, and food processing. Anecdotally, for example, some glass companies have not significantly altered their process lines for a couple decades.[24] However, in many cases risk aversion may be surmountable — for example, see the case study on electric arc furnaces in Section 4.

Familiarity among builders and trades is also a factor. Equipment replacements upon failure have a strong tendency to happen "in kind" using the same fuel (Hopkins et al. 2017), perhaps in part because of the trades required. For example, only a plumber is generally required when replacing a gas water heater; switching to an electric water heater would also require the presence of an electrician (TRC 2016).

Building codes and equipment standards. Regulation affects the relative attractiveness of electric vs. direct-fuel options. The most notable cases are building energy codes and appliance and equipment standards. Codes can encourage one fuel or another in a variety of direct or indirect ways. See Section 3.6 for more on these energy regulations. Other (non-energy) regulations, such as health and safety regulations, may also affect fuel choice.

Electricity delivery infrastructure. Electrification increases the load on electricity delivery infrastructure. While incremental changes in specific buildings are unlikely to have impacts, extensive changes in large industrial facilities, or an accretion of smaller changes in the same area, could require distribution system upgrades (Hopkins et al. 2017, Mullen-Trento 2016) – and, in the long run, transmission system upgrades. Because some of the associated costs will be recovered from all of the utility's customers, distribution system upgrades to accommodate increasing electrification may not pose a barrier in the near term. However, system planners and policymakers should be mindful of the impacts.

Other factors. Many other factors may conceivably come into play. For example, electrically-powered end uses are vulnerable to power outages, which might discourage electrification. However, many direct-fuel furnace and water heaters have electric starters, so they are also non-functional if there is an electric outage. Greater electrification also puts more end uses at risk of cyber attacks on utilities and power infrastructure.

[24] Personal communication with James McMahon, 2011.

2. Electrification potential

2.1 Current trends

2.1.1 Buildings

Electricity's share of total energy usage in residential and commercial buildings has generally been increasing since at least 1960 as usage of electrically-powered devices (such as appliances and air conditioners) has grown.[25] However, this increase has been fairly gradual, and the U.S. Energy Information Administration's (EIA's) *Annual Energy Outlook* forecasts that it will be even more gradual in the future (Figure 1).

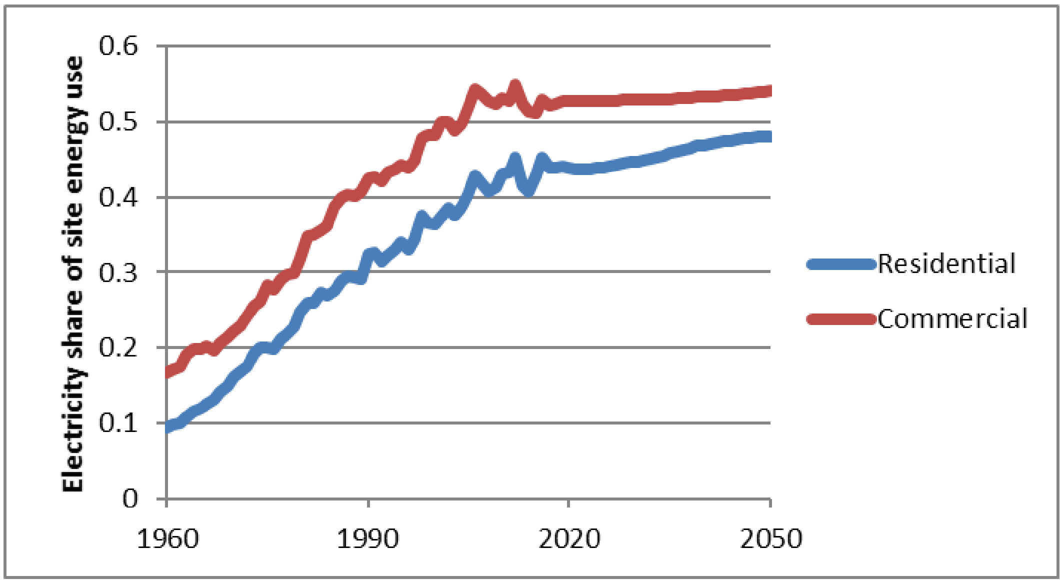

Figure 1. Electricity share of site energy use over time. Past data from the EIA's State Energy Data System (DOE SEDS 2017); future projections from EIA's Annual Energy Outlook Reference Case (DOE EIA 2017)[26]

Most commercial and residential end uses are essentially 100% electrified. The major exceptions are space heating, water heating, clothes drying, and cooking. Space heating uses the significant majority of non-electric energy in both residential and commercial buildings, as shown in Figure 2 and Figure 3 via Sankey diagrams. These diagrams depict the energy flows serving each sector and the end uses each energy type serves.

[25] While this increase likely predates 1960, EIA data go back only that far.

[26] Note that the Annual Energy Outlook's modeling allows for only limited fuel switching. More details for the AEO 2017 buildings demand modules can be found at https://www.eia.gov/outlooks/aeo/assumptions/pdf/residential.pdf and https://www.eia.gov/outlooks/aeo/assumptions/pdf/commercial.pdf.

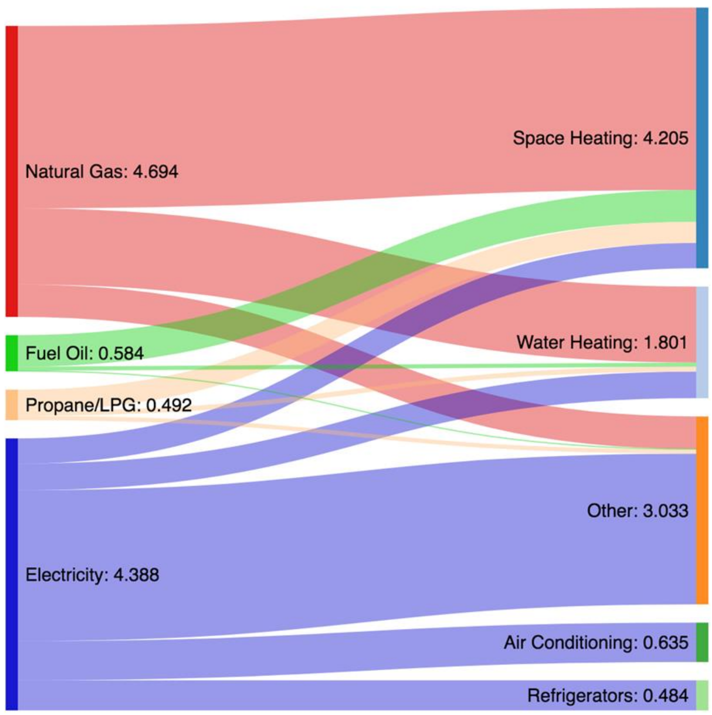

Figure 2. Usage of fuels by end use in U.S. residential buildings, in quadrillion BTU. Data from the Residential Energy Consumption Survey (RECS 2009). Note that cooking is not tracked as a consumption category in residential buildings and is included in "Other."

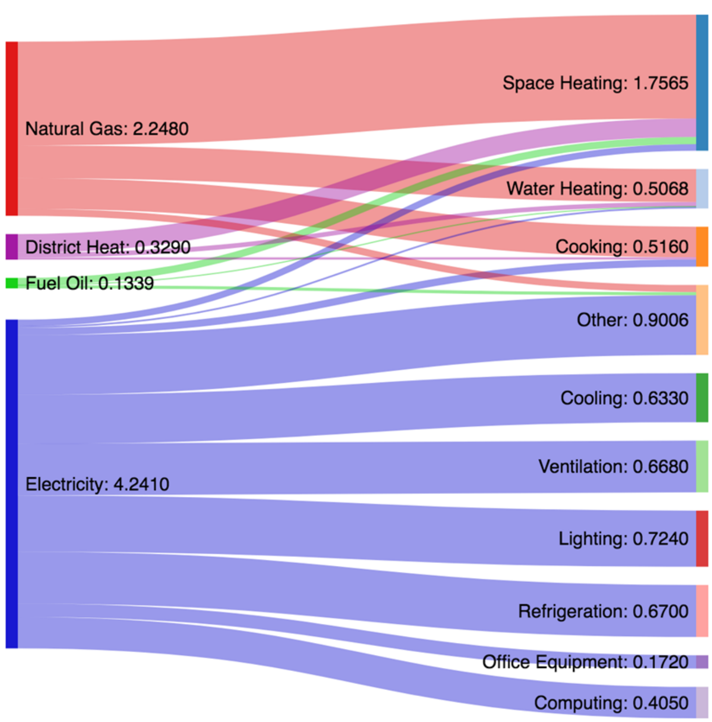

Figure 3. Usage of fuels by end use in U.S. commercial buildings, in quadrillion BTU. Data from the Commercial Buildings Energy Consumption Survey (CBECS 2012).

Space heating is the largest energy end use in buildings and is dominated by non-electric fuels. Figure 4 shows that few residential buildings use electricity as their only fuel, and most buildings that use non-electric fuels use them for space heating. The outlier is the South, where electricity already delivers a somewhat substantial share of space heating. The percentage of all-electric buildings appears to be increasing, especially in the South. However, even in the South, more than 75% of space heating energy use is non-electric; in all other regions at least 89% of space heating energy use is non-electric (RECS 2009). In commercial buildings, at least 93% of heating fuel usage in every region is non-electric (CBECS 2012).

Heat pumps account for 28% of all electric main household heating units and 10% of all total main household heating units (EIA RECS 2015). Both shares are slightly higher in the South (33% and 20%, respectively; EIA RECS 2015). Heat pumps were installed in 49% of new multifamily buildings and 38% of new single-family homes in 2012 (Lapsa and Khowailed 2014, as cited in Jadun et al. 2017), indicating their growing market share. In the South, heat pumps have accounted for more than half of main heating systems in residential buildings annually since 2004 (Baxter et al. 2014).

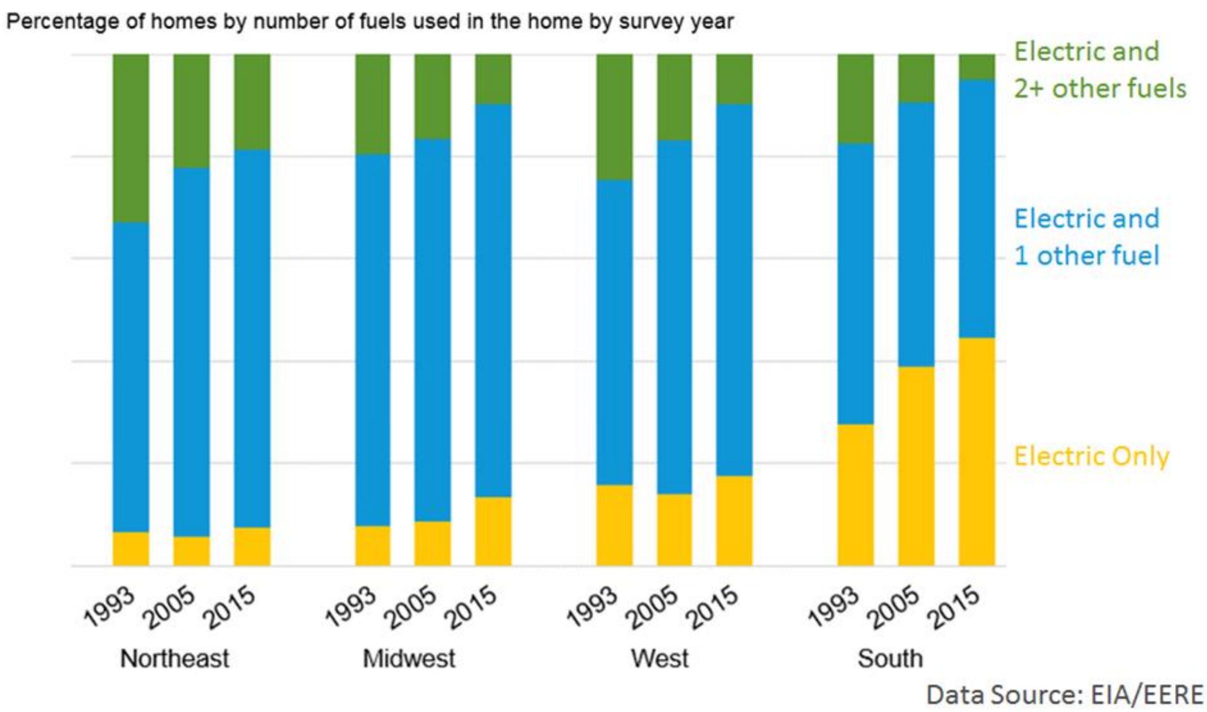

Figure 4. Share of residential buildings using electricity only vs. electricity and other fuels, by region over time. Source: RECS 1993-2015.

2.1.2 Industry

Figure 5 shows that retail electricity sales in industry have been quite stable since 1990 at 3,400 quads per year (about 1,000 TWh/year). Site-level fuel use in 2015 was at about the same level for the industrial sector as in 1990, and electricity retail sales were about 4% higher in 2015 than 1990.

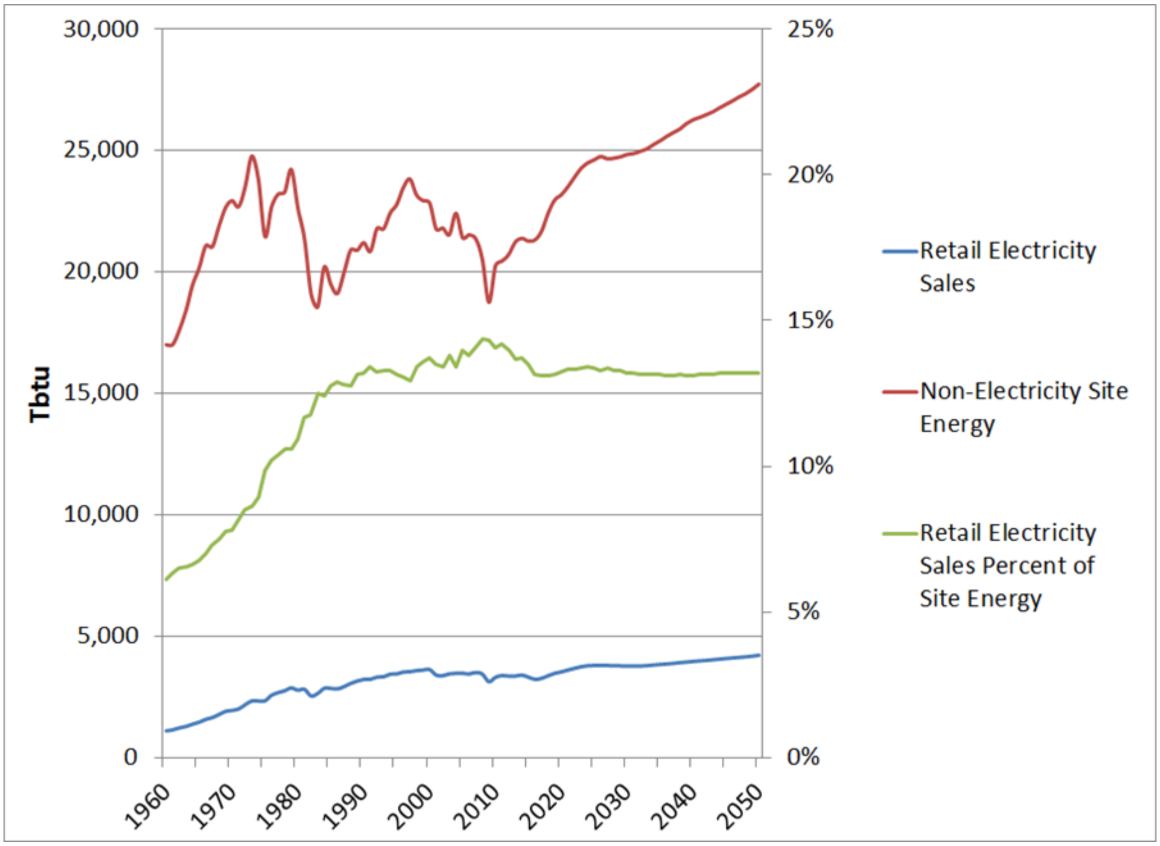

Figure 5. Electricity sales fraction in industrial sector from 1990 to 2015 and projections to 2050. Retail sales of electricity have been stable since 1990 at about 14% of site energy (about 1,000 TWh/year). Site energy use includes electricity and fuel consumption and onsite renewable energy use such as biomass.[27]

Figure 6 shows electricity and non-electricity fuel use by industrial sector in 2015 and projected demands in 2050 according to the *2017 Annual Energy Outlook 2017* Reference case. Electricity sales are only about 14% of site energy in 2017. High energy-consuming sectors (oil and gas refining, chemicals, and iron and steel) are dominated by non-electricity fuel use. The fraction of end-use electricity consumption is projected to be fairly stable from 2015 to 2050.[28]

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[27] https://www.eia.gov/totalenergy/data/monthly/pdf/sec2.pdf.

[28] Limited fuel switching assumptions were made in the AEO2017 industry demand module. More details for the AEO2017 industry demand module can be found at https://www.eia.gov/outlooks/aeo/assumptions/pdf/industrial.pdf.

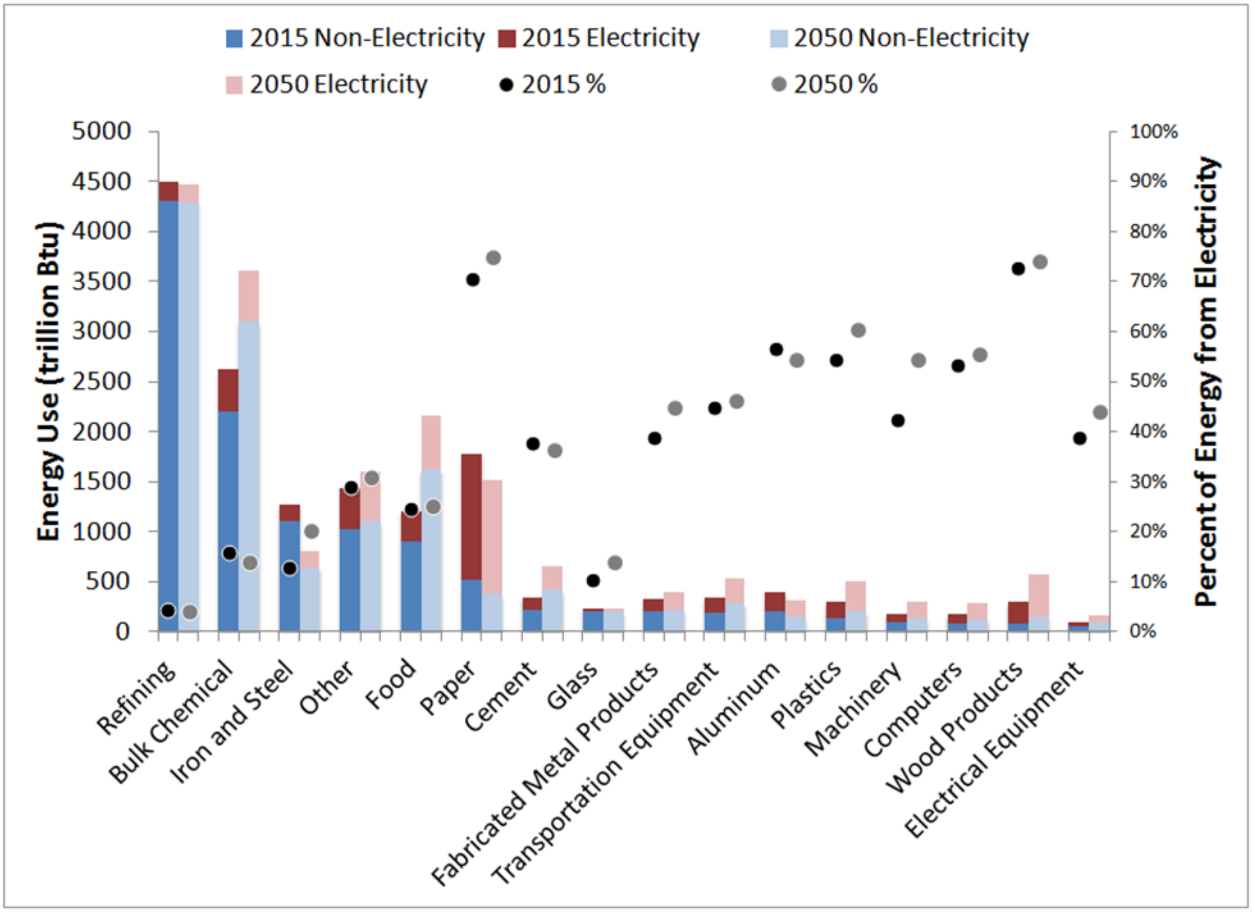


Figure 6. Electricity and non-electricity fuel use by industry sector in 2015 and projection to 2050 (EIA 2017)

A Sankey diagram for the manufacturing sector is shown in Figure 7. This provides an end-to-end pictorial depiction of the energy flows from primary energy to onsite generation (conventional boilers, combined heat and power, and electricity generation) to process and non-process energy (e.g. HVAC) to applied energy and energy losses. From this plot, in 2010, about 23% of process and non-process energy was for steam system fuel, 29% was process heating fuel, and 15% of energy was for electricity with about 33% for electricity losses. The fuel stream in the upper left represents the potential for electrification (fuel used for steam and fuel used for process energy).

