Electrification as an energy efficiency and decarbonization strategy

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Abstract

Energy efficiency and no/low carbon energy can substantially reduce greenhouse gas emissions, but in order to reach the 2050 Paris targets, additional reductions will be needed. A variety of studies in Europe and the U.S. have found that electrifying large portions of energy demand can help to achieve substantial emissions reductions, with the largest reductions in transportation, followed by industry. This paper discusses emerging programs and policies to begin promoting "beneficial electrification" as a form of energy efficiency, which occurs when electrification reduces primary energy use, reduces emissions, and saves consumers money.

In the U.S., electrification market and policy efforts have so far focused on transportation and homes. In transportation, mid-priced electric vehicles (EVs) with ranges of 300 km or more are growing in popularity. EVs are now approaching 10 % of vehicle sales in California. Several major US cities have committed to converting their bus fleets to electricity. For homes, the best conversion economics are for water heating, space heating in new construction, space heating for existing homes in the south and space heating in homes that now use fuel oil or propane. For existing homes in the far north as well as homes that use natural gas outside of the south, conversion economics are often challenging. There has been some electrification in US industry while commercial sector efforts are beginning with high efficiency new buildings. This paper contrasts these efforts with parallel efforts in Europe and discusses next steps.

Introduction

Research by the International Energy Agency (IEA), the American Council for an Energy-Efficient Economy (ACEEE) and others has found that energy efficiency can get the world and the United States about halfway or nearly halfway towards meeting the Paris Treaty goal of reducing greenhouse gas (GHG) emissions by 80 % by 2050 (IEA 2018, Nadel 2016a, Gowrishankar and Levin 2017). For the remaining reductions, the largest opportunities appear to be from use of renewable and other low/no carbon energy sources, and electrification of fossil-fuel loads in the transportation, residential, commercial and industrial sectors. This is illustrated for the US in Figure 1.

While electrification is different from energy-efficiency measures such as weatherization and efficient lighting, heating and cooling equipment, electrification can often be considered an efficiency measure if the use of electricity for an end-use result in less primary energy use than if fossil fuels are used. The term "beneficial electrification" is more broadly used to describe electrification opportunities that provide net societal and participant benefits, particularly reduced emissions and life-cycle cost savings to end-users; it is also energy efficiency where it reduces primary energy use.

Major opportunities for electrification include vehicles, building space and water loads and some industrial process heat applications. In a study on US electrification opportunities by the Electric Power Research Institute (EPRI 2018), vehicles are the largest electrification opportunity, followed by industry and buildings (Figure 2).

Europe is also exploring electrification. For example, Eurelectric has suggested that in order for Europe to meet its goal to reduce greenhouse gas emissions by 95 % by 2050, electricity

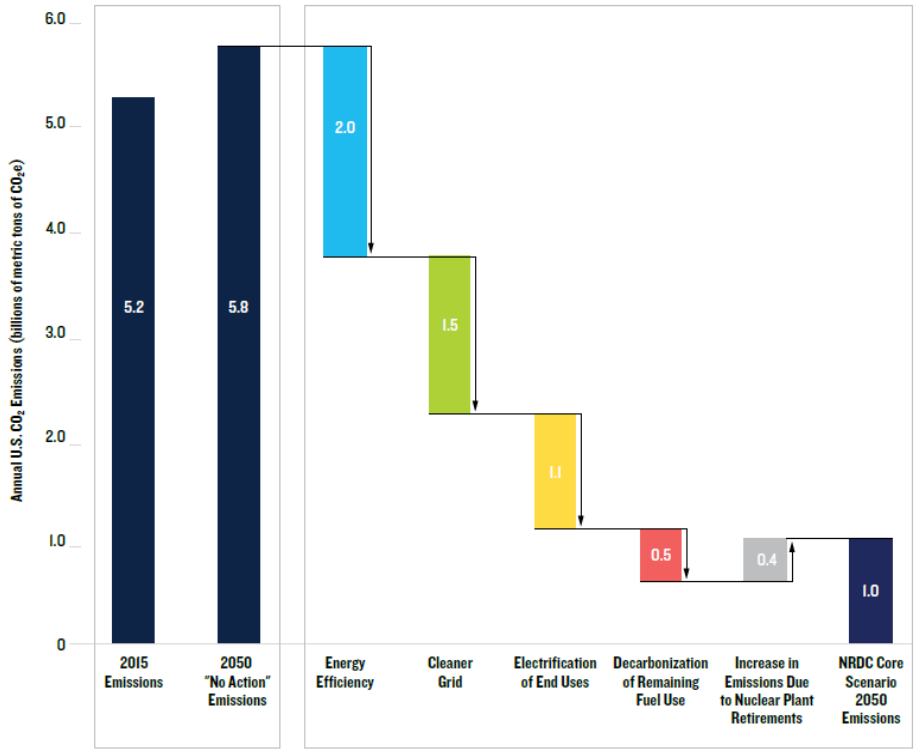


Figure 1. NRDC scenario for 2050 potential carbon dioxide emissions reductions in the US. Electrification is in yellow. "Cleaner grid" means more use of no and low carbon electricity. "End uses" include many of the transportation, buildings and industrial energy uses discussed in this paper. Source: Gowrishankar and Levin 2017.

