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

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# Abstract

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

# Resumo

Como as nações unidas concluíram que é inevitável reduzir as emissões globais, a neutralidade carbónica é um tópico que consta nas agendas legislativas nacionais e regionais. No entanto, os caminhos para alcançá-la permanecem indefinidos.

Este trabalho preenche uma aparente lacuna de conhecimento no tópico e tem como objetivo quantificar os custos e as emissões visando a eletrificação dos sistemas energéticos numa abordagem multissetorial no setor residencial. Um estudo de caso é realizado em residências unifamiliares na cidade de Albany, Califórnia, mas pode ser facilmente implementado em outras cidades.

Pelo uso de diferentes tipos de veículos, níveis de uso de energia, veículos e milhas anuais, a análise do custo total de propriedade (TCO) combina o uso final das famílias unifamiliares da Albany. Uma análise de TCO é realizada para veículos elétricos versus veículos a gasolina e aquecimento de água elétrico versus combustível a gás, aquecimento ambiente e aparelhos de grande porte.

Os resultados mostram que o TCO anualizado varia entre 8,541-10,100 $/ano e 35 milhões $/ano no nível da cidade. Dependendo do país, o custo adicional para descarbonizar é de 1,1 a 14,7%. O total de emissões de carbono economizadas é de 19.313 MtCO$_2$/ano, levando a uma redução no total de emissões da Albany em 40%, para 33.687 MtCO$_2$/ano. As emissões do transporte seriam reduzidas em 40% e as emissões do gás residencial em 62%.

Palavras-chave: Carbono zero líquido, Custo total de propriedade (TCO), Veículo elétrico (EV), Bomba de calor (HP), Eletrificação, Califórnia

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# Nomenclatures

| | |
|---|---|
| AAA | American Automobile Association |
| AB 32 | California Global Warming Solutions Act of 2006 |
| AC | Air-Conditioning |
| AFUE | Annual Fuel Utilization Efficiency |
| BTU | British Thermal Units |
| C40 | C40 Cities Climate Leadership Group |
| CADOF | State of California Department of Finance |
| CAP | Carbon Action Plan |
| CARB | California Air Resources Board |
| CCPI | Climate Change Performance Index |
| $CO_2$ | Carbon Dioxide |
| COPD | Chronic obstructive pulmonary disease |
| DMV | Department of Motor Vehicles |
| DOE | U.S. Department of Energy |
| EBCE | East Bay Community Energy |
| EF | Energy Factor |
| EVs | Electric Vehicles |
| FCEVs | Fuel Cell Electric Vehicles |
| GHG | Greenhouse Gas |
| HES | Home Energy Saver |
| HEVs | Hybrid Electric Vehicles |
| HPSC | Electric Heat Pump Space Conditioner |
| HPWH | Electric Heat Pump Water Heater |
| HSPF | Heating Seasonal Performance Factor |
| ICEs | Internal Combustion Engine Vehicles |
| ICLEI | Local Governments for Sustainability |
| INGWH | Instantaneous Natural Gas Water Heater |
| IPCC | Intergovernmental Panel on Climate Change |
| lbs | U.S. Pound |
| kWh | Kilowatt hour |
| MPGe | Miles Per Gallon Equivalent |
| M&R | Maintenance and Repair |
| MSRP | Manufacturer's Suggested Retail Price |
| Mt | Metric Ton |

| | |
|---|---|
| NDCs | Nationally Determined Contributions |
| NG | Natural Gas |
| NG-Furnace | Natural Gas-Fired Furnace |
| NGWH | Storage Tank Natural Gas Water Heater |
| NHTS | National Household Travel Survey |
| $NO_x$ | Nitrogen Oxides |
| NTSB | National Transportation Safety Board |
| PG&E | Pacific Gas and Electric Company |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PM | Particulate Matter |
| RASS | Residential Appliance Saturation Study |
| RECS | Residential Energy Consumption Survey |
| RPS | Renewable Portfolio Standard |
| SB | Senate Bill |
| SCC | Social Cost of Carbon |
| SEER | Seasonal Energy Efficiency Ratio |
| SHGC | Solar Heat Gain Coefficient |
| sqft | Square Foot |
| SUV | Sport Unity Vehicle |
| TCO | Total Cost of Ownership |
| V2G | Vehicle-2-Grid |
| VMT | Vehicle Miles Travelled |
| VOCs | Volatile Organic Compound |

# Standard to Metric Conversion

| | | | |
|---|---|---|---|
| 1 °F | = | (F° - 32) / 1.8 | °C |
| 1 acre | = | 4,046 | m$^2$ |
| 1 BTU | = | 1,055 | Joules |
| 1 cubic foot | = | 28.32 | liter |
| 1 foot | = | 0.30 | m |
| 1 gallon | = | 3.79 | liter |
| 1 lbs | = | 0.45 | kg |
| 1 mile | = | 1.61 | km |
| 1 short ton | = | 0.907 | t |
| 1 square feet | = | 0.093 | m$^2$ |
| 1 square mile | = | 2.59 | km$^2$ |
| 1 therm | = | 1.055 x $10^8$ | Joules |

# 1. Introduction

## 1.1 Background

Greenhouse gas (GHG) emissions from burning fossil fuels as a result of anthropologic activities have been scientifically proven to be the cause of the global temperature rise [1]. As climate issues are gaining importance and momentum, countries worldwide have pledged to reduce GHG emissions. With the Paris Agreement bringing together nations for the common goal of limiting the temperature rise to well below 2°C compared to pre-industrial levels, and further efforts to limit the increase to below 1.5°C, nearly 200 nations are committing through their nationally determined contributions (NDCs) to cut emissions [2]. However, the measures implemented by countries under the Paris Agreement are not enough to limit the temperature rise to the targets, but are instead expected to increase the global temperature rise to about 3°C by 2100 [1]. 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 11 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 [1].

Recognizing the threats of global warming, over 1000 jurisdictions in 19 countries amounting to 266 million citizens have declared a climate emergency as of September 2019 [3]. In addition, cities and countries globally are setting up goals for a carbon neutral economy by 2050; with Sweden, Denmark, Norway, France, Ireland and the United Kingdom already having the initiative in law, while many others have the matter currently as a policy position [4]. Even though the United States ranked in the bottom five of the most recent Climate Change Performance Index (CCPI) after the announce of the county's pulling out of the Paris Agreement [5], cities, states, and businesses all across the U.S. took a bottom-up approach in order to achieve the national emissions reduction targets even in the absence of federal leadership [6].

The state of California, now having the world's fifth largest economy, is historically known for taking one of the most aggressive actions and policies for reducing environmental impacts. The California Global Warming Solutions Act of 2006, also known as AB 32, requires the reduction of greenhouse gas emissions by law [7]. The Renewable Portfolio Standard (RPS) program was established in 2002, acting as the first requirement for California to achieve 20% of electricity retail sales from renewables by 2017 [8]. The deadlines were accelerated, and the renewable shares were augmented several times to push the rate of adoption of renewables [8]. The latest update to the RPS was the Senate Bill 100 (SB 100) signed by Gov. Edmund G. Brown Jr., codifying 60% reduction target by 2030 and 100% by 2045 to get fossil-fuel free electricity in the state [9]. At the same time, Executive Order B-55-18 was signed as well, creating a state-wide goal to achieve "carbon neutrality as soon as possible, and no later than 2045, and achieve and maintain net negative emissions thereafter" [10]. While the SB 100 commits California to 100% clean electricity by 2045, the electricity sector represents only for 16% of the state's total GHG emissions (emissions from in state and imports added up) [11], and therefore the Executive Order B-55-18 is needed to deal with GHG emission reduction in all the other sectors as well. The economy-wide carbon neutrality in the state of California is only a goal in the form of an Executive Order, not a law, however several current laws started out as an executive order [12]. As the state of California is a leader for environmental policies both in the U.S. and world-wide, the goal of carbon neutrality is set to be five years earlier than the IPCC report suggests.

## 1.2 Motivation

As carbon neutrality is making its way onto more and more agendas, the big question of how to reach it remains. Much research has been conducted on pathways for the decarbonization of the electric system on a country and city-level, both for the United States and world-wide. 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 GHG emissions [11]. The decarbonization of the electricity sector has a high importance since it can reduce emissions in other subsectors where electrification is a feasible option [13]. However, the big issue is that decarbonizing the power sector is easier to do than other sectors, such as transport and heating, because it has fewer point sources and many cost-competitive renewable substitutes [14,15].

Strategies for a low-carbon power sector have already been identified, including a combination of end-use energy efficiency improvements, substitution of no-emission power sources, improved grid flexibility and storage, and carbon capture [15]. Currently, the need to research strategies for an economy-wide carbon neutrality is crucial. 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 [16]. 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 [16].

Legislation is backing these efforts as well, with the signing of Executive Order B-48-18 (the Zero-Emission Vehicle Executive Order) calling for at least 5 million zero-emission vehicles to be on California roads by 2030 [17]; as well as the SB 1477 introducing two new low-carbon heating programs, investigating pilot programs to build all-electric and zero-carbon buildings, coordinating with the California Energy Commission on updates to the state's building (Title 24) and appliance (Title 20) energy efficiency standards, and establishing a building decarbonization policy framework SB [18]. However, legislation is focusing on new vehicles and buildings, while the existing stock in use remains a big issue for emissions.

Simultaneously, with the emergence of Climate Action Plans (CAPs) to reach carbon neutrality, much responsibility is put on the individual level from governments hoping that the people will change their consumption habits, transport modes and fuels, and fuel-switch their homes. A clear knowledge gap has been identified in the CAPs regarding the cost-effectiveness of different actions, as well as the quantified predictions of GHG emission reductions as a result of the different local policies. If citizens are expected to implement strategies towards carbon neutrality, the cost of these actions and the environmental benefits need to be known on the individual level.

While many national and state-wide policies are being set up, cities are taking an increasingly leading role to fight climate change. Change at a city-level can often lead to immediate results, with city mayors directly accountable for their decisive actions that happen at a faster rate than at state and national levels. As cities join forces for a sustainable and low-carbon future with networks such as C40 Cities Climate Leadership Group (C40), connecting over 80 megacities to enable stronger collective climate action, and the Local Governments for Sustainability (ICLEI) with over 1500 cities committed, they are setting the tone for the expectations of governments worldwide [19].

The city of Albany, California, is a small city with big will-power to lead the actions on climate change mitigation in the Bay Area. It is a member of ICLEI since 2006, adopted Resolution No. 2017-48 supporting the Paris Climate Agreement in 2017, and joined the Climate Mayors organization [20]. In parallel to the timeline of this work, the city of Albany is working on updating its Climate Action Plan (CAP 2.0) with the inputs of Cascadia Consulting Group. The CAP 2.0 is expected to result in a set of guidelines and qualitative approaches for reaching 60% GHG reductions by 2035, and net zero emissions by 2050 [21]. The case study is done on the city of Albany because of the city's strong ties with the neighbouring city Berkeley and the Lawrence Berkeley National Laboratory, where this thesis was written as a research work for the laboratory. This work aims to contribute with a quantitative approach to GHG reductions, with significance to the citizens and decision-makers of the city. It is very beneficial to do a techno-economic analysis on a small progressive city that could lead the way and facilitate adoption for other small cities in the area, to then move to a bigger scale. This approach could also be used to serve as an illustration and inspiration for big cities and countries implementing policies for carbon neutrality to start with a case study on a smaller level with a possibilities for a faster and more severe implementation, allowing the bigger cities to achieve the carbon neutrality or net zero carbon goals on time.

The need to fill an apparent knowledge gap in the important topic of carbon neutrality and net zero carbon serves as the motivation behind this thesis work, achieved by connecting a multi-sectoral modelling to the relevant current and future policies, as well as modelling a city of a small size, which has more opportunity for adoption than studies done on a country-level scale.

## 1.3 Terminology

The terms "Carbon Neutrality" and "Net Zero Carbon" have gained increasing popularity due to the growing usage in policymaking and the media. However, an issue arises when these terms do not have a universally accepted definition.

Kennedy and Sgouridis (2011) looked over the different scopes involved and different ways the terms can be interpreted, proposing a clear definition for each of the terms. Different interpretations can lead to big fluctuations in the severity of the GHG emission reduction needed, and whether carbon sequestration methods and new technologies are implemented within the system boundary, or if various types of carbon offsets are bought from outside the system boundary. The definitions use scope 1, 2 and 3 to characterize; scope 1 being internal emissions, scope 2 being core external emissions, and scope 3 being non-core emissions.

Definition of Carbon Neutral [22]:

"Any and all emissions for which the city is responsible under Scopes 1 and 2 can be managed through the purchase of offsets from third parties that lie outside the city's boundaries".

Definition of Net Zero Carbon [22]:

"All carbon emissions within emissions Scope 1 are eliminated, and emissions within scope 2 are balanced through export of low or zero carbon goods, internal or external sequestration, or import substitution of Scope 3 emission."

In the case of carbon neutrality, carbon offsets can be purchased for direct emissions from owned or controlled sources, not requiring innovation in city operations, and heavily relying on whether the purchased offsets lead to an actual GHG emissions reduction [22]. Net Zero Carbon is a preferred term following its definition, as it requires real efforts from the city to meet the goals and less emphasis on carbon offsets. As the definition can be adapted to the capabilities and voluntary efforts of different cities, states and countries, it is important to clarify the definition adopted for the case study. The definition needs to be clearly stated for all case studies. For the city of Albany, the previous definition of Net Zero Carbon is adopted, and the aim is to make a quantitative analysis on the pathways of reaching Net Zero Carbon, without the purchase of offsets.

## 1.3 Objectives

This thesis work is a case study on a specific city, the city of Albany, California, done with the aim to incorporate a methodology that can easily be implemented for other cities to speed up the transition to net zero carbon and give the city's decision makers, as well as the citizens, important quantification on costs. The scope of this work is focusing on single-family households in Albany.

The objectives of this thesis include the modelling of the city, creating packages of typical households and personal vehicles to analyze based on collected data. Once modelled, the objective is to do a techno-economic analysis on different technologies that can facilitate the transition to a net zero carbon city, presented as total cost of ownership (TCO) for different representative households, as well as the $CO_2$ emissions saved. The main objective is to quantify the costs of becoming net zero carbon, while highlighting which groups are at a disadvantage and in need of subsidies the most. By calculating the cost of the measures separately and together, it might be possible to discover interactive effects between them. These objectives are set up in order to help the decision-makers of the city and the population understand the real costs both on a household and city-level.

## 1.4 Thesis Outline

The objectives were realized and structured in the following chapters:

- Chapter 2 refers to the city of Albany, which this case study is based on. The city's CAP is discussed and important background data of population, land use and energy use is presented. The aim of the chapter is to get the reader acquainted with the city and its position in the state of California.
- Chapter 3 focuses on the residential transport sector. Relevant background data on vehicles on a city or state-level are shown. The assumptions used to compare electric vehicles (EVs) with internal combustion engine vehicles (ICEs) are presented, and a TCO analysis is conducted on four vehicle sizes. A sensitivity analysis is done on important parameters and the relevance of EVs is discussed.
- Chapter 4 explains the assumptions made to create typical households and presents the baseline households that can be seen in the city, as well as the upgraded household with and without electrification measures. The Home Energy Saving tool used for the home energy usage modelling is introduced. A TCO analysis is done for the important polluters in the house: water heating, space heating and large appliances, and further reasons for going all-electric are discussed.
- Chapter 5 presents the combined results of the modelling, showing the TCOs of building electrification and residential vehicles. The different households are displayed, combining different house sizes, energy use cases, vehicle models and annual mileages. The least and most favourable combinations are conveyed. The total costs and carbon savings are quantified, both on a household and city-level.
- Chapter 6 presents the conclusions of the work, highlighting achievements and future work needed in the field.

# 2. Case Study: Albany, California

## 2.1 Location

The location of Albany is in Alameda County, on the east shore of the San Francisco Bay estimated 12 miles (19.3 km) northeast from San Francisco (see Figure 1). Albany has an area of 5.5 square miles (14.2 $km^2$), however only 1.8 square miles (4.6 $km^2$) consists of land, making Albany the third smallest land among all of Alameda and Contra Costa counties. In contrast to the lack of land, Albany has a high population density with almost 10,400 people per square mile (4,015 people per $km^2$). Looking at Albany in comparison to the state of California consisting of 468 cities, Albany beholds a ranking of 32 in population density, 302 in population and 436 in land area [23].

*Figure 1: Location of Albany in the Bay Area on a map*

## 2.2 Population

Albany is a small city with a population of around 19,000 inhabitants. The population data was obtained from the demographics estimates of the State of California Department of Finance (CADOF) [24,25], presented in Figure 2. In 2010, Census data reported the population of Albany to be 18,539 people, which is very close to the 18,481 people the CADOF estimated for 2010.

