Pathways to Net Zero Carbon at the City Level – A case study of Albany, California

Nina Hegazy
hegazy@kth.se
Instituto Superior Tecnico, Universidade de Lisboa, Portugal
November 2019

Since the United Nations concluded that it is required to cut global emissions 45% by 2030 and become net zero by 2050 to limit global warming to 1.5°C, net zero carbon is a sought-after topic in national and city-level legislative agendas. However, the pathways to achieve it remain unclear. This work aims to fill a knowledge gap in the topic and quantifies the costs and emission reductions using a multi-sectoral household-perspective approach for going net zero carbon on a city-level, accounting for residential energy use and residential vehicles, identifying the least and most favorable combinations for electrification. A case study is done on single-family households in the city of Albany, California, but can easily be implemented in other cities. By combining different house sizes, energy usage levels, vehicle models and annual mileages, a total cost of ownership (TCO) analysis combining end-uses represent all of Albany's single-family households. A TCO analysis is performed for electric versus gasoline vehicles, and electric versus gas-fueled water heating, space heating, and large appliances. Results show that the TCO ranges between 8,541-10,100 $/year for a single-family household and adds up to over $35 million/year on a city-level. Depending on household characteristics, the additional cost to decarbonize is 1.1% to 14.7%. Households are more likely to invest in home decarbonization seeing the TCO ratio of the combined package with vehicles, which is on average 7.7% more expensive than the gas alternative. The total carbon emissions saved are 19,313 $MTCO_2$/year, decreasing Albany's total emissions by 40%.

Keywords: *Net Zero Carbon, Total Cost of Ownership (TCO), Electric Vehicle (EV), Heat Pump (HP), Electrification, California*

1. Introduction

Findings from the latest UN Intergovernmental Panel on Climate Change (IPCC) special report on the impact of global warming of 1.5°C concluded that we have only 12 years to make massive changes to global energy infrastructure; including transportation, land use, energy production, industrial systems and buildings. To limit global warming to 1.5°C, it is inevitable to cut global emissions by 45% by 2030 and to become net zero by 2050 (IPCC, 2018).

Recognizing the threats of global warming, cities and countries globally are setting up goals for a carbon neutral economy by 2050 (Darby, 2019). As the state of California is a leader for environmental policies both in the U.S. and world-wide, executive Order B-55-18 was passed stating the goal of economy-wide carbon neutrality to be achieved five years earlier than the IPCC report suggests (State of California, 2018).While substantial focus has been put on decarbonizing the electricity production, more efforts are needed to decarbonize the residential and transport sector, making up respectively 7% and 41% of total Californian greenhouse gas (GHG) emissions (California Air Resources Board, 2019).

It has been identified that California will experience extreme difficulties in achieving a 40% GHG emission reduction by 2030 if a high percentage of gasoline-powered vehicles are still on the roads and natural gas appliances are still in operation (Wei *et al.*, 2017). To achieve the set-up state goals, efforts such as building electrification and greater adoption of zero emission vehicles (ZEVs) and heat pumps must start by 2020 (Wei *et al.*, 2017).

A knowledge gap has been identified regarding the cost-effectiveness of different actions, as well as the quantified predictions of GHG emission reductions. A techno-economic analysis on the small, progressive city of Albany in California is performed to facilitate the city's net zero carbon goals and to provide a framework that can be adopted in other locations. The scope of this work is focusing on single-family households in Albany with a multi-sectoral approach, incorporating both residential energy use and residential vehicles.

The objectives of this thesis include the modelling of the city, creating packages of typical households and personal vehicles and performing a total cost of ownership (TCO) analysis combining electric vehicles (EVs), heat pump water heating (HPWH), heat pump space conditioning (HPSC), and large appliances. The main aim is to contribute with a quantitative approach to the total costs of decarbonization and GHG reductions, while highlighting which groups are at a disadvantage and in need of subsidies the most, in order to help the decision-makers of the city and the population understand the real costs of becoming net zero carbon both a household and city-level.

2. Case Study: Albany, California

2.1 Location

Albany is a Californian is on the east shore of San Francisco Bay estimated 12 miles (19 km) northeast from San Francisco, in Alameda County. Albany is a small city with a population of around 19,000 inhabitants (CADOF, 2012, 2018). Albany is unique in geographical placement that puts the city in the risk of flooding, extreme heat, and wildfires. The building stock consists of approximately 4,000 single-family homes, 800 units in town homes and 2-4-unit structures, and 2,000 multi-family apartments and condominiums (City of Albany, 2016).