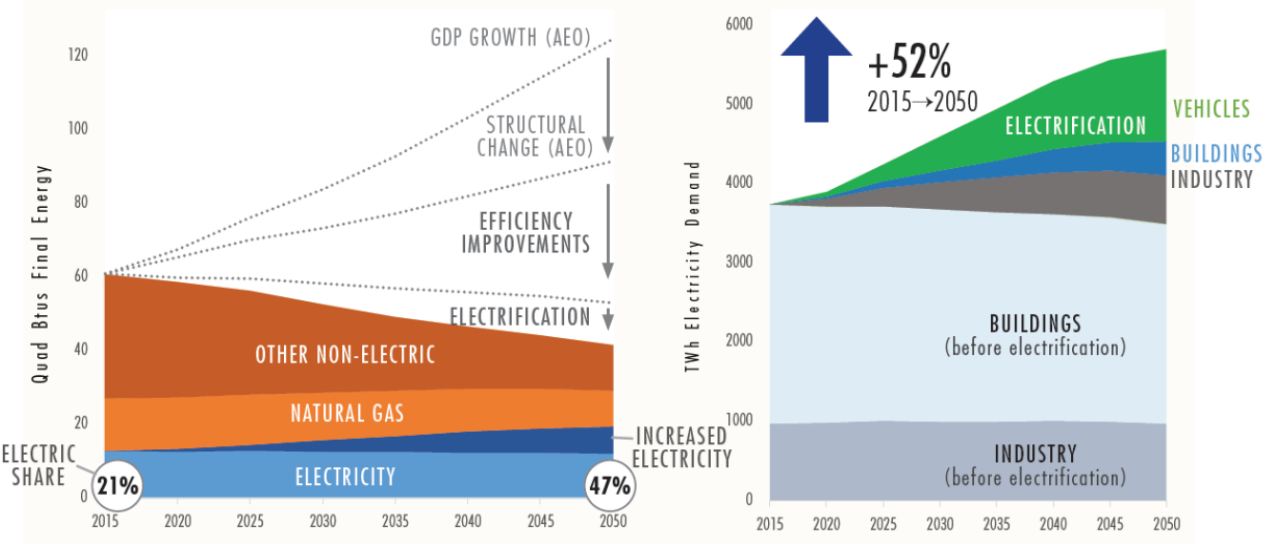


Figure 2. Transformation scenario (aggressive electrification) for the US developed by EPRI. Source: EPRI 2018. Note: One quad of energy equals 1.055 exojoules.

will need to account for at least 60 % of end-use energy, up from 22 % in 2015 (Euroelectric 2018).

In this paper we discuss electrification efforts in the US, looking at market progress, economics and policy. We begin with transportation and progress to the residential, commercial and industrial sectors. We then briefly compare and contrast efforts in the US with those in Europe and conclude with a discussion of next steps.

Transportation

In the US transportation sector, electrification efforts have emphasized passenger vehicles, but efforts to electrify buses are accelerating. We primarily discuss passenger vehicles and briefly address buses. Efforts to electrify trucks, particularly delivery vehicles, are outside the scope of this paper (for an overview on US truck electrification, see NACFE 2018).

PASSENGER VEHICLES

Overview

In the US, as of February 2019, 21 different all-electric passenger models are on the market (EV Rater 2019), plus a few plug-in hybrid models. In 2018, sales are estimated at 325,000 vehicles, with California accounting for more than half. In California, EVs are now approaching 10 % of passenger vehicle sales (EV Adoption 2018). Electric vehicle (EV) sales have primarily been either moderate cost vehicles with a moderate range (e.g. the Nissen Leaf) or high cost vehicles with a much longer range (e.g. luxury Tesla models). In the past year, mid-priced vehicles (approximately $35,000; €30,000) with a range of more than 200 miles (300 km) have become more popular, such as the Chevrolet Bolt and the Tesla Model 3. New vehicle introductions are emphasizing longer range, aided by declines in battery costs.

Energy and Emissions Savings

In the US, the typical EV uses less energy and emits less greenhouse gases than hybrid or conventional options. This is illustrated in Figure 3, which compares two of the most popular EVs with a conventional vehicle and a popular hybrid vehicle on miles per gallon (MPG) (on the left) and GHG emissions per miles (on the right). On official fuel economy tests EVs look very good because power plant inefficiencies are not included. We add these power plant losses as well as upstream losses for gasoline and find that the EVs profiled are much better on fuel economy than the average conventional vehicle and somewhat better than the hybrid vehicle. On emissions, the EVs do better still since the average power plant emissions associated with electricity generation are lower than the emissions associated with burning gasoline. Furthermore, as the electric grid gets cleaner (EIA 2019), the emissions associated with EVs will further decline.

Economics

The economics of EVs vary as a function of the incremental cost of an EV relative to a similar conventional vehicle, the price of conventional fuels, the price of electricity, and how many miles the vehicle is driven each year. Table 1 illustrates the tradeoffs, calculating the simple payback period for an EV relative to a conventional vehicle under a variety of situations. In the US, the average price of gasoline is around $3 per gallon (€0.70 per liter). At this fuel price, the simple payback is generally under 5 years (shaded in yellow in Table 1) if the incremental cost of the EV is $2,500 and the vehicle is driven 10,000 miles per year (16,000 km) or if the incremental cost is $5,000 and the vehicle is driven 15,000 miles per year (24,000 kilometers). For the electricity prices shown, the cost of electricity is secondary. Table 1 also shows higher fuel prices, as are common in Europe. Currently, a $2,500 incremental cost will generally depend on financial incentives, but as battery costs decline, ultimately purchase cost parity is expected to be reached, perhaps as soon as seven years (Hodges 2018). Furthermore, it is important to note that economics is only one consideration in decisions on whether to buy an electric vehicle.

Programs and Policies

A variety of policies and programs have helped to promote EVs in the US including:

- Subsidies for vehicle purchase, such as federal tax incentives of up to $7,500 per vehicle (these incentives phase down after a manufacturer sells 200,000 vehicles), as well as incentives from some states and utilities. Some states also have lower EV registration fees or provide them access to high occupancy vehicle lanes.
- Zero emissions vehicle (ZEV) mandates now in place in 10 states that require a specified percentage of vehicle sales to be EVs or other ZEVs.
- Many efforts to promote public charging stations including along major travel routes, in shopping areas, and at workplaces. These efforts have been led by utilities, cities and states and also by VW subsidiary Electrify America as part of their settlement for cheating on diesel emissions levels.