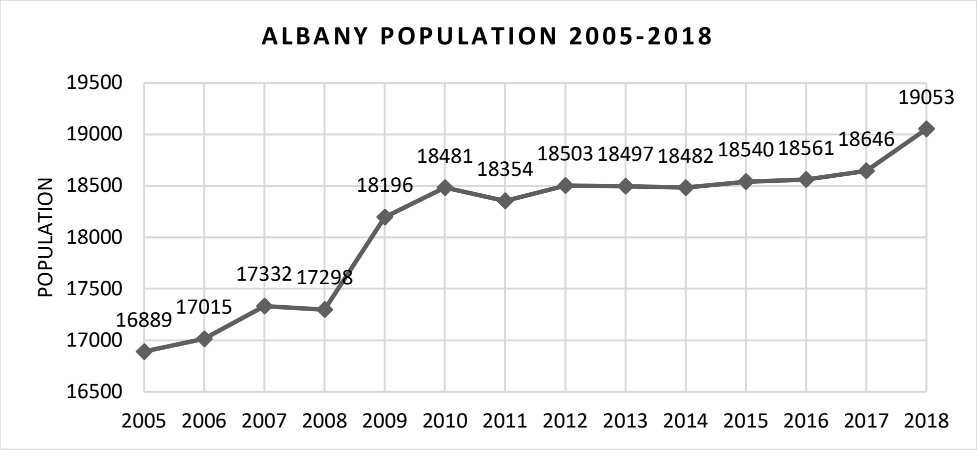


*Figure 2: Albany Population graph 2005-2018*

Albany was recorded to have a modest growth since the 1970's. The continuation of growth in population is correlated with the reconstruction of University Village student and family housing, as well as an increase in the average size of households. Concerning forecast of Albany city, population is forecasted to reach 20 330 in the next 15 years, meaning a yearly growth rate of 0.6% between 2015 and 2035 [23]. The population of Albany has a long history of race diversity and just like its population, there has also been a growth in diversity during the past two decades.

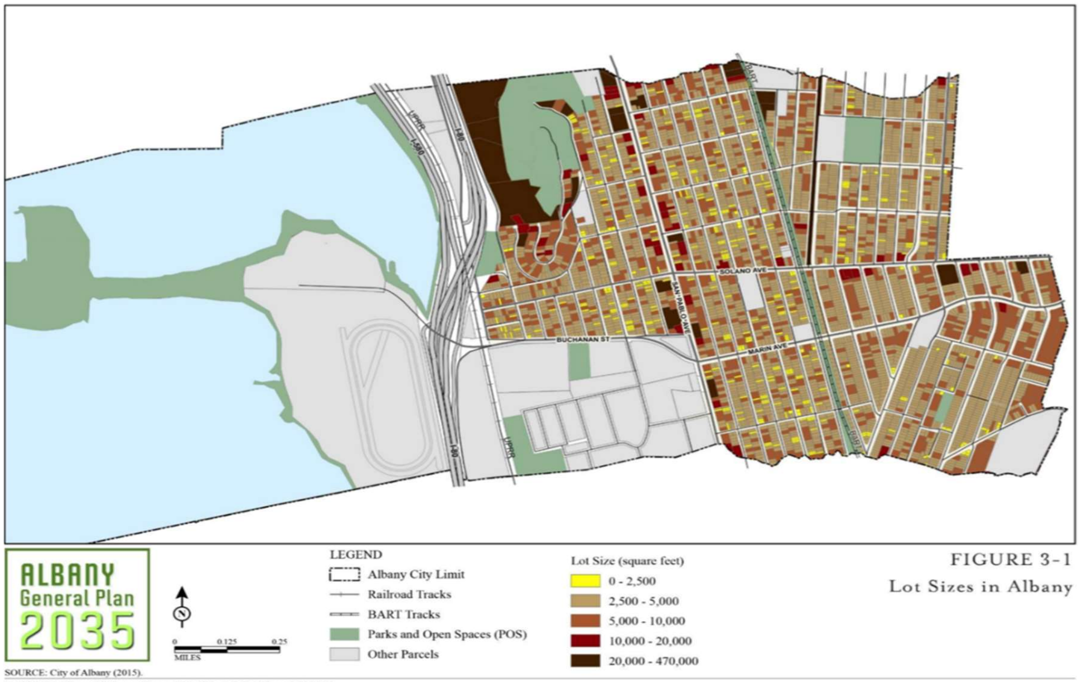
## 2.3 Land Use

Of the total 1,144 acres that the city of Albany beholds, residential uses encompass 37% of the total land. Albany 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. Moreover, 62 acres consist of commercial and industrial areas and 107 are used for commercial and recreational purposes, like service stations, auto body shops, car dealerships, restaurants, banks, small shopping centers, discount stores, retail shops and service businesses [23].

Residential housing can be divided into 3 different categories, low density residential, medium density residential and high density residential. Low density residential is intended for areas where the land use consists of detached single-family homes with yards with a minimum lot size standard of 3,750 square feet (348 $m^2$).

Meanwhile, medium density residential housing is intended for areas with a mix of single-family detached homes, small multi-unit buildings and attached housing types like town homes and duplexes. New development must follow the requirement of 20 units per acre to be a subject of medium density residential. Medium density residentials have many characteristics of lower density neighborhoods, such as yards and driveways, however they have a more diverse mix of housing unit types than low-density areas.

Furthermore, high density residential housing areas are characterized by multi-family housing, however single-family homes and duplexes may be present as well. Figure 3 gives an overview of the city of Albany, tracing the city limits and lot sizes, showing that 72% of all lots have a size smaller than 5,000 square feet (depicted in yellow and beige colors).



SOURCE: City of Albany (2015).
I:\ABY1301 Albany GP\figures\General Plan\Fig_3-1_Lot Sizes.ai (3/8/16)

*Figure 3: Map of lot sizes in Albany* [23]

## 2.4 Energy Use

City-level aggregated data was obtained from the Pacific Gas and Electric Company (PG&E) and the city council of Albany for the electricity and natural gas (NG) usage of the residential and commercial sectors for the years 2005-2016. The electricity usage and related emissions from the residential and commercial sector are displayed in Table 36 and the natural gas usage and tons of CO2 equivalent emissions in Table 37 in Annex 1.

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.

A great dip in natural gas usage was seen between 2013 and 2014, which can be partly linked to warmer weather decreasing the heating needs [21]. This is especially visible in Figure 4, where the warm weather of 2014 creates a large dip, but the trends are increasing since then as the weather becomes colder again. However, even 2016 is considered a hot year compared to Albany average, therefore the city can’t take full credit for the decreases in energy usage compared to the 2005 baseline.

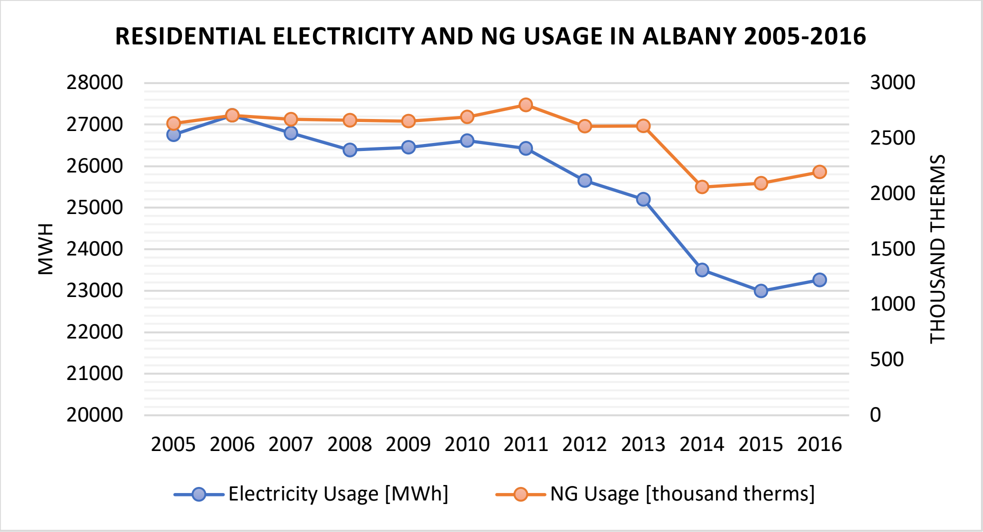


*Figure 4: Residential Electricity and NG Usage in Albany 2005-2016*

## 2.5 Emissions

In the state of California, it is mandatory to create Carbon Action Plans (CAPs) every 5 years. Most of the first-generation CAPs mapped out a policy plan for severe carbon reductions (most commonly 80% below 1990). Currently many cities are in the making of the second edition of the CAP, which this time aims for carbon neutrality by 2050. Albany's first Climate Action Plan was adopted in 2010.

The ambition is to have 60% reduction in greenhouse gas emissions by 2035, carbon-neutral by 2050 and engage in smart, equitable and resilience investments. However, the challenges that Albany faces includes the current emissions of 53,000 Mt CO2e, mostly from transportation and natural gas consumption. Further on, Albany is unique in geographical placement, that puts the city in the risk of flooding, extreme heat, and wildfires.

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). The power mix is at least 40% renewable and an additional 60% carbon-free from large hydropower. 2018 and 2019 data are not yet available, but this action is estimated to be responsible of a carbon emission reduction of 7% (3 884 MTCO2e/year). The quantified emissions from 2005 to 2018 are shown in Figure 5. There has been a 27% GHG emissions reduction between 2005 and 2017, and the reduction is estimated to have reached 33% with the carbon-free electricity between 2005 and 2018 [20].

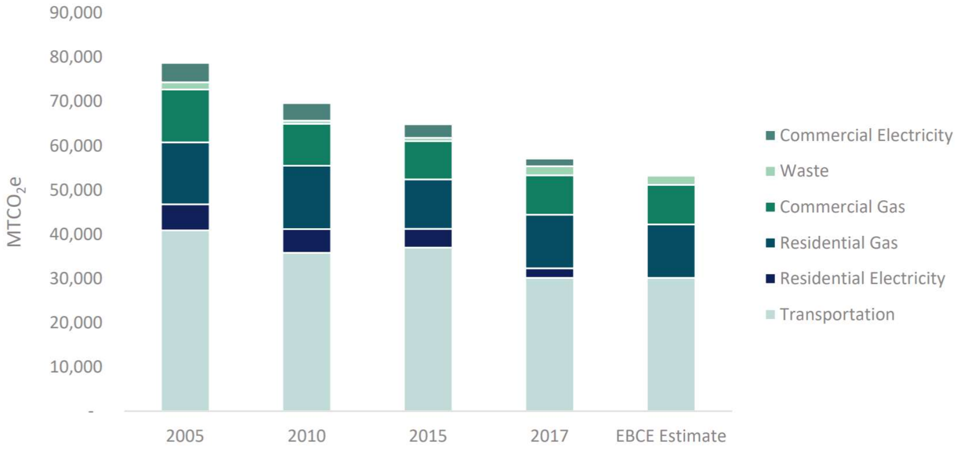


*Figure 5: Albany GHG emissions over time* [20]

In 2017, Albany's greenhouse gas emissions source came mainly from building energy use and transportation. Transportation emissions largely stem from personal passenger vehicles. Emissions from waste was the smallest source. 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, depicted in Figure 6. Transportation and residential gas are most important sectors to target since they make up almost 80% of all emissions, however, in the long run, all sectors need to be targeted to reach net zero carbon.

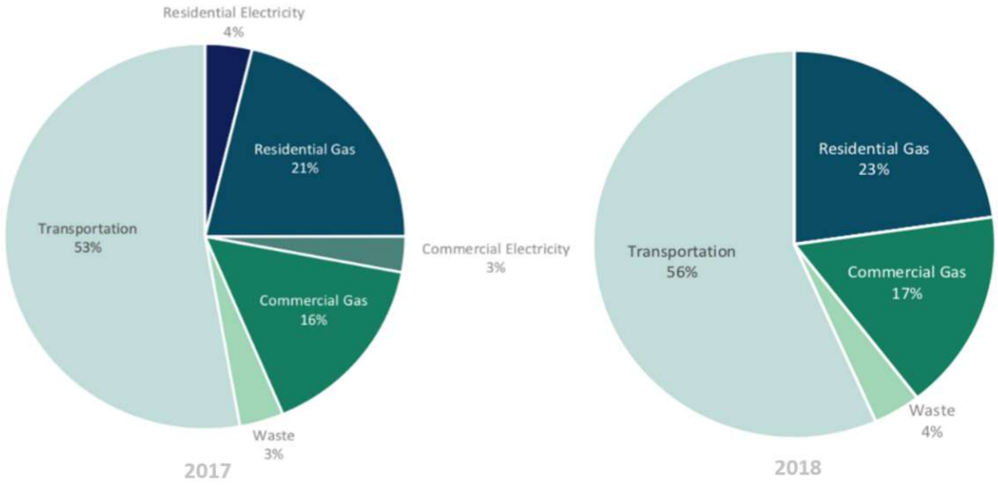


*Figure 6: Albany's share of emission by sector in 2017 (left) and 2018 (right)* [20]

As transportation and residential gas 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

## 3.1 Introduction

The transportation sector was the largest emitter of GHGs in the United States in 2017, accounting for almost a third of all GHG emissions. In the state of California, the transportation sector is responsible for a higher share of emissions than the country average, standing for 41% of the state's GHG emissions, since the electric power generation is cleaner than the U.S. average [26]. Light-duty vehicles account for almost 70% of transport-related emissions [11]. In Albany, the transportation sector accounted for an even higher percentage due to the lack of industry (53% in 2017 and 56% in 2018). These numbers show clearly the need to target light-duty vehicles, on a country, state and city-level, to reduce GHG emissions.

In addition to the GHG emissions, the transportation sector is also highly responsible for reduced air quality due to air pollution. Pollutants that negatively impact air quality, health and welfare include particulate matter (PM), nitrogen oxides ($NO_x$), and volatile organic compounds (VOCs) [27]. Over the past decades, the air quality in California has been a subject of focus due to the large number of often disadvantageous communities suffering the from negative health effects linked to poor air quality [16,28]. Over half of $NO_x$ emissions and over 10% of particulate matter (PM2.5) are attributed to on-road motor vehicles in California [11]. There is therefore a need to reduce air pollution from vehicles, which has been high on the agenda for both regulatory agencies and automobile manufacturers [29].

The United States is the world's third largest electric car market because of California's strong push, following China and Europe with 1.1 million on the road by the end of 2018 [30]. However, this only reflects as a market share of EVs at 2.4% in the U.S. [30]. California, in line with other countries and regions, is aiming to strongly reduce sales of gasoline or diesel-fueled internal combustion engine vehicles (ICEs) while increasing the sales of zero emission vehicles (ZEVs). This is also reflected in regulations with the adoption ZEV mandates calling for at least 1.5 million zero-emission vehicles to be on California roads by 2025 and 5 million by 2030 and have stated an intention to continue to improve vehicle fuel economy [30]. In addition to the mandate, the ZEV action plan proposes to invest USD 900 million to deploy 250,000 EV charging outlets by 2025, of which around 10,000 outlets should be DC fast chargers [31].

In this analysis, the focus is 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), therefore FCEVs are outside of the scope of this work.

The following analysis aims to debunk what the real costs of EVs are compared to their ICE counterparts, in the form of their total cost of ownership (TCO), and to find 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.

## 3.2 Methodology

### 3.2.1 Vehicle categories

To understand the impact that the fuel switching from gas to electric for household vehicles can have on the emissions of the city, it is important to map out the vehicle fleet of the case study location. This methodology can be followed for any U.S. city as the data used is taken from the U.S. Department of Transportation Federal Highway Administration's National Household Travel Survey (NHTS), the Department of Motor Vehicles (DMV) that every state has, and the U.S. Census Bureau.

In 2018, there were 12,359 vehicles registered at the California DMV for the ZIP code corresponding to the city of Albany (72609). Out of these vehicles, 99.3% were light-duty vehicles and the rest were heavy-duty. It is assumed that all 12,276 light-duty vehicles are household vehicles.

This is consistent with the Census estimate for the year 2016 for Albany, where if we assume 3 vehicles for the category of "3 or more vehicles available", the vehicle count is just over 10% lower than the amount registered at the DMV. In addition, it doesn't necessarily mean that all registered vehicles are actually in use at the location where they were registered, and Albany residents can own vehicles registered in other locations. For the scope of this research, it is assumed that all light-duty vehicles registered in Albany are in use in Albany, and no additional vehicles are added accounting for vehicles registered elsewhere but still used locally, as the flux is assumed to cancel out each other. The Census data for vehicles available in Table 1 is also showing that 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.