2.2 Vehicles

In 2018, the city had 12,276 light-duty vehicles assumed to be all household vehicles, of which 84% were gasoline vehicles and only 1.56% of were EVs (DMV CA, 2018). Approximately 92% of households have at least one vehicle available, and therefore studying the household vehicles is of high relevance. On average, there are 1.48 vehicles per household. There is also high potential for the 44% of households having 2 or more vehicles to switch one of them to an EV and keep and ICE for few longer trips (U.S. Census Bureau, 2016).

2.3 Energy Use

Even though the population saw an almost 10% increase from 2005 to 2016, the residential electricity usage decreased 13% from 26,757 MWh to 23,360 MWh and the residential natural gas usage decreased 17% compared to the 2005 baseline to 1.5 million therms in 2016. The commercial sector saw a more modest decrease of 2% and 9% for electricity and NG usage.

In 2018, Albany city council acted to enroll the community in “Brilliant 100”, a 100% carbon-free electricity source offered by East Bay Community Energy (EBCE), an action estimated to be responsible of a carbon emission reduction of 7% (3 884 MTCO2e/year). The challenges that Albany faces includes the current emissions of 53,000 MT CO2e, mostly from transportation and natural gas consumption responsible for almost 80% of all emissions.

As the emissions from the residential and commercial electricity sector disappear with the carbon-free electricity, the share of emissions from transportation and residential gas sector are estimated to grow to be 56% and 23% respectively. As these are most important sectors to target for emissions reduction, the following chapters will tackle the decarbonization of residential transportation sector and residential gas sector for single-family households in Albany.

3. Residential Transport Sector

In this analysis, the focus was on plug-in battery electric vehicles (onwards simply referred to as “EVs”), since conventional gasoline hybrid electric vehicles (HEVs) don’t offer the potential for the substantial emissions reductions needed. Fuel cell electric vehicles (FCEVs) are also zero emission but are not as commercialized and widely adopted as EVs and are still considerably more expensive than internal combustion engine vehicles (ICEs).

The following analysis debunks what the real costs of EVs are compared to their ICE counterparts, in the form of their total cost of ownership (TCO), and finds out for which type of household it is more beneficial to get an EV depending on their annual vehicle miles travelled (VMT) and the car size category.

3.1 Methodology

A set of assumptions were chosen for the TCO analysis. Four vehicle categories were examined: subcompact, compact, mid-size and full-size, with a representative vehicle model for both EVs and ICEs chosen for the TCO analysis. The EVs within each category were chosen from the U.S. Department of Energy (DOE) "Find Electric Vehicle Models" service (US DOE, 2019a), and the ICEs were chosen to be typical rental car vehicle types. Table 1 summarizes of the vehicle models chosen for each vehicle category.

Table 1: Summary of vehicle models used for TCO comparison

	EV	ICE
Sub-compact	2019 Fiat 500e	2019 Chevrolet Spark
Compact	2018 Ford Focus EV	2018 Honda Civic
Mid-size	2019 Nissan LEAF	2019 Honda Accord
Full-size	2018 Tesla Model X	2019 Cadillac Escalade ESV

The average annual VMT for Albany is approximately 11,300 miles per vehicle (18,200 km/year) or a daily mileage of 31 miles per vehicle (50 km/day). The VMT was split into 3 cases: low (8,000 miles/year), average (11,300 miles/year) and high (15,000 miles/year) to identify households that would benefit and be penalized by EV adoption policies.

Due to high average ownership time of 7-years and the 12-year average age of light-vehicle on U.S. roads in 2016, the cost of ownerships were chosen to be compared for 10 years, as done in the study of Weldon *et al.* (2018). The depreciation for the 10-year period was taken as the square of the estimated depreciation calculated by Edmunds after 5 years (Edmunds, 2019).

The maintenance costs for EVs were assumed to be 27.3% cheaper than for their gasoline counterpart, as it was the mean value of findings in literature (Edmunds, no date; Propfe *et al.*, 2012; Logtenberg, Pawley and Saxifrage, 2018; Palmer *et al.*, 2018). A battery replacement was assumed occur in year 8 (2027), with the forecasted battery pack price of 102.6 $/kWh, which was the average estimated cost in literature findings for the years 2025 and 2030 (Lutsey & Nicholas, 2019).

Fuel prices were selected as the Californian average between January and September 2019, and annual price increases were deducted from EIA projections (EIA, 2019c, 2019d, 2019b, 2019a). The electricity has zero emissions, but gasoline has an emissions factor of 8.91 kg CO_2/gallon (EIA, 2011). All assumptions are summarized in Table 2.