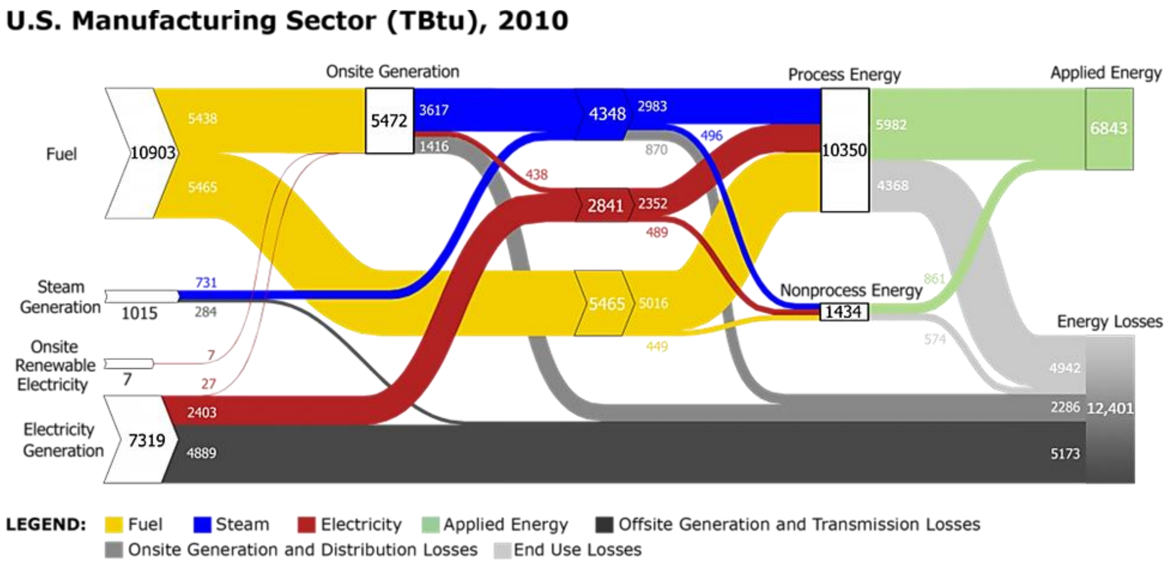


Figure 7. Sankey Diagram of US manufacturing sector.

Source: https://www.energy.gov/eere/amo/static-sankey-diagram-full-sector-manufacturing, accessed 11/20/17

Figure 8 shows the breakdown of non-electricity fuel use into end-use type (process heating, CHP systems, and boiler systems) by industrial sector. This breakdown has important implications for electrification potential. Also of note:

- Several sectors have a high CHP fraction of fuel use (e.g., paper, chemicals, petroleum, and food).
- Process heating dominates fuel use in many sectors (e.g., petroleum and coal products, primary metals, iron and steel, nonmetallic mineral products).
- Conventional boiler use is a relatively small fraction of overall fuel use.

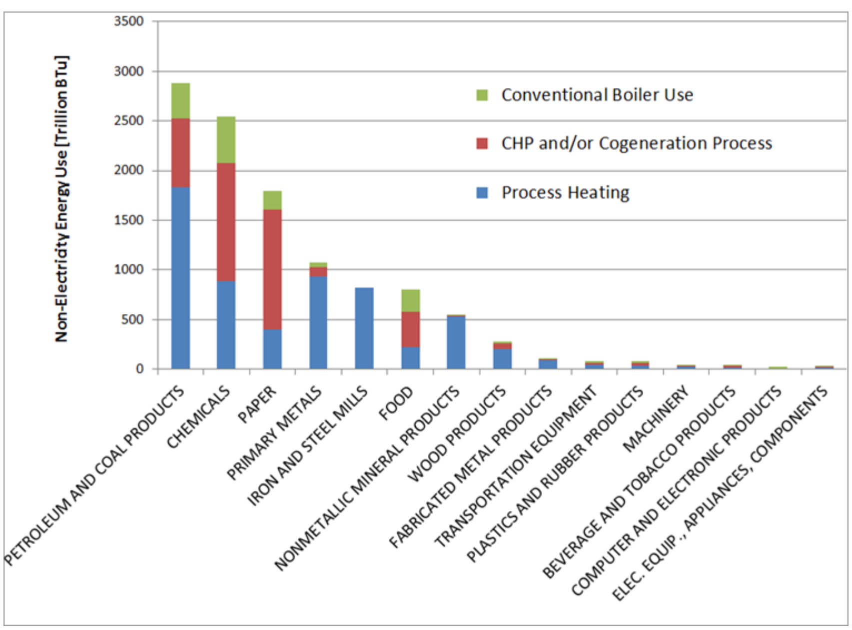
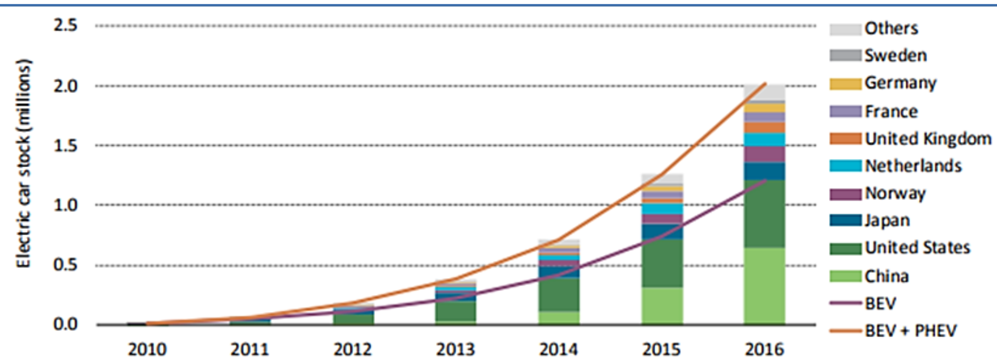


Figure 8. Breakdown of non-electric fuel uses by industry sector (EIA 2010)

Electrification of Transportation as an Indicator

Global electric car stock grew to an estimated two million vehicles in 2016, an estimated 0.17% of the global stock of 1.2 billion passenger vehicles worldwide. Global EV sales grew by 72% in 2015 and 41% in 2016; U.S. sales dropped by 5% in 2015 and grew by 37% in 2016. The U.S. had 503,167 electric vehicles (EVs) at the end of 2016, about 0.19% of the overall U.S. stock, with about half of all EVs in California.[29]

Increasing adoption of plug-in EVs offers load-shifting opportunities from flexible, controlled vehicle charging (Saxena et al. 2015). An additional degree of freedom and synergy in future energy systems is introduced with distributed storage that can offer flexible controlled charging and discharging back to the grid (Yilmaz and Krein 2013).



Notes: The electric car stock shown here is primarily estimated on the basis of cumulative sales since 2005. When available, stock numbers from official national statistics have been used, provided good consistency with sales evolutions.

Sources: IEA analysis based on EVI country submissions, complemented by EAFO (2017a), IHS Polk (2016), MarkLines (2017), ACEA (2017a, 2017b) and EEA (2017).

Figure 9. Global trend of electric vehicle car stock from 2010 to 2016.[30]

2.2 Technical potential for electrification

2.2.1 Definition

Technical potential for building electrification is the sum total of fuel-powered end uses that can be electrified today with existing technologies that are available on the market today. This definition is similar to that used in prior studies for technical potential of energy efficiency where "best in class" and existing technologies are included in a technical potential assessment. For example, advanced heating and cooling technologies that are largely in the research phase are not included, but an advanced heat pump that uses CO_2 refrigerant and is available on the market today is included.[31]

The definition for technical potential in industry is similar to that for buildings. However, the stipulation that the technology is available on the market today is less strict for industry since high temperature process heating currently is not widely deployed in the United States, although high temperature heating demonstrations have occurred (Orfeuil 1987).

[29] https://www.forbes.com/sites/rrapier/2017/02/05/u-s-electric-vehicle-sales-soared-in-2016/#5026a82d217f.
[30] https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf.
[31] According to EPRI, technical potential "represents the maximum, technically-feasible impacts that would result if the selected electric end-use technologies were to displace fossil-fueled technologies." (EPRI 2009)

For this report, our general approach for determining technical potential is to consult the literature for potential for electrification in the building and industry sectors and augment it with additional analysis based on available data, studies, and energy service requirements.

2.2.2 Buildings

In short, the technical potential for electrification in residential and commercial buildings is nearly 100% of all energy use in buildings. Space heating, water heating, and cooking account for the vast majority of direct fuel usage in residential and commercial buildings. Electric technologies exist, and are in use today, that can deliver similar services to direct fuel technologies for all of these end uses. Some other direct-fueled end uses – such as backup generators – may not have existing electrical substitutes, but these end uses represent a very small fraction of energy use in buildings.

As such, the primary challenges for electrification are economic. That does not mean, however, that there is no role for technological improvement. The rate of improvements in the performance and efficiency of electric space heating and water heating technologies – most notably, heat pumps – may prove critical to the economic prospects for electrification.

In the recent past, heat pump technologies were only considered an appropriate heating technology for relatively mild climates. However, cold-climate heat pump technologies have made considerable progress, and are now viable in nearly all U.S. climates.[32] Still, there are some places where the current crop of heat pump technologies is not suitable. Regardless, electric resistance technologies can be deployed in these locations, so electric delivery of heating in these climates is technically possible regardless of heat pump performance.

The academic literature on electrification pathways generally calls for high rates of electrification in the buildings sector:

- The model in Greenblatt et al. (2012) assumes that 70% of space heating in California buildings will be electrified by 2050.
- Williams et al. (2012) calls for 65% electrification of current direct fuels in California buildings by 2050.
- Wei et al. (2013) assumes 100% electrification of space and water heating in California buildings by 2050.
- Yang et al. (2014) foresees a 55% reduction of natural gas in California buildings by 2050 in two scenarios.
- In two U.S.-wide scenarios, Weiss et al. (2017) and Steinberg et al. (2017) assume that all U.S. residential and commercial end uses are electrified by 2050. Buildings sector electrification

[32] Per DOE's Quadrennial Technology Review, standard heat pumps lose 60% of their heating capacity and operate at half their full efficiency at -13° F, and generally begin to rely on backup electric resistance heating when temperatures drop below about 40° F. Cold-climate heat pumps supported by DOE's Building Technologies Office lose only a quarter of their capacity and efficiency at -13° F and accordingly can operate at temperatures well below zero without backup electric resistance heating.

alone increases 2050 electricity demand by more than 25% in the Steinberg et al. (2017) reference case.

Importantly, these studies develop scenarios – generally developed to meet specific policy goals – rather than forecasts or assessments of either technical or economic potential. Nonetheless, the studies generally reflect an understanding on the part of the analysts that these scenarios are feasible.

2.2.3 Industry

The overall technical potential for (direct) industry electrification is high, but there are significant challenges in cost and engineering development, especially for high temperature direct electrification processes such as cement production (see Section 1.4 above on electrification barriers). Potential for indirect industry electrification through electrolytic production of hydrogen is also high but also faces significant barriers in investment and infrastructure requirements and requires further technological development to reduce costs for hydrogen production and storage.

Although there are many U.S. and international studies on industry electrification, there is a lack of detailed techno-economic studies for industry electrification in term of process designs, efficiency, and "form values" for many industrial sectors and end-use applications. Existing estimates for industry electrification in the long term (e.g., 2050) are largely qualitative or at best semi-quantitative, and are largely insufficient to develop quantitative estimates for long term electrification potential, beyond the 100% technical potential quoted in many studies.

Depending on the production objectives in industry and varying policy frameworks (e.g., those emphasizing greater efficiency, decarbonization, improved air quality, etc.), industry electrification is one pathway that may work in combination with other pathways such as product redesign and product recycling, innovation in basic material formulations, greater biomass-fuel utilization or bioenergy, greater utilization of renewable energy for process heating (Vannoni et al. 2008), greater utilization of byproduct or waste heat for process heating (McMillan et al. 2016), and possibly carbon capture and storage in heavy industry (Brolin et al. 2017). Thus any assessment for the potential of industry electrification needs to be specific to the industrial application and to be evaluated in the context of other competing technological options. Ultimately it will be industry that is making these evaluations and decisions on how to meet their competitive production objectives and how best to comply with evolving policy guidelines.

2.2.3.1 Technical potential for direct electrification

Industry electrification generally is difficult for several reasons: some processes have no existing or currently available replacement; lack of data and proprietary information regarding existing industry practices; lack of data on whether new technologies can work; and the presence of older, functioning equipment that has already been amortized.[33] Further challenges stem from heterogeneity across sectors (e.g., food vs. oil vs. chemicals) and within sector (e.g., the chemical sector includes organic

[33] Eric Masanet, LBNL Seminar, IEA Energy Scenarios for 2050, August 2017.

chemicals, inorganic chemicals, fertilizers, and pharmaceuticals). In addition, the industrial sector is dynamic. Although overall industry primary energy level has remained fairly stable since 1990, it masks changes within sectors.

Several studies in the US and Europe looked at technical potential (Long et al. 2011, Williams 2012, European Climate Foundation 2010, Wei et al. 2013) for industry fuel-switching and concluded that the electrification of building and industry heating (boiler systems and process heating) is critical for long-term decarbonization, in conjunction with the transition to a low carbon electricity supply. However, these studies generally are at a high level of analysis or are “top down” analyses of industry efficiency and electrification potential, without detailed quantification of individual sectors or costs associated with a large-scale transformation to electrified heating. Other recent studies that include discussion of industry decarbonization do not cover or discuss industry electrification in any detail.[34] There is an acute lack of public cost data associated with electrified heating for industry.

International studies also quote the potential for long term industry electrification without details on process designs or cost effectiveness. For example a recent study on industry decarbonization in China (Khanna et al. 2017) includes reducing fossil fuel consumption in the glass sector by replacing 30% of fossil-fuel fired melting with electricity by 2050, but the UK study on which this is based (UK 2015) does not provide details on the electrification equipment, energy consumption or cost effectiveness analysis. Similarly a recent European study from 2017 on industry electrification is more a technology roadmap and scoping document than one that contains detailed technical or economic potential (Brolin et al. 2017).

For industry, the basic building-block technologies of electrical heating exist but are not widely deployed in most industrial applications. Deployment is technically possible for all industrial applications (Schmidt 1984, Lovins 2011), but the process equipment and process designs for many industrial applications tend to be limited (Brolin et al. 2017).

Table 2 summarizes technical electrification potential of the industrial sector analyzed in three recent studies. Overall the potential is seen to be very high for the high-temperature process heating sectors shown here (cement, glass, iron and steel), and thus the technical potential in lower temperature process heating sectors not shown here is also essentially 100%. Note that for iron and steel, the 21% potential in the Steinberg et al. 2017 study is due to projected future limitations in recycled steel supply but this is expanded to 100% in the other two studies with the inclusion of other electrotechnologies such as electrowinning.[35]

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[34] Napp et al. (2014) has very little on electrification. Similarly, Åhman et al. (2016) is primarily a policy-based discussion. MacKay (2013) is supply-side focused and does not discuss how to electrify industry. Pye et al. (2015) mentions some challenges to industry electrification in the context of decarbonizing the U.K.’s energy system, but does not discuss specific processes or industry sectors.

[35] Electrowinning refers to the reduction of iron ore by transformation of ore into metal and oxygen using only electrical energy and is a less mature technology.

Table 2. Electrification potential summary of three recent industry electrification studies.

Sector	Direct Electrification of Process Heating -- Potential by 2050	Reference	Technologies
All sectors – conventional boilers	100%	Steinberg et al. (d)	All conventional boilers electrified
Cement	100% (a)	Lechtenböhmer et al. 2016; Purr et al. 2014	Electrification of end uses (e.g., plasma-based heating), electrolysis production of hydrogen, and renewable natural gas production for fuel
Chemicals	100%	Steinberg et al. 2017(d)	Industrial process heat pumps
Chemicals (chlorine and ammonia)	100% (b)	Lechtenböhmer et al. 2016	Electrification of end uses, electrolysis production of hydrogen
Chemicals (petrochemicals)	0% (c)	Lechtenböhmer et al. 2016	No direct electrification; fossil fuels replaced by electrolysis production of hydrogen and renewable natural gas production for both process fuel and petro chemical feedstocks
Food	100%	Steinberg et al. 2017(d)	Industrial process heat pumps
Food	100%	Purr et al. 2014	Various electro technologies
Glass	100%	Steinberg et al. 2017(d); Lechtenböhmer et al. 2016; Purr et al. 2014	Electrification of end uses, resistance heating and melting
Iron and steel	21%	Steinberg et al. 2017(d)	Electric arc furnaces
Iron and steel	100%	Lechtenböhmer et al. 2016; Purr et al. 2014	Electric arc furnaces, electrowinning; plasma or induction ovens for smelting
Lime	100%	Lechtenböhmer et al. 2016	Electrification of direct end uses
Metal fabrication	100%	Steinberg et al. 2017(d)	Induction heating
Metal fabrication (foundries)	> 50%	Purr et al. 2014	Electric furnaces
Nonferrous metals, excluding aluminum	100%	Steinberg et al. 2017(d)	Electrolytic reduction
Pulp and paper	100%	Steinberg et al. 2017(d)	Industrial process heat pumps

(a) Purr et al. 2014 describes the transition away from fossil fuel-based heating in the production of cement to a combination of electrification of direct end uses, electrolysis production of hydrogen, and renewable natural gas production for fuel. Electrification potential is quoted as 100% here, because this report also states that high temperature furnace processes for cement can be fully electrified.

(b) Electrolysis-produced H2 is used as a feedstock for ammonia.

(c) Zero direct electrification of end uses is assumed, but electricity is used extensively for hydrogen and syngas/Fischer-Tropsch naphtha production.

(d) Steinberg et al. 2017 recently modeled the impact of high electrification of end uses by 2050 on the US electricity grid. The Steinberg et al. study is largely based on market potential analysis conducted by the Electric Power Research Institute (EPRI 2010). The "high electrification scenario" in Steinberg et al. assumes the following: (i) all conventional boilers converted to electric boilers by 2050; and (ii) all process heating is 100% electrified by 2050 in the following sectors: electrolytic reduction of nonferrous metals (excluding aluminum), induction heating for metal fabrication, resistance heating and melting for glass, and industrial heat pumps in the food, pulp and paper, and chemicals sectors. Iron and steel is assumed to be 21% electrified by 2050. This cap is due to "the nascence of the arc furnace production route and the limits to available scrap that would be required for expanded arc furnace production." Key electro-technologies include induction melting, resistance heating and melting, and heat pumps.

For comparison, EPRI provides estimates for near-term fuel switching potential (EPRI 2009). High adoption technologies in 2030 are electric boilers, heat pump space heating, induction melting, and electric arc furnaces, similar to Table 2. Technical potential energy savings in 2030 results in 1.27 quads of savings out of 35 quads of total primary energy, or a 3.6% savings in primary energy. The EPRI report estimates are based on the organization's judgment and industry experience; economic analysis was out of scope. "Realistic potential" based on this engineering criteria is 0.802 quads of savings, or a 2.3% savings in primary energy. The EPRI study is not fully disaggregated by sector — e.g., only a few distinct sectors are mapped to electro-technology potentials (Paper, Wood, Textiles, etc.; Primary Metals, and Other). Table A-1 in Appendix A shows the realistic and technical potential market adoption by electric end use assumed in the EPRI study.