*Table 1: Estimate of vehicles available in Albany 2016* [32]

| VEHICLES AVAILABLE | | |
|---|---:|---:|
| Occupied housing units | 7395 | 100% |
| No vehicles available | 599 | 8% |
| 1 vehicle available | 3540 | 48% |
| 2 vehicles available | 2396 | 32% |
| 3 or more vehicles available | 860 | 12% |

Even though the state of California has the highest market share of EVs in the U.S., it doesn't necessarily translate down to city-level for all small cities. The DMV registration data breaks down the registered vehicles per fuel type, presented in Figure 7. Only 1.56% of vehicles were battery electric in Albany in 2018. Hybrid vehicles are gaining popularity with hybrid gasoline and plug in hybrid vehicles accounting for almost 12% of the vehicle fleet, however gasoline vehicles still make up almost 84%.

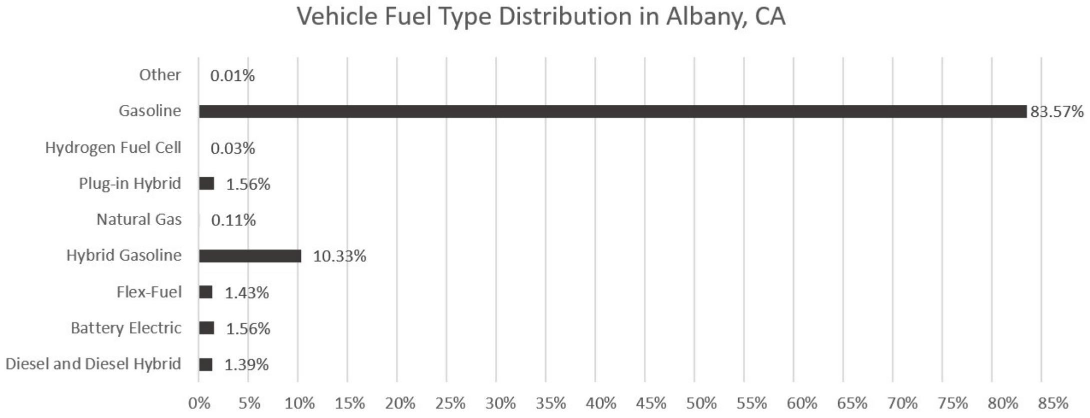


*Figure 7: Vehicle Fuel Type Distribution in Albany* [33]

The Census data on the number of vehicles available per household and the DMV data on vehicle fuel distribution are for all types of vehicles. Further understanding of the distribution of vehicle types is gained through the Federal Highway Administration's data on a national level in Table 2, and the DMV on a county-level in Table 3.

*Table 2: Distribution of household personal vehicle type on a national level* [34]

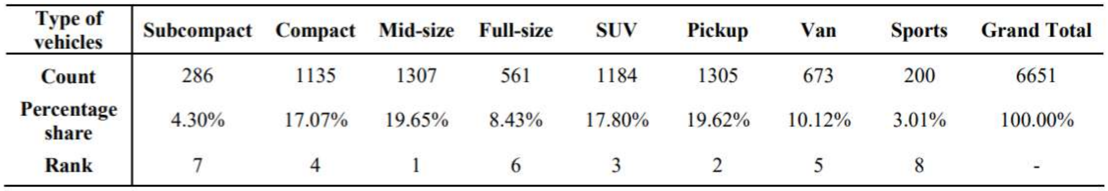
| Vehicle Type | Percentage |
|---|---|
| Automobile/Car/Station Wagon | 49.6% |
| Van (Mini/Cargo/Passenger) | 6.1% |
| SUV (Santa Fe, Tahoe, Jeep, etc.) | 23.7% |
| Pickup Truck | 15.9% |
| Other Truck | 0.5% |
| RV (Recreational Vehicle) | 0.6% |
| Motorcycle/Motorbike | 3.3% |
| Something Else | 0.3% |
| All | 100.0% |

*Table 3: Distribution of registered vehicle type on a county-level January 1-December 31, 2018* [33]

| | Alameda | Percentage |
|---|---|---|
| Autos | 1,078,950 | 80.2% |
| Trucks | 179,272 | 13.3% |
| Trailers | 53,443 | 4.0% |
| M/C | 32,840 | 2.4% |
| Total | 1,344,505 | 100.0% |

Although it is not known exactly to how big percentage of the vehicle fleet in Albany each of these classes make up, with the assumption that national and county-level data can represent Albany, the numbers show that this TCO comparison can affect a big part of the fleet. Over 80% of vehicles in Alameda county are autos, while on a national level the corresponding group of automobiles, vans and SUVs make up 79.4%, meaning that there is a similarity of the distribution on a national and county-level.

Kim (2011) attempted to transform the 2001 NHTS data set from the eight categories of car, van, SUV, pickup truck, other truck, recreational vehicles, motorcycles and other, to the more specified classification of subcompact, compact, mid-size, full-size, SUV, pickup truck, van (including minivan) and sports car. This classification is almost consistent with Consumer Reports classification system, first grouping the vehicles by size, and then adding special categories such as sports, SUV and pickup. The results of the transformed classification are shown in Figure 8. Even though the NHTS data sets are from different years, the classification in Figure 8 shows that 49.45% of vehicles are in the sub-compact to full-size sedan range, which is very close to the automobile category in Table 2. Midsized vehicles are the most common types of vehicles.



| Type of vehicles | Subcompact | Compact | Mid-size | Full-size | SUV | Pickup | Van | Sports | Grand Total |
|---|---|---|---|---|---|---|---|---|---|
| Count | 286 | 1135 | 1307 | 561 | 1184 | 1305 | 673 | 200 | 6651 |
| Percentage share | 4.30% | 17.07% | 19.65% | 8.43% | 17.80% | 19.62% | 10.12% | 3.01% | 100.00% |
| Rank | 7 | 4 | 1 | 6 | 3 | 2 | 5 | 8 | - |

*Figure 8: Distribution of household vehicles recently acquired in 2001 from NHTS data*

From the range of data available, it is chosen for this study to examine the size-based categories of subcompact, compact, mid-size and full-size. Even though SUVs are a very popular vehicle type, SUVs can furthermore be classified into regular and luxury, as well as by size ranging from x-small to large, as classified by Edmunds [36]. Focusing on the categories of subcompact to full-size, approximately 50% of household vehicles are affected. For the city of Albany, this would mean over 6,100 vehicles.

### 3.2.2 Vehicle Models

For the four vehicle categories examined (subcompact, compact, mid-size and full-size), a representative vehicle model for both EVs and ICEs were chosen for the TCO analysis. The electric vehicles within each category were chosen from the U.S. Department of Energy (DOE) “Find Electric Vehicle Models” service, which makes it possible to search by market class, showing a total of 185 full-electric vehicles to choose from [37]. The ICEs within each vehicle category were chosen to be typical rental car vehicle types, as they are representative for each category by rental car companies and are widely accepted by the public [38]. The summary of the vehicle models chosen for each vehicle category for EVs and ICEs respectively is presented in Table 4.

It is important to point out that it is difficult to do a fair “apples to apples” comparison, and the difference in the TCO between the representative EV and ICE model is highly dependent on which vehicle is chosen to represent the category. Vehicle ownership costs vary with location and with vehicle model. Comparing ICEs and EVs poses a challenge since their attributes are not directly comparable, and it can be discussed which models can be compared based on usage and price range. Therefore, the methodology for vehicle selection is very important. As the aim of the TCO is to compare vehicles currently possible to buy for Albany and U.S. residents, vehicles of 2018 or newer models are chosen. In addition, another criterion is for the model to have a 5-year ownership cost estimate made by Edmunds on maintenance, depreciation and insurance costs [39].

For subcompact EVs, the DOE shows only four different main models available: the BMW i3, Chevrolet Spark EV, CODA, and the Mitsubishi i-MiEV. The BMW i3 is a luxury electric car and is not suitable as a representative option for subcompact EVs. The Chevrolet Spark EV was discontinued in 2016, the Mitsubishi i-MiEV was discontinued in 2017 and CODA filed for bankruptcy in 2013. As these are older models, it is the mini-compact 2019 Fiat 500-e that will serve as the representative EV for subcompacts. It is clear to say that there are not many subcompact EVs on the market. In comparison for subcompact ICEs, the 2019 Chevrolet Spark is used, as it is often used as a typical economy car rental vehicle.

The Ford Focus is the most commonly used car to represent compact cars in car rental companies, used as an example at Avis, Budget, Dollar, Payless and Thrifty. Therefore, for compact EVs, the 2018 Ford Focus EV is chosen to as the representative vehicle. It is compared to the 2018 Honda Civic, which is a popular compact vehicle frequently seen on the streets of California.

For mid-size EVs, the 2019 Nissan LEAF is used as a representative vehicle, since it is classified as a mid-size car by the DOE. It is also ranking forth on Edmunds list of best electric cars. The Nissan LEAF has been a popular EV used in literature [40–44]. It is compared against the ICE 2019 Honda Accord, which ranked as the best mid-size sedan on Edmunds.

For the full-size category, there are not many EVs to choose from. The only large sized EV model proposed by the DOE is the Tesla Model S. Looking at the vehicle market class of standard sport utility 4-wheel drive vehicle, which are also large vehicles but are SUVs rather than compact cars, the EVs available are the Tesla Model X and the Audi e-tron. Only the Tesla Model X has available data on the estimated maintenance, depreciation and insurance costs on Edmunds. It is however a luxury vehicle with a starting manufacturer's suggested retail price (MSRP) at over $80,000. The fair comparison would be with a luxury ICE vehicle that someone thinking about buying a Tesla Model X would consider as an option, like the BMW X7, the Cadillac Escalade, the INFINITI QX80 or the Lincoln Navigator, all being the top 4 large luxury SUVs ranked by Edmunds. The 2018 Cadillac Escalade will be used as the ICE for comparison. However, there are countless affordable full-size ICEs on the market, like the Ford Fusion, Ford Taurus, Chevrolet Impala and Chevrolet Tahoe (full-size SUV), that car rentals use as typical full-size cars. It is crucial to call attention to the issue that if someone was going to buy a full-size car and wanted to compare EV to ICE options, there wouldn't be any EVs currently on the market competing with an affordable ICE.

*Table 4: 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 |

### 3.2.3 Total Cost of Ownership

#### 3.2.3.1 Ownership time

Due to high average ownership times and average age of vehicle fleet in the U.S., the cost of ownerships are chosen to be compared for 10 years, as done in the study of Weldon *et al.* (2018). Other studies have also chosen to look at longer time periods for total cost calculations; 15 years in Lipman and Delucchi, (2006), 13 years in Al-Alawi and Bradley, (2013) and 130,000 miles travelled in Hutchinson *et al.* (2014). The longer time period for the TCO has also the benefit of including the battery replacement cost in the EV's lifetime, which in the U.S. in 2015 made up more than 57% of the total cost in a mid-sized vehicle [48], but is projected to lower significantly. The 10-year period chosen reflects a good middle-ground between the almost 7-year average length of ownership and the almost 12-year average age of light-vehicle on U.S. roads in 2016 [49].

#### 3.2.3.2 Depreciation

Different literatures use varying approaches to the TCO analysis comparison of EVs and ICEs. One approach is to assume a short period of ownership, after which the vehicle is resold, and consider the depreciation value of the vehicle, which is the amount by which the value of a vehicle declines during the time it is used. The issue arising with this approach is that the depreciation value of EVs is still unsure due to the lack of long-term data [44,50]. Early EV models suffer high depreciation rates, due to the rapid improvements in the battery life and overall performance of newer models, lowering the resale value of older EV models [50]. Current projections of depreciation for new EV models show higher value loss for EVs than their ICE counterparts [36,41,43], however it is projected for EVs to match the depreciation rates of ICEs or even depreciate slower due less moving parts that can break and possible carbon tax raises [50] or even reach a higher resale value [51]. It is unknown how the tackling of battery recycling and deterioration will affect the depreciation [44]. Having considered the factors of uncertainty, the depreciation is taken as the square of the estimated depreciation calculated by Edmunds after 5 years, assuming that the resale occurs to a private party and the vehicle will be in clean condition after a yearly VMT of 15,000 miles (24,000 km) [39].

#### 3.2.3.3 Maintenance cost

While initial costs, such as the vehicle price and sales tax, are easy to obtain from Edmunds.com and the State of California Department of Motor Vehicles (DMV) Fee Calculator respectively, the value of some annual costs vary by source. The maintenance costs for EVs compared to ICEs have largely differed in literature with some comparisons concluding higher maintenance costs for EVs, while others concluding the opposite.

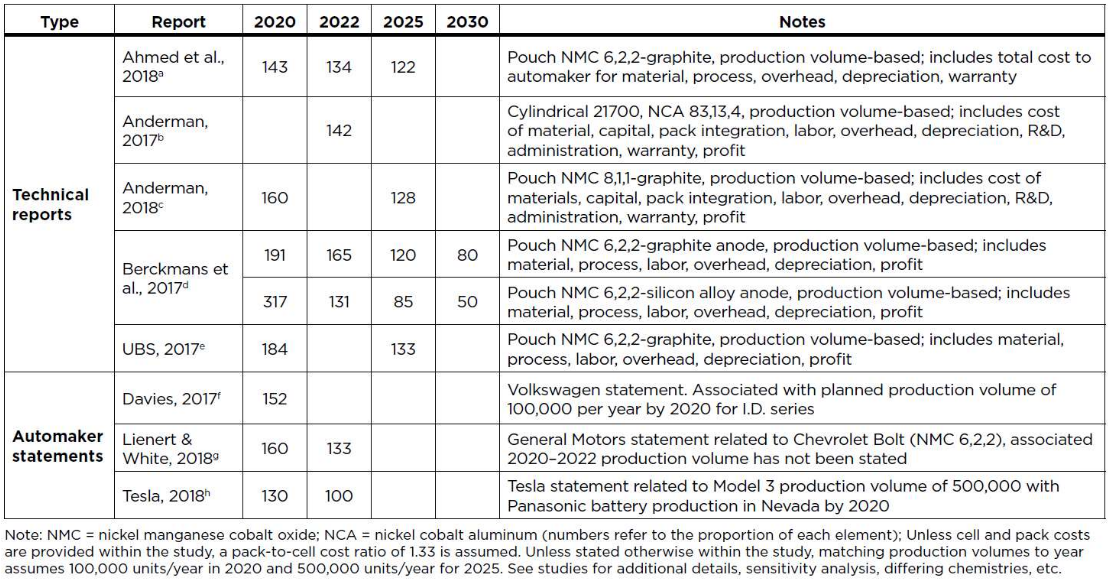
The American Automobile Association (AAA) showed higher maintenance costs per mile for the category of Electric Car (including the vehicle models BMW i3, Chevrolet Bolt, Ford Focus, Kia Soul and Nissan Leaf) than the category of Small Sedan (including the vehicle models Chevrolet Cruze, Ford Focus, Honda Civic, Hyundai Elantra and Toyota Corolla); estimating 7.60 dollar cents for the former and 7.25 dollar cents for the latter [41]. However, the AAA included battery change in the maintenance. Comparing the EV Nissan Leaf and the ICE Honda Accord with Edmunds.com's TCO® tool, performing all scheduled maintenances in the vehicle's owner's manual in the U.S. showed a slightly lower 5-year cost for the Nissan Leaf when driven 15 000 miles per year, with the difference being less than $600 and the EV maintenance cost being 14.4% cheaper for that period. Propfe *et al.*, (2012) estimated the maintenance and repair (M&R) costs of EVs to be approximately 18% lower than for ICEs after breaking down the costs for 31 drivetrain components. Palmer *et al.* (2018) compared maintenance costs of the Nissan Leaf with the Toyota Corolla and found the EV maintenance cost to be 30.2% lower for the year 2015 in California. In contrast, Logtenberg *et al*. (2018) found the average annual maintenance cost in Canada to be 46.5% lower for EVs than ICEs. The range of results in the maintenance cost differences show that M&R costs vary largely depending on methodology and location, however, it can be concluded that the maintenance costs of EVs are lower than of ICEs due to the absence of a gear box, transmission and less moving parts that could break down, as well as the savings because of avoided regular maintenance of oil and filter replacements that occur with ICEs [43,44,51,52].

In this study, we assume that the maintenance costs for EVs are 27.3% cheaper than for their gasoline counterpart, as it is the mean value of the findings in literature.