Table 2: Summarizing Table of Vehicle TCO assumptions

Ownership time (years)	10	EV Tax Credit ($)	7500
Discount rate	7%	Electricity Price ($/kWh)	0.09
Bank Interest	4.21%	Gasoline Price ($/gallon)	3.54
Number of payments (years)	5	Electricity price increase/year	0.4%
Conversion kWh/Gallon eq	33.7	Gasoline price increase/year	0.6%
Low VMT (miles/year)	8000	Battery Pack price in 2027 ($/kWh)	102.6
Average VMT (miles/year)	11300	Charging station price incl. installation ($)	1000
High VMT (miles/year)	15000	Gasoline EF (kg CO2 / gallon)	8.91

3.2 TCO Analysis

The TCO analysis gave an annualized cost for each component accounted for: bank loan, taxes & fees, maintenance, battery & charging station, insurance, fuel cost and resale value. As the fuel costs vary with changing mileages driven, but the rest of the inputs stay the same, the share of components change for the same model at low, average or high VMT. A large difference in the share of fuel costs is seen between the two types of vehicles. The fuel costs for a subcompact make up 5% of the TCO for EVs while it is making up 23% for the ICE, and for all EVs make up a lower portion of the total costs than for ICEs. The bank loan, meaning the yearly payment for the upfront purchase cost of the car, is the most substantial cost component of all TCOs and is larger for EVs than ICEs for all four vehicle categories.

The compact, midsize and fullsize EVs are 1.4%, 4.5% and 11.9% cheaper than their ICE counterparts driven at average mileage when the $7,500 tax credit is implemented. The federal tax credit is an important rebate program that allows EVs to be cost competitive with ICEs, and without rebate, subcompact, compact and mid-size EVs would have a higher TCO ratio than ICEs and would loose their competitive edge. The possible emission savings are depending on the vehicle model and the VMT, but are in the range of 2.2 to 7.9 tCO_2/year.

The results for all transport related TCOs are presented as a TCO ratio between EVs and ICEs, a way of display also adapted by Palmer *et al.* (2018). The TCO ratio of >1 means that EVs are more expensive than ICEs, and a TCO ratio of <1 means the inverse, meaning that EVs are more favorable over their ICE counterparts.

To further see the effects of the VMT and to conclude over what mileage the EVs are more affordable than ICEs, the VMT is varied from 5,000 to 25,000 miles/year, seen in Figure 1. In the sub-compact category, the EV remains 5.4% more expensive than the ICE even when used 25,000 miles/year. The full-size on the contrary remains cheaper over the analysis, with the ratio reaching more than 1 at a yearly mileage of 300 miles/year, which would be using the vehicle for just 32 average Californian trip lengths of 9.4 miles (Federal Highway Administration, 2019).

For the compact and mid-size vehicle, the VMT is an important factor when choosing a vehicle, since the ratio flips at mileages that could commonly be seen in Albany. The TCO ratio flips at around 10,000 miles travelled per year for compact vehicles and 7,000 miles/year for midsize vehicles, meaning that an EV is more favorable over those mileages.