2.2.3.2 Oil Refineries

Oil refineries are not included in Table 2. There are two immediate difficulties for electrification of oil refineries and a looming one for the future. First, the high degree of process integration in oil refining would require major process re-design and re-engineering. Second, refineries "own-use" energy is extremely high — in other words, the energy required to make refined oil products uses byproducts in the refining process. Not using these products would constitute a major issue for oil refinery electrification in terms of energy costs, energy utilization, and capture. More globally, recent policy directives phasing out the sales of internal combustion engine vehicles by 2040 in France and Great Britain (Castle 2017) and movements in that direction in Germany (Schmitt 2016) may impact future overall petroleum product demands, and more widespread global policy changes may make major investments in overhauling oil refinery processing an even larger hurdle.

2.2.3.3 Power-to-Gas and Long-Term Energy Scenarios from the EU

Germany has developed a broad road map to achieve economy-wide greenhouse gas (GHG) neutrality by 2050 (Purr et al. 2014). The road map addresses the difficulty in transitioning industrial uses to 100% electrification through "power-to-gas" pathways that increase demand for electricity in part through electrification of industrial end uses and provide an alternative to conventional natural gas and electricity as a source of heating energy. The first pathway is to produce renewable H2 with electrolysis using wind, solar, and other renewable sources of electricity. The second pathway is to generate "renewable natural gas" from H2 and CO2 inputs with a methanation process (Figure 10). A source of CO2 is needed for this process and could be provided by CO2 capture from fossil fuel combustion, biomass gasification, waste, or atmospheric CO2 capture. The resultant renewable natural gas can be fed back into the natural gas pipeline and used for heating applications in buildings or industry, or converted to electricity with turbines or CHP systems. As mentioned in Section 1.2, we do not highlight indirect electrification of buildings with power-to-gas pathways since there are more economic direct electrification opportunities and existing technologies on the market for electrifying building heating.

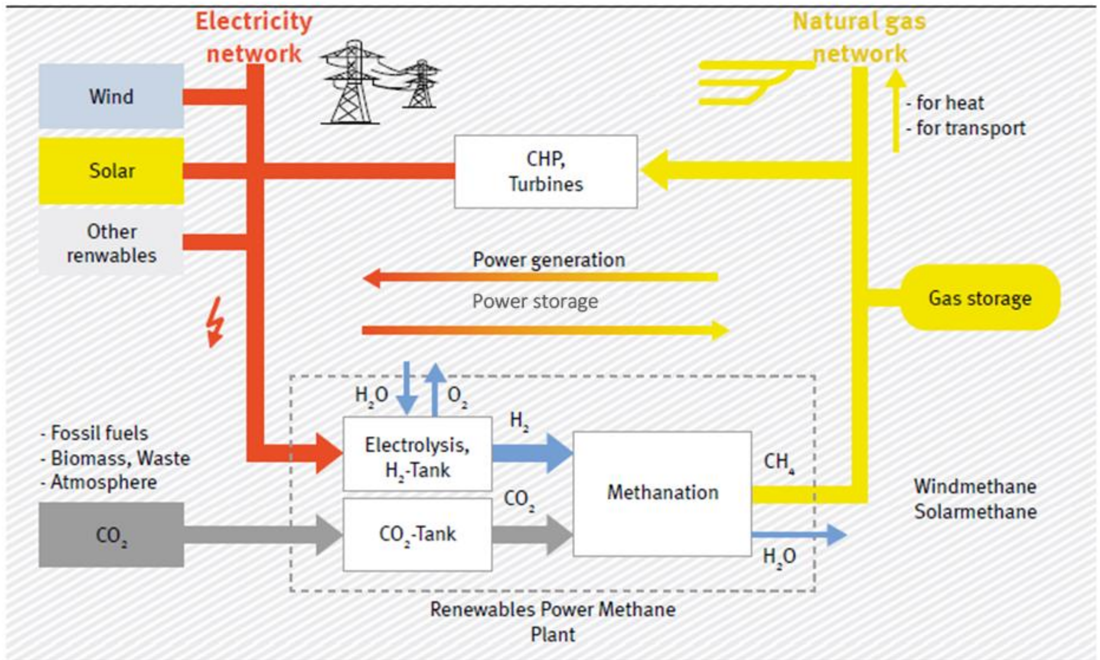

Figure 10. Indirect electrification of industry and building sectors by electrolytic production of hydrogen (Purr et al. 2014)

Hydrogen Produced By Electricity

While predominantly produced today through the decomposition of natural gas through the process of steam-methane reforming, hydrogen can also be produced by electricity via the electrolysis of water into oxygen and hydrogen with a similar efficiency. Electrolytically produced hydrogen can be used as a transportation fuel for fuel-cell powered vehicles; as a direct substitute for natural gas-fired heating equipment either from onsite production of hydrogen gas (H2) or from injection of H2 into the existing natural gas pipeline; or as an industrial feedstock (e.g., in the production of ammonia (NH3), a critically important industrial chemical largely used for fertilizer). Hydrogen produced by renewable electricity resources would provide a clean energy carrier for transportation and industry, and electrolytic H2 production has important potential benefits for the electricity grid as a large flexible load during low-cost, off-peak hours. While a detailed treatment of hydrogen is out of scope for this report, hydrogen pathways are active areas of research and development at the U.S. Department of Energy (DOE).[36]

This technical vision relies on several factors to mitigate the difficulty in fully electrifying industry:

- Ability to make use of existing end-use equipment and existing natural gas distribution system
- Potential use of the gas pipeline network for energy storage of excess electricity
- Plentiful, economic, and sustainable electricity resources to make hydrogen
- Collection and appropriate distribution networks for H2 and captured CO2
- A large scaling up of H2 production, CO2 collection and methanation

[36] See, for example, https://www.hydrogen.energy.gov/pdfs/review17/tv043_saxena_2017_o.pdf and presentations by Bryan Pivovar and Mark Ruth at https://www.hydrogen.energy.gov/annual_review17_validation.html.

Currently, renewable natural gas is several times more expensive than conventional natural gas (Gotz et al. 2016).

Hydrogen production from water electrolysis can be used for multiple purposes:

- *Direct fuel for transportation vehicles.* These include passenger vehicles that have already been introduced to the market (e.g., Toyota Mirai and Hyundai Tucson) and potentially heavy duty trucks in the future. Recent demonstrations have shown the viability of hydrogen powered heavy duty trucks (IEA 2017).
- *Direct feedstock replacement in industrial processes* — e.g., NH3 hydrogen feedstock rather than H2 produced from natural gas
- *Feedstock production for synthetic natural gas and petrochemical feedstock replacement*
- *Potential long-term energy storage* — e.g., excess production of electricity from renewable energy sources can be stored as H2 to reduce or eliminate curtailments and then returned to the electricity system

Lectenbohmer et al. 2016 examines the technical potential for direct electrification of end uses, electrolysis production of hydrogen, and renewable natural gas production to reduce use of fossil fuels in the EU basic materials industry (steel, cement, glass, lime, petrochemicals, chlorine, and ammonia) and concludes that it is technically possible. Renewable H2 is used for fuel and also for feedstock to produce hydrocarbons such as methane as in Figure 10, in addition to other intermediate products such as methanol and Fischer-Tropsch-naptha (FT-naphta). These would replace the petrochemical feedstocks currently derived from fossil fuels for products such as polyethylene and PVC. Renewable H2 is also assumed to replace fossil-fuel derived H2 as a feedstock in the production of ammonia. The carbon required to produce replacement hydrocarbons is assumed to be either captured CO2 from power plants, from the CO2/CO portion of syngas (CO2/CO + H2), or from air-capture. The study assumes that high temperature processes in cement and glass can be fully electrified, but does not provide details regarding the transition, timing, implementation, process equipment, or economic costs of the transition.

Table 3 provides a summary of energy consumption and feedstock energy in the industrial production of basic materials. Energy consumption in 2010 reflects heavy fossil fuel consumption for both fuel use and feedstock, while 2050 presents a technically possible scenario with indirect electrification and heavy utilization of hydrogen as both a fuel and feedstock. End use electricity consumption for basic materials increases by a factor of more than 10, from 125 TWh to 1,713 TWh, assuming a similar production volume of basic materials in 2050 as 2010. Overall consumption of electricity for all industrial sectors (including for production of basic materials) is projected to increase during that timeframe from 1,000 TWh to 2,588 TWh, or by 159% (Lechtenbohmer et al. 2016).

These results can be viewed as a rough proxy for 2050 electricity demands in the U.S., assuming these types of pathways, based on two key observations: (1) overall US production in 2015 was about 1,158 TWh, similar to the EU's 1,000 TWh and (2) the relative mix of fossil fuels to fossil fuel feedstock for basic materials is similar in the US to the EU (63% of total non-electricity fuel energy consumption in US in 2010 vs 56% in the EU).

Table 3. Fuel switching in the industrial production of basic materials (Lectenbohmer et al. 2016). Energy consumption in 2010 reflects heavy fossil fuel consumption for both fuel use and feedstock, while 2050 presents a technically possible scenario with indirect electrification and heavy utilization of hydrogen as both a fuel and feedstock.

2010 Basic Materials		2050 Basic Materials	
125	TWh electricity	513	TWh electricity
851	TWheq fossil fuels	106	TWh for direct H2 energy use
671	TWheq fossil fuel feedstock	671	TWh for hydrocarbon feedstock production
		423	TWh from H2 production energy loss
1,647	TWh total (including TWheq)	1713	TWh total

2.3 Economic potential for electrification

2.3.1 Definition

Economic potential for buildings electrification is the sum of all fuel-powered end uses for which economically attractive electric alternatives exist. By “economically attractive” we mean that electric technologies have reached approximate lifecycle cost parity with fuel-powered alternatives while providing similar services. The specific economics in any given building or industrial application vary based on a number of factors, as we review below. Careful study is therefore needed to clarify which option is lower cost in a given case.

2.3.2 Buildings

As noted in section 2.2.2, given the current commercial availability of electric technologies for all building end uses, the relative economics of electric and direct fuel options is of central importance to potential progress on electrification.

2.3.2.1 Local studies of economic potential

Mullen-Trento et al. (2016) assess the economics of fully electric (space, water, clothes dryer, and cooking) and mostly electric (with gas heating) new homes in the service area of Sacramento Municipal Utility District (SMUD). The researchers account for differences in costs to builders, homeowners, and SMUD, and consider capital costs of equipment and appliances, costs of extending gas or electric service to the household, distribution system costs to SMUD, home energy costs, and revenues to SMUD. They model load shapes from the homes and match these to SMUD rate schedules and marginal costs to estimate operating costs and revenues. The study assumes air source heat pumps with a Heating Seasonal Performance Factor of 8.5 and heat pump water heaters with an Energy Factor of 3.4.

As Table 4 shows, the study concludes that the all-electric home is cheaper for the homeowner, the builder (in the presence of a small incentive), and SMUD. The all-electric home satisfies each of several different cost-effectiveness tests. For all-electric homes, the study finds an incremental upfront cost to builders of $127. The higher builder cost of electric induction cooking is approximately offset by avoided neighborhood gas infrastructure costs, and the cost of electric service upgrades is offset by avoided in-home gas infrastructure. While the electric heat pump heating and water heating units are more expensive than their gas alternatives, lower installation costs plus the avoided cost of a separate air conditioning unit almost completely offset this difference. Consumers, who purchase and install electric resistance dryers rather than gas dryers, enjoy upfront savings of $290. Annual maintenance is $69 lower for the homeowner, and annual total energy costs are $94 less. The electric home receives a lower Time-Dependent Valuation score, reflecting superior compliance with California building energy codes. The estimated incremental distribution system cost to SMUD is $100 per home for labor and equipment required to add transformers to supply the increased load. Assuming a $500 builder incentive for a SMUD pilot (more than sufficient to offset the additional builder costs), the study estimates 15-year additional revenue to SMUD of $2,272 per home.

It is important to note that SMUD is an electric-only utility, and the study does not consider impacts to the gas utility whose service would be displaced. Also, the study contemplates a new home, with the attendant ability to avoid neighborhood and in-home gas service costs – though the mostly-electric option does require some gas infrastructure and is still cost-effective. Finally, the study estimates additional potential savings of $24 per year from shifting load to less expensive times using the heat pump water heater (see the case study on water heaters and demand response in Section 4). Most values in the SMUD analysis are estimated or modeled. The utility is currently conducting a pilot program to assess outcomes in the field.

TRC (2016) evaluates the economics of heat pump space and water heating in a variety of residential and commercial building types in Palo Alto, California. The study accounts fully for the details of the City of Palo Alto Utility District electric and gas rates. It accounts for in-building electric service requirements and potentially avoided costs of natural gas infrastructure, but does not consider potential costs of electric distribution system upgrades outside the building. The study considers both new build and retrofits. It does not consider the utility's perspective, except as part of a societal cost-effectiveness test. Residential space heating is provided by an air-source heat pump with Heating Seasonal Performance Factor of 8.5; commercial HSPFs are not specified. Heat pump water heaters have an Energy Factor of about 3.2.

Table 4. Results from SMUD All-Electric Homes Deep Dive (Mullen-Trento et al., 2016)

	Equipment	Install	Flue	TOTAL	Incremental Installed Cost to Builder	Incremental Cost to Customer	Annual Maintenance Cost	Incremental Maintenance Cost
Baseline HVAC (gas heat)	$4,800	$375	$100	$5,275	$25	N/A	$100	$0
ASHP	$5,300	$0	N/A	$5,300			$100	
Base Tankless Gas Water Heater	$1,346	$530	$100	$1,976	-$4	N/A	$85	$69
HPWH, 50 Gallon	$1,862	$110	N/A	$1,972			$16	
Baseline Gas Cooking	$823	$100	N/A	$923	$1,056	N/A	-	$0
Electric Cooking, w/ Induction	$1,879	$100	N/A	$1,979			-	
Baseline Gas Dryer	$1,000	$160	N/A	$1,160	N/A	-$290	-	$0
Electric Dryer	$760	$110	N/A	$870			-	
Electric In-home Infrastructure (panel and two extra circuits)				$600	$50	N/A	N/A	N/A
Gas In-home Infrastructure (pipes and stub four end uses)				$550			N/A	N/A
Electric Neighborhood Infrastructure				$0	-$1,000	N/A	N/A	N/A
Gas Neighborhood Infrastructure				$1,000			N/A	N/A
Total Incremental Cost					$127	-$290	-	$69

Note: Green shaded are BEopt new costs (from model, not database), yellow shaded are from AEO2015. Other data is based on builder input. In all cases these numbers are in line with the information gathered from builders, P170 research, BEopt, and *AEO2015* modeling inputs.

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	Cumulative 15-yr Per Home	Cumulative 15-yr Development Total
Revenue (NPV)	$4,158	$145,541
Present Worth of Lifetime Net Marginal Generation Costs	$1,286	$45,004
Electric Infrastructure Upgrade Cost	$100	$3,500
Builder Incentives	$500	$17,500
Total SMUD Net Revenue (NPV)	**$2,272**	**$79,537**
CO2 Savings – Societal Benefit	29 tons	1,015 tons

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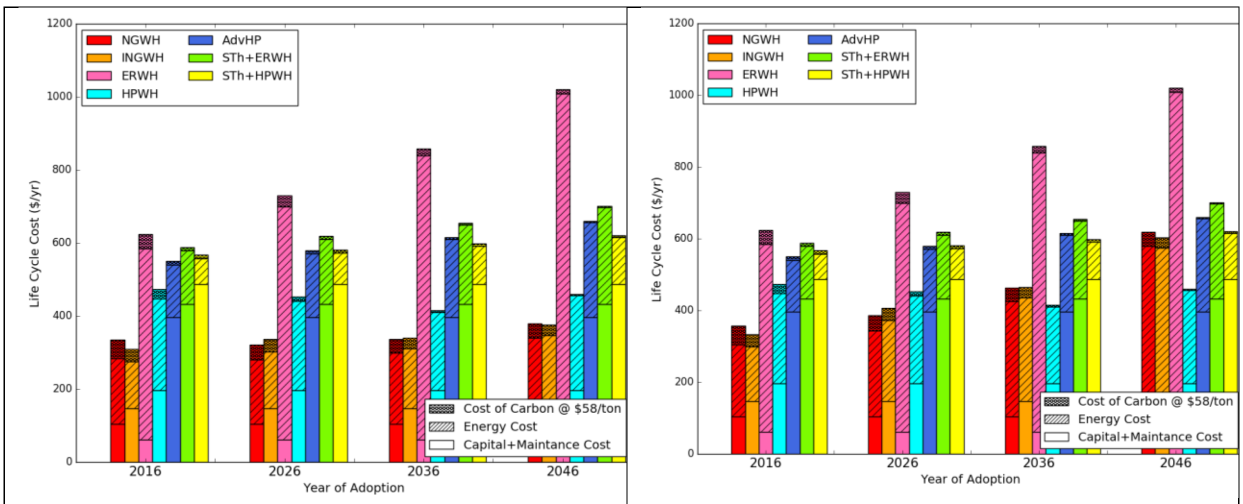
Among the study's findings:

- Considered in isolation, heat pump space heating is cost-effective for customers in new single-family homes and in both new and existing multifamily homes. Heat pump space heating is not cost-effective in existing single-family homes (though it is quite close) or in small or medium office buildings.
- Heat pump water heating is only cost-effective in new medium-size office buildings (though it is quite close in new small office buildings).
- A package of both heat pump space and water heating is cost-effective from the customer's perspective in new single- and multifamily buildings and in small office buildings if a gas connection can be avoided, but is not cost-effective if a gas connection is still required.

The Sacramento and Palo Alto studies demonstrate that electrification with heat pump technologies is cost-effective now in certain circumstances. These technologies are likely to be more cost-effective in new buildings than in existing buildings. Avoiding the need for a gas connection promotes cost-effectiveness, though it is not always necessary to achieve cost parity. And the Palo Alto study suggests that heat pump technologies are more often cost-effective for space heating than for water heating, at least in residential buildings.

A recent University of California Berkeley/Berkeley Lab study on water heating decarbonization in California (Raghavan et al. 2017) describes several scenarios to decarbonize residential water heating in 2050 to meet the state's 80% greenhouse gas reduction target in 2050. The study estimates customer life-cycle costs (capital, fuel, and maintenance costs) for several water heating technologies: conventional natural-gas heating, tankless natural-gas water heating, heat pump-based water heating, advanced heat pumps, electric resistance heating, and solar thermal water heating. While heat pump water heating is more expensive today than natural gas-based heating, cost reductions and efficiency improvements in heat pump water heaters are expected from economies of scale and technological learning in high-heat pump deployment scenarios. The overall cost of heat pump water heating electrification scenarios will depend on future cost reductions in heat pump-based equipment, energy prices, equipment lifetime, and hot water consumption. For example, if natural gas and electricity prices both increase by 2% per year, heat pumps will continue to be more expensive than natural gas water heaters, while heat pump water heaters can reach cost parity in about 2030 for a higher annual increase in natural gas prices (4%) vs. electricity prices at 2% per year (Figure 11).



(a)	(b)

Figure 11. (a) Annual estimated life-cycle cost ($/yr) for various water heating technologies for natural gas and electricity price increases of 2% per year. (b) Annual estimated life-cycle cost ($/yr) for various water heating technologies for natural gas price increase at 4% per year and electricity price increase at 2% per year. NGWH is natural gas water heater; INGWH is instant (tankless) natural gas water heater; ERWH is electric resistance water heater; HPWH is heat pump water heater; AdvHP is advanced heat pump water heater; STh is solar thermal water heater. Source: Raghavan et al. (2017)

All three of these studies were conducted in California and may not be broadly applicable to other parts of the country.[37] California experiences mild winters, and heat pump technologies are more

[37] Both studies are also recent, and therefore conducted at a time where natural gas prices are low relative to electricity prices; if prices change, so might cost-effectiveness results.

efficient in these climates. On the other hand, California utilities – including those that serve Sacramento and Palo Alto – charge higher prices per kilowatt-hour for electricity and lower prices per therm for natural gas than the U.S. average, making the economics of electrification there more challenging.

2.3.2.2 National studies of economic potential

Wilson et al. (2017) considers electrification of existing single-family residential space and water heating on a state-by-state basis, accounting for highly granular variation in weather (216 climate locations), existing equipment stock, and consumer energy prices (utility-specific rates). The analysis shows that almost one-third of the potential additional electricity demand from residential space heating electrification is economic – having a positive net present value for the household.

According to Wilson et al., the significant majority of this economic potential is in the Northeast (Figure 12). There is a good deal of technical potential in the Northeast, due to high heating loads and a dense population. Additionally, the economics of equipment replacement are stronger when replacing fuel oil furnaces and water heaters than when replacing gas furnaces (Figure 12). The Northeast is the only region of the country where fuel oil boilers and furnaces are common. The Midwest also has high technical potential, but relatively low economic potential in the absence of existing fuel oil technologies. Working against the economics of heat pump electrification in the Northeast are the region's cold winters. The study does consider climate, however, concluding that replacing fuel oil systems with heat pumps is cost-effective even in cold climates.