#### 3.2.3.4 Battery Costs

Batteries of electric vehicles have for long been the bottleneck of EV development [53]. The lifespan of a battery can be expressed as the time it can be stored with minimal discharges before the diminishing of its capacity, or as the number of charge-discharge cycles before losing its performance criteria [54]; often deemed to have reached its end-of-life when used in EVs at 80% of its capacity [55]. The end-of-life of an EV battery has been assumed in several studies to be 8 years [40,44], and therefore the battery lifetime was assumed to end before the vehicle's end of life. However, improvements in battery development have led to manufacturers claiming that the battery life will surpass the vehicle life and will have enough capacity to be collected and repurposed [56–58]. In addition, the Vehicle-to-Grid Simulator (V2G-Sim) developed at Lawrence Berkeley National Laboratory showed that 80% remaining capacity shouldn't necessarily be considered as end-of-life, since EV batteries continue to meet the needs of U.S. drivers beyond the 20% degradation [59]. Most manufacturers have a battery warranty of 8 years / 100,000 miles, but recently the warranty time has been extended to 10 years / 150,000 miles in American states where the California Vehicle and Emissions Warranty Periods have been adopted [60]. An appropriate assumption would be that EV batteries need replacing at the end of the warranty period, which is at the 10-year mark in Albany, but for the sake of including the battery replacement cost, a replacement is assumed after 8 years. The battery cost is included in a sensitivity analysis, ranging between different projections, as well as zero to simulate if the battery doesn't need replacement.

The high cost of battery pack production for EVs have been the main reason for EVs being more expensive than ICEs. The price of lithium-ion battery packs dropped 85%, from an average of 1,160 $/kWh in 2010 (in real 2018 $) to an average of 176 $/kWh in 2018 [61]. The battery price currently represents in average 42% of the total EV cost and is predicted to reduce to only 18% of total cost by 2030 [62]. However, considering the battery pack size with the 176 $/kWh price, the battery makes up 20% of the 2018 Ford Focus EV purchase price and 24% of the 2018 Nissan LEAF. BloombergNEF (2009) predicts in its lithium-ion price outlook 94 $/kWh in 2024 and 62 $/kWh in 2030 with an 18% learning rate. These projections are in line with findings from other technical reports and automaker statements, summarized by Lutsey & Nicholas (2019) in Figure 9.



| Type | Report | 2020 | 2022 | 2025 | 2030 | Notes |
|---|---|---|---|---|---|---|
| **Technical reports** | Ahmed et al., 2018[a] | 143 | 134 | 122 | | Pouch NMC 6,2,2-graphite, production volume-based; includes total cost to automaker for material, process, overhead, depreciation, warranty |
| | Anderman, 2017[b] | | 142 | | | Cylindrical 21700, NCA 83,13,4, production volume-based; includes cost of material, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit |
| | Anderman, 2018[c] | 160 | | 128 | | Pouch NMC 8,1,1-graphite, production volume-based; includes cost of materials, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit |
| | Berckmans et al., 2017[d] | 191 | 165 | 120 | 80 | Pouch NMC 6,2,2-graphite anode, production volume-based; includes material, process, labor, overhead, depreciation, profit |
| | | 317 | 131 | 85 | 50 | Pouch NMC 6,2,2-silicon alloy anode, production volume-based; includes material, process, labor, overhead, depreciation, profit |
| | UBS, 2017[e] | 184 | | 133 | | Pouch NMC 6,2,2-graphite, production volume-based; includes material, process, labor, overhead, depreciation, profit |
| **Automaker statements** | Davies, 2017[f] | 152 | | | | Volkswagen statement. Associated with planned production volume of 100,000 per year by 2020 for I.D. series |
| | Lienert & White, 2018[g] | 160 | 133 | | | General Motors statement related to Chevrolet Bolt (NMC 6,2,2), associated 2020–2022 production volume has not been stated |
| | Tesla, 2018[h] | 130 | 100 | | | Tesla statement related to Model 3 production volume of 500,000 with Panasonic battery production in Nevada by 2020 |

Note: NMC = nickel manganese cobalt oxide; NCA = nickel cobalt aluminum (numbers refer to the proportion of each element); Unless cell and pack costs are provided within the study, a pack-to-cell cost ratio of 1.33 is assumed. Unless stated otherwise within the study, matching production volumes to year assumes 100,000 units/year in 2020 and 500,000 units/year for 2025. See studies for additional details, sensitivity analysis, differing chemistries, etc.

*Figure 9: Electric vehicle battery pack cost ($/kWh) for 2020-2030, from technical reports and industry announcements [63]*

As per the battery replacement assumption of made in year 8 (2027), the battery pack price is assumed to be 102.6 $/kWh which is the average of all values presented for 2025 and 2030. However, due to the large spread of values, a sensitivity analysis of the TCO is done with the battery price for replacement ranging from 50-135 $/kWh, as well as zero to simulate the case where no battery replacement is needed.

#### 3.2.3.5 Fuel Cost

Fuel Prices

To calculate the annual fuel costs for the two types of vehicles, the price of gasoline and electricity has been chosen as the Californian average. The California regular all formulations retail gasoline price of $3.54 per gallon is used, being the 2019 average between January and September [64]. For electricity used for EV charging, 9.26 dollar cents per kWh is used, given as the average price of electricity to ultimate customers in California in July 2019 for transportation uses [65].

Long-term projections of gasoline prices from 2018 to 2050 range from $2.51 per gallon in the Low Oil Price case to $5.57 per gallon in the High Oil Price case [66]. These scenarios translate into a yearly fuel price change of -1.1%, +0.6% or +1.5%. For electricity, prices range from 9.7 cents/kWh to 11.6 cents/kWh across scenarios by 2050, due to the effects of natural gas prices on the projections, translating into an electricity price increase in that period of 0.1-0.7% per year [66]. The long-term price projections on a national level in the U.S. can be seen in Figure 10.

The annual fuel price increase for gasoline and for electricity used in the TCO analysis are assumed to be 0.6% and 0.4% respectively for the 10-year period.

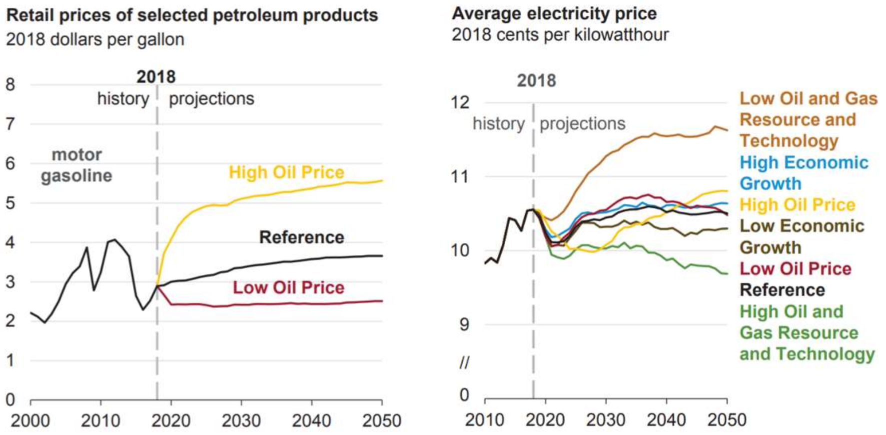


*Figure 10: Retail price projections of motor gasoline (left) and electricity (right) until 2050* [66]

Fuel prices are an important parameter for the assessment of the payback time, with high gasoline prices leading to shorter payback periods for EVs [47]. In addition, Diamond (2009) concluded that fuel price has a bigger impact on vehicle adoption than incentives. Therefore, a sensitivity analysis is conducted for gasoline and fuel price.

Vehicle Miles Travelled

Further needed for the fuel cost calculation is the fuel economy of the vehicles as well as the annual mileage or vehicle miles travelled (VMT) per vehicle. The fuel economy used for all vehicles in the combined miles per gallon equivalent (MPGe) of highway and city driving. The aggregated VMT is obtained on a county-level for Alameda county from the California Air Resources Board (CARB) EMFAC2017 model, which combined with data on the number of vehicles in Alameda from the DMV gives the average annual VMT of approximately 11,300 miles per vehicle (18,200 km/year) or a daily mileage of 31 miles per vehicle (50 km/day). The EMFAC emissions model is approved by the U.S. Environmental Protection Agency and is used for assessing emissions from on-road vehicles including cars, trucks, and buses in California [68]. In comparison, the average annual VMT per vehicle in 2009 for light-duty vehicles was 11,117 miles [69], and in 2017 the daily VMT per driver was 28.49 miles [70]. As this study also aims to identify households that would benefit and be penalized by EV adoption policies, the mileage is varied and split into low, medium and high usage similarly to Weldon *et al.* (2018) and Wu *et al.* (2015). The medium mileage is the average of 11,300 miles/year, while the low is chosen to be 8,000 miles/year (13,000 km/year) and the high is 15,000 miles/year (24,000 km/year).

#### 3.2.3.6 Initial Costs

It is assumed that the sales tax is payed upfront, however a bank loan is taken for the vehicle. The mean interest rate on a 60-months loan for a loan taker with a median credit score of 706 is expected to pay a 4.21% rate [72]. A 7% discount rate is assumed when calculating the future yearly payments per vehicle in 2018 $. The purchase price used is the MSRP presented by Edmunds. The total yearly registration fees and total one-time sales tax are found for each individual vehicle model through the California DMV's fee calculator, assumed that the vehicle is bought in Albany on September 1st, 2019. The federal EV tax credit of $7,500 is added in the TCO, with a sensitivity analysis varying from no rebate to full rebate to see if the importance of the EV incentive and whether it is still needed. An additional cost for EVs is the level 2 charging station with installation. Although many EV owners will be able to meet their daily driving range requirements by charging overnight with AC Level 1 equipment, requiring no additional cost or installation, a level 2 charging equipment can be beneficial for drivers with less regular schedules, or longer commutes. Therefore, the TCO analysis is done with a sensitivity on the level 2 charging equipment initial costs of $1,000 [73,74]. The TCO is shown in an annualized form ($/year) through the Payment (PMT) function of Excel used on the Net Present Value (NPV) of the total costs over 10 years with a 7% discount rate.

#### 3.2.3.7 Insurance Costs

When comparing two vehicles driven by the same person and same mileage, the insurance still differs and depends on the vehicle value, however the variation in insurance costs between EVs and ICEs is negligible. Long-term data on insurance differences are lacking to draw a strong conclusion on insurance costs for comparison [50]. The insurance in assumed to be the same for both vehicles, as done in several previous studies [43,44,47]. The insurance costs are set at $1,200 for sub-compact, $1,500 for compact and mid-size and $2,000 for full-size vehicles.

#### 3.2.3.8 CO2 emissions

As the city of Albany has opted for 100% carbon-free electricity, the emissions factor of the electricity is not the PG&E average for the area, estimated to be 401 lbs $CO_2e$/MWh electricity (182 kg $CO_2e$/MWh), but instead an emissions factor of 0 is used [75]. The emissions factor for motor gasoline is the EIA value of 8.91 kg $CO_2$/gallon [76].

The emissions factor of 0 for electricity is an over-simplification, since the carbon-free electricity from the East Bay Community Energy (EBCE) is carbon free as an average over the year, but there are times during the day when the electricity used is not coming from renewable sources. In addition, the EBCE can provide carbon-free electricity to households and cities joining currently (like the city of Albany), but if the whole area wanted to join, the capacity would not allow for renewable electricity to be delivered to all households. Solar panels on households would then be a sought-after solution to assure carbon-free electricity.

### 3.2.4 Table of Assumptions

Table 5 summarizes the assumptions explained in the TCO methodology that are valid for all four vehicle categories.

*Table 5: Summarizing Table of Vehicle TCO assumptions*

| | | | |
|---|---|---|---|
| Ownership time (years) | 10 | EV Tax Credit ($) | 7,500 |
| Discount rate | 7% | Electricity Price ($/kWh) | 0.09 |
| Bank Interest | 4.21% | Gasoline Price ($/gallon) | 3.54 |
| Number of payments (years) | 5 | Electricity price increase/year | 0.4% |
| Conversion kWh/Gallon eq | 33.7 | Gasoline price increase/year | 0.6% |
| Low VMT (miles/year) | 8,000 | Battery Pack price in 2027 ($/kWh) | 102.6 |
| Average VMT (miles/year) | 11,300 | Charging station price incl. installation ($) | 1,000 |
| High VMT (miles/year) | 15,000 | Gasoline EF (kg CO2 / gallon) | 8.91 |

## 3.3 Results

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.

### 3.3.1 Subcompact Vehicles

The inputs used for the TCO calculation for the subcompact vehicles are presented in Table 6.

*Table 6: Inputs for TCO Analysis Subcompact EV vs. ICE Vehicle*

| Vehicle Model[1] | 2019 Fiat 500e | 2019 Chevrolet Spark |
|---|---:|---:|
| Fuel Type | Electric | Gas |
| Purchase Price[2] ($) | 34,705 | 13,220 |
| Total Registration Fees[3] ($) | 435 | 265 |
| Total Use / Sales Tax[3] ($) | 3,384 | 1,289 |
| Maintenance[2] ($/year) | 715 | 984 |
| Insurance[2] ($/year) | 1,200 | 1,200 |
| Fuel Economy[2] (MPGeq) | 103 | 33 |
| Battery Pack[2] (kWh) | 24 | 0 |
| Resale value after 10 years[2] ($) | 5% | 13% |

*Sources:* [1][37], [2][36], [3][33]

The subcompact comparison between the EV Fiat 500e and the ICE Chevrolet Spark in Table 7 shows that no matter if the vehicle is driven a low, average or high VMT per year, the fuel cost savings from the EV don't even out the costs. Table 7 shows the results from the annualized TCO comparison for the three scenarios for the subcompact EV and ICE. The yearly costs for the EC range from 7,319 – 7,550 $/year, and 5,477 – 6,300 $/year for the ICE. The carbon savings in the scenarios range from 2.2 to 4.1 tons of $CO_2$/year.

*Table 7: TCO Comparison Table Subcompact EV vs. ICE*

| | Fiat 500e | | | Chevrolet Spark | | |
|---|---:|---:|---:|---:|---:|---:|
| | Low VMT | Average VMT | High VMT | Low VMT | Average VMT | High VMT |
| Bank Loan ($/year) | 4,898 | 4,898 | 4,898 | 1,866 | 1,866 | 1,866 |
| Sales Tax ($/year) | 482 | 482 | 482 | 184 | 184 | 184 |
| Tax Credit ($/year) | -1,068 | -1,068 | -1,068 | 0 | 0 | 0 |
| Registration Fees ($/year) | 465 | 465 | 465 | 284 | 284 | 284 |
| Maintenance ($/year) | 765 | 765 | 765 | 1,052 | 1,052 | 1,052 |
| Charging Station ($/year) | 142 | 142 | 142 | 0 | 0 | 0 |
| Battery Replace ($/year) | 218 | 218 | 218 | 0 | 0 | 0 |
| Insurance ($/year) | 1,284 | 1,284 | 1,284 | 1,284 | 1,284 | 1,284 |
| Fuel cost ($/year) | 263 | 372 | 494 | 940 | 1,328 | 1,763 |
| Resale ($/year) | -132 | -132 | -132 | -132 | -132 | -132 |
| Total TCO ($/year) | 7,319 | 7,428 | 7,550 | 5,477 | 5,865 | 6,300 |
| Δ TCO ($/year) | 1,842 | 1,563 | 1,250 | 0 | 0 | 0 |
| TCO Ratio | 1.336 | 1.266 | 1.198 | 1 | 1 | 1 |
| Total CO2 (kg/year) | 0 | 0 | 0 | 2,160 | 3,051 | 4,050 |

From the comparison table, it is possible to do the cost breakdown of each component taken into account for the TCO (bank loan, taxes & fees, maintenance, battery & charging station, insurance, fuel cost and resale value). The component breakdown of the average VMT case is depicted in Figure 11. It is interesting to note that the bank loan, meaning the yearly payment for the upfront purchase cost of the car, is 66% of the annual TCO cost for the average EV case, while it is only 32% of the TCO cost for the average ICE. Even though the resale value after 10 years is expected to be 4% of the initial purchase price for the EV and 13% for the ICE, the resale is making up only approximately 2% of the TCO for both. The fuel costs make up 5% of the TCO for EVs while it is making up 23% for the ICE. The charging station cost and the battery replacement, which both are costs that are not necessarily faced by an average EV owner, make up only roughly 5% of the total TCO.