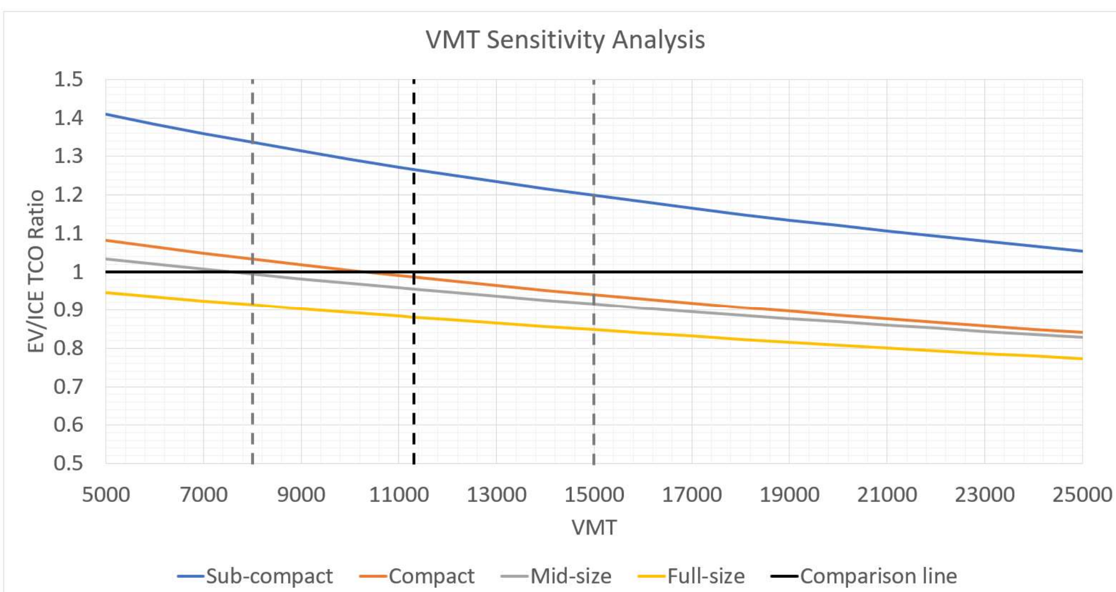

Figure 1: VMT Sensitivity Analysis for different vehicle models

The TCO and carbon savings serve as an estimation since EV owners are often likely to incur additional transport related costs and emissions. While ICE owners always have the option for long-range drive, if a household only owns EVs, the long-distance travel will most likely be made by renting an ICE, or by taking alternative transportation methods, such as train or flight. These are additional costs that are not accounted for in the analysis. The carbon savings can quickly be lost if a long-distance drive that poses difficulties for EVs are done by flight. On the other hand, EV benefits such as vehicle-to-grid (V2G) technology, energy storage, back-up power supply, improvement in air quality and health benefits linked to it, as well as the environmental benefits are not quantified to lower the TCO.

4. Household

4.1 Methodology

There are countless combinations of home sizes, ages, geometry, construction, insulation type and appliances in a single-family home in Albany that make each household unique and shift slightly the TCO of decarbonization. To be able to make an analysis relevant to the largest number of single-family households, three typical households were created. These typical households have varying area, but are using other average inputs from data gathered from the Census, tax assessor data, the 2019 California Residential Appliance Saturation Study (RASS), summary data from Greenbanc on over 100 homes in the Bay Area on Home Energy Score assessments, and energy audit data on 15 homes in Albany.

A range of inputs regarding occupants, building year, building design, such as building geometry, level of insulation, air tightness, duct sealing and type of foundation, attic, roof, walls and windows, were used to construct typical Albany homes. These homes were then modelled in the U.S. Department of Energy's Home Energy Saver (HES) tool giving energy estimations for end-uses such as heating, cooling, water heating and major appliances (US DOE, 2019b).

Three different house sizes were modelled to represent all of Albany’s single-family housing stock, presented in Table 3: Area representation of single-family houses for low, average and high area case**.** In addition, three different energy use cases were used, low (50% less than average), average and high (30% more than average), with the average energy usage coming from HES outputs.

Table 3: Area representation of single-family houses for low, average and high area case

Size	*Area Range (sqft)*	*Area modelled in HES (sqft)*	*% of all Single-Family Homes*
Low	<800 - 1100	900	30.3%
Average	1100 - 1700	1350	47.4%
High	1700 - >2600	1800	22.3%

To calculate the Total Cost of Ownership (TCO) for the different options households can choose when upgrading their current water heating, space heating and natural gas fueled large appliances, the purchase cost, installation cost and maintenance cost are needed, as well as the energy usage for calculating fuel costs.

4.2 Water Heating

The water heating energy use is independent of house size and is the same for all three house area cases. The options compared for water heaters is electric heat pump water heater (HPWH), storage tank natural gas water heater (NGWH), and instantaneous natural gas water heater (also known as tankless natural gas water heater) (INGWH).

The TCO results for water heaters for the three different usage show that HPWHs are 11.2-16.5% more expensive than the low efficiency NGWH depending on the energy usage case. Figure 2 shows the six different water heater options against each other for low, average and high energy usage. The results show that the NGWH with EF=0.66 is the cheapest option for all energy usage cases. The second cheapest TCO depends on the energy use level, for low energy use the HPWH with EF=2.0 is the runner-up, while for the average and high scenarios it is the INGWH with EF=0.87.

The results show that it pays off to get an electric HPWH instead of a high efficiency NGWH for all cases, but the heat pump remains more expensive than low efficiency storage tank water heaters, and even tankless water heaters when the energy use is average or high.