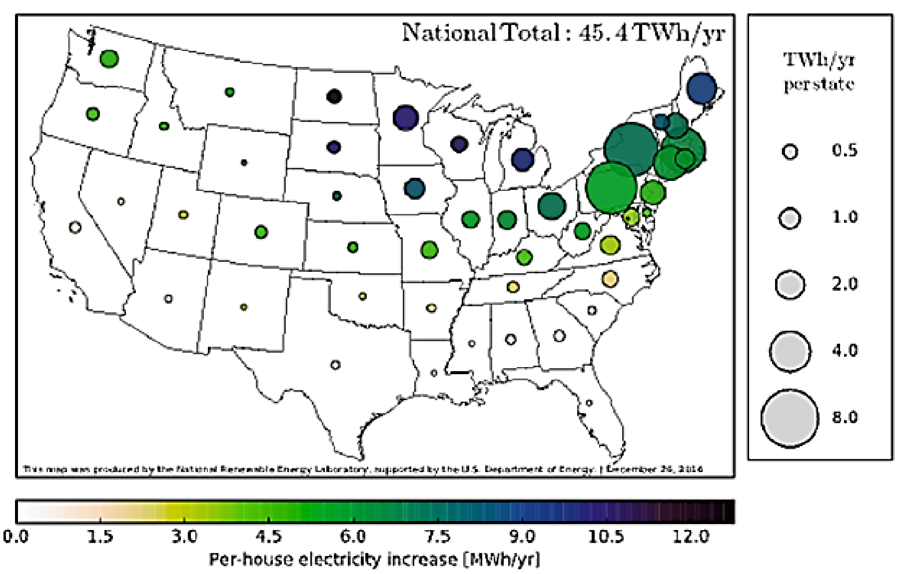


Figure 12. Increased electricity demand from cost-effective electrification. Source: Wilson et al. (2017)

Figure 13, from Wilson et al. (2017), also emphasizes the fact that the economics of heat pump adoption are much stronger when it displaces an air conditioner in addition to – or instead of – a furnace or boiler. Mullen-Trento et al.'s (2016) analysis of electrification in SMUD territory – discussed above – also makes this point. While some studies have shown electrification of space heating is more cost-effective in new buildings, Wilson et al. (2017) shows that it is often cost-effective in existing buildings with worn out air conditioners – such that both heating and air conditioning are replaced at the same time – even if the residence originally had a gas furnace.

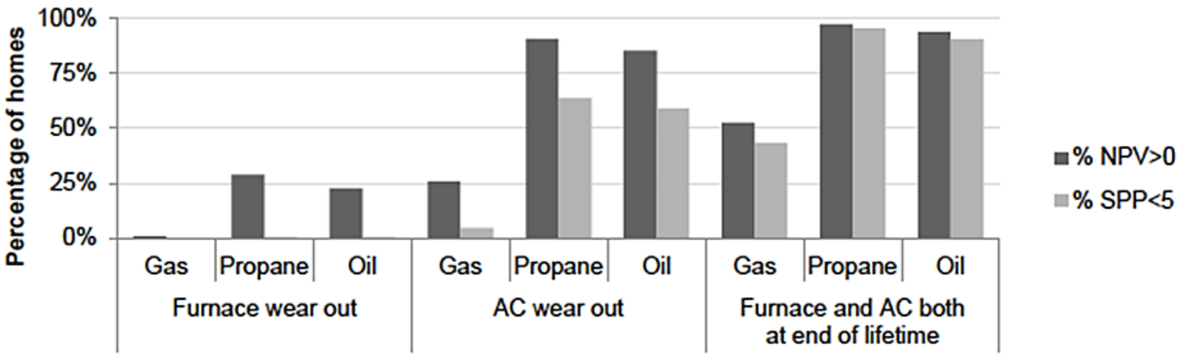


Figure 13. National percentage of homes passing cost-effectiveness thresholds for replacement of furnace/air conditioner with variable-speed heat pump, under three wear-out scenarios. Source: Wilson et al. (2017). NPV>0 means that the lifetime cost of a heat pump replacement is positive considering both capital and operating costs. SPP<5 means that the simple payback period for the heat pump is five years or fewer, again accounting for both capital and operating costs. The analysis assumes a variable-speed heat pump with a SEER of 22 and a HSPF of 10. SEER is Seasonal Energy Efficiency Ratio (a cooling metric); HSPF is Heating Seasonal Performance Factor.

The Wilson et al. study finds that oil-to-heat pump water heating replacements are generally not cost-effective. The study does not analyze gas-to-heat pump water heating "because previous analysis determined that these upgrades were rarely cost-effective."[38]

Nadel (2016) also examines the economics of residential heat pumps for space and water heating in 16 states and two regions (each with two states), accounting for state or regional differences in climate and energy prices including seasonal price variation. Relative to natural gas furnaces, this analysis finds that the economics of heat pump replacements are generally favorable in warm states where they can avoid the capital cost of both an air conditioner and a furnace, though they are never favorable where they do not offset air conditioning capital costs. Figure 14 presents these results.

[38] The study does find that propane-to-heat pump water heating upgrades are cost-effective about 50% of the time; however, propane-fueled water heaters have a smaller share of the market than fuel oil water heaters, and a much smaller share than gas water heaters.

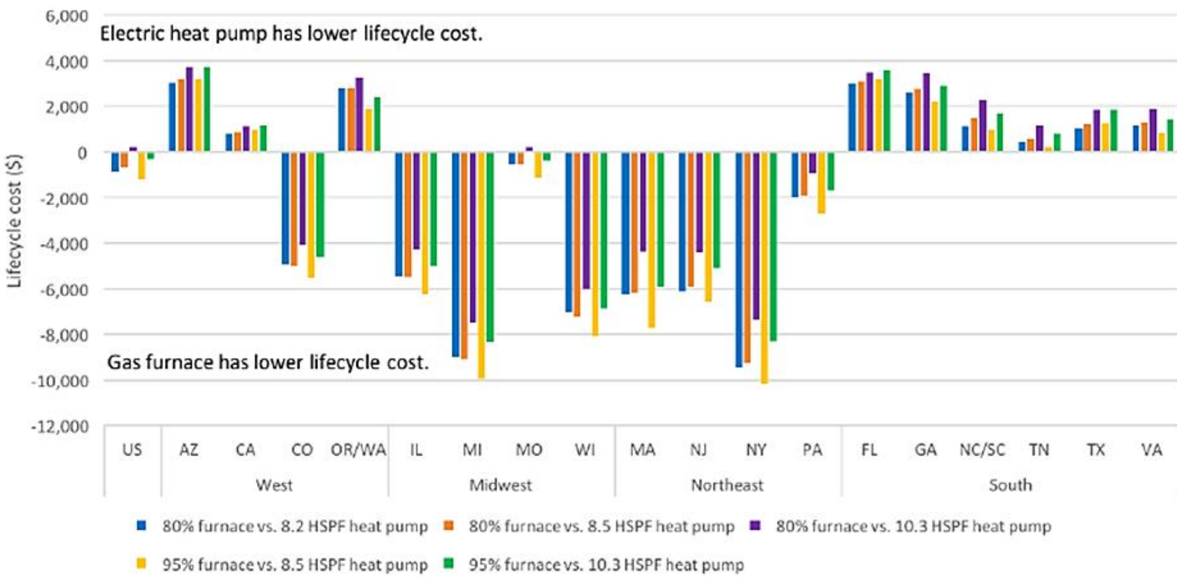


Figure 14. Life cycle cost comparison of furnaces and heat pumps for cases in which a heat pump can replace a central air conditioner. Source: Nadel (2016). Percentages for furnaces refer to Average Fuel Use Efficiency; HSPF is Heating Seasonal Performance Factor. In both cases higher numbers reflect more efficient equipment. The most efficient (10.3 HSPF) heat pump has similar efficiency to the heat pump considered in Wilson et al. (201) above (10 HSPF); the less efficient heat pumps are comparable to those assumed in the local studies above.

Nadel (2016) notes that the annual energy savings from heat pumps, where cost-effective, are on the order of $25-195 per year, which may not motivate homeowners to take them up in the face of the higher up-front costs.

Nadel's simple economic analysis of heat pump water heaters using national average energy prices suggests that they have slightly lower lifecycle costs than gas water heaters – a more favorable result than for space heating.

Jadun et al. (2017) presents potential cost scenarios for natural gas and heat pump technologies for residential and commercial space and water heating from today to 2050. The authors project total installed costs for both standard and cold-climate heat pumps based on unit costs and installation costs, developing slow, moderate, and rapid technological advancement scenarios for each technology in each subsector. The study projects that installed costs of heat pump technologies for both space and water heating will decline in both residential and commercial buildings. The authors also project improvements in energy efficiency from these units in most scenarios. Most scenarios emphasize efficiency improvements over cost reductions.

The study calculates total levelized costs of both heat pump and natural gas-fired space and water heating technologies in residential and commercial buildings based on fuel cost, maintenance cost, and equipment lifetime projections from EIA's *2017 Annual Energy Outlook 2017*. In projections for 2020, heat pump technologies have slightly higher capital costs in most residential applications and much higher capital costs in commercial applications relative to gas and electric resistance technologies. Heat pump fuel and maintenance costs are broadly comparable and in some cases lower than gas-fired technologies, and are consistently much lower than electric resistance technologies.

The study considers the economics of heat pump technologies from today through 2050 for space heating in warm and moderate climates, space heating in cold climates, and water heating (Figure 15). In 2020, none of the heat pump technologies are lower-cost than the gas alternatives, with the exception of residential heat pump water heaters in some scenarios. However, over time, the study finds that this gap narrows, and in the residential sector heat pump space and water heating become the lowest-cost options for space heating in most scenarios and for water heating in all scenarios. In the commercial sector air source heat pumps for space heating become lowest-cost in warm and moderate climates, and also become lowest-cost in cold climates in some scenarios. While not relevant to electrification, the levelized cost of heat pump technologies is lower than electric resistance technologies in all cases studied.

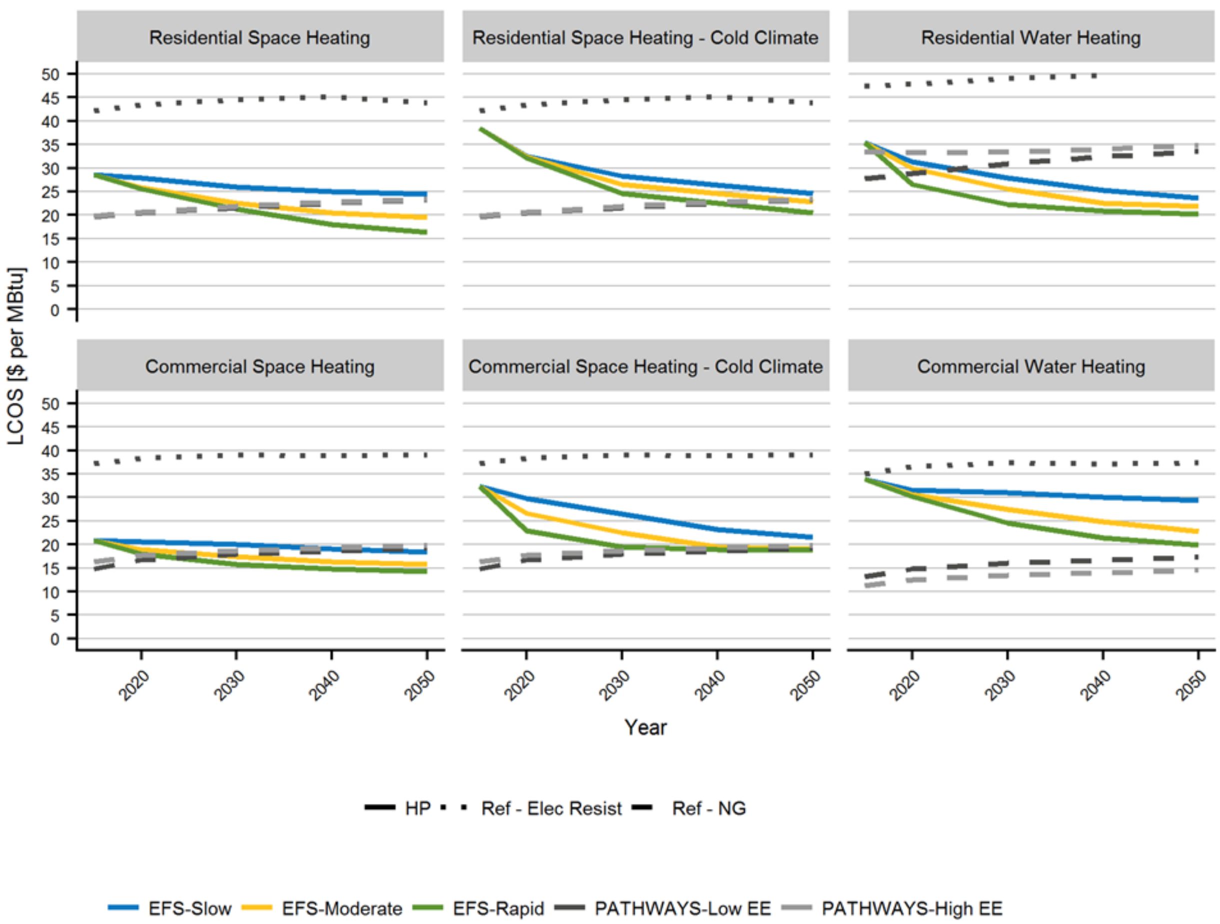


Figure 15. Projections for the levelized cost of heat pump and natural gas technologies, 2017-2050. Source: Jadun et al. (2017). LCOS is levelized cost of service; HP is heat pump; NG is natural gas; EFS is Electricity Futures Study; EE is energy efficiency; Ref stands for reference case (gas or electric resistance).

Regional and even local variation would affect these calculations – especially in the case of electricity rates. As discussed above, temperature also affects the efficiency of heat pump performance — more so than for gas-fired technologies. Therefore, variations would be expected for these projections if they were customized for the location of the building.

Jadun et al. assumes the competing direct-fuel technology is natural gas. While this is true in most parts of the country, some buildings in the Northeast lack access to natural gas and use fuel oil for space and water heating. Given current and projected fuel prices, electric heat pump technologies may be more easily cost-competitive when displacing fuel oil technologies (Hopkins et al. 2017), although heat pump space heating cannot yet meet full heating demand in very cold regions of the Northeast (Vermont Department of Public Service 2016).

2.3.2.3 Outlook for economics of electrification in buildings

Collectively, the literature and data on usage suggests that electric heat pump technologies are already economically competitive with other space and water heating technologies in some cases – specifically, the South and other mild climates (e.g., California). Heat pump technologies are most likely cost-competitive:

- where incumbent technologies are more expensive (e.g., fuel oil-fired systems in the Northeast);
- where winter temperatures are mild, though technological progress on cold-climate heat pumps is making this less important;
- where electricity prices are low;
- when replacing both heating and cooling units (e.g., replacing both a furnace and air conditioning unit with a heat pump);
- in residential rather than commercial buildings; and
- in new buildings rather than renovations of existing buildings – and especially where local natural gas infrastructure could be entirely avoided (e.g., an all-electric new housing development).

While the reviewed literature does not support precise quantification, the economic potential for heat pumps in residential space heating is already considerable, and heat pump technologies appear poised for greater inroads over time in other applications. The relative economics strongly depend on uncertain factors, most notably energy prices, which cannot be forecast with certainty. Even where the economics of heat pump electrification are mildly favorable, non-cost barriers may prevent uptake. In our view the economics are not overwhelming enough in enough applications to catalyze rapid and widespread heat pump electrification on the scale suggested by the scenarios referenced in section 2.2.2 absent sizeable shifts in economics or policy.

The literature discussing the economics of potential electrification focuses on electric heat pump technologies. Electric resistance technologies are also readily available and enjoy substantial market share in space and (especially) water heating. Electric resistance technologies are much less energy-efficient than heat pumps and therefore more expensive to operate. However, their capital costs are lower, and they offer greater potential for load-shifting given their greater electricity usage. That load-shifting could be a positive in some situations, but a negative in others. For example, an increase in inefficient electric resistance heat in cold climates could yield winter demand peaks far higher than current system peaks. Electric resistance water heaters, in particular, are attracting attention for demand response applications (see the demand response case study in Section 4). Flexibility services and utility load-building may prove powerful policy drivers for electrification, as discussed in Section 3.

2.3.3 Industry

A simple cost comparison for heating energy illustrates the unfavorable economics for electrified heating compared to natural gas-fired heating, driven by the current low cost of natural gas. We assume current 2017 industrial prices for natural gas and electricity: $4.10 per MMBtu of natural gas ($0.014 per kWh-thermal) and $0.053 per kWh for an industrial electricity rate.[39] On an energy basis, the price of natural gas is four times cheaper than for electricity, so an electric heating application would need to be four times more efficient than its natural gas counterpart to have the same energy costs. Typically, electricity-powered equipment is more efficient than gas-fired equipment, and we highlight again that if the "form values" for electric heating are superior (product quality, product yield, process time, process controllability, process flexibility, etc.), electrical heating can be the preferred option even with a higher cost of energy.

Two examples illustrate this energy cost barrier:

- For an electric boiler with 100% end-use efficiency versus a gas-fired boiler with 80% efficiency, the cost of energy is 4.2 times higher for the electric boiler. Similar cost comparisons for electric boilers are found in Jadun et al. (2017).
- For an electric heat-pump water heater with a coefficient of performance (COP) of 2.0 versus a gas-fired heater at 0.8 COP, the cost of energy is 2.1 times higher for the electric case.

To achieve energy cost parity, the price of natural gas would have to double to $8.20/MMBtu and the price of electricity would need to be reduced by 33% to $0.036/kWh for the electric boiler. For an electric heat pump water heater, the price of natural gas would have to increase by 50% or the price of electricity drop by 33%, or the heat pump would need a COP of 3.0.[40] These values do not take into account capital costs, installation costs, equipment lifetime, and maintenance costs, which can vary by type of equipment. For example, electric boilers can be less expensive than gas-powered boilers (Jadun et al. 2017) but lifetimes can be shorter, while heat pump equipment costs can be higher than conventional gas heating equipment.

[39] In some cases, large industrial users of electricity contract directly for their electricity. These rates could be lower (closer to wholesale rates) than the average rate here and improve the relative economics for electrified end uses.

[40] Efficient heat pumps in relatively mild climates can deliver this level of performance today.

2.3.3.1 *Outlook for the economics of electrification in industry*

One important complication for electrification in industry is the intensive degree of integrated process design including extensive use of CHP in several sectors and, in particular, in the oil and gas refining and chemicals/petrochemical sectors. Further, the oil refining industry has extensive "own-use" fuel consumption where byproducts of the oil refining process (e.g., refinery or still gases obtained during the distillation of crude oil) are used as fuel in upstream or downstream processes. Attempting to electrify these processes would complicate the design and increase the energy cost over and above a sector that does not have this type of extensive process integration and own-use energy consumption.

Table 5 provides an outlook for industry electrification. Beyond technical potential and the critical form values described above, other practical barriers to end-use electrification must be addressed: (1) potentially higher cost of energy, (2) a high degree of process design and integration, and (3) the degree to which CHP systems are utilized. Each of these factors would pose a practical challenge for a vendor or manufacturer to convert to electrified processes — e.g., having to pay higher energy costs, re-engineer manufacturing processes, and either redesign or move away from existing tightly integrated CHP processes. Based on these three factors, ideal candidates for industrial electrification include facilities with low to medium process temperatures; less integrated existing process designs; and a lower fraction of CHP processes.

Thus, a more layered approach is needed for considering industry economic potential which considers both technical potential and the degree of practical difficulty in re-engineering (or re-inventing) existing large-scale industrial sectors. One way of viewing industrial electrification economic potential is as a "subtractive approach," or rough rank of "realizability" or "degree of difficulty." This approach first determines what would be extremely difficult, impractical, or expensive to electrify. Some sectors such as the oil refining industry would pose the largest practical challenges to electrify and would probably face prohibitive barriers to wide-scale electrification.

Combined Heat and Power (CHP)

Efficiency of CHP systems can be much higher than for electricity and heat produced separately. For example, a CHP "topping cycle" (the most common form of CHP) has onsite generation with waste heat recovery for heating or pre-heating applications. Essentially the cost of one unit of energy in electricity provides approximately one free unit of heat energy. But in an electrified end-use case without CHP, for each unit of electricity, the customer has to procure and pay for an additional unit of heat energy. Switching to all-electric heating may be economically challenging for industrial facilities that rely on CHP systems.