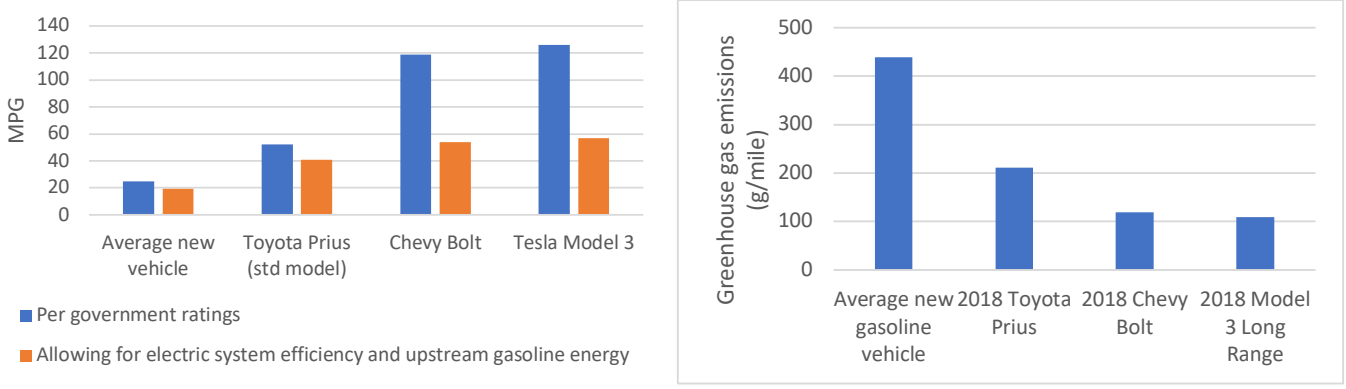


Figure 3. Comparison of two EVs, a hybrid car and the average new vehicle on fuel economy and emissions per mile. Based on US government fuel economy and emissions tests for 2018 vehicles. The adjustments for upstream system losses are by ACEEE and are based on a 45 % efficient power plant and 28 % upstream gasoline losses (the latter derived from Oak Ridge National Laboratory's GREET model). Greenhouse gas emissions derived by ACEEE from government data.

Table 1. Simple Payback for Purchasing an EV Relative to a Conventional Vehicle Under Several Scenarios.

Gasoline price ($/gal)		$ 2.00	$ 2.00	$ 2.00	$ 2.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 4.00	$ 4.00	$ 4.00	$ 4.00	$ 5.00	$ 5.00	$ 5.00	$ 5.00
(Euros/liter)		€ 0.46	€ 0.46	€ 0.46	€ 0.46	€ 0.70	€ 0.70	€ 0.70	€ 0.70	€ 0.93	€ 0.93	€ 0.93	€ 0.93	€ 1.16	€ 1.16	€ 1.16	€ 1.16
Electric price ($/kWh)		$ 0.05	$ 0.10	$ 0.15	$ 0.20	$ 0.05	$ 0.10	$ 0.15	$ 0.20	$ 0.05	$ 0.10	$ 0.15	$ 0.20	$ 0.05	$ 0.10	$ 0.15	$ 0.20
(Euros/kWh)		€ 0.012	€ 0.023	€ 0.035	€ 0.046	€ 0.012	€ 0.023	€ 0.035	€ 0.046	€ 0.012	€ 0.023	€ 0.035	€ 0.046	€ 0.012	€ 0.023	€ 0.035	€ 0.046
Miles/year	Incre. Cost	Simple payback period in years															
10000	2500	4.6	6.0	8.6	15.0	2.9	3.3	4.0	5.0	2.1	2.3	2.6	3.0	1.6	1.8	1.9	2.1
(16090 km)	5000	9.2	12.0	17.1	30.0	5.7	6.7	8.0	10.0	4.1	4.6	5.2	6.0	3.2	3.5	3.9	4.3
	10000	18.5	24.0	34.3	60.0	11.4	13.3	16.0	20.0	8.3	9.2	10.4	12.0	6.5	7.1	7.7	8.6
	15000	27.7	36.0	51.4	90.0	17.1	20.0	24.0	30.0	12.4	13.8	15.7	18.0	9.7	10.6	11.6	12.9
15000	2500	3.1	4.0	5.7	10.0	1.9	2.2	2.7	3.3	1.4	1.5	1.7	2.0	1.1	1.2	1.3	1.4
(24135 km)	5000	6.2	8.0	11.4	20.0	3.8	4.4	5.3	6.7	2.8	3.1	3.5	4.0	2.2	2.4	2.6	2.9
	10000	12.3	16.0	22.9	40.0	7.6	8.9	10.7	13.3	5.5	6.2	7.0	8.0	4.3	4.7	5.2	5.7
	15000	18.5	24.0	34.3	60.0	11.4	13.3	16.0	20.0	8.3	9.2	10.4	12.0	6.5	7.1	7.7	8.6
20000	2500	2.3	3.0	4.3	7.5	1.4	1.7	2.0	2.5	1.0	1.2	1.3	1.5	0.8	0.9	1.0	1.1
(32180 km)	5000	4.6	6.0	8.6	15.0	2.9	3.3	4.0	5.0	2.1	2.3	2.6	3.0	1.6	1.8	1.9	2.1
	10000	9.2	12.0	17.1	30.0	5.7	6.7	8.0	10.0	4.1	4.6	5.2	6.0	3.2	3.5	3.9	4.3
	15000	13.8	18.0	25.7	45.0	8.6	10.0	12.0	15.0	6.2	6.9	7.8	9.0	4.9	5.3	5.8	6.4
Gas MPG	30	Gas KPL		12.8													
Elec miles/kWh	4	Elec kM/kWh		6.4													

Notes: Simple paybacks of five years or less are shaded in yellow. This analysis does not include costs for vehicle maintenance and insurance nor costs for installing a charger at home. Source: Calculations by the author.