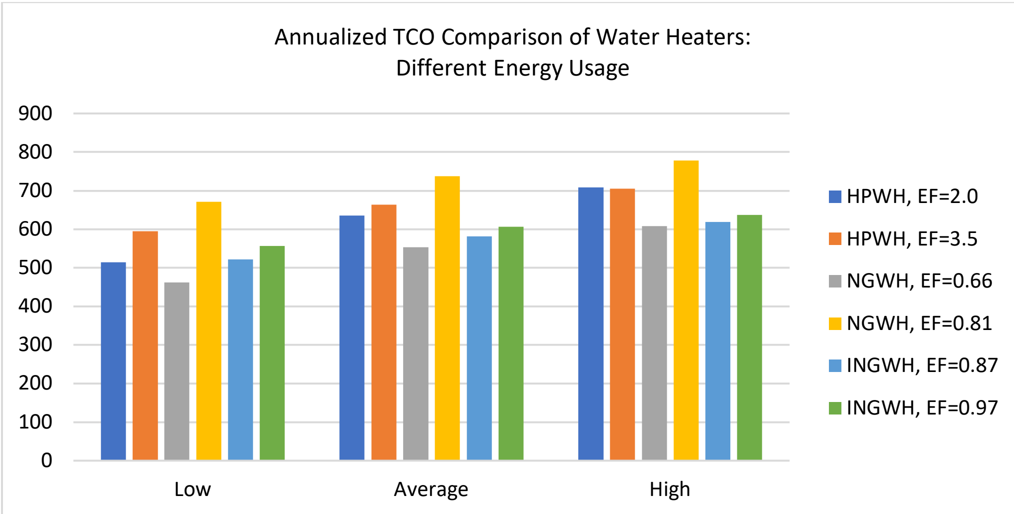

Figure 2: TCO comparison for Water Heaters with different energy uses

4.3 Space Heating

Space heating TCOs will vary depending on whether a small, average or large single-family home is modelled. The space heating equipment compared in the TCOs are electric heat pump space conditioners (HPSC) and natural gas-fired furnaces (NG-furnace) with different heating efficiencies. Two different scenarios are explored for space heating: the first scenario being a scenario where there is no need for cooling and the second scenario including cooling equipment in the TCO.

The inputs for space heating are the same for both scenarios, with the difference that in one scenario there isn't any cooling modelled, and in the other scenario the heat pump is also used to provide cooling or room ACs are combined with the NG furnace. Currently, most Albany homes don't need cooling, but with the trends of warmer weather, up to 35 additional days of extreme heat are expected by the end of the century under the high emissions scenario, which could lead to more people purchasing cooling equipment.

Integrating cooling changes the results greatly. The initial cost of the HPSCs is 2.3 times as expensive as the NG-furnace in the no cooling scenario, but this number halves when cooling equipment are added to the furnace, making the initial cost of the low efficiency HPSC 1.16 times as expensive as the low efficiency NG-Furnace. The electric heating solutions have a TCO ratio of 1.772 to 2.780 depending on energy use and home size but can drop to 1.123-1.421 when cooling is integrated. Figure 3 shows the effects of the integration of cooling regarding the TCO of the two NG-furnaces and two HPSCs. The additional cooling costs are minimal for the HPSCs, but the TCO jumps for NG-furnaces in the cooling scenario due to the additional purchase of room ACs and their operational costs.