Table 5 below illustrates this general outlook for industrial sector electrification based on a synthesis of studies reviewed. The following are some key insights:

- Several industry sectors are highlighted as promising candidates for induction heating: primary metals, fabricated metal products, and machinery. As noted in Table 1 above, induction heating can offer better product quality, higher yield, greater operational flexibility, and other manufacturing advantages.

- A few sectors feature low process temperature and relatively low CHP adoption (wood products, plastics and rubber products), but overall energy consumption is small for these sectors. Some sectors have only a few high temperature steps such as lime kiln firing in the paper sector and sugar product-charcoal regeneration and lime kiln firing in the food processing sector. If these could be electrified, most other process heating steps in these sectors could be electrified as well.
- Heating, ventilating and air-conditioning (HVAC) using onsite fuel sources are a small fraction of overall industry fuel use (about 5%), but these end uses could be electrified. For example, HVAC comprises a relatively large fraction of fuel consumption in transportation equipment, machinery, fabricated metal products, plastics, and rubber products.
- Several sectors have a high fraction of CHP or co-generation. This CHP fraction is a proxy for a high degree of process integration. These industries may find it most challenging from a design and cost perspective to redesign their process lines and potentially incur lower overall energy efficiency.
- The considerations in Table 5 are a starting framework for the feasible or economic potential of industry electrification but industry electrification in specific sectors and end use applications may be driven as much by potential product benefits in productivity, process control, etc. as the factors in Table 5. A detailed accounting or quantification of these product benefits would require more product-specific process modeling and is beyond the scope of this report.

Table 5. Industrial sector breakdown of onsite fuel consumption, representative process temperatures, and general outlook for electrification.

Industrial Sector	Boiler System	CHP	Process Heating	Facility HVAC	High temperature process steps [Brown, 1996]	Temp L/M/H	Approximated Potential for Electrification	Disposition for electrification
	Percentage On-site Fuel Consumption							
Primary Metals excluding steel	3.9%	7.4%	74.8%	5.8%	Primary Al Furnace 2200F (1200C); Copper furnace 1200C; Zinc Furnace (1260C)	HIGH	HIGH	Induction melting candidate
Fabricated metal products	7.2%	6.6%	61.2%	19.7%	Al sheet, foil furnace melting 1250F (680C); preheating 1000F (540C); annealing 800F (430C)	HIGH	HIGH	Induction heating/melting candidate, but low overall energy consumption
Machinery	4.2%	4.2%	38.9%	45.8%	Farm and construction equipment Heat Treatment 1350F (732C)	HIGH	HIGH	Induction heating candidate, but low overall energy consumption
Iron and Steel Mills	0.0%	0.0%	87.0%	4.1%	Blast furnace 2600F(1430C) Basic oxygen furnace 2800F (1540C)	HIGH	HIGH	Electric arc furnace; electrowinning
Wood Products	4.8%	14.3%	50.0%	9.5%	Fiberboard Stabilization/Drying 350F (180C)	MED	HIGH	Good candidate for electrification, but low overall energy consumption
Transportation equipment	13.6%	12.1%	32.6%	31.1%	Motor vehicle car body Drier 300F (150C); Vehicle parts Furnace 2900F (1600C)	MED/ HIGH	HIGH	Driers ok for electrification but furnace challenging; but low overall energy consumption
Plastics and rubber products	19.4%	24.3%	33.0%	20.4%	Polystyrene Heater 500F (260C); Synthetic Rubber Dryer 180F (82C)	LOW/ MED	HIGH	Good candidate for electrification, but low overall energy consumption
Food and beverages	25.0%	40.3%	24.9%	4.2%	250-350°F boiler (121-149°C); 450°F (232°C) baking oven; 930°F charcoal regen. (cane sugar) (499°C); 600°F lime kiln (beet sugar) (316°C)	MED/ HIGH	MED	Good candidate except high degree of CHP systems
Chemical manufacturing	16.8%	43.0%	32.0%	1.3%	H2, Ammonia – 1550°F furnace (840°C), Ammonia 600°F boiler (315°C); Pharma. 250°F (121°C) boiler, drying; Ethanol cooker/dryer 212°F (100°C) Boiler 250°F (121°C)	HIGH	MED	See text for basic chemicals e.g., Ammonia, chlorine; and for petro chemicals; high degree of CHP systems
Paper Mills	10.0%	63.3%	21.2%	2.2%	Pulp/Paperboard mill lime kiln 1200F (650C)	HIGH	LOW	High degree of integrated process design (high CHP)
Non-metallic mineral proc	0.6%	1.4%	90.1%	3.2%	Flat glass (2900°F, 1593°C furnace, 1600°F (870°C) final heat treatment; Cement 2700°F (1482°C) dry kiln; Brick 2100°F (1149°C) kiln	HIGH	LOW	Very high temperatures make this challenging but technically possible
Petroleum and coal products manufacturing	11.4%	22.0%	57.9%	0.4%	e.g.: Catalytic cracking 900°F (482°C), Catalyst reforming 1000°F (538°C), Boiler 422°F (217°C)	HIGH	LOW	Hard b/c high degree of process design and own-use fuel consumption

Note: MECS 2010 does not specify end-use fuel uses for all industrial subsectors. In particular, the “Other” unspecified component of fuel use is a large component for many sectors. We use the reported fuel use for specified end uses for the percentages above and do not attempt to allocate any of the Other unspecified fuel uses.

2.3.3.2 Near-term electrification growth areas in industry

Dennis (2016) highlights several industrial growth areas for electric technologies from 2015 to 2020 (Table 6). The increase in demand of 20,800 GWh represents about a 2% increase in electricity sales over the five-year period. About 90% of the growth is from the following six end-use technologies: cryogenics,[41] direct arc melting, induction heating, resistance heating and melting, ultraviolet curing, and infrared processing. Note that there is overlap with the technologies in Table 6 (direct arc-melting for iron and steel, induction melting for metal processing, and UV curing and IR processing for lower temperature heating, potentially in the plastics and food/beverage sectors, respectively). Also, growth drivers are a mix of factors but primarily are product quality and industry growth. However, this table does not delineate how much of the increased demand is from industry growth vs. fuel switching, or how much fuel switching is driven by product quality considerations.

[41] Cryogenics typically utilizes liquid nitrogen for cooling applications in many industries including food and beverages, healthcare, metallurgy, and electronics. Applications include coolant for computer servers and food preservation and packaging applications among others. (http://www.marketsandmarkets.com/PressReleases/cryogenic.asp, accessed October 4, 2017).

Table 6. Top ten industrial growth areas to target electric technologies (Dennis 2016)[42]

	Electricity Consumption (Million kWh)					
Electrotechnology	2015	2020	Growth	5-Year Growth %	% of 5-Year Growth in GWh	Primary Growth Drivers
Cryogenics	15,500	19,700	4,200	27%	20%	Product Quality, Industry Growth (Industrial Gases)
Direct Arc Melting	32,600	36,300	3,700	11%	18%	Steel Industry Growth, Productivity
Induction Heating	21,100	24,300	3,200	15%	15%	Product Quality, Industry Growth (Metals Industries and Transportation Equipment)
Resistance Heating and Melting	37,300	40,200	2,900	8%	14%	Industry Growth (Plastics, Mineral Products, Chemicals, Other Manufacturing Industries)
Ultraviolet Curing	7,700	9,900	2,200	29%	11%	Product Quality, Environment, Efficiency, Industry Growth (Printing and Curing)
Infrared Processing	5,900	7,900	2,000	34%	10%	Product Quality, Fuel Switching, Industry Growth (Transportation, Plastics, Other)
Water Supply Reverse Osmosis (Desalination)	2,300	3,200	900	39%	4%	Environmental Benefits/Requirements
Induction Melting	2,900	3,600	700	24%	3%	Productivity, Industry Growth (Primary Metals)
Membrane Processes	2,200	2,800	600	27%	3%	Industry Growth (Chemicals, Food), Fuel Switching, Product Quality
Electroslag, Vacuum and Plasma (Combined)	1,900	2,300	400	21%	2%	Product Quality, Industry Growth (Primary Metals)
TOTAL	**129,400**	**150,200**	**20,800**	**16%**	**100%**	

[42] Indoor agriculture is projected to grow from 2.3M square feet to about 8 to 16M square feet by 2022 (http://stateofindoorfarming.agrilyst.com/). Assuming an annual energy consumption of about 200kWh/ft2 (https://www.westernenergy.org/news-resources/indoor-agriculture-and-the-energy-implications-for-utilities/ and http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_(2014_forward)/PPD%20-%20Prop%2064%20Workshop%20Report%20FINAL.pdf implies an increase in electricity demand from 460 GWh in 2017 to 1680-3300 GWh in 2022.

3. Policy approaches to enable electrification

This section focuses on actions that federal, state, and local governments can take to enable beneficial electrification. We address nine categories of actions: technology research and development; incentives for technology deployment; electricity rate design; demand response program and electricity market design; target-setting; codes and standards; awareness, education, and outreach; energy planning; and air quality regulation. We do not presume here that the goal is to electrify everything. Rather, we offer this discussion to inform policymakers who may decide that some electrification is desirable.

3.1 Technology research, development, and demonstration (RD&D)

Significant progress on electric technologies will be required if buildings and industry are to be substantially electrified. For buildings applications, heat pumps are the obvious focus. Further research and development on heat pumps will lower their cost, raise their efficiency, and extend their temperature range – all of which may prove pivotal to their economic prospects and the pace of electrification in buildings, as discussed in Section 2 of this report. In industry, RD&D needs are far more diverse. Process development and redesign will be necessary in a wide variety of applications. RD&D is also necessary for both direct and indirect electrification to determine the best path forward in various applications.

The U.S. Department of Energy (DOE) runs several programs that support RD&D of electric technologies. For example, DOE's Building Technologies Office runs at least two programs to support the development of cold-climate heat pumps.[43] DOE's Advanced Manufacturing Office has funded several electrotechnology projects including induction heating for carbon fiber production and material heat treatment, electric arc technology for syngas production, and electro-chemical processing for high-temperature materials processing (Thekdi et al, 2017). The Electric Power Research Institute does extensive RD&D on electric technologies,[44] and universities, states, utilities, and regional actors (such as the Northeast Energy Efficiency Partnerships and the Northwest Energy Efficiency Alliance) have participated in technology demonstrations.[45]

Additional RD&D projects on electric technologies could be highly valuable for industry. Industrial electrification may benefit from collaboration with international research and development programs, given the progress, especially on indirect electrification, in Europe (see section 2.2.3.2).

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[43] Split-System Cold Climate Heat Pump — https://energy.gov/eere/buildings/downloads/split-system-cold-climate-heat-pump, and Residential Cold Climate Heat Pump with Variable-Speed Technology — https://energy.gov/eere/buildings/downloads/residential-cold-climate-heat-pump-variable-speed-technology

[44] See https://www.epri.com/#/portfolio/en/2018/programs/all for EPRI's research activities.

[45] See, for example, Eklund 2015.

3.2 Incentives for technology deployment

End-user incentives for the purchase of energy-efficient technologies, including electric alternatives to combustion-fuel models, are common in the buildings sector. Heat pump technologies often receive rebates, typically offered by utilities. For example, utility incentives for heat pump water heaters are common in the Northeast (Hopkins et al. 2017). Incentives can also be offered upstream of the end user to retailers, contractors, builders, and manufacturers. For example, the SMUD all-electric homes pilot (Mullen-Trento et al. 2016) is offering incentives to builders, which may be a particularly powerful means of driving cost-effective electrification in new housing developments or office parks due to avoided cost of local gas infrastructure. Utilities in many parts of the country also offer incentives to industrial customers for energy-efficient equipment and processes.[46]

Most incentives for heat pump adoption do not specifically encourage the replacement of non-electric units. Rather, they either apply regardless of the technology replaced, or apply only if replacing a unit with a new unit using the same source of fuel. This latter case creates a barrier to electrification (Hopkins et al. 2017). One potential exception is in Rhode Island, where the utility National Grid is considering rebates specifically for replacing fuel oil units with electric heat pumps (Rhode Island Public Utilities Commission 2017).

Electric utilities have strong incentives to promote electrification given slowing load growth in recent years (Weiss et al. 2017, Dennis 2016). Widespread electrification of buildings, industry, and transport could create sufficient electricity demand to restore these utilities to a strong load growth position (Steinberg et al. 2017).[47] Electrification may also provide opportunities for utilities to better meet customer demands at lower total system costs through improvements in load factors[48] and better optimization of resources (Dennis 2016). Electrification incentives are strongest for electric-only utilities; utilities providing both electric and gas service may still have strong incentives to encourage customers to replace equipment powered by other fuels such as fuel oil.

Incentives offered to end users or builders are only likely to drive deployment of electric technologies where they are near parity with non-electric competitors. However, as discussed in Section 2 of this report, such parity exists today in certain buildings and in certain parts of the country. As the economics of electric technologies improve, regions of cost parity will expand. Efficient use of

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[46] For a summary of industrial energy efficiency programs across the United States, see pp. 87-98 in State and Local Energy Efficiency Action Network (2016). *SEE Action Guide for States: Energy Efficiency as a Least-Cost Strategy to Reduce Greenhouse Gases and Air Pollution and Meet Energy Needs in the Power Sector.* Prepared by: Lisa Schwartz, Greg Leventis, Steven R. Schiller, and Emily Martin Fadrhonc of Lawrence Berkeley National Laboratory, with assistance by John Shenot, Ken Colburn and Chris James of the Regulatory Assistance Project and Johanna Zetterberg and Molly Roy of U.S. Department of Energy.

[47] Transportation electrification, which is not the topic of this paper, offers an equally powerful avenue for load growth. In their base electrification scenario, Wilson et al. (2017) shows that approximately 50% of load growth via electrification would occur from transportation and the other 50% from buildings and industry.

[48] A load factor is average demand divided by peak demand for a given time period. Higher load factors indicate that a greater share of capacity is being used, on average. Systems with higher load factors are generally more cost-effective, as they are using their capital-intensive resources more efficiently.

incentives will require careful targeting, such that incentives are employed where they are likely to be consequential and not where electric technologies would be chosen even in their absence.

3.3 Electricity rate design

Electricity rates are important to the prospects of electrification in several respects. Naturally, lower rates will encourage electrification and higher rates will discourage it. However, rate design also is an important factor:

- **Increasing block rates.** Many utilities use tiered rates, typically increasing block rates,[49] especially for residential customers. This form of pricing charges customers a higher rate for each incremental block of electricity consumption.[50] Increasing block rates can potentially create a disincentive to electrification (RAP 2017, Weiss et al. 2017). Many utilities set the threshold for each block (baseline) differently for electrically-heated buildings to reflect their higher electricity usage. If utilities were diligent about switching the customer's baseline after conversion to electric space heating, this would greatly ameliorate the issue. Still, it would not resolve issues arising from inclining block rates with respect to electrification of other end uses, such as water heating, cooking, and clothes drying, that currently don't typically affect the baselines used to set block thresholds.
- **Demand charges.** Many commercial and industrial rates, and some residential rates, include a demand charge. Demand charges are most typically based on the highest demand a given customer exerts on the system in any given time period (often, the highest hourly demand). Demand charges could create a disincentive for electrification where the newly-electrified end use – such as space heating, water heating, clothes drying, or an electrified industrial process – would establish a peak hourly demand higher than the user's peak demand would be otherwise.[51] Furthermore, space and water heating peak demand may not coincide with electricity system peak demand, and therefore may not be directly related to actual costs experienced by the utility. Demand charges are meant to proxy for distribution system costs imposed by a building's energy usage, but even these costs are only very roughly related to that building's peak demand (Wood et al. 2016). On the other hand, where electricity users can be flexible about their electricity use and manage it to avoid creating large peaks, those users may be able to enjoy lower electric bills in the presence of demand charges than they would without them, encouraging electrification.
- **Time-varying pricing.** Time-varying rates are becoming more widespread and may be a powerful driver of electrification for many end uses. These rates charge different prices per

[49] A 2008 survey (BC Hydro 2008) found that 18 of 61 U.S. utilities had increasing block tariffs year-round, and an additional seven had increasing block tariffs in the summer only.
[50] Conversely, under declining block rates, prices decrease as electricity usage increases. Declining block rates have largely fallen out of favor because they do not reflect the increased utility costs associated with greater energy usage.
[51] This issue pertains to transportation electrification as well. In response, some electric vehicle tariffs for commercial customers do not include demand charges. For example, Southern California Edison has recently gained approval for a commercial electric vehicle tariff that does not include a demand charge. See https://evroadmapconference.com/program/presentations17/RateDesign-MicheleChait.pdf.

kilowatt-hour consumed depending on the time of day, season, and in some cases type of day (e.g., critical peak day) to better align prices with costs of producing and delivering electricity. In buildings, space heating loads generally peak in the morning, which is not currently a high-cost time of day for electricity generation in most places.[52] Residential water heating loads also tend to peak in the morning. Given diversity of industrial loads, industrial peaks vary. Some industrial processes can shift run times with relative ease, allowing them to take advantage of times with lower electricity prices. To the extent that newly electrified end uses would face below-average prices on time-varying rates for any of the above reasons, their economic prospects would improve where these rates are in use.

Increased electrification for buildings and industry would create feedbacks in electricity rate structures. For example, greater electrification in morning hours would raise average costs, and thereby prices, of electricity during those hours. At the same time, greater electrification may well improve electricity load factors, potentially lowering electricity prices relative to gas prices. Electricity infrastructure could be used more cost-effectively to the extent that new usage is off-peak and does not require a proportional increase in generating and delivery capacity (New York Public Service Commission 2016) – and natural gas infrastructure would be used less intensively. Fixed costs are thereby spread over more kilowatt-hours, potentially lowering electricity rates, while fixed costs of direct use of gas (e.g., for space heating) are spread over fewer therms, potentially raising gas rates. This could create a self-reinforcing cycle of electrification (Hopkins et al. 2017). Better understanding of the dynamic impacts of electrification on energy prices would enable better forecasts of the economics of electrification in the future.

Overall, modernizing electricity rate designs may prove a significant boon to electrification. Time-varying rates are broadly seen as best practice. Revising rate structures to incorporate more time-varying pricing will improve the economics of electrification.

3.4 Demand response program and electricity market design

Program and market design may prove consequential for electrification. Here we review two related issues: demand response programs for retail customers and market designs. In both cases, demand response can serve multiple purposes, including load-shifting and flexibility.

Demand response programs for retail customers encourage load-shifting in a similar fashion to time-varying rates: by giving financial incentives to end users to shift their consumption or to reduce consumption during system peaks. Demand response programs can be designed in a variety of ways (Potter and Cappers 2017; Schwartz et al. 2017, Chapter 6). Where newly electrified loads can readily be shifted away from system peaks, demand response programs offer a potential revenue stream to electrified end uses. See the case study in Section 4 on the role of electric water heaters in demand response programs.

[52] See http://loadshape.epri.com/enduse.

As variable electricity generation resources continue to increase their share of generation capacity, flexibility becomes more important to the operability and economic efficiency of the grid (Mills and Seel 2015; Pierpont et al. 2017; RAP 2017). As such, policymakers are considering how to encourage flexible resources (New York Public Service Commission 2016). More electrified end uses – particularly those that can be equipped with smart controls – offer more opportunities for rapidly ramping electricity demand up or down to adjust for variability of energy output – for example, by pre-heating water, pre-cooling buildings (Hopkins et al. 2017; Rhode Island Public Utilities Commission 2017) or by shifting industrial processes. Flexible resources, from demand-responsive loads to fast-ramping generators, can be encouraged to participate in centrally-organized wholesale markets by making such resources eligible for markets that provide services they can deliver, considering the value of flexibility for payments, and/or requiring at least a minimum level of flexible capacity.[53]

3.5 Target-setting

Another way to drive electrification is by setting policy targets whose achievement will encourage it. For example, Vermont suggests the installation of 35,000 cold-climate heat pumps by 2025 as one of the means to meet utility targets set under its Renewable Energy Standard (Vermont Department of Public Service 2016).

Targets can also create impediments to electrification. States and utilities may set separate energy reduction targets for electricity and natural gas that may discourage electrification if care is not taken to account for increasing electrification. For example, if a building replaces an inefficient natural gas boiler with an efficient heat pump, this should not count as an increase relative to the baseline electricity demand used to set the target. Also, California is currently considering how to handle electrification in a rulemaking that will set energy savings targets (CEC 2017).