Issues

Several issues are emerging for EVs which merit discussion. First, as is typical for all new vehicles, purchases are disproportionately made by upper income households as shown in Figure 4. Lower income households disproportionately purchase used vehicles, but the current supply of used EVs is small. To put these data in perspective, in 2017, according to the US Census Bureau, the median US household had an income of $61,372 (€54,157). Some programs are trying to address this issue including a pilot program to introduce shared EVs in low-income sections of Los Angeles (www.bluela.com), pilot efforts to promote and incentivize EVs in a few low-income communities (Heitner 2017), and a program now being developed by Lyft to encourage drivers in low-income communities to rent EVs at low or no cost as long as drivers meet minimum weekly rides-provided targets (Ershow 2018). Likewise, due to longer driving distances and other barriers, there is a lower proportion of EVs in rural than in urban and suburban areas, even though rural residents may have more to gain from EVs due to the longer distances they drive and their greater use of less-efficient older vehicles (Gatti 2018). As vehicle ranges increase and public chargers are installed in rural areas, this problem may decrease.

Second, there is an issue of when EVs get charged and the impact on the electric grid. Available data indicate that most EV charging occurs during the evening and overnight (Schey et al. 2012). In parts of the US, there is a growing tendency for daytime demand for utility power to decrease (due particularly to end-user solar systems) and for evening peaks to grow when the sun sets and people get home from work. This phenomenon has been called the "duck curve" and is illustrated in Figure 5. If EVs charge in the evening, that exacerbates this trend and there is growing interest in encouraging charging in the middle of the night through lower rates or direct utility control over chargers. Also, DC fast chargers can use 100 kW of power or more, requiring reinforcements to distribution systems in some cases. Careful siting is needed to minimize these problems.

Projections

Projections of future EV market share vary widely. In 2017, Bloomberg New Energy Finance estimated that 50 % of US new vehicle sales would be EVs by about 2033 while the Energy Policy Simulator projects that milestone in 2037 (Risman 2017). The Edison Electric Institute (a trade association of investor-owned utilities) estimates 22 % of sales will be EVs in 2030 (Cooper and Schefter 2018), putting them on the same trajectory as the Energy Policy Simulator. On the other hand, the US Energy Information Administration is much more conservative, estimating that in 2040, only 14 % of US light-duty vehicle sales will be EVs (EIA 2019).

BUSES

On a total (lifecycle) cost of ownership basis, e-buses can be less expensive, particularly buses that are driven farther each day (Marcacci 2018). Electric buses have recently gained significant momentum in the US. As of the end of 2017 there were about 300 "e-buses" on US roads, but in 2018 the federal government awarded funding for 52 projects in 41 states and several major cities. E-buses cost more (e.g. about $750,000 for an e-bus versus $435,000 for a standard diesel bus), but operating costs are substantially lower (e.g. $25,000–50,000 per bus annually, depending on a variety of factors (Blanco 2018)). Given the high initial costs, creative financing options, such as leasing can be employed. New York, Los Angeles and San Francisco have made commitments to switch all municipal buses from diesel to e-buses by 2030–2040 (varying by city) (Marcacci 2018).

Residential Sector

OVERVIEW

In the US, 62 % of US homes and apartments use central warm air furnaces for heating. These systems heat and distribute warm air around a home via a system of ducts. Furnaces most commonly burn natural gas, but some use fuel oil, propane or electricity. Heat pumps are used in 12 % of homes, hot water

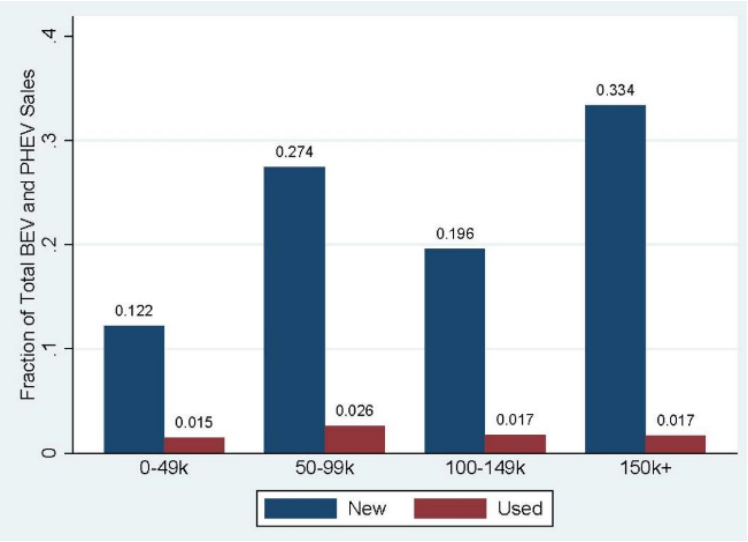


Figure 4. California EV sales by income in 2011–2015. All bars total to 1, which is 100 % of sales. Source: Muehlegger and Rapson 2018.

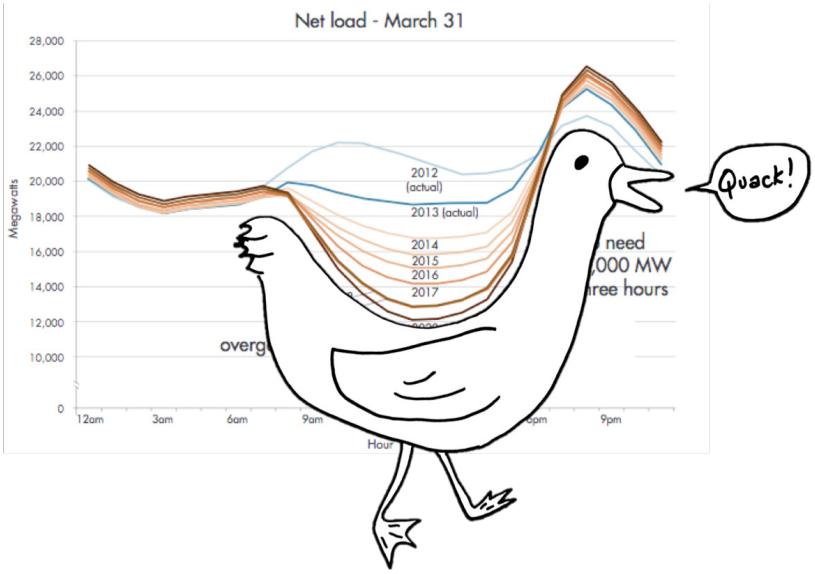


Figure 5. Springtime electricity demand in California by year and time of day. Source: Wirfs-Brock 2014.

and steam systems in 8 %, and electric baseboard heaters in 8 %, with various other systems accounting for the remainder (EIA 2018). Historically, heat pumps achieved significant penetration in warm parts of the US, but they did not function well at cold temperatures. In recent years, a wide variety of "cold climate heat pumps" have been developed that can meet heating needs down to about 5 °F (-15 °C) and sometimes lower. Various studies have looked at opportunities to convert homes using fossil fuels to modern heat pumps, and programs and policies to encourage such conversions have begun, primarily on the West coast and in the Northeast.