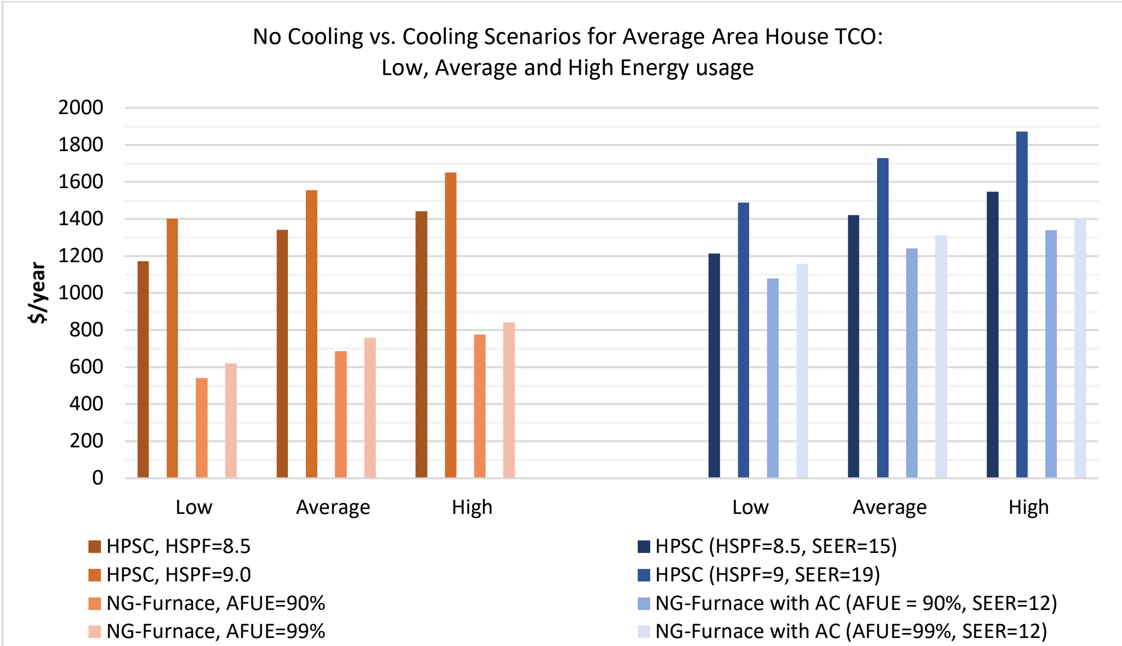

Figure 3: Space Heating and Cooling TCO

4.4 Large Appliances

The large appliances analysis is from the point of view of electrification to achieve net zero carbon on a household level, therefore the focus is on clothes dryers, stoves and ovens, which typically use natural gas, and what the total cost of ownership would be if the existing old appliances were to be upgraded to new NG-fuelled appliances or new electrical appliances. All three large appliances have a TCO ratios of above 1, meaning that the electric version of all three large appliances are more expensive than the NG version. The electric dryers are 20-60% more expensive, the electric stove 32-39% and the electric ovens 2-17% more expensive than their NG counterparts depending on the energy use, although this translates into a small monetary difference between 4-127 $/year.

5. The Big Picture

Even though a large set of combinations of the results are possible, a set of typical combinations are created and assumed to represent the single-family households in Albany. The three house area cases were crafted together to represent all of Albany's single-family housing stock, the low area including 30.3% of all single-family houses, the average area including 47.4% and the high area including 22.3%.

For each house size, 50% of houses are assumed to have average energy consumption, 25% have low energy use and the 25% have high energy use. Human behaviour and habits are among the most important aspects determining energy use. Since the heating systems are not interlinked, it is possible to have high energy use for water heating and low energy use for space heating. However, when creating the groupings of households, it is assumed that a household with an average energy use will have average energy use for all aspects considered: water heating, space heating and large appliances. The same idea is carried across the board for low and high energy use as well.

The vehicle models incorporated into the combination are compact and mid-size EVs, as these are the most affordable and cost competitive compared to their ICEV versions. We assume that VMT is independent of house characteristics; therefore, all three levels of VMTs are presented for both types of vehicle models for all house sizes and energy uses.

Table 4 summarizes the results from the two tables and presents the highest and lowest TCO-related numbers and emission savings from all simplified household combinations with compact or midsized EVs. Even though the HPSCs had a very high TCO ratio (1.772-2.298), the combination of all categories lowered the total TCO ratio to 1.011-1.147. The lowest additional cost to electrify compared to purchasing the cheapest gas-fueled alternatives is 1.1%, which occurs for a small or average-sized house with low energy use, having a midsized EV driven at a high VMT. The highest additional cost to electrify is 14.7%, seen for a small home with high energy usage, having a compact EV driven at a low VMT.

Table 4: Summary of min. and max CO2 and TCO-related results from different households with compact or midsized EV

	Total TCO ($/year)	Δ TCO ($/year)	TCO ratio	Emissions saved (kg CO2/year)
Lowest	8541	98	1.011	3055
Highest	10100	1202	1.147	7415

Estimating the percentage of households fitting each household combination TCO, the total costs and emissions savings can be estimated on a city-level, presented in Table 5**.** The total estimated cost for all 3,751 single-family households to go all-electric is approximately $35 million/year. This is 7.7% more expensive than the cost of upgrading the house and vehicle to a newer gas-fueled version. The estimated cost for the city is presented as a yearly cost since the annualized TCO was used to fairly compare solutions that had different lifetimes. However, the initial costs for purchasing an EV, HPSH, HPSC and electric large appliances for an individual household is between $40,300 to $42,300.

Table 5: Decarbonization TCO and emission saving estimates on a city level for Albany

Total TCO ($/year)	34 932 898	Emissions Saved from Transport (tCO2/year)	11 726
Δ TCO ($/year)	2 482 952	Emissions Saved from Housing (tCO2/year)	7 587
TCO ratio	1.077	Total Emissions Saved (tCO2/year)	19 313

An additional cost approximately $2.5 million per year on a city-level for all single-family households would lead to an important emissions reduction of 19,313 tons of CO2 per year, with 61% of the reduction coming from the shift to EVs and 39% from electrifying the single-family homes (see Figure 4). The results show that emissions from transportation would reduce by 40% and the emissions from the residential sector by 62%.