Greenhouse gas emissions targets may also discourage electrification if they cover only electricity generation and not other fuels. This is the case, for example, for the Regional Greenhouse Gas Initiative in the Northeast. As currently designed, increases in power sector emissions due to electrification would make it more difficult for generators to attain their targets, even if total emissions decrease due to reductions in direct fuel usage. In a counterexample, California's cap-and-trade system includes natural gas distributors in the cap and therefore does not discourage electrification.

[53] See Glazer, et al. 2017. The California Independent System Operator implemented a flexible ramping product in late 2016, and demand response is eligible for compensation under this product – see https://www.caiso.com/informed/pages/stakeholderprocesses/flexiblerampingproduct.aspx.

3.6 Codes and standards

Building energy codes and appliance and equipment standards establish minimum energy performance for buildings and equipment. Appliance and equipment standards are generally set separately for gas-fired and electric technologies, while energy codes are written comprehensively to apply to buildings regardless of the energy sources used.[54] Codes are set at state and sometimes local levels, while appliance standard are mostly set at the federal level.[55]

Codes and standards can create incentives or disincentives for electrification, often in unintended ways. For example, the City of Austin's building energy code does not allow electric resistance space heating as a primary heat source in most buildings, and does not allow electric resistance water heating as the primary water heating source where gas connections are available, though it does allow more efficient electric heat pumps for both space and water heating. Additionally, most energy codes allow performance-based compliance. If using this pathway for compliance, most current codes require that the building's simulated energy *cost* be equal to or lower than a simulated version of the building that exactly meets prescriptive code pathway requirements. If the cost of electricity used by the simulation is higher than the actual cost the building would experience – for example, by not accounting for time-varying rates or neglecting higher demand response earnings that electric end uses enable – the code may effectively favor natural gas over electricity (Mahone et al. 2016). Finally, code compliance software may not account – or account properly – for some electric end uses, such as new heat pump technologies, that are not commonly deployed, creating a practical barrier to adoption (TRC 2016).

Appliance and equipment efficiency standards are set separately for electric and combustion-fueled devices. For example, there is a separate standard for gas water heaters and electric water heaters. There is no explicit consideration of the relative efficiency and cost-effectiveness of electric appliances and equipment relative to non-electric alternatives in the standard-setting process. An electrification policy strategy would need to account for this separation in standards, which is not necessarily conducive to advancing one fuel over another.

3.7 Awareness, education and outreach

Programs can serve several awareness and educational functions to help overcome potential barriers to electrification. In buildings, outreach to builders and contractors may be particularly important, especially where direct-fueled technologies are chosen today by rote with little or no evaluation of electric alternatives. In existing buildings, many space heating and water heating replacements take place upon failure of the existing unit, and tend to be replaced by units that use the same fuel (Hopkins et al. 2017). Contractors and energy services companies play a key role in these replacements (see, e.g., Fuller et al. (2010) on residential energy improvements generally and TRC (2016) on the

[54] For more details on these policies see Schwartz et al. 2017.
[55] Individual states can, and sometimes do, set standards for appliances and equipment that do not have a federal standard, but cannot set different standards from federal standards where they do exist.

importance of contractors for electrification), and outreach to them may be the easiest way to counter this default tendency. Knowledge-sharing resources such as heat pump installer guides (Rhode Island Public Utilities Commission 2017) may be part of a successful outreach strategy. Incorporating advanced electric products into existing programs is also important – for example, including heat pump water heaters in the Energy Star labeling program was important to draw manufacturers' attention to them (Broad et al. 2014).

For industry, joint research and knowledge-sharing regarding process electrification strategies may be particularly important to ensure that process redesign costs are minimized. Given the huge diversity of end uses and processes in industry, DOE's industrial programs focus more on knowledge-sharing and capacity-building than direct research support. For example, DOE's Industrial Assessment Centers provide technical analytic support to industrial partners and disseminate information.

As discussed throughout this report, while electrification is often economic on its own (Wilson et al. 2017), electrification is economically viable in additional cases when considered alongside other activities, such as participation in demand response programs, adoption of time-varying rates, electric vehicle and rooftop PV integration, and industrial process improvements. Utilities, contractors, builders, energy advisors and the like will play an important role in helping building and industrial facility owners and operators interpret the incentives they face and explain the merits of electrification. Electrification may also provide business opportunities for utilities and third-party energy services providers to help their customers navigate this environment in pursuit of cost-effective electrification (Hopkins et al. 2017).

Electric utilities in particular should have strong incentives to promote electric technologies to their customers. Electric sales have leveled off over the past decade on average in the United States (EIA SEDS), and utilities' financial standing has worsened as they are no longer experiencing the steady revenue growth they have in the past (Lowry et al. 2017). Widespread electrification presents an opportunity to grow electric utility sales again, which could markedly improve their fortunes (Weiss et al. 2017; Steinberg et al. 2017; also see Section 3.2).

3.8 Energy planning

States, utilities, and grid operators engage in planning activities to coordinate the complex set of decisions required to plan for power generation and delivery moving into the future. Given the complex set of policies that affect prospects for electrification of buildings and industry, planning could be an important forum to coordinate efforts (Weiss et al. 2017). For example, a serious electrification push will impact electricity demand and modify hourly and seasonal load factors (Hopkins et al. 2017; Rhode Island Public Utilities Commission 2017). It also may require additional generation, transmission, and distribution infrastructure, as well as redesign of programs and incentives for demand-side management. Alignment of incentives, rate and market design, and infrastructure planning will be required for judicious electrification, and integrated resource planning (in vertically integrated states) is likely the best single forum for coordination. Transmission and distribution planning processes also are important venues for discussion of electrification issues. California, Minnesota, Rhode Island, Vermont, and Washington are among the states that are considering electrification as part of broader planning processes.[56]

3.9 Air quality regulation

Attainment of existing air quality standards could encourage the greater use of electrified equipment, especially in industrial facilities located in areas where existing air quality is poor. Targeted policies and incentives for improving air quality and public health in disadvantaged communities – for example, port electrification – would also promote electrification, as air quality tends to be poor in such communities.

Greenhouse gas (GHG) regulations may promote or inhibit electrification where the level of regulations impacts fuel choice. GHG regulations that cover electricity generation but not direct fuel use may tend to discourage electrification by providing a disincentive for emissions from electricity generation but not for emissions from direct fuel use (see discussion in section 3.5). Where all fuels are subject to GHG regulations, they will promote electrification if the GHG intensity of delivered electricity is lower than the carbon intensity of direct fuel combustion. As the carbon intensity of electricity generation declines, GHG regulations could drive electrification. As such, electrification and GHG regulations have a dynamic relationship.

[56] For example, for California, see http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M158/K663/158663325.PDF; for Minnesota see Great River Energy's 2017 integrated resource plan at http://greatriverenergy.com/wp-content/uploads/2017/04/GRE-2017-IRP-Final.pdf; for Rhode Island, see http://www.ripuc.org/utilityinfo/electric/PST%20Report_Nov_8.pdf; for Vermont, see Case No. 17-3142-PET at https://epuc.vermont.gov/?q=node/64/86887; for Washington, see Puget Sound Energy's 2017 integrated resource plan at https://pse.com/aboutpse/EnergySupply/Documents/8a_2017_PSE_IRP_Chapter_book_compressed_110717.pdf (main document) and https://pse.com/aboutpse/EnergySupply/Documents/25_2017_PSE_IRP_Appendices_book_compressed_110817.pdf (appendices).

4. Use cases and case studies of successful approaches to electrification

4.1 Air-source heat pump space heating

Instead of using energy to directly condition the temperature of air or water, heat pumps use electricity to move heat from one place to another in order to heat or cool air or water.[57] They may be used in place of an air conditioner or a furnace (for space heating or cooling) or a boiler or electric resistance water heater (for water heating).

There are three types of heat pumps based on the medium they use to transfer heat: air source (the most common type of heat pump), ground source and water source.[58] Air-source heat pumps are by far the most common. They use a compressor, coils and liquid refrigerant to extract heat from outdoor air. The heat is then released indoors to provide space heating. The system can be reversed to cool indoor air (DOE, n.d.). Advances in technology have made heat pumps more energy-efficient, quieter and longer lasting. These advances also have improved comfort and enabled air-source heat pumps to operate at lower temperatures (DOE, n.d.). In the past, heat pumps were not considered a candidate for heating in cold climates; however, cold-climate heat pumps now perform even in outdoor temperatures well below freezing (Alpine, n.d.; Rheem, n.d.).

Heat pumps can deliver 2 to 4 times[59] as much heat energy as they consume in electrical energy. Although their heating efficiency can depend on the source temperature, they are generally much more energy-efficient than electric resistance technologies. Importantly, a single heat pump can provide both heating and cooling. Heat pumps are generally more expensive to install than standard heating and cooling equipment, even if they are less expensive to operate. However, where a single air-source heat pump unit provides both heating and cooling, heat pump economics are often very favorable, driving increased electrification.

Heat pumps have steadily been increasing market share in recent years (EIA). Over 2.4 million air-source heat pumps were shipped in 2016 (up 7% over 2015) (AHRI, 2017). Most electrification forecasts (including all those reviewed in Section 2.2.2) assume that heat pump technologies will become the dominant space heating technology in the future.

Incentive programs for heat pumps are potentially important drivers of electrification. These programs are widespread, generally offered through loans, rebates or tax incentives. For example, the Massachusetts Clean Energy Center offers a program funded by the Massachusetts Renewable Energy Trust offering rebates of between $2,500 and $30,000 for the purchase of qualifying air-source heat

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[57] Dual-fuel or absorption heat pumps may use other fuels.
[58] Ground-source heat pumps may also be called geothermal heat pumps, GeoExchange, or earth-coupled (DOE n.d.).
[59] See https://www.ahridirectory.org/Search/QuickSearch?category=8&searchTypeId=3&producttype=7&SubmenuId=2&ProgramId=69 for rated efficiencies of heat pumps.

pumps for residential (including multifamily) utility customers. Between 2014 and Q3 2016, the program provided over $5.8 million in rebates on over 4,000 units (MassCEC, n.d.).

The Tennessee Valley Authority (TVA) has offered on-bill loans for heat pumps since the late 1970s through TVA's Energy Right Solutions program.[60] Annually, the program makes about $50 million in loans for heat pumps and, since 1997, TVA has lent more than $500 million for heat pumps to customers in the service territory of their electric distribution companies (SEE Action Network, 2014).

Illustrating the widespread availability of these incentives, the Database of State Incentives for Renewables and Efficiency lists 847 different financial incentives for heat pumps offered by a state, local government, or utility.[61]

As noted in section 3.2 above, National Grid in Rhode Island is currently considering incentives that would specifically reward replacing fuel oil-powered units with heat pumps.

4.2 Electric water heaters and demand response

Demand response programs provide system planners and operators a tool to manage the grid's electrical load through reducing peak capacity needs and balancing electricity supply and demand (DOE, n.d.) in real time. Demand response programs induce changes in electricity consumption in response to changes in electricity prices or incentive payments during times of high wholesale market prices or system reliability needs (FERC, 2012). Demand response is comprised of a number of strategies for controlling electricity consumption. A 2012 Federal Energy Regulatory Commission report noted that 80% of total potential peak reduction came primarily from four demand response strategies (FERC, 2012):

1. **Load as a capacity resource.** Demand-side resources (e.g., water heaters) that commit to make pre-specified load reductions when system contingencies arise. Participation obligates a customer to reduce demand of certain end uses when called on to do so. These programs may or may not use a separate device to control the end use's electricity consumption. Participants grant authority for load reductions to program administrators or aggregators, and demand reductions from these programs can be bid into wholesale energy markets.
2. **Interruptible load.** A customer agrees to curtail electric use when the utility requests it — typically for large commercial and industrial customers (EIA, n.d.). The customer maintains some control over how to respond, and reductions from interruptible load programs are not typically bid into capacity markets.
3. **Direct load control.** A utility, program administrator, or third-party aggregator may directly control electricity supply to individual end uses on a customer's property (requires hardware or software to allow remote control).

60 On-bill loans are paid back on the borrower's utility bills.
61 http://www.dsireusa.org/, accessed 10/22/17.

4. **Time-varying rates.** Rate design that incentivizes utility customers to consume electricity at certain (lower demand) times of day.

The first three strategies generally use incentives to attract participants, including special (lower) electricity rates, payments for participation in the demand response program, or payments given each time a participant reduces consumption in response to a demand response event. Time-of-use rates encourage building and facility owners or operators to shift consumption to times of lower load demand through time-differentiated pricing.

Air conditioners are often the target end use for demand response programs in the residential and commercial sectors, as cooling load tends to drive summer electricity consumption. Water heaters are another common demand response target, offering an opportunity for additional revenue from electric water heaters that other water heating technologies do not offer. If these incentives are large and widespread, they may represent a significant driver for electrification.

Although a slight majority of U.S. households heat their water using primary energy sources like natural gas, over 45% of U.S. households use electric water heaters (EIA, 2017). By far the most common electric water heating technology is electric resistance, which immerses an electrically heated element in the water. A more efficient option is a heat pump water heater, which pulls heat from ambient air to heat water. Electric resistance water heaters are less energy-efficient than heat pumps and more expensive to operate over the life of the unit. However, their upfront cost is generally lower than a heat pump, and electric resistance water heaters may better allow for shifting consumption that can support grid reliability, balancing grid supply and demand, shaving peak power capacity needs and providing other grid services (see the Text Box in this section for more).

Water heaters can become flexible loads that can be shifted, curtailed or turned on as needed. A 2016 report by the Brattle Group identified four strategies for water heaters to enhance the "reliability, economics, and environmental footprint of the power grid" (Hledik, Chang, & Lueken, 2016).[62] These include peak shaving (reducing peak demand), thermal storage (heating water at times of low demand or oversupply of generation and then curtailing heating during times of high system demand),[63] fast response (allowing real-time response to supply fluctuations, potentially alleviating the need for fast-ramping generation), and a controlled heat pump water heater strategy (in which the efficiency of a heat pump water heater is combined with heating curtailment to cut system peak demand).

[62] The report includes a fifth strategy, not included here because it is not specifically a demand response approach. The Uncontrolled Heat Pump Water Heater strategy relies purely on the energy efficiency benefits of heat pump water heaters.
[63] Storage capability for 50-gallon tanks can allow curtailment of heating for up to four hours while still providing acceptable provision of hot water, whereas 80-gallon tanks could allow 16 hours of curtailment (Hledik, Chang and Lueken 2016).

Some programs are using standard electric resistance water heaters to offer DR and related services. For example, Mosaic Power, a third-party aggregator,[64] runs the Water Heating Efficiency Network, which attaches internet-controlled devices to existing electric resistance water heaters[65] to coordinate the energy demand of a network of approximately 14,000 water heaters in the PJM Interconnection region with the needs of the electric grid.[66] Using this network Mosaic regularly provides up to 3 MW of power for the PJM ancillary services market (Vaudreuil, 2017).[67]

Electric resistance vs. heat pump water heaters: Tradeoffs between demand response and energy efficiency

Heat pump water heaters are much more energy-efficient than electric resistance water heaters. However, their very efficiency may work against them in a demand response context if it limits the amount of load that such programs can shift in order to deliver grid services and support variable output electricity generation sources. Additionally, heat pump water heaters may not be able to respond as quickly as electric resistance to some demand response requests (Vaudreuil, 2017), and cycling them too often may damage the units and require early replacement. There may be situations where the higher consumption – and greater load-shifting potential – of an electric resistance water heater make it on balance better able to minimize pollution and other negative effects of electricity generation than a more efficient heat pump. On the other hand, most heat pump water heaters have resistive elements, which may enable them to provide many of the same grid services as electric resistance water heaters when the value of these services exceeds the value of the higher efficiency heat pump.

The electrification scenarios reviewed in Section 2.2.2 of this report assume heat pumps become the dominant technology for both space and water heating. As flexibility becomes more important to a diversifying electricity generation sector, this may not be the case — especially in local areas where load shifting may be particularly important. Careful electricity market design, and consideration of the entire set of services offered by these systems when setting equipment incentives, will be required to encourage the appropriate technologies.

Hawaiian Electric Company and Steffes, an equipment manufacturer, are joining forces to provide demand response-enabled electric resistance water heaters in Hawaii where the variable energy output from high penetrations of solar PV make flexible loads more valuable. Some 449 Grid-

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[64] Third-party aggregators enable provision of demand response (and other distributed energy resources (DERs)) at scale (Burger, et al. 2016), which helps facilitate these markets, through combining and coordinating DER services from many individual projects.

[65] Neither the Mosaic program nor the Hawaiian Electric Company program includes HPWHs. See the Text Box in this section for more on heat pump water heaters and demand response.

[66] Mosaic can shift or reduce consumption among their network units, which are in six states and Washington, D.C.

[67] "PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia" (http://www.pjm.com/about-pjm/who-we-are.aspx). PJM's ancillary services market helps balance the transmission system as it moves electricity from generation to customer. Ancillary services include the Synchronized Reserve Market, Non-Synchronized Reserve Market, the Day-Ahead Scheduling Reserve Market and the Regulation Market (http://www.pjm.com/markets-and-operations/ancillary-services.aspx).

Interactive Electric Thermal Storage systems have been installed. Their consumption can be remotely aggregated through devices inserted inside the units during manufacturing (Murphy, 2017).

4.3 Zero-net energy buildings

A zero-net-energy (ZNE) building (or zero energy building, ZEBs) is *"An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy"* (NIBS, 2015). These buildings can reduce the building sector's non-renewable energy demand and reduce air pollutant emissions.

ZNE buildings are receiving increased attention, guidance and policy support. In 2016, the New Buildings Institute (NBI) identified 53 verified ZNE buildings in 23 states (NBI, 2016).[68] In California, Executive Order B-18-12 directs "all new State buildings and major renovations beginning design after 2025 be constructed as Zero Net Energy facilities with an interim target for 50% of new facilities beginning design after 2020 to be Zero Net Energy" (Brown, 2012). California's Energy Efficiency Strategic Plan requires that all new residential construction meet its ZNE standard by 2020, and all new commercial construction by 2030.

ZNEs have been built by diverse parties, from Walgreens (whose Evanston, Illinois, retail store was built to ZNE standards) to contractors' unions (who built the Zero Net Energy Center, a training center for clean energy contractors, in San Leandro, California) (Robbins, Skelton, & Olden, 2015; Hummel, Benton, Kuettel Desmond, & Grant, 2015).
There are various strategies for either constructing a ZNE building or retrofitting buildings so that they have zero net energy consumption. They include reducing consumption through efficiency improvements, heat recovery and cogeneration, energy conservation, reduced plug loads, and the addition of renewable generation (NIBS, 2015).[69]

ZNEs may promote electrification in two ways. First, depending on the way ZNE standards are defined[70] (and depending on the specifics of a project), it may be easier to reach ZNE through an all-electric building than with a hybrid (a building that uses both gas and electricity). Second, if all-electric buildings are more attractive for other reasons, such as cost, efficiency, or emissions intensity, policies promoting ZNEs may effectively promote electrification.

A study in San Leandro, California, modeled four scenarios (low-, mid-, and high-performance) for all-electric vs. hybrid ZNE home retrofits. It found that the all-electric ZNE retrofit is more cost-effective

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[68] NBI defines "verified" as a building that has achieved ZNE for at least one full year (NBI 2016).
[69] If energy efficiency – which reduces a building's energy consumption – is pursued before installing renewable generation (such as solar PV), the property may require a smaller amount of generation to reach ZNE which could increase the project's cost-effectiveness and in turn increase adoption of ZNE buildings.
[70] Current ZNE definitions allow combustion fuel consumption in a building to be offset – in some way – by on-site renewable energy generation. At high levels of ZNE adoption, this offset would become unworkable as many buildings would be generating excess electricity while very few would require electricity from the grid. As such, ZNE definitions may eventually need to disallow such offsets, which would encourage electrification.

over the life cycle of the project, consumes less energy, and emits fewer air pollutants than the hybrid model in all scenarios (CPUC, 2017).[71] Where, as in this case, new construction or retrofits can achieve ZNE designations more cost-effectively by electrifying some or all end uses, ZNE-promoting policies could effectively promote electrification of buildings.