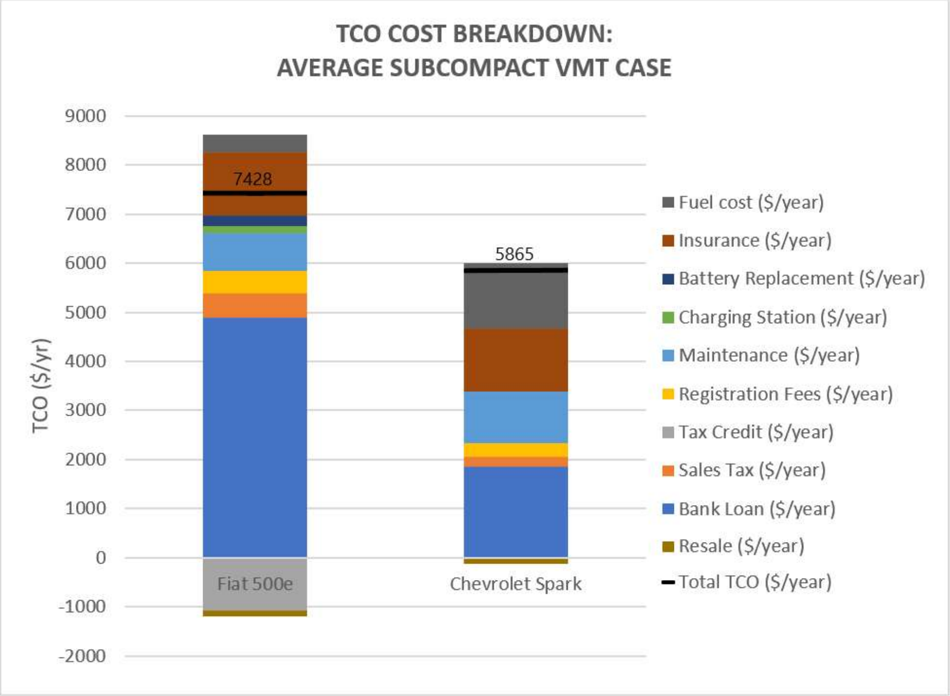


*Figure 11: TCO Cost Breakdown for the Average VMT case of Subcompact EV vs. ICE*

From the TCO ratios in Figure 11, it is seen that the Fiat 500e is 33.6% more expensive than the Chevrolet Spark when driven 8,000 miles/year and 19.8% more expensive when driven 15,000 miles. This phenomenon of the price gap closing up the more the vehicle is driven is visualized in Figure 12, showing the effects of the gasoline price boosting the annualized TCO cost for the subcompact ICE by over $820 when driven 7,000 miles more.

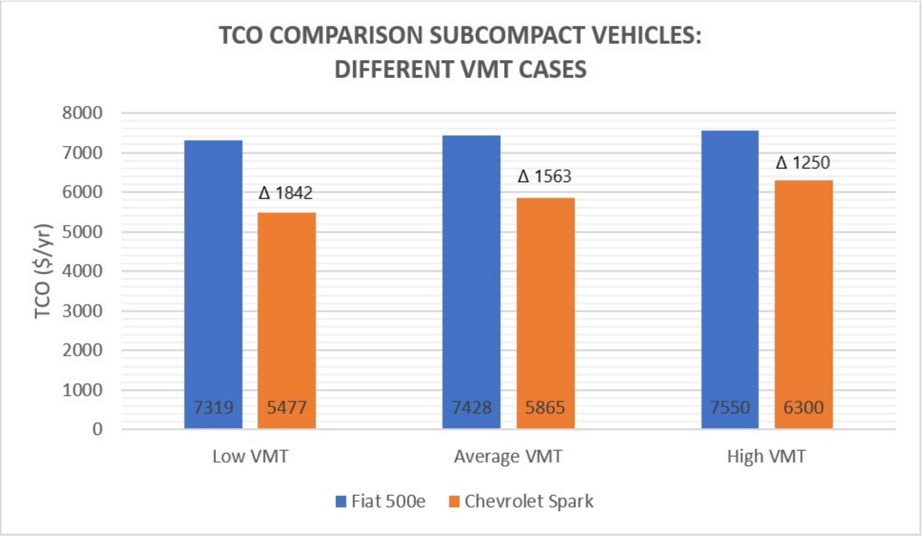


*Figure 12: TCO Comparison for Subcompact EV vs. ICE vehicles for 3 VMT cases*

### 3.3.2 Compact Vehicles

The compact vehicles compared were the 2018 Ford Focus EV and the 2018 Honda Civic. The inputs specific to these compact vehicles are presented in Table 8.

*Table 8: Inputs for TCO Analysis Compact EV vs. ICE Vehicle*

| Vehicle Model[1] | 2018 Ford Focus EV | 2018 Honda Civic |
|---|---|---|
| Fuel Type | Electric | Gas |
| Purchase Price[2] ($) | 29,120 | 19,835 |
| Total Registration Fees[3] ($) | 398 | 308 |
| Total Use / Sales Tax[3] ($) | 2,840 | 1,934 |
| Maintenance[2] ($/year) | 544 | 749 |
| Insurance[2] ($/year) | 1,500 | 1,500 |
| Fuel Economy[2] (MPGeq) | 115 | 32 |
| Battery Pack[2] (kWh) | 33.5 | 0 |
| Resale value after 10 years[2] ($) | 16% | 38% |

*Sources:* [1][37], [2][36], [3][33]

The results of the TCO comparison of the compact vehicles are presented in Table 9. In contrary to the subcompact results, the compact EV is more favorable that the ICE in two out of the three VMT cases. The negative Δ TCO signifies $89 or $420 savings per year with the Ford Focus EV compared to the Honda Civic when driven at an average or high VMT. The TCO ratio is just over 1 for the low VMT case, meaning that the EV is 3.3% more expensive than the ICE. However, in the other two cases, the TCO ratio is below 1, showing that the total yearly cost of the EV is 1.4% cheaper than its ICE counterpart for an average VMT and 6% cheaper when the annual mileage is 15,000 miles. The carbon savings are very similar to the subcompact vehicle, since the Honda Civic and the Chevrolet Spark have similar fuel economies (32 vs. 33 MPG).

*Table 9: TCO Comparison Table Compact EV vs. ICE*

| | Ford Focus EV | | | Honda Civic | | |
|---|---|---|---|---|---|---|
| | Low VMT | Average VMT | High VMT | Low VMT | Average VMT | High VMT |
| Bank Loan ($/year) | 4,110 | 4,110 | 4,110 | 2,800 | 2,800 | 2,800 |
| Sales Tax ($/year) | 404 | 404 | 404 | 275 | 275 | 275 |
| Tax Credit ($/year) | -1,068 | -1,068 | -1,068 | 0 | 0 | 0 |
| Registration Fees ($/year) | 426 | 426 | 426 | 330 | 330 | 330 |
| Maintenance ($/year) | 582 | 582 | 582 | 801 | 801 | 801 |
| Charging Station ($/year) | 142 | 142 | 142 | 0 | 0 | 0 |
| Battery Replace ($/year) | 305 | 305 | 305 | 0 | 0 | 0 |
| Insurance ($/year) | 1,605 | 1,605 | 1,605 | 1,605 | 1,605 | 1,605 |
| Fuel cost ($/year) | 254 | 358 | 476 | 970 | 1,370 | 1,818 |
| Resale ($/year) | -357 | -357 | -357 | -583 | -583 | -583 |
| Total TCO ($/year) | 6,404 | 6,508 | 6,626 | 6,198 | 6,598 | 7,046 |
| Δ TCO ($/year) | 206 | -89 | -420 | 0 | 0 | 0 |
| TCO Ratio | 1.033 | 0.986 | 0.940 | 1 | 1 | 1 |
| Total CO2 (kg/year) | 0 | 0 | 0 | 2,228 | 3,146 | 4,177 |

There is still a significant difference in the initial price, with the compact EV being almost $9,300 more expensive (before the EV tax credit) than the compact ICE, however the price gap is smaller than for the subcompacts. It is also interesting to discover that a household might choose an ICE subcompact over an EV subcompact, however, if a household was determined to purchase an EV, it would be more economic to buy a compact EV over a subcompact one, relative to the ICE option. If the choices are broadened and the compact EV was to be compared with the subcompact ICE (because it is cheaper than the subcompact Fiat 500e), the ICE is only between 17% and 5% more expensive than the EV, compared to the range of 34% and 20% seen before in Table 7.

The initial purchase price makes up 63% of the total TCO for the EV, which is similar to the share observed for the subcompact EV but makes up a higher percentage for the compact ICE, resulting in 42% for the regular VMT case. The insurance costs make up almost the same percentage of the total TCO, but fuel and maintenance costs make up a lower portion for the EVs than the ICEs, while a bigger gain is made for the ICEs from resale. The cost breakdown for the components of the TCO for the compact vehicles is presented in Figure 13.

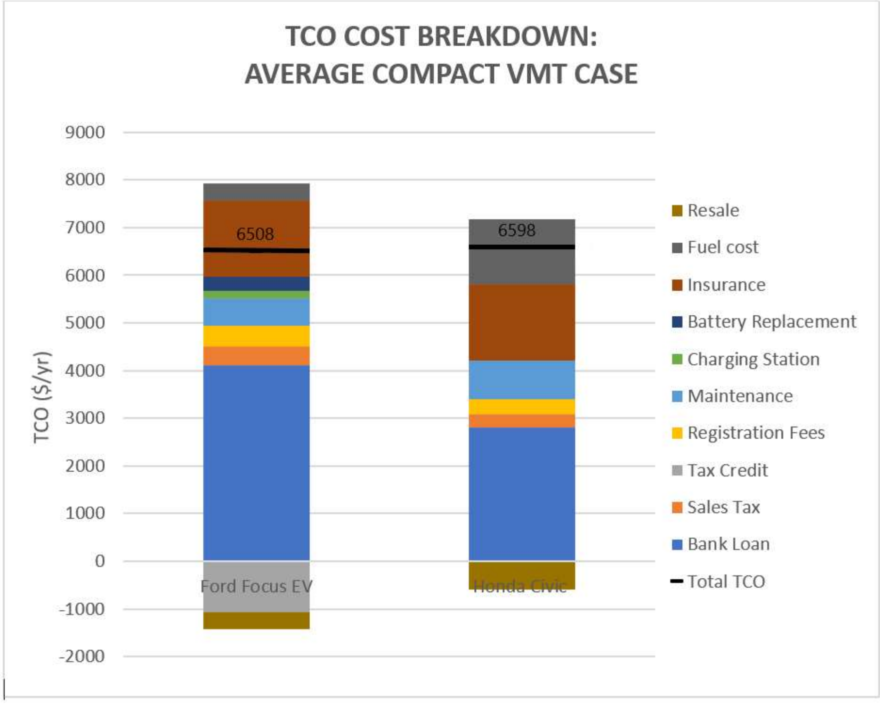


*Figure 13: TCO Cost Breakdown for the Average VMT case of Compact EV vs. ICE*

The side-by-side comparison of the three VMT cases in Figure 14 shows clearly that the choice between compact EVs and ICEs depend on the VMT driven. When comparing the cases, it is seen that the TCO costs increase less for the EV than the ICE. This is due to the important effects of fuel costs for the ICE, where the share of the fuel costs increased from 16 to 26% from the low to high VMT case, while the increase in share was only from 4 to 7% for the EV.

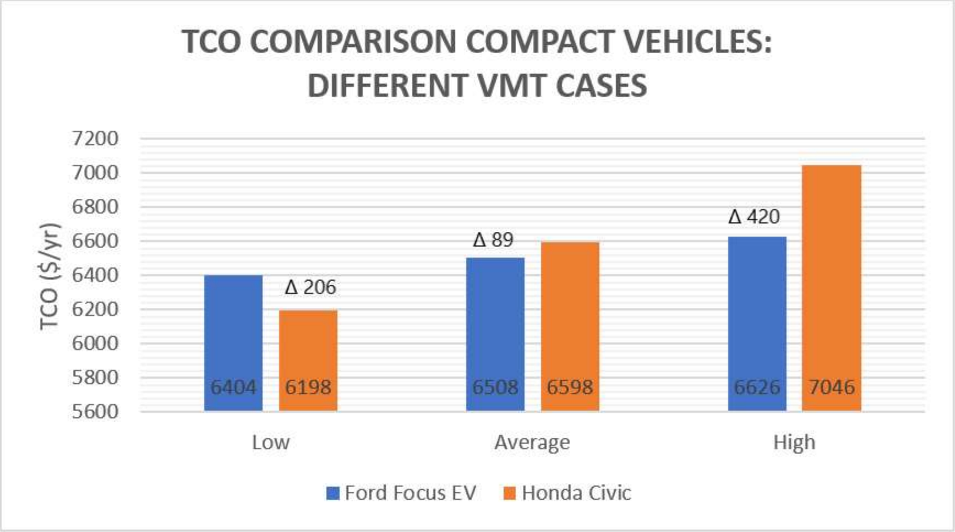


*Figure 14: TCO Comparison for Compact EV vs. ICE vehicles for 3 VMT cases*

### 3.3.3 Mid-size Vehicles

The vehicle model specific inputs for the mid-size TCO are presented in Table 10. It is interesting to point out that the purchase price for the mid-size EV is almost the same as for the compact EV, while the mid-size ICE is slightly more expensive than its compact version. The fuel economies of both fuel types are similar between the vehicle categories presented until now.

*Table 10: Inputs for TCO Analysis Mid-size EV vs. ICE Vehicle*

| Vehicle Model[1] | 2019 Nissan Leaf | 2019 Honda Accord |
|---|---:|---:|
| Fuel Type | Electric | Gas |
| Purchase Price[2] ($) | 29,990 | 23,720 |
| Total Registration Fees[3] ($) | 403 | 333 |
| Total Use / Sales Tax[3] ($) | 2,924 | 2,313 |
| Maintenance[2] ($/year) | 578.3 | 795.4 |
| Insurance[2] ($/year) | 1,500 | 1,500 |
| Fuel Economy[2] (MPGeq) | 112 | 33 |
| Battery Pack[2] (kWh) | 40 | 0 |
| Resale value after 10 years[2] ($) | 5% | 28% |

*Sources:* [1][37], [2][36], [3][33]

The results from the TCO comparison shown in Table 11 are showing that the TCO ratio is lower than 1 for all three VMT scenarios, meaning that it is more favorable to buy an EV than an ICE when it comes to mid-size cars. For the low VMT case, EVs are cheaper by 0.6% when looking at the total yearly cost over the 10-year ownership period, and 8.5% cheaper when the vehicles are compared at high mileage.

*Table 11: TCO Comparison Table Mid-size EV vs. ICE*

| | Nissan LEAF | | | Honda Accord | | |
|---|---:|---:|---:|---:|---:|---:|
| | Low VMT | Average VMT | High VMT | Low VMT | Average VMT | High VMT |
| Bank Loan ($/year) | 4,233 | 4,233 | 4,233 | 3,348 | 3,348 | 3,348 |
| Sales Tax ($/year) | 416 | 416 | 416 | 329 | 329 | 329 |
| Tax Credit ($/year) | -1,068 | -1,068 | -1,068 | 0 | 0 | 0 |
| Registration Fees ($/year) | 431 | 431 | 431 | 356 | 356 | 356 |
| Maintenance ($/year) | 619 | 619 | 619 | 851 | 851 | 851 |
| Charging Station ($/year) | 142 | 142 | 142 | 0 | 0 | 0 |
| Battery Replace ($/year) | 364 | 364 | 364 | 0 | 0 | 0 |
| Insurance ($/year) | 1,605 | 1,605 | 1,605 | 1,605 | 1,605 | 1,605 |
| Fuel cost ($/year) | 242 | 342 | 454 | 940 | 1,328 | 1,763 |
| Resale ($/year) | -118 | -118 | -118 | -519 | -519 | -519 |
| Total TCO ($/year) | 6,867 | 6,967 | 7,079 | 6,911 | 7,298 | 7,733 |
| Δ TCO ($/year) | -44 | -332 | -654 | 0 | 0 | 0 |
| TCO Ratio | 0.994 | 0.955 | 0.915 | 1 | 1 | 1 |
| Total CO2 (kg/year) | 0 | 0 | 0 | 2,160 | 3,051 | 4,050 |

The results also show that even though the TCO ratio is lower for the mid-size EVs than compact EVs, the actual TCO cost is slightly higher for mid-size than compacts. Focusing on the cost breakdown in Figure 15, the shares of the different components calculated in the TCO are starting to be similar between the EV and the ICE, with the bank loan being the lowest the EV with average driving mileage has seen over the three vehicle classes and the highest for the ICE. In the mid-size class, the annualized cost of the purchase price (without the EV tax credit) is 61% for the EV and 46% for the ICE. The insurance costs make up almost a quarter of the TCO for both types of vehicles, while the fuel costs are the third most important contributor to the ICE TCO after the bank loan and insurance costs.