ENERGY AND EMISSIONS SAVINGS

The energy and emissions savings from electrification depend on the efficiency and emissions of power generation as well as the efficiency of fossil fuel and electric space and water heating systems. Nadel (2018) looked at a variety of combinations for these variables and concluded that new heat pumps (COP of about 2.4 or more) will generally save energy compared to a new furnace if power comes from a typical combined cycle power plant, or another generating source of equal or better efficiency. The study also found that heat pumps will often reduce emissions in most US states, except for some states in the Midwest US where use of coal is still high. The study assumed that heat pumps would be the sole source of heat without a backup heating system.

ECONOMICS

The best economics for using heat pumps are in new, efficient homes. In new construction, efficiency keeps energy use down and money can be saved by not installing gas service. In existing homes, heat pumps can save money in homes using oil or propane for space heat when an existing central air conditioner, furnace and/or boiler needs to be replaced (with the excep-

tion of very cold regions such as the Upper Midwest). However, at current low US natural gas prices, heat pumps often have higher lifecycle costs than natural gas heating systems, except in very warm regions (Billimoria et al. 2018, Nadel 2018, Nadel 2016b). These results are illustrated for five US cities in figure 6. These analyses are primarily for installing central ducted heat pumps. Ductless heat pumps that heat one or a few rooms can be useful for replacing electric baseboard or radiator heat and for efficient new homes (Nadel and Kallakuri 2016, Nadel 2018). For water heaters, Nadel (2016b and 2018) found that heat pump water heaters generally have lower lifecycle costs. Simple payback periods for heat pump water heaters are typically around four years or less when replacing oil or propane water heaters, and on the order of nine years when replacing a natural gas water heater.

PROGRAMS AND POLICIES

From coast to coast, several programs are starting to help homeowners switch from space and water heating fuelled by oil, propane, and natural gas to high-efficiency heat pumps powered by electricity. Nadel (2018) profiles multiple programs, primarily in California and the Northeast, that are promoting electrification and often combining equipment incentives with other energy efficiency measures.

Perhaps the most aggressive program is operated by the Sacramento Municipal Utility District (SMUD), a municipal utility serving Sacramento, California. SMUD recently started a program that offers a $2,500 rebate for replacing a gas furnace with a heat pump (and also sealing ducts and installing a smart thermostat), a $3,000 rebate for replacing a gas water heater with a heat pump water heater, and an additional $2,500 for taking specified steps to move toward becoming an efficient all-electric home (SMUD 2019). Because this program is new, results are not available yet. SMUD is also planning to give rebates for new all-electric homes and is considering a smaller rebate for homes that are electric ready, meaning they have adequate electric service, breakers, wiring, and plugs to be easily converted to all electric, even if some gas appliances are installed at the time of construction (Blunk 2018). California is also about to begin a pilot program to convert about 1,600 homes to heat pumps that now use propane and wood (Borgeson 2018). Efficiency Maine, the state of Maine's primary efficiency program