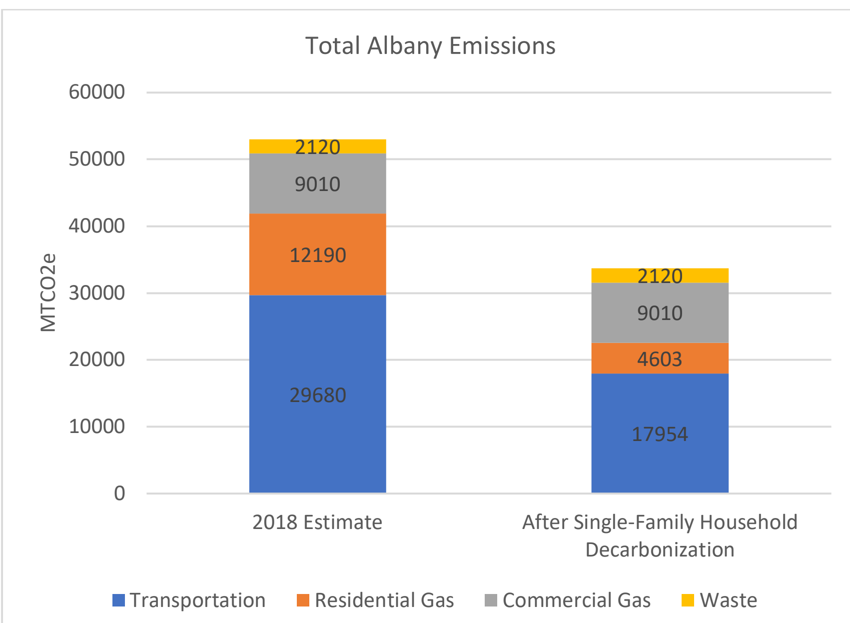

Figure 4: Total Albany Emissions

6. Conclusions

This paper quantified the total cost of decarbonization for single-family households and their residential vehicles, as well as the emission savings it induces on an annual basis were calculated on a household and city-level.

The conclusions answering the objectives can be summarized as the following:

- The annualized total cost of ownership for a single-family Albany household range between 8,541 to 1, 100 $/year, translating into an additional cost of 98 to 1202 $/year compared to carbon-emitting alternatives.
- The additional cost to electrify compared to purchasing the cheapest gas-fueled alternatives is between 1.1% and 14.7%.
- The electrification of homes could be better marketed if the focus of TCO isn't per end-use by itself, but instead as a package.
- The biggest cost after the vehicle purchase is the space heating, which can have a TCO over twice as expensive as a NG-Furnace. The possible incorporation of cooling due to a warming local climate can be a major selling point for HPSCs, lowering significantly the additional costs compared to furnaces
- Households are more likely to invest in home decarbonization seeing the TCO ratio of the whole package of the house and vehicle, which is on average 7.7% more expensive than the gas alternative.
- The total costs of decarbonizing are about $60/months more per household or on average about 7.7% more expensive that fossil fuel-based alternatives.
- The total carbon emissions saved on a city-level are 19,313 $MTCO_2$ / year, leading to the decrease of Albany's total emissions by 40% to 33,687 $MTCO_2$ / year. Emissions from transportation would reduce by 40% and the emissions from the residential sector by 62%.

References

CADOF (2012) *E-4 Population Estimates for Cities, Counties, and the State, 2001-2010, with 2000 & 2010 Census Counts*. Sacramento, California. Available at: http://www.dof.ca.gov/Forecasting/Demographics/Estimates/E-4/2001-10/ (Accessed: 8 October 2019).

CADOF (2018) *E-4 Population Estimates for Cities, Counties, and the State, 2011-2018 with 2010 Census Benchmark*. Sacramento, California. Available at: http://www.dof.ca.gov/Forecasting/Demographics/Estimates/E-4/2010-18/ (Accessed: 8 October 2019).

California Air Resources Board (2019) *GHG Current California Emission Inventory Data*. Available at: https://ww2.arb.ca.gov/ghg-inventory-data (Accessed: 22 September 2019).

City of Albany (2016) *Albany 2035 General Plan | City of Albany, CA*. Available at: https://www.albanyca.org/departments/planning-zoning/albany-2035-general-plan (Accessed: 8 October 2019).