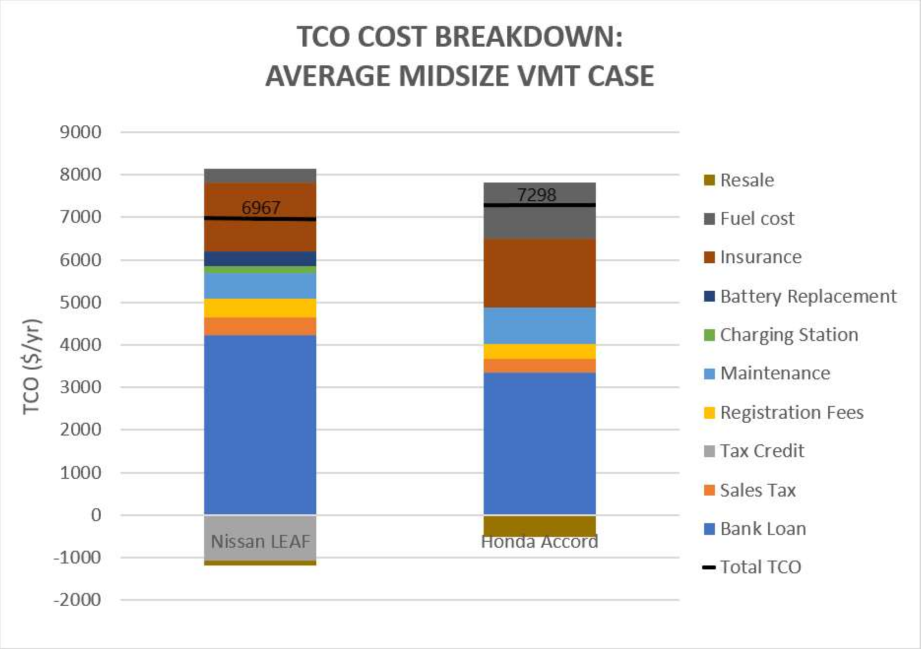


*Figure 15: TCO Cost Breakdown for the Average VMT case of Mid-size EV vs. ICE*

When examining how the yearly driven mileage affects the TCO, the comparison for mid-size vehicles in Figure 16 shows that the gap of the yearly TCO between the EV and ICE increases with increasing VMT. The increase in the gap means is due to the higher rate of fuel price increase for ICEs over EVs. It also translates into a larger saving in monetary terms for fuel. It is possible to save between 700 $/year (low VMT case) and 1,300 $/year (high VMT case) on fuel costs when getting an EV over an ICE.

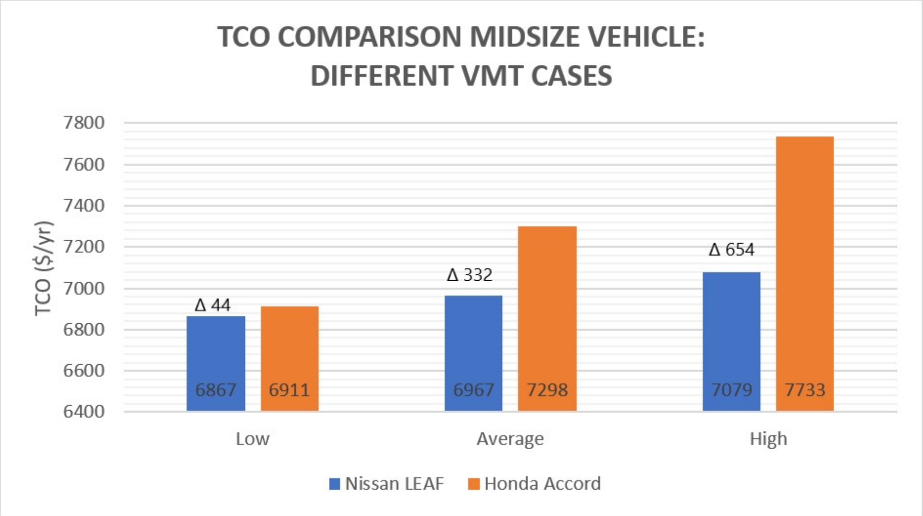


*Figure 16: TCO Comparison for Mid-size EV vs. ICE vehicles for 3 VMT cases*

### 3.3.4 Full-size Luxury Vehicles

As explained in 3.2.2 Vehicle Models, the full-size vehicle TCO comparison only shows a part of a story, but this comparability is the most optimal version to be done with the current vehicles on the market. A discussion about future potential can be read in 3.5.4 Additional EV sizes. The inputs used in the full-size vehicle EV vs. ICE comparison are presented in Table 12.

*Table 12: Inputs for TCO Analysis Full-size EV vs. ICE Vehicle*

| Vehicle Model[1] | 2019 Tesla Model X | 2019 Cadillac Escalade |
|---|---|---|
| Fuel Type | Electric | Gas |
| Purchase Price[2] ($) | 81,000 | 78,195 |
| Total Registration Fees[3] ($) | 811 | 812 |
| Total Use / Sales Tax[3] ($) | 7,898 | 7,624 |
| Maintenance[2] ($/year) | 905.0 | 1,244.8 |
| Insurance[2] ($/year) | 2,000 | 2,000 |
| Fuel Economy[2] (MPGeq) | 96 | 17 |
| Battery Pack[2] (kWh) | 75 | 0 |
| Resale value after 10 years[2] ($) | 17% | 21% |

*Sources: [1][37], [2][36], [3][33]*

The results in Table 13 show that once again, the EV has lower TCO costs than the ICE for all three VMT scenarios. The TCO Ratio is the lowest for all scenarios out of the four vehicle classes. It is 8.6% cheaper to get the Tesla Model X over the Cadillac Escalade when driving low VMT, while it becomes 11.9% and 15.2% cheaper respectively for average and high VMT. The difference in TCO is also the largest for this vehicle class, showing results of between 1,470 and 2,820 $/year savings. Even though the TCO difference and ratio are the most favourable, the actual TCO cost is more than double for the average driven full-size EV than the corresponding mid-size EV. When the EV and ICE luxury full-size vehicles are compared, the TCO shows that the EV version is cheaper. However, it is important to keep in mind that there are many non-luxury full-size ICEs on the market, while the choice of full-size EVs is currently limited to the luxury range.

*Table 13: TCO Comparison Table Full-size EV vs. ICE*

| | Tesla Model X | | | Cadillac Escalade | | |
|---|---|---|---|---|---|---|
| | Low VMT | Average VMT | High VMT | Low VMT | Average VMT | High VMT |
| Bank Loan ($/year) | 11,432 | 11,432 | 11,432 | 11,036 | 11,036 | 11,036 |
| Sales Tax ($/year) | 1,124 | 1,124 | 1,124 | 1,085 | 1,085 | 1,085 |
| Tax Credit ($/year) | -1,068 | -1,068 | -1,068 | 0 | 0 | 0 |
| Registration Fees ($/year) | 868 | 868 | 868 | 869 | 869 | 869 |
| Maintenance ($/year) | 968 | 968 | 968 | 1,332 | 1,332 | 1,332 |
| Charging Station ($/year) | 142 | 142 | 142 | 0 | 0 | 0 |
| Battery Replace ($/year) | 682 | 682 | 682 | 0 | 0 | 0 |
| Insurance ($/year) | 2,140 | 2,140 | 2,140 | 2,140 | 2,140 | 2,140 |
| Fuel cost ($/year) | 283 | 399 | 530 | 1,825 | 2,578 | 3,423 |
| Resale ($/year) | -1,036 | -1,036 | -1036 | -1,281 | -1,281 | -1,281 |
| Total TCO ($/year) | 15,537 | 15,654 | 15,784 | 17,007 | 17,760 | 18,604 |
| Δ TCO ($/year) | -1,470 | -2,106 | -2,820 | 0 | 0 | 0 |
| TCO Ratio | 0.914 | 0.881 | 0.848 | 1 | 1 | 1 |
| Total CO2 (kg/year) | 0 | 0 | 0 | 4,193 | 5,923 | 7,862 |

The breakdown for the full-size vehicles shows that the initial price is a high percentage of the TCO for both types of vehicles, coming in at 73% and 62% for EVs and ICEs respectively. For ICEs, the bank loan has been in the range of 32-46% of the TCO when looking at sub-compacts to mid-size. The high increase in percentage for full-size ICEs also suggests that there is a premium payed on the vehicle for factors that are not taken into account in this TCO, like quality of materials and brand image. The insurance remains a large chunk of the VMT, especially considering that more luxurious vehicles have higher yearly insurance rates. An interesting insight from the cost breakdown in Figure 17. is that the share of resale is almost equally big for both types of cars, while for other size classes, the resale of EVs has been significantly lower. This is due to the fact that the less expensive EVs are projected to lose value faster, while the new generation Tesla vehicles are projected to depreciate at almost the same rate as other luxury cars.

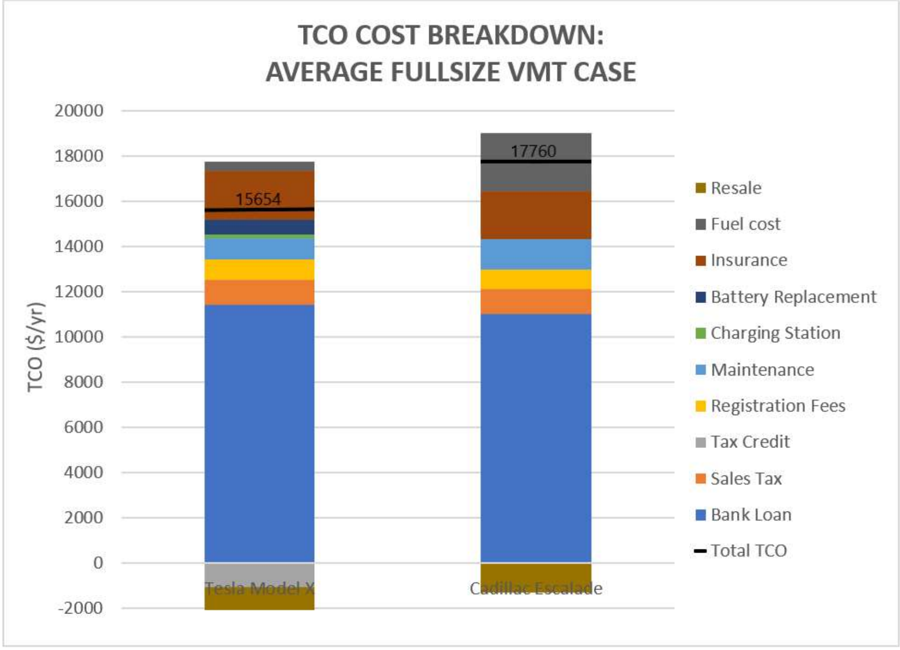


*Figure 17: TCO Cost Breakdown for the Average VMT case of Full-size EV vs. ICE*

The comparison of the different VMT cases highlights more than before the weight of the fuel cost for ICEs when driving more, since full-size vehicles have lower fuel economy. The drastic increase in TCO costs for the full-size ICE compared to the EV seen in Figure 18, shows that substantial money can be saved in fuel costs. From Table 13, a fuel cost saving of over 1,500 $/year in the low VMT case and up to almost 3,000 $/year in the high VMT case can be calculated. Because of the low fuel economy, the carbon savings now range from 4.2 to 7.9 tons of $CO_2$/year (instead of the 2.2 to 4.1 tons of $CO_2$/year seen in the three smaller vehicle classes).

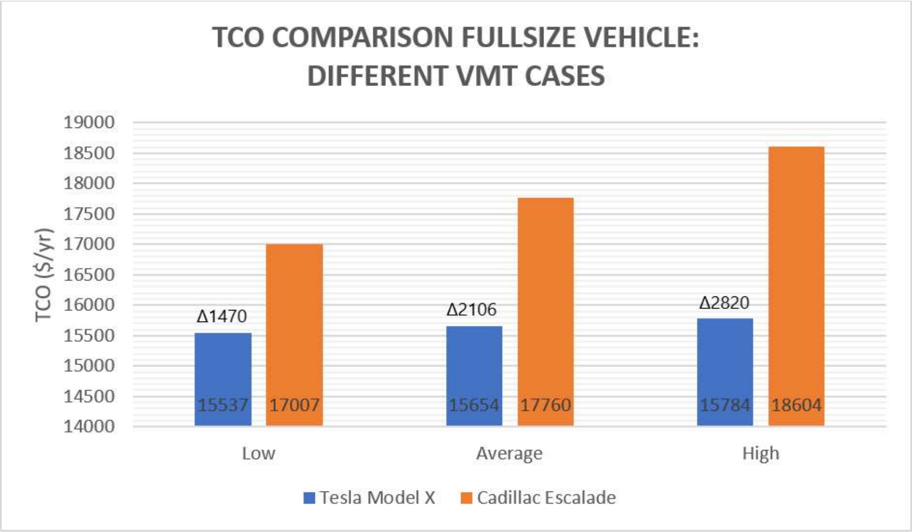


*Figure 18: TCO Comparison for Full-size EV vs. ICE vehicles for 3 VMT cases*

## 3.4 Sensitivity Analysis

As the assumptions made for the TCO analysis have an extensive impact on the results, and several values of inputs varied largely in literature, a sensitivity analysis is done to get a fairer comparison and to find which inputs have the largest effect on the total annualized cost of ownership.

The EV/ICE TCO ratio is used as a measure of comparison between the models. As previously pointed out in the results, a low ratio means that the EV is more favorable than the ICE in the particular vehicle class, but this display doesn't show the change in monetary $/year costs only the changing ratio. Setting up the analysis in this way allows for all four vehicle classes to be examined in the same way and leaves room for discussion on which cases it is cheaper to choose an EV when a buyer is looking for a specific size class.

### 3.4.1 VMT

Already the division of driving styles into three cases of low, average and high VMT gave a sensitivity analysis showing the importance of fuel costs. In the case of compact vehicles, the variation from low to average miles travelled shifted the profitability of the EV over the ICE, where in the first case the ICEs had a lower TCO and in the second it was the EV. The more miles travelled, the more the gap between the two TCOs grew and the TCO ratio diminished.

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. 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 9.35 miles during a whole year [34]. 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. For compact vehicles, the ratio flips at around 10 000 miles travelled per year, meaning that for households using the vehicle for over 10 000 miles, an EV is more favorable. This flip is seen at an even lower VMT for mid-size vehicles, where the TCO of EVs become lower than the one of ICEs at over 7,000 miles/year. The importance of VMT is further shown in the steepness of the lines representing the vehicle classes in Figure 19, where the change from 5,000 to 25,000 miles/year can alter the ratio by 17-35%.

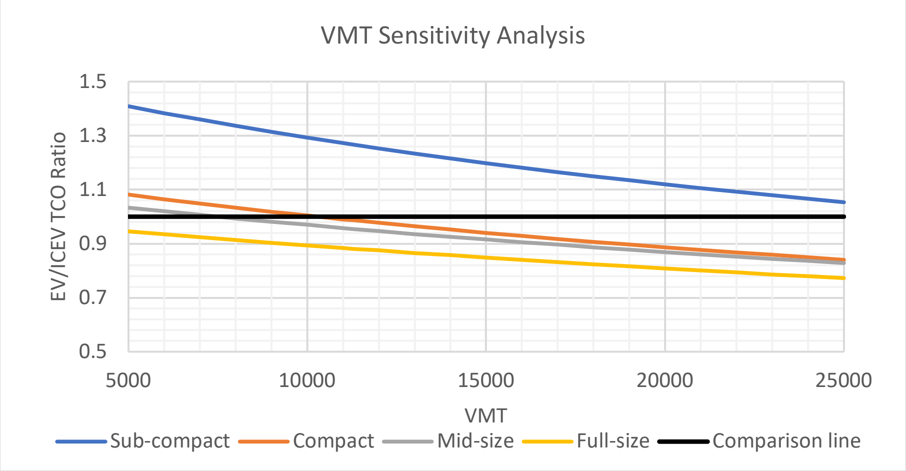


*Figure 19: VMT Sensitivity Analysis using EV/ICE TCO Ratio*

### 3.4.2 EV Rebate Program

California has an extensive rebate program aimed at ZEVs. Firstly, the federal tax credit has been a widely used incentive, introduced in 2010. All battery electric vehicles are eligible for the full $7 500 one-time federal tax credit. Since the federal EV tax credit amount is affected by the tax liability of the buyer, it doesn't always translate into $7,500 savings and could be less if the amount owed in taxes are of lesser amount [77].

However, the phasing out of the tax credit is currently underway. The first part of the phasing out happens the calendar year after an automaker sells 200,000 battery-dependent vehicles counted from 2010, including EVs and plug-in hybrids. Once the unit limit is hit, a grace period of the next two quarters with the full amount stays in place, but then the tax credit is halved for the following two quarters and again cut in half for the last two quarters before the complete phase-out [77].

Tesla already reached the 200,000-unit sales threshold in 2018, leading to the rebate dropping to $3 750 on January 1, 2019, and again halving $1,875 for units sold on or after July 1, with the altogether expiration on December 31, 2019. General Motors hit the 200,000-unit mark near the end of 2018, with the rebate being $1 850 from October 1, 2019 until its elimination on March 31, 2020. Nissan is the next automaker predicted to reach the 200,000-unit mark. Although Tesla counteracted the loss of tax credit with lowered prices, it is unclear how the price of the EV market will be affected, and the $7500 tax rebate is a very important incentive to make EVs more price competitive with ICEs.

Since the tax rebate directly affects customers and the TCO of EVs, a sensitivity analysis is done varying the rebate amount from the full $7,500 to no rebate, with the halving steps used for manufacturers. The base case assumes the total $7,500 federal tax rebate.