In Vermont, the Zero Energy Now program coupled weatherization, heat pumps for space heating, heat pump water heaters, and solar PV. Participating homes saved 79% of their energy usage and an average of $3,700 annually on energy bills in 22 participating homes, yielding an 11.9% return on customers' investment.[72]

4.4 Electric arc furnaces

Electric arc furnaces (EAFs) using recycled steel for steelmaking have comprised an increasing share of overall U.S. steel production since the 1990s. Figure 16 shows that the share of U.S production using electric arc furnaces steelmaking process has steadily increased from about 40% of production in 1995 to about 62% in 2014 (and to about 67% in 2016), with a corresponding drop in production from blast furnaces/basic oxygen furnaces. Inputs for the process include scrap material and scrap supplements. The primary driver for EAF overtaking blast furnaces/basic oxygen furnaces is economic, as building new blast furnaces in the U.S. is more challenging, as described below.

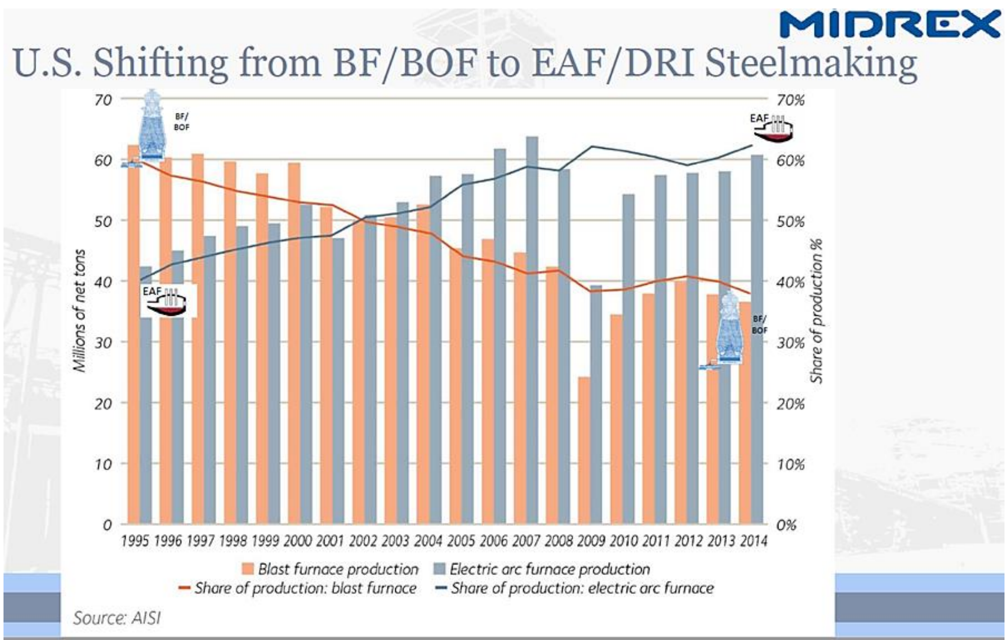

Figure 16. U.S shift from blast furnaces (BF)/basic oxygen furnaces (BOF) to electric arc furnaces (EAF)/direct reduced iron (DRI) in steelmaking. (Ripke 2017)

EAF "mini-mills" have additional operational advantages: smaller, nimbler and more flexible operation; higher utilization and less slack capacity (Schmidt 1984), and improved energy efficiency compared to

71 The study authors note that results may vary in climates that differ from the mild climate of the model building.
72 See http://zeroenergynowvt.com/program-results/.

BF/BOF plants (Pardo et al. 2013). They are easier to build due to lower capital costs and have less environmental impacts, such as lower criteria pollutant emissions. The United States has a more developed supply chain for recycled steel than other countries such as China, driving domestic demand for EAFs. Additional R&D needs in the iron and steel industry for existing and emerging technologies are focused on safety, quality, efficiency, and rate (throughput), and include the electrolysis of Fe_xO_y[73] for ultra-low CO_2 steelmaking (Ripke 2017).

4.5 Electric boilers

Using electrical boilers is technically possible, but such boilers are not efficient from an energy system-wide perspective using thermally produced electricity.[74] They can be favorable from a CO_2 and criteria emissions perspective, however, when powered by low-carbon electricity sources (e.g., solar, wind, hydro and nuclear power) compared to natural gas-fired boilers. Hybrid natural gas/electric boilers have been used in the past in the Southeast when inexpensive off-peak nuclear power is available (e.g., at Duke Energy in South Carolina).[75] However, with relatively low natural gas prices today, it is hard to make the economics of electric boilers favorable.

Previously, electric boilers have been used in a dual boiler configuration with gas-fired boilers when natural gas prices were high and electricity rates were low. Positive return on investment was found in three years or less (see Figure A-1 in Appendix A). In times when electricity rates were very low at certain times of the day and natural gas prices were high, it was economic to switch to an electric boiler. However, current EIA projections for the ratio of electricity prices to natural gas prices are too high to support electric boilers.

Still, in the case of falling electricity prices due to large quantities of renewable electricity coming online and outstripping demand (e.g., see CAISO 2016, Denholm 2015), there may be cases during the day when low cost (or negative cost) electricity is available. For solar PV for example, the marginal value of each kW of installed PV drops as the overall installed capacity increases (Mills and Wiser 2012). In California, there are already hours of the day when excess renewable electricity can be exported to neighboring states (Penn 2017) and the California ISO is paying off-takers up to $25/MWh for this power. Curtailed power is expected to increase with greater adoption of wind and solar. Electric boilers are a relatively simple technology implementation, provided there is space to accommodate additional equipment and any required electrical upgrades can be made. The same low-cost electricity from excess renewable power could be used for electric process heating or even process heat thermal storage, but electric boilers are perhaps the simplest industrial electrification implementation and hybrid gas-electric boilers are an example with a recent precedent in the United States.

[73] See http://www.sustainableinsteel.eu/p/532/ulcos_=_ultra_low_co2_steel_making.html for more information on the electrolysis of iron ore.
[74] For example, from an efficiency and cost viewpoint, we would not build a system that generates steam to create electricity that is subsequently transmitted and distributed to an industrial site to generate steam.
[75] See Figure A.2 in Appendix A for capital costs for hybrid boilers.

5. Conclusions

5.1 Key findings

The technical potential for electrification of buildings and industry is large. In buildings, nearly 100% of energy use can be electrified with today's technologies. In industry, more technological progress is necessary due to the much greater diversity of energy-using processes. Ultimately, however, the constraints on electrification are cost and other practical barriers, rather than lack of deployable technologies.

In buildings, some advanced electric technologies – notably, air-source heat pumps for space heating – are already economically viable in many buildings in many parts of the country. Construction of integrated all-electric buildings is also economically viable in many places. Forecasts (Jayun et al. 2017) suggest that the economics of electric technologies in buildings will likely improve over time relative to their gas-fired competitors.

Depending on the specific setting, electrification of some end uses may be cost-effective in a wide variety of buildings. In general, electrification is more cost-effective:

- in new buildings (as opposed to alterations of existing buildings);
- in residential buildings (as opposed to commercial);
- when a single electric heat pump can provide both heating and cooling;
- for all-electric buildings, where some gas infrastructure costs can be avoided; and
- in locations with mild winters.

In industry, electrification is most viable in processes:

- with relatively low energy costs;
- where the degree of process complexity and process integration is more limited and extensive process re-engineering would not be required;
- where combined heat and power is not used;
- where induction heating technologies are viable; and
- where process heating temperatures are lower.

See Table 5 in Section 2.2.3.1 depicting these factors.

Successful rapid and widespread electrification would require a suite of policy revisions to existing instruments, including electricity rate design, market design, and building codes and appliance and equipment standards, as well as equipment-level incentives and outreach and educational efforts. Policies, regulatory changes, and programs that make it less expensive to use electricity off-peak, including time-varying rates, zero net energy building codes, demand response programs, and payments for flexible loads, can significantly improve the economics of electrification for the many end uses that can operate at these times. These measures would also improve the efficiency of the electricity delivery system generally through improved load factors, potentially lowering electricity costs and further encouraging electrification. Electrification also offers electric utilities a means of reversing concerns with slowing load growth.

5.2 Future research needs

The literature on electrification of buildings is somewhat more developed than that on electrification of industry. Still, there is considerable work to be done in both sectors to better understand and advance beneficial electrification. Research needs include:

- More disaggregated (regional and utility-level) modeling of electrification potential to target incentives and outreach, and to guide infrastructure planning
- Explicit consideration of the potential for electricity rate structures and electricity market design to encourage or inhibit electrification, to inform policy design
- Detailed study of the value of additional electrification to the electricity system – nationally and by utility system and by power market – including improvements in capacity factors, load shifting, flexibility, and electricity price impacts
- Greater policy development and related incentives exploring electrification, especially in industry
- Consideration of how best to realize flexible load benefits of existing electrified equipment – for example, electric resistance water heaters already in place
- Further quantification of the benefits of electrification, such as air quality, health benefits, economic development, better grid management, and quality of industrial products
- Case studies on specific electrification efforts to quantify impacts, including load growth, consumer benefits, environmental benefits, and grid management benefits
- In buildings:
    - Research and development on heat pump technologies to continue improving cold-weather performance and lower costs
    - Additional research on the economic viability of electrification at regional levels for a range of building types, accounting for variation in climate, energy prices, and other factors
- In industry:
    - More exploration on the applicability and expansion of induction heating
    - Further process-level analysis and modeling to identify which sectors or processes to prioritize for electrification
    - Development of direct electrification process designs, equipment costs, and demonstrations
    - Demonstrations of hydrogen electrolytic production and integration as a feedstock replacement
    - Comparisons of costs and benefits of direct vs. indirect (via hydrogen production) electrification

6. References

Åhman, Max, Nilsson, Lars J., Johansson, Bengt. (2016). Global climate policy and deep decarbonization of energy-intensive industries. Climate Policy, 17(5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

Air-Conditioning, Heating, & Refrigeration Institute. (2017). *AHRI Releases December 2016 U.S. Heating and Cooling Equipment Shipment Data*. Retrieved from http://www.ahrinet.org/App_Content/ahri/files/Statistics/Monthly%20Shipments/2016/December_2016.pdf

Alpine. (n.d.) Specifications: BLUERIDGE BMKH12-15YN4GA 15 SEER Single Zone Ductless Mini-Split Heat Pump System. Alpine Home Air Products.

Alstone, Peter, Potter, J., Piette, M. A., Schwartz, P., Berger, M. A., Dunn, L. N., Smith, S. J., Sohn, M. D., Aghajanzadeh, A., Stensson, S., Szinai, J., Walter, T., McKenzie, L., Lavin, L., Schneiderman, B., Mileva, A., Cutter, E., Olson, A., Bode, J., Ciccone, A. and Jain, A. (2017). 2025 California Demand Response Potential Study, Final Report and Appendices on Phase 2 Results: Charting California's Demand Response Future. Lawrence Berkeley National Laboratory. Prepared for California Public Utilities Commission. April.

Baxter, Van D; Groll, Dr. Eckhard A.; Abdelaziz, Omar; Shen, Bo; Groff, Mr. Gerald; Sikes, Karen et al. IEA HPP Annex 41 Cold Climate Heat Pumps: Task 1 Report Literature and Technology Review United States - ORNL/TM-2013/472, report, October 1, 2013; [Tennessee]. (digital.library.unt.edu/ark:/67531/metadc865746/m1/8/: accessed February 21, 2018), University of North Texas Libraries, Digital Library, digital.library.unt.edu; crediting UNT Libraries Government Documents Department.

Bell, Michelle L., & Ebisu, Keita. (2012). Environmental Inequality in Exposures to Airborne Particulate Matter Components in the United States. *Environmental Health Perspectives*, *120*(12), 1669–1704. https://ehp.niehs.nih.gov/1205201/

Broad, Diane, Christensen, Kurt, Dragoon, Ken, Lee, Kalin, Spielman, Kenji, & Parkinson, Simon. (2012). *Smart End-use Energy Storage and Integration of Renewable Energy*. ECOFYS. Retrieved from http://www.ecofys.com/files/files/ecofys_2012_smart-end-use-energy-storage_bpa_project_overview.pdf

Broad, Diane, Spielman, Kenji, & Dragoon, Ken. (2014). Heat Pump Water Heaters for Demand Response and Energy Storage (No. E14-296). Northwest Energy Efficiency Alliance. Retrieved from https://neea.org/docs/default-source/reports/final-hpwh-dr-report-and-summary.pdf?sfvrsn=6

Brown, Edmund G. (2012). "Executive Order B-18-12." California Governor's Office, April 25.

Brown, Harry, et al., (1996). Energy Analysis of 108 Industrial Processes, U.S. Department of Energy, Fairmont Press, GA.

Burger, Scott, Chaves-Avila, Jose Pablo, Batlle, Carlos, & Perez-Arriaga, Ignacio J. (2016). The Value of Aggregators in Electricity Systems. MIT Center for Energy and Environmental Policy Research.

California Energy Commission. (2017). *Senate Bill 350: Doubling Energy Efficiency Savings by 2030* (No. CEC-400-2017-010-CMD). Retrieved from http://docketpublic.energy.ca.gov/PublicDocuments/17-IEPR-06/TN220927_20170828T144323_Senate_Bill_350_Doubling_Energy_Efficiency_Savings_by_2030.pdf

California Energy Commission (CEC), & California Public Utilities Commission (CPUC). (2015). *New Residential Zero Net Energy Action Plan 2015-2020.*

California ISO (CAISO) (2016). What the duck curve tells us about managing a green grid, California ISO Fast Facts, Folsom CA. https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Castle, Stephen. (2017, July 26). Britain to Ban New Diesel and Gas Cars by 2040. *New York Times*. Retrieved from https://www.nytimes.com/2017/07/26/world/europe/uk-diesel-petrol-emissions.html?mcubz=0&_r=0

California Public Utilities Commission. (2017) "Jeff Harkness Comments Building energy modeling and analysis show that zero net energy all-electric retrofits are cost effective, energy efficient and far lower in greenhouse gas emissions." CPUC Docket 17-IEPR-06, Doubling Energy Efficiency Savings. September 21.

Darghouth, Naïm R., Wiser, Ryan H., Barbose, Galen, & Mills, Andrew D. (2016). Net metering and market feedback loops: Exploring the impact of retail rate design on distributed PV deployment. *Applied Energy, Volume 162*, 15. January. Pages 713-722, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2015.10.120

Denholm, Paul, O'Connell, Matthew, Brinkman, Gregory, & Jorgenson, Jennie. (2015). "Overgeneration from Solar Energy in California: A Field Guide to the Duck 25 Chart," National Renewable Energy Laboratory, Tech. Rep. NREL/TP-6A20-65023, Nov, 2015.

Dennis, Allen. (2016). "Electrification of Industry." presented at the EPRI-IEA Workshop on Clean Energy and Electrification, Washington, D.C., November 30.

Dennis, Keith. (2015). Environmentally Beneficial Electrification: Electricity as the End-Use Option, *The Electricity Journal, Volume 28*, Issue 9, November, Pages 100-112, ISSN 1040-6190, https://doi.org/10.1016/j.tej.2015.09.019

Dennis, Keith, Colburn, Ken, & Lazar, Jim. (2016). Environmentally beneficial electrification: The dawn of "emissions efficiency." *The Electricity Journal*, *29*(6), 52–58. https://doi.org/10.1016/j.tej.2016.07.007

Electric Power Research Institute. (2009). The Potential to Reduce CO2 Emissions by Expanding End-Use Applications of Electricity. Palo Alto, CA: EPRI Report 1018871. https://www.epri.com/#/pages/product/1018871/

Energy Information Administration (2017). Annual Energy Outlook 2017, January 5. Washington, D.C. https://www.eia.gov/outlooks/aeo/

Energy Information Administration. (n.d.). Glossary. https://www.ferc.gov/legal/staff-reports/12-20-12-demand-response.pdf

Energy Information Administration. (2010). Manufacturing Energy Consumption Survey (MECS). https://www.eia.gov/consumption/manufacturing/data/2010/

Energy Information Administration. (2017). "Residential Energy Consumption Survey (RECS): Table HC8.1 Water heating in U.S. homes by housing unit type, 2015."

EPRI. 2010. *Electrotechnology Reference Guide, 2010.* Palo Alto, CA: Electric Power Research Institute (EPRI).

European Climate Foundation. (2010). ROADMAP 2050: A Practical Guide to a Prosperous, Low-Carbon Europe. (The Hague, NL). Available at http://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf

Brolin, Magnus, Fahnestock, Jesse, & Rootzén, Johan. (2017). Industry's Electrification and Role in the Future Electricity System: A Strategic Innovation Agenda, Technical Report, SP Technical Research Institute of Sweden and Chalmers University of Technology, February.

Federal Energy Regulatory Commission (FERC). (2012). Assessment of Demand Response & Advanced Metering, Staff Report.

Fuller, Merrian. C., Kunkel, Cathy, Zimring, Mark, Hoffman, Ian M., Soroye, Katie. L., & Goldman, Charles. A. (2010). Driving Demand for Home Energy Improvements (No. LBNL-3960E). Berkeley, CA: Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/driving-demand-home-energy

Götz, Manuel, Lefebvre, Jonathan, Mörs, Friedemann, McDaniel Koch, Amy, Graf, Frank, Bajohr, Siegfried, Reimert, Rainer, & Kolb, Thomas. (2016). Renewable Power-to-Gas: A technological and economic review, Renewable Energy, Volume 85, Pages 1371-1390.

Greenblatt, Jeffrey, Wei, Max, & McMahon, Jim. (2012) California's Energy Future: Buildings and Industrial Energy Efficiency, California Council on Science and Technology. http://ccst.us/publications/2011/CEF%20index.php.

Gurlaskie, George. "Heat Pump Water Heaters for Demand Response." Duke Energy, February 28, 2016.

—. Heat Pump Systems. (n.d.). https://energy.gov/energysaver/heat-pump-systems (accessed September 22, 2017).

Hledik, Ryan, Chang, Judy, & Lueken, Roger. (2016). The Hidden Battery: Opportunities in Electric Water Heating. The Brattle Group, prepared for NRECA, NRDC, and PLMA.

Hopkins, Asa S., Horowitz, Ariel, Knight, Pat, Takahashi, Kenji, Comings, Tyler, Kreycik, Philip, Veilleux, Neil, & Koo, Jeremy. (2017). *Northeastern Regional Assessment of Strategic Electrification*. Northeast Energy Efficiency Partnerships. Retrieved from http://www.neep.org/sites/default/files/DRAFT%20Strategic%20Electrification%20Summary.pdf

International Energy Agency. (2017). Future of Trucks. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf

Jadun, Paige, McMillan, Colin, Steinberg, Daniel, Muratori, Matteo, Vimmerstedt, Laura, & Mai, Trieu. (2017). Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050 (No. NREL/TP-6A20-70485). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy18osti/70485.pdf

Jones, Melissa, Michael Jaske, Michael Kenney, Brian Samuelson, Cynthia Rogers, Elena Giyenko, and Manjit Ahuja. 2017. Senate Bill 350: Doubling Energy Efficiency Savings by 2030. California Energy Commission. Publication Number: CEC-400-2017-010-CMD.

Khanna, Nina, Fridley, David, Zhou, Nan, Karali, Nihan, Zhang, Jingjing, & Feng, Wei. (2017). *China's Trajectories beyond Efficiency: CO2 Implications of Maximizing Electrification and Renewable Resources through 2050*. Berkeley Lab. Retrieved from http://eta-publications.lbl.gov/sites/default/files/1-142-17_zheng_khanna_final.pdf

Lazar, Jim and Gonzalez, Wilson. (2015). Smart Rate Design for a Smart Future. Montpelier, VT: Regulatory Assistance Project. Available at: http://www.raponline.org/document/download/id/7680

Lechtenböhmer, Stefan, Nilsson, Lars J., Åhman, Max, & Schneider, Clemens. (2016). "Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand." In Energy, Volume 115, Part 3, Pages 1623-1631.

Long, Jane C. S. (2011). *California's Energy Future - The View to 2050* (Summary Report). California Council on Science and Technology. Retrieved from http://ccst.us/publications/2011/2011energy.pdf

Lovins, Amory B. (2011). Reinventing Fire: Bold Business Solutions for the New Energy Era. Rocky Mountain Institute. Chelsea Green Publishing, White River Junction, VT.