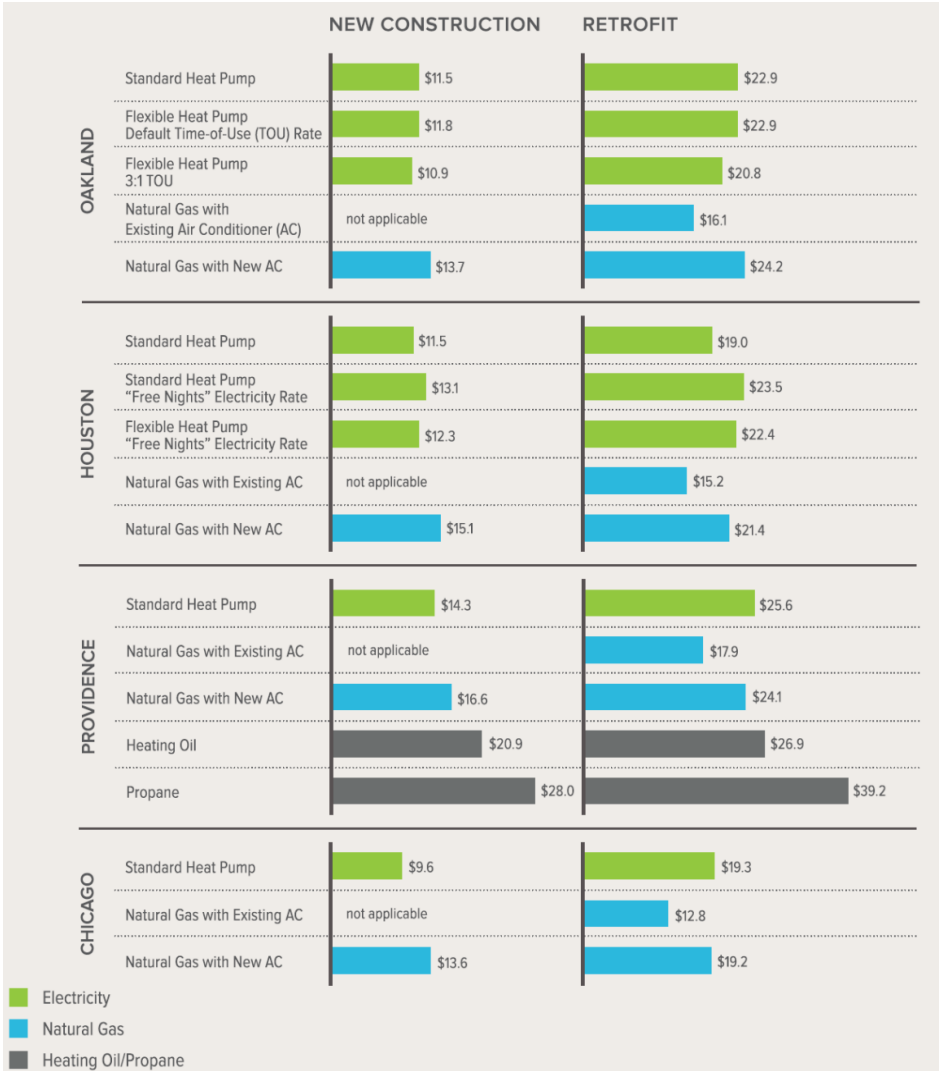


Figure 6. Comparison of 15-year net present value costs ($1,000) for space conditioning and water heating in five US cities. Source: Billimoria et al. 2018.

administrator, offers a ductless heat pump program for residential and commercial customers. For example, residential customers can receive a $500 rebate for the first indoor unit and $250 for a second one. Since 2011, more than 25,000 units have been installed through the program. Administrators attribute the high adoption rate to the large cost savings from switching from oil to high-efficiency electric heat pumps, particularly during years of high oil prices. The high rebate amounts have also encouraged a substantial number of customers to adopt the technology (Nadel 2018).

Vermont's 2016 Comprehensive Energy Plan identifies heat pumps as a strategy for meeting its goals for reducing fossil fuel consumption. Efficiency Vermont (a statewide "efficiency utility") launched a ductless heat pump program in 2014 that provides a $600–800 per unit "midstream" incentive to wholesale distributors; distributors are required to pass the savings to contractors through an instant discount. In addition, customers can receive incentives from their electric utilities, which are driven in part by a state requirement to help customers reduce fossil fuel use. Homeowners can also rent a ductless heat pump. Monthly rates range from $41.99 to $54.99 depending on the equipment size; agreements run for 15 years. Installation, materials, and maintenance are built into the flat monthly fee. To date, the programs have incentivized more than 8,200 heat pumps, including more than 1,000 leased units. Efficiency Vermont attributes this success largely to the sizable upstream incentives, made possible by using both electric savings and fossil fuel savings in its cost-benefit calculation. These large incentives, paired with strong supply chain engagement, have driven participation (Nadel 2018).

ISSUES

From these early program and policy efforts, several issues have emerged which merit discussion. First, in the northern US, heat pumps need to work well in cold weather. There are many ductless cold climate heat pumps, but there are only a few cold climate heat pumps designed for use with ducts. Since, as noted earlier, more than 60 % of US homes have ducts, increased manufacturer attention to ducted cold climate heat pumps is needed.

Second, heat pump loads tend to peak on cold winter mornings. In much of the US, electric loads peak on hot summer days, but if heat pumps become much more common, the system peak could well shift to winter mornings. This has been documented for both the northeast and southeast (Nadel 2016c and 2017). Such a shift in peak in turn will require some adjustments to the grid, as well as a need for more research on winter demand response strategies to help manage these peaks.

Finally, while electric utilities appreciate the increased sales associated with heat pumps, gas utilities have sometimes sought to slow such efforts, seeking to retain their share of the space and water heating market. Gas utilities often promote high efficiency gas options and may contest whether public policy should encourage electrification, as opposed to leaving consumer decisions to the market.

PROJECTIONS

EPRI (2018), as part of the study summarized in Figure 2, estimates that by 2050, about 15 % of residential energy use will electrify in their reference case, increasing to about 25 % in their transformation case. NREL, in their 2050 reference scenario, estimates that the heat pump share of the residential space heating market will increase only a few percent, but in their high electrification scenario, as much as two-thirds of residential space heating in 2050 will be by heat pumps (Mai et al. 2018). In the Northeast, the Acadia Center (a clean energy advocacy group) finds that less than 1 % of Northeast homes are currently served by heat pumps, but that by 2030 this will increase to 3 % in their reference case and 13 % in their primary Energy Vision scenario (Acadia Center 2018). And in California, a recent study examined an aggressive scenario in which one-third homes were heated with electricity by 2030, up from less than 10 % today (Hopkins et al. 2018).

Commercial Sector

The National Renewable Energy Laboratory (NREL) has estimated larger electrification impacts in the commercial sector than the residential sector (i.e. 33 % growth in commercial sector electricity sales over the 2016–2050 period in their medium electrification scenario versus 7 % growth in the residential sector) (Mai et al. 2018). However, this is a very approximate analysis based on top-down estimates of electric technology potential penetration as illustrated in Figure 7. They did not look at details by building type and construction nor do any economic analysis.

The EPRI electrification assessment summarized in Figure 2 looks at "buildings" and does not separate the residential and commercial sectors. A modelling study by researchers at Mississippi State University looked just at medium-sized offices, comparing rooftop units (air conditioning plus gas for heating) with variable refrigerant flow (VRF) heat pumps in 16 US cities. They concluded that the VRF systems have lower operating costs in all but the very coldest locations (Alaska and Montana) (Kim et al. 2017). We are not aware of any other studies that examine electrification opportunities in the US commercial sector in any detail. Studies are needed on a variety of building and system types. In particular, more work is needed to examine large buildings now served by central boiler systems; replacing such systems with heat pumps can be challenging.