The sensitivity analysis in Figure 20 displays that the rebates are still needed for most vehicle classes to be competitive with ICEs (with the exception of sub-compact EVs that are more expensive than ICEs even with the rebate). The mid-size EV would respond the best to the 50% cut in the tax credit, becoming 2.8% more expensive than ICE, but it was also the category having the lowest TCO ratio with the rebate. If the tax credit was to be completely phased out with the present-day purchase price, the EVs would respectively be 45%, 15% and 10% more expensive than their ICE counterparts for in the sub-compact, compact and mid-size, and 7% less expensive for the full-size categories. Vehicle manufacturers will have to balance out this gap by making cheaper EVs that can compete TCO pricewise with ICEs to continue the trend of increasing EV sales. The TCO ration for full-sized category being under 1 doesn't mean that no tax credit is needed, it just means that the full-size luxury vehicles analyzed don't need the it. A rebate will be necessary to make full-size EVs cost competitive with non-luxury ICEs.

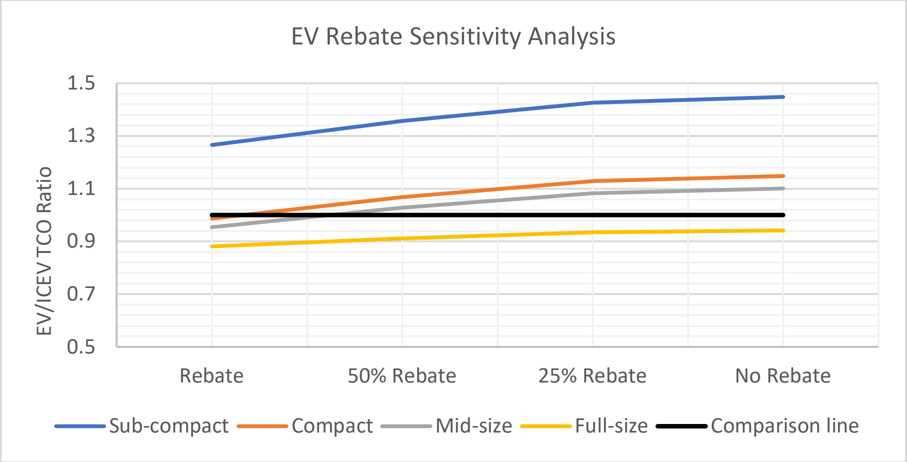


*Figure 20: EV Rebate Sensitivity Analysis using EV/ICE TCO Ratio*

### 3.4.3 Maintenance Cost

As discussed in the methodology in 3.2.3.3 Maintenance cost, there are varying numbers on the maintenance cost of EVs compared to ICEs. Due to the fewer moving parts, EV maintenance costs should be lower, but an additional cost could be the cost of labor by mechanics not used to electric motors. By the time the vehicle's warranty expires, the odds are that all mechanical garages will have become familiar with EVs and labor costs won't differ. Even though most papers concluded lower maintenance costs, and the EVs maintenance cost was assumed to be the average of 72.7% of the ICEs, the sensitivity analysis explores the EV maintenance costs from the unrealistic case of no maintenance cost to the other end of the spectrum of EV maintenance being 50% more expensive than for ICEs, presented in Figure 21.

The lower (or no) maintenance cost for sub-compacts will not make the EV/ICE ratio less than 1, and the higher maintenance cost for full-size vehicles will not make EVs more expensive than the ICE option. However, if the EV maintenance cost percentage would have been assumed to be 16% cheaper instead of 27.3%, the compact EV driven at average VMT would have become more expensive than the ICE. This would happen for mid-size vehicles if the EV maintenance cost was 12% higher than of the ICE. The maintenance cost was not the most important part of the TCO but made up 6-10% of the EV TCO. With every 10% increase of the cost compared to ICEs, results in an average increase of 1.2% of TCO in absolute change.

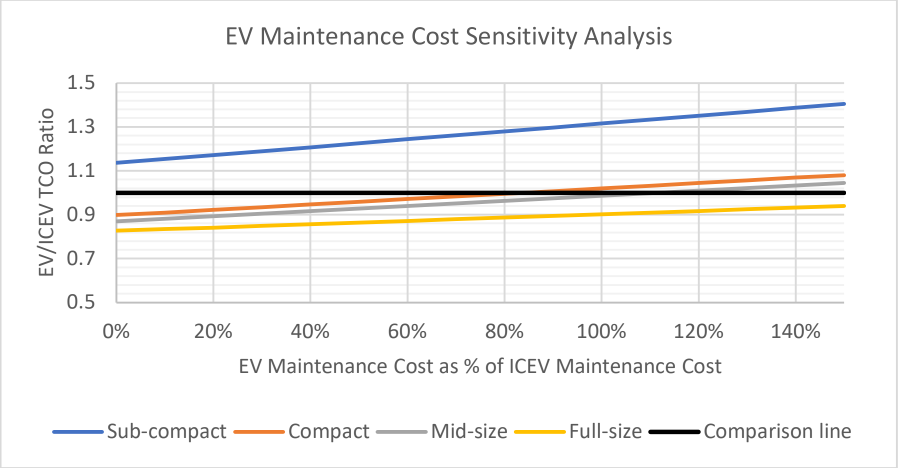


*Figure 21: EV Maintenance Cost Sensitivity Analysis using EV/ICE TCO Ratio*

### 3.4.4 Battery Costs

The sensitivity of the battery cost per kWh was done for the approximate cost in 2027, assumed between 50 and 135 $/kWh, as the range predicted in scientific papers predicts [63]. The result in Figure 22 show a flatness of the lines, meaning that the price of the battery pack doesn't have a big effect on the TCO. Using the average cost of 102.6 $/kWh, the battery pack when changed would be less than $2,500 for the sub-compact Fiat 500e, less than $3,500 for compact Ford Focus EV, $4,100 for the mid-size Nissan LEAF and $7,700 for the full-size Tesla Model X. As discussed in 3.2.3.4 Battery Costs, it is not likely that a replacement of the batteries will be needed, or will be payed by the customer due to the battery warranty. In addition, the rise of businesses focusing on second life use of EV batteries could lower the cost even more since the old battery could be sold instead of being discarded.

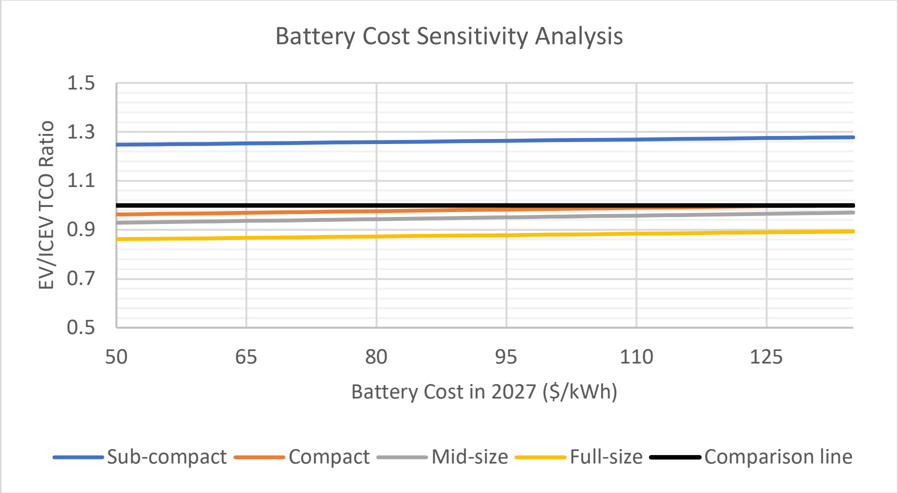


*Figure 22: Battery Cost Sensitivity Analysis using EV/ICE TCO Ratio*

### 3.4.5 Fuel Price Change

A common argument for EVs is connected to the price volatility of gasoline. In addition to seasonal changes in demand affecting prices, gasoline prices can change rapidly if there is a disruption in crude oil supplies, refinery operations, or gasoline pipeline deliveries [78]. Even though the disruptions can influence the household economies, the average yearly increase of gasoline for long-term projections are of the range of -1.1% to +1.5% per year.

Similarly, the electricity price increase is projected in the range of 0.1-0.7% per year, even though some electric utilities are offering lower electricity prices for households with EVs and the charging happening in off-peak hours can also result in lower prices.

Therefore, for both gasoline and electricity the annual fuel price increase is varied between -3% to +5% per year, presented in Figure 23 and Figure 24. The slopes of the TCO ratios are slightly higher when varying the gasoline price rather than the electricity price. In either case, the analysis concludes that the fuel prices, within the sensible range of -3% to 5% yearly increase, don't have a large effect on the TCO ratio. Even in the worst case scenario of the gasoline price decreasing at 3% per year for 10 years and the electricity price increasing at a 5% rate, the TCO ratio for sub-compacts goes from 1.266 to 1.319, for compacts from 0.986 to 1.025, for mid-size from 0.955 to 0.988, and for full-size from 0.881 to 0.903.

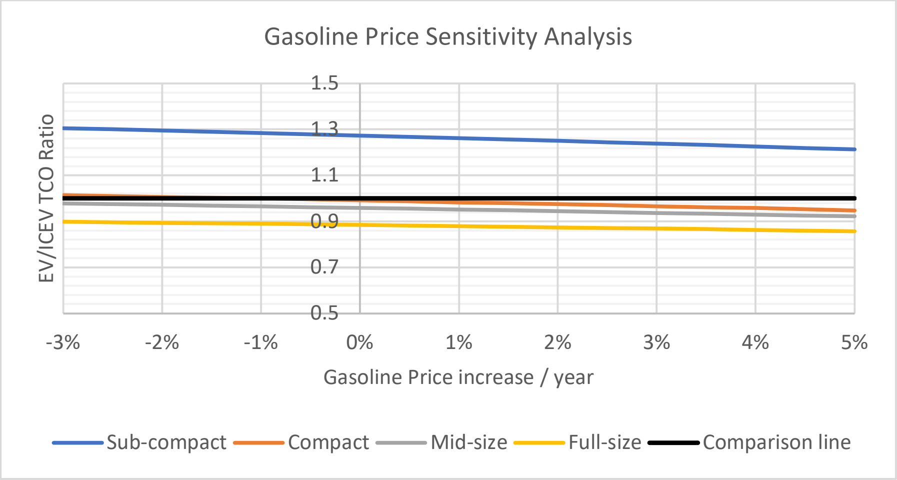


*Figure 23: Gasoline Price Sensitivity Analysis using EV/ICE TCO Ratio*

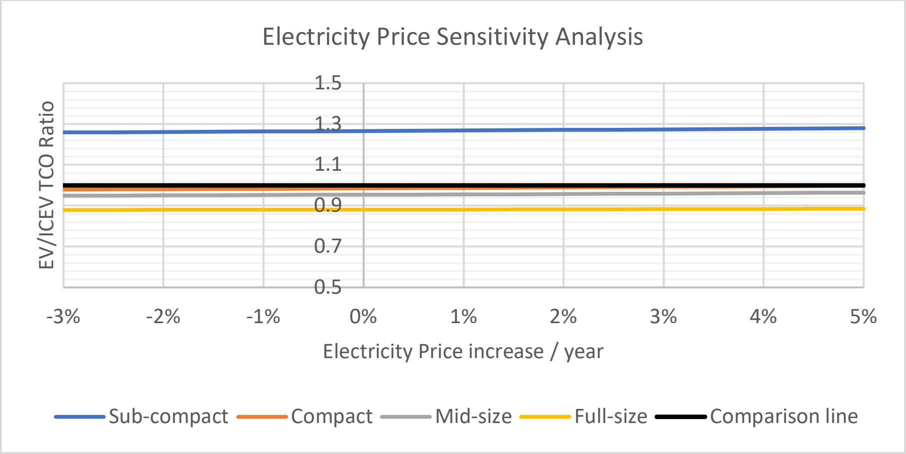


*Figure 24: Electricity Price Sensitivity Analysis using EV/ICE TCO Ratio*

## 3.5 Discussion

### 3.5.1 TCO relevance

There are several reasons why the TCO comparison of new vehicles are of high relevance currently.

Firstly, the phasing out of the one-time federal tax credit of $7,500 established in 2010 is undergoing. As the sensitivity analysis concluded, the $7,500 tax rebate is a very important incentive to make EVs more price competitive with ICEs and the phasing out of the rebate increases the EV/ICE TCO ratio. Households should aim to make the fuel switching of their vehicles in the close future, or they can miss out on the benefits and get an EV that is more expensive when looking at the total annual costs over the 10-year ownership period.

Secondly, looking at the age distribution of the vehicle fleet in Albany, but also on a national level, the average age of a vehicle is very high. Over 35% of the vehicle fleet is pre 2006 model (older than 13 years). From the DMV data for Alameda county, assuming 14 years of age for all pre 2006 vehicles (when in reality they can be much older), the average age of the vehicle fleet is 9.3 years, which is slightly lower than the national average of 10.1 years for automobiles in 2017 [79]. The lifespan of a car is 13-17 years. Many cars are reaching their end of life; therefore, policies are needed to ensure the new vehicles bought are electric, as well as showcasing new information on the TCOs to educate the purchasing households. There's also an important intervention opportunity – if residents don't know about EVs they may purchase an ICE which locks in 13-17 years of fuel GHGs.

In addition, EVs are a suitable option when examining the vehicle miles travelled (VMT) for Albany. In addition to the average daily VMT of 31 miles/day (50 km/day), the 2017 NHTS concludes that the mean trip length is 9.35 miles (15 km) in the state of California. As battery technologies advance, the range of EVs keep on improving. Currently, the average EV range exceeds 200 miles (320 km) in a single full charge, which is a high average due to Tesla's inputs, but even the smallest new cars with the shortest range exceed 90 miles (145 km) [80]. The average range for the vehicles used in this analysis is 150 miles. Therefore, EVs are suitable for most trips for an average household. This is also backed by Census data, showing that 63.8% work within the county and 35.7% work outside of the county, still adding up to 99.5% of Albany residents working within the state. It is only for 11% that the trip to work takes one hour or more, while over 50% of workers have a travel time of less than 30 minutes [32]. Especially with a growing number of charging infrastructure provided at workplaces, EVs are a safe option regarding range for travels to work and everyday errands. For the small fraction of households that the range wouldn't suffice, the ranges on EVs available in the U.S. are expected to average at 275 miles (440 km) by 2020 and could reach 400 miles (640 km) by 2028 [81], but even currently the 2019 Tesla Model S Long Range goes 375 miles (600 km) in the world harmonized light-duty vehicles test procedure, meaning that range will be less and less the issue for not buying EVs.

Lastly, the city of Berkeley's Environmental Commission is currently discussing banning the use of combustion vehicles and the sale of gasoline by 2045, a measure also discussed by the city council of Albany. Local policies of progressive cities are going in the direction of banning fossil fuels, and it is therefore a prime time to be one step forward and not be affected by bans.

### 3.5.2 Additional costs

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, like for instance the popular destinations of Los Angeles or Las Vegas from the Bay Area that can be done by both travel modes.

An additional cost not accounted for in the TCO analysis is the social cost of carbon emissions (SCC). The social cost of carbon is the monetary measure of the economic harm of the externalities and damages of the carbon emissions. The use of social cost of carbon was affirmed by the U.S. Court of Appeals for the Seventh Circuit to be included in the DOE's analysis, considering all current and future impacts of climate change to both the U.S. and countries outside of its borders [82]. This mirrors the importance and acceptance of the social cost of carbon that is higher than the carbon pricing set by the carbon tax. Although many experts argue that this figure is too low, the current central estimate of the social cost of carbon for the U.S. is around $50 per ton [83,84]. A literature review by Ricke *et al.*, (2018) concluded that the range for SCC estimations range from 10-1000 $ per tCO2, with a mean SCC of approximately US$150–200 per tCO2. The carbon savings of 2.1-7.9 tCO2 per year depending on distance driven and vehicle size, translates into an additional cost of 100-400 $/year for ICEs when taking 50 $/tCO2, but could go up to 1,600 $/year when taking the mean SCC of 200 $/tCO2. This would be enough to swing the TCO ratios even for the subcompact category.

### 3.5.3 Additional Benefits

EVs are a significant type of distributed energy resource that can be a crucial part of the future energy system. The switch to EVs on a larger scale can provide flexibilities to grid operators by improving frequency regulations, improving resiliency and cost mitigation [85]. EVs can participate in the vehicle-to-grid (V2G) technology, participating in the bidirectional power flow between the grid and the EV, acting as energy storage at times. The benefits of V2G could be seen as a subset of benefits attributed to EVs. The technical benefits include storage superiority and grid efficiency at a low cost, high power capacity and quick reaction times [86]. EVs could act as back-up power supply, which is important especially in California where power outages can occur due to wildfires and earthquakes. For EV owners, the potential integration into the grid could mean a revenue stream, lowering the TCO additionally. Finally, the important social benefits include the improvement in air quality and health benefits linked to it, as well as the environmental benefits.