Darby, M. (2019) *Which countries have a net zero carbon goal?*, *Climate Home News*. Available at: https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/ (Accessed: 22 September 2019).

DMV CA (2018) 'Department of Motor Vehicles Estimated Vehicles Registered By County', (916), p. 8008. Available at: https://www.dmv.ca.gov/portal/wcm/connect/add5eb07-c676-40b4-98b5-8011b059260a/est_fees_pd_by_county.pdf?MOD=AJPERES.

Edmunds (2019) *Cost of Car Ownership - 5-Year Cost Calculator | Edmunds.com*. Available at: https://www.edmunds.com/tco.html (Accessed: 3 October 2019).

Edmunds (no date) *Compare Cars - Car Comparator Tool • Edmunds*. Available at: https://www.edmunds.com/car-comparisons/?veh1=401735658&veh2=401734188&undefined=401781618 (Accessed: 7 July 2019).

EIA (2011) *Environment - U.S. Energy Information Administration (EIA) - U.S. Energy Information Administration (EIA)*. Available at: https://www.eia.gov/environment/emissions/archive/coefficients.php (Accessed: 6 October

2019).

EIA (2019a) *Annual Energy Outlook 2019 Table: Energy Prices by Sector and Source Case: Reference case | Region: Pacific*. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2019&region=1-9&cases=ref2019&start=2017&end=2050&f=A&linechart=~ref2019-d111618a.5-3-AEO2019.1-9&map=ref2019-d111618a.4-3-AEO2019.1-9&ctype=linechart&sourcekey=0 (Accessed: 13 October 2019).

EIA (2019b) *Annual Energy Outlook 2019 with projections to 2050*. Washington. Available at: https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf (Accessed: 5 October 2019).

EIA (2019c) *California Regular All Formulations Retail Gasoline Prices (Dollars per Gallon)*. Available at: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emm_epmr_pte_sca_dpg&f=m (Accessed: 5 October 2019).

EIA (2019d) *Electricity Data - Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector, by State, July 2019 and 2018 (Cents per Kilowatthour)*. Available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a (Accessed: 5 October 2019).

Federal Highway Administration (2019) *2017 National Household Travel Survey (NHTS)*. Available at: https://nhts.ornl.gov/ (Accessed: 3 October 2019).

IPCC (2018) 'Global Warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty - Summary for Policymakers'. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf (Accessed: 22 September 2019).

Logtenberg, R., Pawley, J. and Saxifrage, B. (2018) 'Comparing Fuel and Maintenance Costs of Electric and Gas Powered Vehicles in Canada', (September), p. 22. Available at: https://www.2degreesinstitute.org/reports/comparing_fuel_and_maintenance_costs_of_electric_and_gas_powered_vehicles_in_canada.pdf.

Lutsey, A. N. and Nicholas, M. (2019) 'Update on electric vehicle costs in the United States through 2030', (April). doi: 10.13140/RG.2.2.25390.56646.

Palmer, K. *et al.* (2018) 'Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan', *Applied Energy*. Elsevier, 209(July 2017), pp. 108–119. doi: 10.1016/j.apenergy.2017.10.089.

Propfe, B. *et al.* (2012) 'Cost Analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values Implementing Agreement on Hybrid and Electric Vehicles', *Proceedings of 26th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, 5, pp. 886–895. Available at: http://elib.dlr.de/75697/1/EVS26_Propfe_final.pdf.

State of California (2018) 'Executive Order B-55-18 to Achieve Carbon Neutrality'. Available at: https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf (Accessed: 22 September 2019).

U.S. Census Bureau (2016) 'American FactFinder - 2012-2016 American Community Survey 5-Year Estimates'. Available at: https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk (Accessed: 3 October 2019).

US DOE (2019a) *Find Electric Vehicle Models | Department of Energy*. Available at: https://www.energy.gov/eere/electricvehicles/find-electric-vehicle-models (Accessed: 3 October 2019).

US DOE (2019b) *Home Energy Saver Methods*. Available at: http://homeenergysaver.lbl.gov/consumer/documentation (Accessed: 13 October 2019).

Wei, M. *et al.* (2017) *Building a Healthier and More Robust Future: 2050 Low-Carbon Energy Scenarios for California*. doi: CEC-500-2019-033.

Weldon, P., Morrissey, P. and O'Mahony, M. (2018) 'Long-term cost of ownership comparative analysis between electric vehicles and internal combustion engine vehicles', *Sustainable Cities and Society*. Elsevier, 39(February), pp. 578–591. doi: 10.1016/j.scs.2018.02.024.