MacKay, David J.C. (2013). "Could energy-intensive industries be powered by carbon-free electricity?" Phil Trans R Soc A 371: 20110560. http://dx.doi.org/10.1098/rsta.2011.0560

Mahone, Amber, Mahone, Douglas, & Hart, Elaine. (2016). What If Efficiency Goals Were Carbon Goals? Presented at the 2016 ACEEE Summer Study on Energy Efficiency in Buildings, ACEEE. Retrieved from https://aceee.org/files/proceedings/2016/data/papers/9_284.pdf

MassCEC. (n.d.). Air-Source Heat Pumps. http://www.masscec.com/air-source-heat-pumps

McMillan, Colin, Boardman, Richard, McKellar, Michael, Sabharwall, Piyush, Ruth, Mark, & Brigg-Sitton, Shannon. (2016, November).
Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions. Presented at the EPRI-IEA-Workshop, Washington D.C. Retrieved from https://www.iea.org/media/workshops/2016/epriieawashingtondc/McMillanEPRIIEAWorkshop.pdf

Mills, Andrew, & Seel, Joachim. (2015). *Flexibility Inventory for Western Resource Planners* (No. LBNL-1003750). Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/flexibility-inventory-western

Mills, Andrew, & Wiser, Ryan H. (2012). Changes in the economic value of variable generation at high penetration levels: a pilot case study of California Lawrence Berkeley National Laboratory Paper LBNL-5445E (2012)

Mills, Andrew, & Wiser, Ryan H. (2015). Strategies to mitigate declines in the economic value of wind and solar at high penetration in California, Applied Energy, Volume 147, 1 June 2015, Pages 269-278, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2015.03.014

Morrow III, William R., Marano, John, Sathaye, Jayant, Hasanbeigi, Ali, & Xu, Tengfang. (2013). *Assessment of Energy Efficiency Improvement in the United States Petroleum Refining Industry*. LBNL Report. July.

Mullen-Trento, Sara, Narayanamurthy, Ram, Johnson, Brandon, & Zhao, Penn. (2016, May). SMUD All-Electric Homes Deep Dive. Presented at the CA Building Decarbonization Research + Resources Synthesis.

Murphy, Kelly, interview by LBNL. (September 19, 2017).

Nadeau, Kari, McDonald-Hyman, Cameron, Noth, Elizabeth M., Pratt, Boriana, Hammond, S. Katharine, Balmes, John, & Tager, Ira. (2010). Ambient air pollution impairs regulatory T-cell function in asthma. *Journal of Allergy and Clinical Immunology*. Volume 126, Issue 4, Pages 845-852.e10. ISSN 0091-6749, http://dx.doi.org/10.1016/j.jaci.2010.08.008

National Institute of Building Sciences (NIBS). (2015). A Common Definition for Zero Energy Buildings. Prepared for the U.S. Department of Energy.

Napp, T.A., Gambhir, A., Hills, T.P., Florin, N., & Fennell, P.S. (2014). A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries, *Renewable and Sustainable Energy Reviews*. Volume 30, Pages 616-640. ISSN 1364-0321. http://dx.doi.org/10.1016/j.rser.2013.10.036

New Buildings Institute (NBI). (2016). 2016 list of zero net energy buildings.

Lowry, Mark Newton, Makos, Matthew, & Deason, Jeff. (2017). *State Performance-Based Regulation Using Multiyear Rate Plans for U.S. Electric Utilities* (No. LBNL-2001039). Retrieved from https://emp.lbl.gov/publications/state-performance-based-regulation

Obama, Barack. "Executive Order 13693--Planning for Federal Sustainability in the Next Decade."

Orfeuil, Maurice. (1987). Electric Process Heating: Technologies, Equipment, Applications. *Battelle Press*. Jan 1.

Nadel, Steven. (2016). Comparative Energy Use of Residential Furnaces and Heat Pumps (No. A1602). ACEEE. Retrieved from http://aceee.org/comparative-energy-use-residential-furnaces-and

Nicolás Pardo, José Antonio Moya, Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry, Energy, Volume 54, 2013, Pages 113-128, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2013.03.015

Paulus, Moritz, & Borggrefe, Frieder. (2011). The potential of demand-side management in energy intensive industries for electricity markets in Germany. *Applied Energy.* Volume 88, Pages 432-441. https://doi.org/10.1016/j.apenergy.2010.03.017

Penn, Ivan. (2017, June 22). California invested heavily in solar power. Now there's so much that other states are sometimes paid to take it. *Los Angeles Times*. Retrieved from http://www.latimes.com/projects/la-fi-electricity-solar/

Pierpont, Brendan, Nelson, David, Posner, David, & Goggins, Andrew. (2017). Flexibility: the path to low-carbon, low-cost electricity grids. Climate Policy Initiative Energy Finance. Retrieved from https://climatepolicyinitiative.org/publication/flexibility-path-low-carbon-low-cost-electricity-grids/

Potter, Jennifer, & Cappers, Peter. (2017). *Demand Response Advanced Controls Framework and Assessment of Enabling Technology Costs* (No. LBNL-2001044). Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/demand-response-advanced-controls

Purr, Katja, Strenge, U., Werner, K., Nissler, D., Will, M., Knoche, G., & Volkens, A. (2014) *Germany in 2050—a greenhouse gas-neutral country*. Umweltbundesamt, Dessau-Roßlau.

Pye, Steve, Anandarajah, Gabrial, Fais, Birgit, McGlade, Christophe, & Strachan, Neil. (2015). Pathways to deep decarbonization in the United Kingdom. UCL Energy Institute. SDSN e IDDRI. http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_GBR.pdf

Raghavan, Shuba V., Wei, Max, & Kammen, Daniel. M. (2017). Scenarios to decarbonize residential water heating in California. Energy Policy, 109, 441–451. ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2017.07.002

Rheem. (n.d.). "Classic Series Heat Pump (RP14 Series)." Product Manual.

Rhode Island Public Utilities Commission Staff, Division of Public Utilities and Carriers, & Office of Energy Resources. (2017). *Initial Principles for Utility Proposals to Support Beneficial Electrification*. Retrieved from http://www.ripuc.org/utilityinfo/electric/Draft%20Initial%20Electrification%20Principles.pdf

Ripke, Jayson. (2017) Innovative Uses of Hydrogen In Steelmaking. Midrex Technologies, Inc. Presentation at U. S. Department Of Energy 2@Scale Workshop. Houston Texas. May 23. https://energy.gov/sites/prod/files/2017/05/f34/fcto_may_2017_h2_scale_wkshp_ripke.pdf

Robbins, Jason, Skelton, Benjamin, & Olden, Rob. (2015). High Performing Buildings: Case Study Walgreens, Revealing Net Zero. High Performing Buildings.

Saxena, Samveg, MacDonald, Jason, Black, Doug, & Kiliccote, Sila. (2015.) "Quantifying the Flexibility for Electric Vehicles to Offer Demand Response to Reduce Grid Impacts without Compromising Individual Driver Mobility Needs." *SAE International*. Technical Paper 2015-01-0304. https://doi.org/10.4271/2015-01-0304

Schmidt, Philip. (1984). Electricity and industrial productivity: a technical and economic perspective, New York. *Pergamon Press*.

Schmitt, Bertel. (2016). Germany's Bundesrat Resolves End Of Internal Combustion Engine. Retrieved from https://www.forbes.com/sites/bertelschmitt/2016/10/08/germanys-bundesrat-resolves-end-of-internal-combustion-engine/#1e65ca0860bd

Schwartz, Lisa C., Leventis, Greg, Schiller, Steven R., & Fadrhonc, Emily Martin. (2016). SEE Action Guide for States: Energy Efficiency as a Least-Cost Strategy to Reduce Greenhouse Gases and Air Pollution and Meet Energy Needs in the Power Sector (No. LBNL-1004338). Berkeley, CA: Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/see-action-guide-states-energy

Schwartz, Lisa, Wei, Max, Morrow III, William R., Deason, Jeff, Schiller, Steven R., Leventis, Greg, Smith, Sarah Josephine, Leow, Woei Ling, Levin, Todd, Plotkin, Steven, Zhou, Yan, & Teng, Joseph. (2017). *Electricity end uses, energy efficiency, and distributed energy resources baseline* (No. LBNL-1006983). Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/electricity-end-uses-energy

State and Local Energy Efficiency Action Network (SEE Action Network). (2014). Financing Energy Improvements on Utility Bills: Market Updates and Key Program Design Considerations for Policymakers and Administrators.

State of New York Public Service Commission. (2016). *CASE 14-M-0101 - Proceeding on Motion of the Commission in Regard to Reforming the Energy Vision.* (Order Adopting a Ratemaking and Utility Revenue Model Policy Framework). Retrieved from http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7BD6EC8F0B-6141-4A82-A857-B79CF0A71BF0%7D

Steinberg, David, Bielen, Dave, Eichman, Josh, Eurek, Kelly, Logan, Jeff, Mai, Trieu, McMillan, Colin, Parker, Andrew, Vimmerstedt, Laura, & Wilson, Eric. (2017). *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization* (No. NREL/TP-6A20-68214). Retrieved from https://www.nrel.gov/docs/fy17osti/68214.pdf

Thekdi, Arvind, Nimbalkar, Sachin, & Thirumaran, Kiran. (2017). Energy and Productivity Potential of Electrotechnologies in Industrial Process Heating Systems (DOE) Mat Sci & Technology Meeting. Pittsburg, PA. October 9.

TRC Energy Services. (2016). *Palo Alto Electrification*. Retrieved from http://www.cityofpaloalto.org/civicax/filebank/documents/55069

U.S. Department of Energy. (n.d.). Air-Source Heat Pumps. https://energy.gov/energysaver/air-source-heat-pumps

U.S. Department of Energy. (n.d.). Demand Response. https://energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response

U.S. Energy Information Administration. (2017). *Annual Energy Outlook 2017* (No. AEO2017). Retrieved from https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf

U.S. Energy Information Administration. (2012). *Commercial Buildings Energy Consumption Survey (CBECS)*. Retrieved from https://www.eia.gov/consumption/commercial/

U.S. Energy Information Administration. (2009). *Residential Energy Consumption Survey (RECS)*. Retrieved from https://www.eia.gov/consumption/residential/

U.S. Energy Information Administration. (2017). *Residential Energy Consumption Survey (RECS): Table HC8.1 Water heating in U.S. homes by housing unit type, 2015.* Energy Information Administration (EIA).

U.S. Energy Information Administration. (2017) State Energy Data System (SEDS). https://www.eia.gov/state/seds/

Vairamohan, Baskar. (2014), Energy Savings with Induction Heating Overview, Applications and Case Studies, Electric Power Research Institute, Inc. Industrial Center of Excellence. December 17. Available at https://www.slideshare.net/sustenergy/eci-energy-savings-with-induction-technology-dec172014v2

Vannoni, Claudia, Battisti, Riccardo, & Drigo, Serena. (2008). *Potential for Solar Heat in Industrial Processes.* Department of Mechanics and Aeronautics - University of Rome "La Sapienza." Retrieved from http://www.aee-intec.at/0uploads/dateien561.pdf

Vaudreuil, Laurie, interview by LBNL. (September 18, 2017).

Vermont Department of Public Service. (2016). *Comprehensive Energy Plan 2016*. Retrieved from https://outside.vermont.gov/sov/webservices/Shared%20Documents/2016CEP_Final.pdf

Wei, Max, Nelson, James H., Greenblatt, Jeffrey B., Mileva, Ana, Johnston, Josiah, Ting, Michael, Yang, Christopher, Jones, Chris, McMahan, James E., & Kammen, Daniel M. (2013). Deep carbon reductions in California require electrification and integration across economic sectors. *Environmental Research Letters*, *8*(014038), 10. https://doi.org/doi:10.1088/1748-9326/8/1/014038

Weiss, Jürgen, Hledik, Ryan, Hagerty, Michael, & Gorman, Will. (2017). *Electrification: Emerging Opportunities for Utility Growth* (White Paper). The Brattle Group. Retrieved from http://www.brattle.com/system/news/pdfs/000/001/174/original/Electrification_White paper_Final_Single_Pages.pdf?1485532518

Williams, James H., DeBenedictis, Andrew, Ghanadan, Rebecca, Mahone, Amber, Moore, Jack, & Morrow III, William R. (2012). The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *SCIENCE*, *335*(6 January 2012), 53–59. https://doi.org/10.1126/science.1208365

Wilson, Eric, Christensen, Craig, Horowitz, Scott, Robertson, Joseph, & Maguire, Jeff. (2017). Energy Efficiency Potential in the U.S. Single-Family Housing Stock (No. NREL/TP-5500-68670). Golden, CO: National Renewable Energy Laboratory (NREL). Retrieved from https://www.nrel.gov/docs/fy18osti/68670.pdf

Wood, Lisa, Hemphill, Ross, Howat, John, Cavanagh, Ralph, Borenstein, Severin, Deason, Jeff, & Schwartz, Lisa C. (2016). *Recovery of Utility Fixed Costs: Utility, Consumer, Environmental and Economist Perspectives* (Future Electric Utility Regulation No. LBNL-1005742). Berkeley Lab. Retrieved from https://emp.lbl.gov/publications/recovery-utility-fixed-costs-utility

Yang, Christopher, Yeh, Sonia, Ramea, Kalai, Zakerinia, Saleh, McCollum, David, Bunch, David, & Ogden, Joan. (2014). *Modeling optimal transition pathways to a low carbon economy in California: California TIMES (CA-TIMES) model*. Institute of Transportation Studies, University of California, Davis. Retrieved from https://www.arb.ca.gov/research/apr/past/09-346.pdf

Yilmaz, Murat, & Krein, Philip T. (2013). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics*, 28 (5), pp. 2151-2169.

Appendix A. Additional Industry Data

Table A - 1. Market shares of electric end uses in 2030 for the industrial sector (EPRI 2009)

Electric Technology	Displaced Fossil-Fueled Technologies	End-Use Areas	Displaced Fuels	Industrial Subsectors (3-digit NAICS code)	Technical Potential Market Share	Realistic Potential Market Share
Electric Boilers	Fossil-Fueled Boilers	Boilers	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.85	0.4
				Primary Metals 331	0.85	0.4
				Others	0.85	0.4
			Fuel Oil	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.85	0.5
				Primary Metals 331	0.85	0.5
				Others	0.85	0.5
			Coal	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.85	0.5
				Primary Metals 331	0.85	0.5
				Others	0.85	0.5
Electric Drives	Steam Drives	Boilers	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.15	0.05
				Primary Metals 331	0.15	0.05
				Others	0.15	0.05
			Fuel Oil	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.15	0.1
				Primary Metals 331	0.15	0.1
				Others	0.15	0.1
			Coal	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.15	0.1
				Primary Metals 331	0.15	0.1
				Others	0.15	0.1
Heat Pumps	Fossil-Fueled Furnaces	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.15	0.1
				Primary Metals 331	0.05	0.02
				Others	0.1	0.075
		Other (Space Heating)	*Natural Gas*	All NAICS	0.75	0.5

Electric Technology	Displaced Fossil-Fueled Technologies	End-Use Areas	Displaced Fuels	Industrial Subsectors (3-digit NAICS code)	Technical Potential Market Share	Realistic Potential Market Share
Induction Heating	Direct-Fired Natural Gas	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.11	0.05
				Primary Metals 331	0.05	0.05
				Others	0.1	0.05
Radio Frequency Heating	Direct-Fired Natural Gas	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.11	0.05
				Primary Metals 331	0	0
				Others	0.1	0.05
Microwave Heating	Direct-Fired Natural Gas	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.11	0.05
				Primary Metals 331	0	0
				Others	0.1	0.05
Electric Infrared Heating	Direct-Fired Natural Gas	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.11	0.05
				Primary Metals 331	0.05	0.01
				Others	0.3	0.15
UV Heating	Direct-Fired Natural Gas	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.225	0.1
				Primary Metals 331	0.05	0.01
				Others	0.3	0.15
Electric Arc Furnace	Coke Blast Furnace	Process Heating	Coke	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0	0
				Primary Metals 331	1	0.5
				Others	0	0
Induction Melting of Metals	Natural Gas Furnace	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0	0
				Primary Metals 331	0.5	0.4
				Others	0	0
Plasma Melting	Natural Gas Furnace	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.075	0.025
				Primary Metals 331	0.2	0.1
				Others	0	0
Electrolytic Reduction	Natural Gas Furnace	Process Heating	Natural Gas	Paper, Wood, Textiles, etc. 313 321 322 324 325 326 327	0.11	0.05
				Primary Metals 331	0.1	0.05
				Others	0	0

Production Improvement Services

What if...

You could reduce your energy costs and risks?

Hybrid Electric Boiler Systems

THE PROBLEM: WHAT NOW?

Recent natural gas prices, while trending upward, have varied dramatically from month to month. Such volatility and unexpected increases in costs wreak havoc with yearly energy budgets. As natural gas costs continue to escalate already strained energy budgets are severely impacted.

THE SOLUTION: WHAT ABOUT...?

The good news is that the solution may be as simple as taking advantage of Duke Energy's special rates by using an electric boiler when electric prices are lowest. In many cases it may only involve re-using an existing electric boiler that has been idle. Or, if you don't have an existing electric boiler, the cost to install one may be well worth the expense based on energy savings. A hybrid system consisting of both electric and natural gas boilers can maximize cost savings while minimizing energy price risk.

Duke Energy customers enjoy some of the lowest and most stable electric rates in the country. As a result, there are opportunities to deploy electric boilers to generate significant cost savings for many businesses.

Hybrid Electric Boiler Systems

Hybrid electric boiler systems use both electric and natural gas (and propane, fuel oil, etc.) equipment resulting in lower costs than any one fuel source alone could achieve. Having two energy sources also mitigates the risk of energy price volatility.

Simply use electric boilers when electric rates are lowest and natural gas boilers at other times. By using stable, low-cost electricity for many hours throughout the year, the impact of fuel price volatility is minimized.

Payback

The following chart represents average installed costs and approximate simple paybacks for electric boilers. Actual costs may vary.

Boiler (BHP)	Cost	Payback
50	$50,000	3.1 Years
100	$70,000	2.6 Years
200	$120,000	2.2 Years
400	$240,000	2.2 Years
800	$440,000	2.1 Years
2,000	$800,000	1.5 Years
4,000	$1,000,000	1.3 Years

Payback assumes natural gas costs $6.50/MMBTU at the burner tip.

Duke Energy

Production Improvement Services

What if...

You achieved total operational excellence?

Savings

The following chart estimates cost savings using annual natural gas prices and annual gas consumption.

POTENTIAL ANNUAL SAVINGS
(Dollars in thousands)

Natural Gas Price	Annual Consumption (Dekatherms) 25,000	50,000	100,000	500,000	1,000,000
$5.50	$9	$19	$38	$188	$376
$6.00	$19	$38	$76	$378	$757
$6.50	$29	$58	$117	$585	$1,170
$7.00	$40	$80	$159	$795	$1,591
$7.50	$50	$101	$201	$1,007	$2,015
$8.00	$61	$122	$244	$1,223	$2,447
$8.50	$72	$144	$289	$1,442	$2,886
$9.00	$83	$166	$332	$1,661	$3,324
$9.50	$94	$188	$376	$1,882	$3,764
$10.00	$105	$210	$420	$2,101	$4,202

(1) Natural Gas Prices are in $/MMBTU at the burner tip
(2) Savings assume an 80% efficient gas boiler
The above savings are estimates based on average conditions. Specific results may vary.

Benefits

Easy Integration

Electric boilers are easily integrated with existing natural gas units to create a hybrid electric boiler system. No major modifications or additions to the existing boiler equipment are normally required. Every installation is unique however, and requires proper professional design.

Reliability

Creating a hybrid electric boiler system can increase the overall reliability of your operation. Although the primary reason to utilize an electric boiler is to save money, having an alternate energy source provides valuable redundancy for single boiler systems. Furthermore, electric boilers are very reliable and extremely simple to operate.

Other Benefits

- Electric boilers may be sited almost anywhere.
- Electric boilers maintain high efficiency throughout their output range. Natural gas equipment tends to be less efficient at lower operating conditions.
- Electric boilers do not require combustion air. If combustion air is drawn from inside conditioned spaces, it increases HVAC costs.
- Electric boilers do not have an exhaust stack avoiding troublesome roof penetrations.
- Electric boilers require no air emissions permitting.
- Electric boilers do not require backup fuel storage and the necessary permitting and spill prevention.
- Electric boilers require no additional specialized feed-water treatment.

Summary

Electric boilers, especially those used in a hybrid electric boiler system, offer an immediate solution to the escalating cost of natural gas and insulate your energy budget from market volatility.

Simple paybacks for incorporating electric boilers are often very attractive and typically range from 1 to 3 years.

Duke Energy

FOR MORE INFORMATION

For more information on how an electric boiler can benefit your business, please contact your Duke Energy account manager or call us at 1-800-777-7475.

J#06-3581

What's next for your business?

Figure A - 1. Hybrid boiler information and costs from Duke Energy (2006)