In terms of program, policy and implementation activity, some of the residential programs discussed in the section above also apply to small commercial facilities. There are also some individual commercial sector projects that are pursuing electrification. For example, the University of California recently established a policy that "no new UC buildings or major renovations after June 2019, except in special circumstances, will use on-site fossil fuel combustion, such as natural gas, for space and water heating." Stanford University has also moved forward with electrification, phasing out an aging natural gas-fired plant and nearing a decision to go all electric in a new student housing complex (Gerdes 2018). Other institutions that care about climate change are also good targets for electrification, particularly for new construction. And for highly efficient new buildings more broadly, such as zero energy commercial buildings, use of electric heat pumps, including ground-source and variable refrigerant flow systems is a common choice (Maor and Snyder 2016).

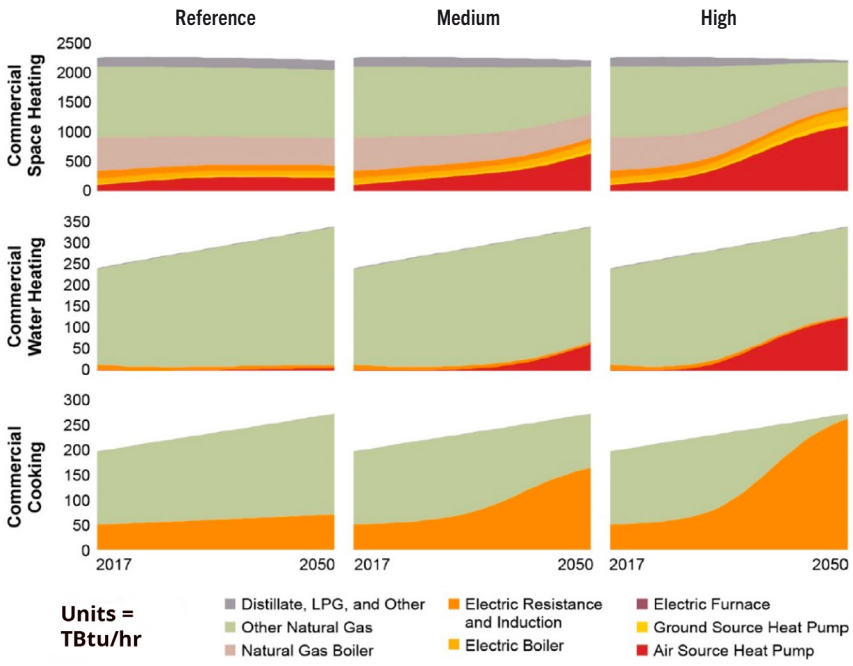


Figure 7. Projected equipment shares for US commercial sector in NREL electrification scenarios. A TBtu is equivalent to 1.055 Terajoules. Source: Mai et al. 2018.

Industrial Sector

In the US, moderate industrial electrification efforts have proceeded for several decades, particularly for processes where electro-technologies can provide productivity or quality improvements. In the past few years, due to climate concerns, decarbonisation has received more attention. Electrification is one among several decarbonisation strategies – other major ones are continued efforts to improve energy efficiency and minimize waste, substitution of less carbon-intensive materials for carbon-intensive materials such as steel and cement, development of new processes and materials with reduced greenhouse gas impacts, carbon capture and storage, and use of hydrogen and biomass, both as a fuel or feedstock.

Several studies have looked at industrial electrification opportunities and impacts. For example, the EPRI study summarized in Figure 2 finds more electrification potential in industry than in buildings, but this is a high-level modelling exercise without detailed end-use breakdowns or economic analysis (EPRI 2018). Likewise, NREL finds an industrial electrification opportunity similar to the opportunity they estimate for the commercial sector (i.e. 30 % growth in industrial sector electricity sales over the 2016–2050 period in their medium electrification scenario versus 33 % in the commercial sector. This estimate is based on increased use of electro-technologies for curing, drying, other process heat, boilers and space heating as shown in Figure 8. This analysis does not consider process changes or material substitutions.

Deason et al. (2018) take a subjective look at industrial electrification opportunities by sector; these opportunities are summarized in Table 2. They note that combined heat and power (CHP) systems are highly efficient, and replacing them with electric systems can be economically challenging.

Dennis (2016) comes at industrial electrification opportunities a different way, looking at electro-technologies that have potential for rapid growth over the 2015–2020 period. His top ten opportunities (in order of kWh growth) are cryogenics, direct arc melting, induction heating, resistance heating and melting, infrared processing, water supply reverse osmosis, induction melting, membrane processes, and electroslag/vacuum/plasma. He suggests that many of these are good opportunities because they can improve product quality, production productivity, address environmental requirements or are of use in fast-growing industrial sectors.

Looking more broadly, Dee Pee et al. (2018) look at electrification as just one of several decarbonization strategies for the industrial sector. They looked at four industrial sectors (cement, steel, ammonia and ethylene), finding opportunities to electrify heat in the cement sector, for electrical reduction of iron in the steel sector, and for electrochemical processes for monomer production in the in the ethylene sector. This study also finds that the costs of decarbonization will be substantial – they estimate a global cost of roughly $21 trillion to fully decarbonize just these four industrial sectors by 2050.

While industrial sector electrification and decarbonization are the subject of much study, thus far actual electrification is driven by market realities and appears to be concentrated in the types of equipment discussed by Dennis (2016). For the future, economics is likely to remain a primary consideration.

Comparison to Europe

Due to extensive information sharing across the Atlantic as well as the fact that many firms are active in both Europe and North America, electrification efforts in Europe and the US are proceeding at roughly a similar pace. For example, in 2018, EVs are estimated to be a little over 2 % of European light duty vehicle car sales (Shahan 2018), similar to the US (EV Adoption 2018). In Europe, the EV percentage varies substantially

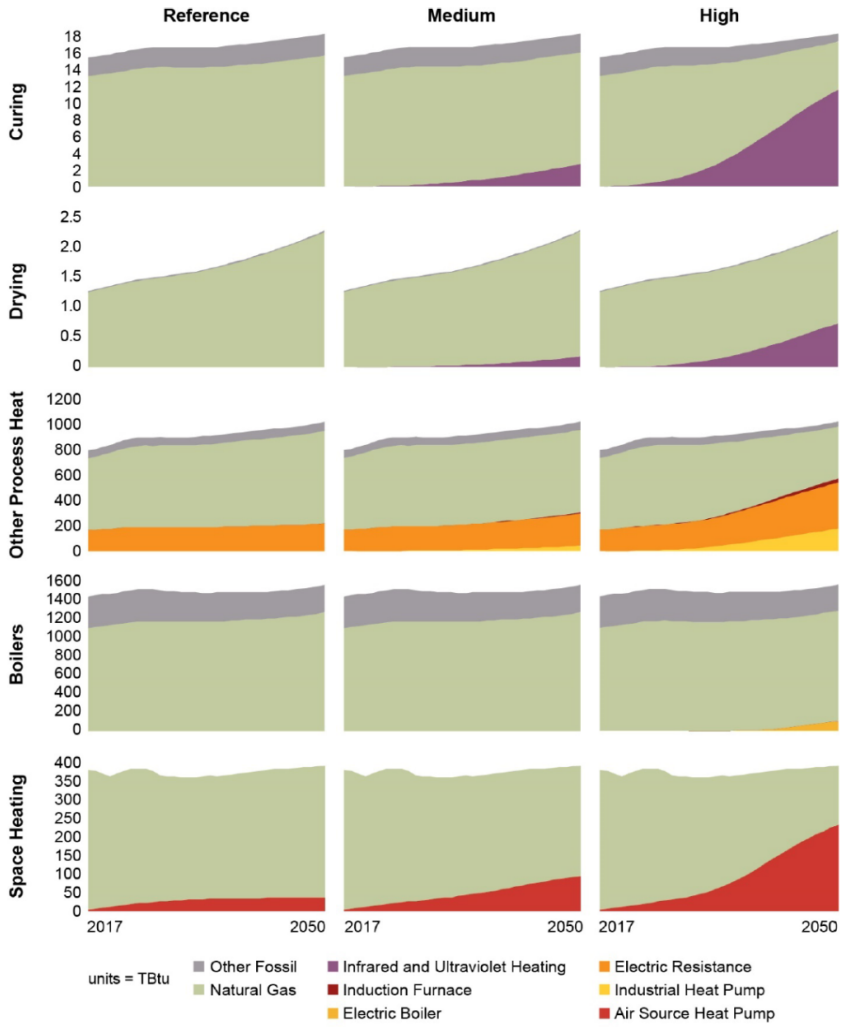


Figure 8. Projected energy use shares by type of equipment for the US industrial sector in NREL electrification scenarios. A TBtu is equivalent to 1.055 Terajoules. Source: Mai et al. 2018.

Table 2. General Outlook for Electrification by Sector.

Industrial Sector	Typical Temperatures	Potential for Electrification	Notes
Primary metals excluding steel	High	High	Induction melting candidate
Fabricated metal products	High	High	Induction heating/melting candidate but low overall energy consumption
Machinery	High	High	Induction heating candidate but low overall energy consumption
Iron and steel mills	High	High	Electric arc furnace; electrowinning
Wood products	Medium	High	Good candidate for electrification but low overall energy consumption
Transportation equipment	Med./high	High	Driers okay for electrification, furnaces challenging, but low overall energy consumption
Plastics and rubber products	Low/med.	High	Good candidate for electrification but low overall energy consumption
Food and beverages	Med./high	Medium	Good candidate except high degree of CHP systems
Chemical manufacturing	High	Medium	Varies by chemical; high degree of CHP systems
Paper mills	High	Low	High degree of integrated process design including CHP
Non-metallic mineral products	High	Low	Very high temperatures make this very challenging but technically possible
Petroleum and coal products	High	Low	Hard because high use of process design and own-use fuel consumption

Source: Deason et al. 2018.

by country, just as this percentage in the US varies by state. On the other hand, electric buses appear to have progressed farther in Europe – estimates are that in mid-2018 Europe had approximately 2,500 e-buses (Gonzalez 2018), versus about 600 in the US (Slobe 2018). Comparing very limited market data for Europe and the US, it appears that the market share of electric delivery vehicles is higher in Europe (ICCT 2017) than the US (EIA 2019).

Regarding buildings, currently about 12 % of US and European space heating is provided by electricity (EIA 2018 and Fleiter et al. 2017). As discussed above, in the US, programs to encourage electrification of buildings are underway in several regions. In Europe, there have been proposals for extensive electrification efforts (Paardekooper et al. 2018) but not yet much in the way of actual programs.

And for the industrial sector, a key difference between Europe and the US is energy prices, with electricity and many fuel prices higher in Europe and natural gas prices in particular much lower in the US. As a result, deployment of electrification is likely higher in Europe. Since about 2010, low natural gas prices appear to have slowed electrification efforts in the US (Elliott 2018).

Conclusions and Next Steps

This paper shows that electrification efforts in the US are nascent but growing, with the most activity in transportation, followed by the residential sector, studies on these two sectors show substantial opportunities for energy savings and emissions reductions; analyses on the other sectors are limited. US electrification activity is most extensive on the West coast and in the Northeast.

Electrification in the transportation sector is poised for rapid growth. Next steps will include expansion of charger infrastructure (particularly in underserved neighbourhoods and at key locations in the transportation system – e.g. on intercity routes and for use by on-demand transportation drivers), continued efforts to reduce battery prices and increase range, and growing attention to buses and commercial delivery vehicles.

Electrification in the residential sector is likely to proceed more slowly and in the near-term will likely emphasize new construction and replacing oil and propane systems. Next steps include expanding programs now begun in several states and incorporating electrification into new construction building codes.

Interest in electrification and other decarbonization strategies is growing in the commercial and industrial sectors. For these latter sectors, the economics of electrification will be a primary consideration and more analysis is needed on applications that are most likely to be cost-effective today.

As electrification proceeds, there will be substantial impact on the electric grid that will need to be managed, particularly to address evening peaks driven by home and EV charging loads, and early morning winter peaks driven by use of heat pumps.

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