### 3.5.4 Additional EV sizes

Most EVs are in the DOE's definition of compact and mid-size sedan class, a vehicle market that has been on the decline while SUVs have increased. Even from older 2001 data seen in Figure 8, the SUV market made up 17.8%, however, 2018 numbers show the rise of SUVs being 48% of all new vehicle sales in the U.S. [87]. SUVs are on the rise, and following Tesla's success, many manufacturers are in the process of making EVs to take on the

Model X [88]. Known luxury brands Jaguar, Audi, Mercedes-Benz and BMW, as well as more affordable brands such as Volvo, Volkswagen, Nissan, Subaru, Ford and Kia, have all planned electric SUVs or crossovers for 2020. The more models available will be able to fill the gap in the market for full-size vehicles to compete with ICEs. The increase in popularity of SUVs as well as electric vehicles make electric SUVs primed for success and drive up sales of BEVs [89]. For this reason, a TCO comparison for full-size vehicles or SUVs will be interesting to conduct in a year.

In addition to the rise of EV SUVs in the near future, as battery technologies are improving enough to have the power of towing, electric pickup trucks are also anticipated to hit the market in 2021, with the Tesla Truck, Rivian R1T, Atlis XT, Fisker pickup, and the electric Ford F-150 taking the charge [90]. China is already seeing affordable electric pickup trucks with Nissan partnering with Dongfeng with the Dongfeng Rich 6 EV hitting the market in 2019 [91].

### 3.5.5 Additional ZEVs

Even though other types of ZEVs than EVs were outside of the scope of this work, it is interesting to mention the emergence of other options that could be options for residents to achieve Net Zero Carbon. Fuel-cell vehicles have qualities that match ICEs, such as driving range and quick refueling, which are the main issues faced with EVs [29]. However, due to FCEVs and their charging stations being at early stage development, there are not many FCEVs in use. The high price is an issue for current adoption. Wei, Smith and Sohn, (2017) found that a learning rate of 18% for the Japanese fuel cell deployment program and a near-zero learning rate in the California market. Taking the 18% learning rate, FCEVs are estimated to be cost competitive with ICEs by 2025, but could take 25 years longer with an 8% learning rate instead [93]. As the Net Zero Carbon goals are for 2045 or 2050 in many places, FCEVs could become an important player with EVs to decarbonize the transport sector.

### 3.5.6 Charging infrastructure

This analysis focuses on single family households where the level 1 or level 2 charging stations can easily be set up on own property but setting up a charging station can be problematic for multi-family homes. There are several programs in place to help the transition to EVs, like the PG&E EV Charge Network program aiming at installing 7,500 EV chargers at multi-family houses and workplaces, covering the cost of make-ready and installation [94].

# 4.Households

## 4.1 Introduction

Building GHG emissions are the second biggest emitting source, responsible for 25% of California's emissions, with over 50% coming from fossil fuels in furnaces and water heaters. Natural gas is the fuel used in 90% of homes in the state for space heating, water heating or both [95]. Similar shares can be seen in Albany, where emissions from residential electricity and natural gas use in Albany accounted for one fourth of total emissions before switching to carbon-free electricity. The estimated share of residential contribution after the switch is still 23%, accounting for 11,668 tCO2 in 2016 and approximately 12,762 tCO2 in 2018 [96].

The emission estimations are based on natural gas usage in homes, but in reality, the emissions can be way higher. A recent report examining urban emissions on the East Coast of the U.S. found that emissions can be twice as high as EPA inventories when including end-use emissions and estimates on leaking [97]. This can be attributed to fugitive natural gas losses which have large effects on emission numbers since the potent GHG methane is the main component of natural gas, especially in old and leak-prone cities [97].

As the electricity gets cleaner state-wide until reaching carbon-free by 2045, the share of building emissions due to natural gas usage will keep on growing, with space heating and water heating taking the blame [95]. Efforts need to be made to focus the previous mindset of net-zero energy to zero-emission buildings. Electrification of end uses such as space heaters, water heaters and appliances using efficient technologies is a key strategy in order to achieve net zero carbon in the sector [98–100].

In July 2019, the City of Berkeley adopted an ordinance that prohibits natural gas hook-ups in all new construction. It was the first city in the U.S. to adopt an ordinance of its kind [101]. Additional cities in California are considering adoption of such reach codes and municipal code amendments as well, with the cities of Windsor, San Mateo, Davis, and San Jose already passing similar measures. The city of Albany is in the process of adopting the same ordinance put in place simultaneously to the new 2020 California Building Standards Code, which becomes effective January 1, 2020.

The natural gas ban in new construction is a huge step towards electrification, however, it is the existing building stock that is responsible for most emissions, both because of the volume of existing stock compared to planned construction projects, as well as the inefficient equipment. The ban might expand to existing buildings as well in the future, but retrofits can mean large costs for the households, while in new construction, an all-electric design eliminates costs associated with installation of natural gas infrastructure. For these reasons, this research aims to get an estimate for total cost of ownership when existing houses are electrified to become net zero carbon.

## 4.2 Methodology

### 4.2.1 Single-Family Households

To map out the building stock, the main source of data was tax assessor data for the region purchased from Digital Map Products, Census data and the Albany 2035 general plan made by the city's planning division. The tax assessor data included information on ownership, property identification, characteristics, values and legal description. The most important data used were construction and use codes, building year, building area, number of stories, number of bedrooms, number of bathrooms, number of units on parcel, ownership status and ownership occupation. Often times, the data was incomplete, especially for apartments, condominiums, multi-family houses and townhouses. For single-family houses, the data was mostly complete and was deemed reliable to use.

From the Albany 2035 general plan, it is known that Albany 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 condominium [23]. Comparing to the tax assessor data, giving 3,751 single family households, 699 townhomes and 2-4-unit structures, and 2,076 multi-family homes, condominiums and 5+ unit apartments, we can conclude that the numbers match up approximately, totaling at 6,526 households. Another 973 units of multi-family housing exist within the so-called University Village housing units, which is classified as a "public" land use despite its residential character [23]. This results in approximately 7,500 households in Albany.

Looking at the building stock, most buildings are single-family houses, as seen in the official zoning map in Figure 25, where they are depicted as a light-yellow area. According to tax assessor data, out of the residential zoning designations, 87.3% of the buildings are single-family houses. However, when looking at households and accounting for the University Village, half of all households are single-family households.

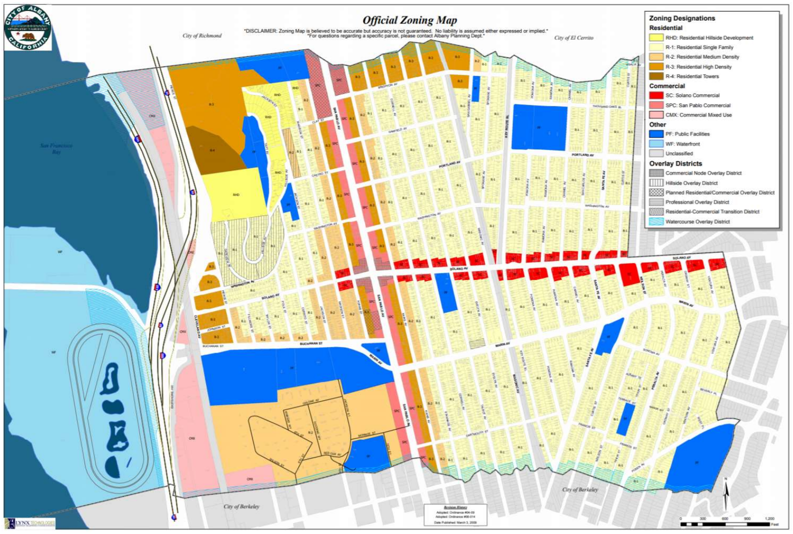


*Figure 25: Official Zoning Map of Albany*

There are several reasons why the choice of focusing on single-family households has been made. Firstly, because Albany is mostly made up of single-family houses, therefore it would have high significance for the city from the view of building stock that needs to be decarbonized. Secondly, as half of all households live in single-family houses, this work could provide cost estimates for around 9,400 people (assuming 2.5 people per household in line with Census data). Thirdly, single-family houses are 79.3% owner-occupied, meaning that there is incentive for owners to change out inefficient natural gas heating equipment and appliances to electric ones if they have a lower TCO. Multi-family houses are renter-occupied in a larger share, since overall Albany houses are 48.3% owner-occupied and rented by 51.3% [23]. Housing is already a big cost for most households, since according to the Census, almost one third of the City's homeowners and almost 48 percent of its renters spend over 35 percent of their incomes on housing. It is harder to achieve change when the property is rented out, since the high upfront costs of investments are on the homeowner, while the benefits of lower energy bills usually fall on the renters. Therefore, single-family houses are targeted in this analysis.

### 4.2.2 Home Energy Saver Tool

The Home Energy Saver (HES) tool is based on models and data developed at the U.S. Department of Energy's Lawrence Berkeley National Laboratory, including all end-uses such as heating, cooling, water heating, major appliances, small appliances, and lighting [102]. The HES tool calculates the energy consumption of a modelled house. The tool uses the Residential Energy Consumption Survey (RECS), basing space heating consumption and water heating consumption on the RECS variables of fuel specific heating energy. RECS variables combined with Census division data were used for electrical consumption for appliances.

RECS data collection is administered by the EIA to collect energy characteristics on housing units, usage patterns, and household demographics, made on a nationally representative sample of housing units. The survey results are combined with data from energy suppliers to estimate energy costs and usage for heating, cooling, appliances and other end-uses [103]. The newest RECS includes energy usage estimates for 20 new end-uses, such as electric and natural gas cooking and clothes dryers [104].

The HES calculates heating and cooling consumption using the building simulation program DOE-2 (version 2.1E), developed by the U.S. Department of Energy. THE DOE-2 does annual simulations on a house for a typical weather year, using air temperatures, relative humidity and solar radiation, broken down as 8,760 hourly calculation. The calculations use detailed information on dimensions, materials, construction of the foundation, walls, doors, windows, ceiling and roof, all through which heat flows. It takes into account the number of occupants and their schedules, appliances, lighting and other equipment that generate heat inside. In addition, it uses information on heating and cooling equipment, such as sizes, efficiencies and schedules. In three steps, the DOE-2 determines the heating and cooling requirements based on weather data, calculates the energy used for heating and cooling systems operation and how well the systems satisfy the conditions of comfort given, and lastly, calculates the energy need of central heating and cooling if there is any [102].

The energy use for water heating is calculated with a different model developed at Lawrence Berkeley National Laboratory. It first estimates the average daily hot water use based on the local climate, the number of occupants and their ages, water temperature settings and tank size, and the presence of appliances such as dishwasher and clothes dryer. Once the hot water use is estimated, the energy use by the water heater is calculated using energy consumption characteristics determined by the DOE Energy Factor test, displayed as a yearly fuel consumption [102].

The HES tool is used to first get an estimation of the baseline typical household's energy use per end-use, using typical values for all inputs needed in the model. The outputs give the energy use per fuel type for space heating, cooling, water heating, large appliances, small appliances and lighting, although this analysis focuses on the first four end-uses in order to decarbonize a household. The upgrade function of the tool is not used, which aims to show efficiency upgrades to the baseline house, instead, a new run is done to model how the energy consumption of the upgraded house would look like. For each category of space heating, water heating and large appliances, the upgrade, consisting of higher efficiency natural gas equipment or electric equipment, is done one by one and combined.

In the following chapters, the methodology behind how the typical households were created and why the inputs used for the modelling were chosen are explained in 4.2.3 Typical Households, and the inputs used for the new equipment that TCOs were done on are explained in 4.2.4 Total Cost of Ownership.

Some correction factors were introduced to the HES tool to make the outputs better resemble real energy bills in Albany. These correction factors are explained in Annex 2: Correction Factor for HES.

### 4.2.3 Typical Households

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 are 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. The typical household creation is an important step to assure the relevance of the TCO for the citizens.

#### 4.2.3.1 Occupants

Census data for Albany suggests that there are on average 2.46 people per household. For this reason, two occupants between the ages 14-64 and one child between the ages 6-13 were modelled. One adult is present at home on the weekdays.

#### 4.2.3.2 Building Year

Using the tax assessor data on single-family houses, it is seen that most houses were built between 1920-1940 when looking at the distribution curve of the houses for age (see Figure 26). 68% of all single-family houses were built between 1920 and 1940, with the average house building year being 1932. It is only 4% of houses that were built post 1960. As the age distribution shows a high concentration for a specific year range, the average building year of 1932 is used to model all typical single-family houses in Albany.

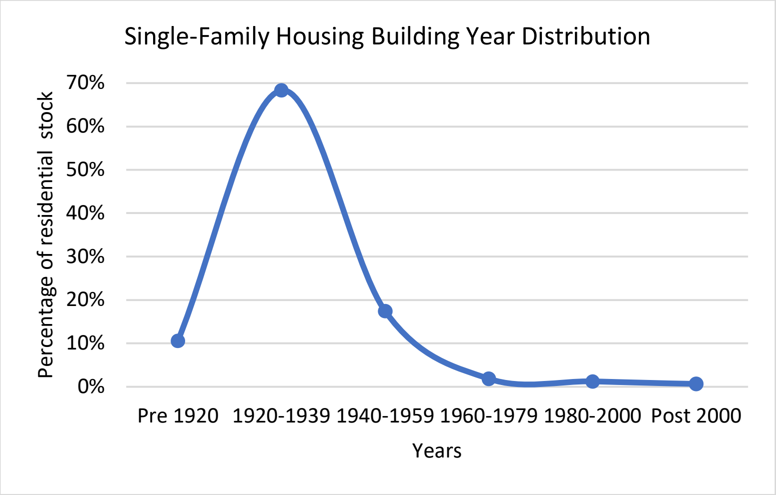


*Figure 26: Single-Family House Building Year Distribution*

### 4.2.3.3 Building Size

Looking at the size distribution of single-family houses, most houses are between 800 and 1600 square feet (sqft) (see Figure 27). The average house area is 1390 sqft. Since the distribution has a wide range, three different cases were chosen for area: low, average and high. These three sizes are to embody the whole range of areas, as presented in Table 14. One specific area size representing each range was used to model the house in the HES tool. The low case represents 30.3% of homes, the average case represents 47.4% and the high case represents 22.3% of homes. Understanding the share of homes each case embodies will also determine the total carbon savings on a city-level.

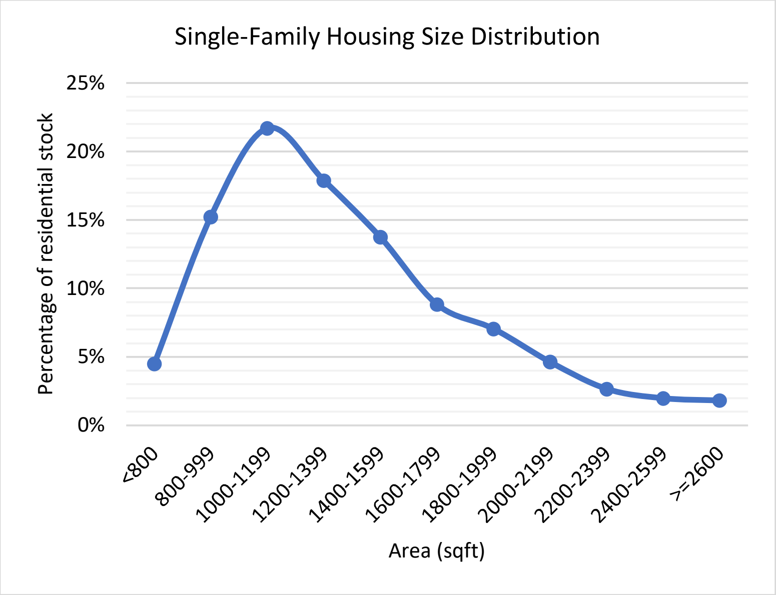


*Figure 27: Single-Family Housing Size Distribution*

*Table 14: 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% |

#### 4.2.3.4 Building Design

The building design, such as building geometry, level of insulation, air tightness, duct sealing and type of foundation, attic, roof, walls and windows, all affect the energy use in a building. From the tax assessor data, there is on average one story above ground for single-family homes in Albany. It is known from the summary of Home Energy Scores on over 100 homes in the Bay Area that 87% of houses have an attic insulation below the recommended R-30 level, and 27% of homes have no attic insulation at all. Even fewer homes have any insulation when it comes to walls and floors, with 67% of homes having no wall insulation and 80% having no floor insulation [105]. Therefore, all insulation levels for the typical houses are set to R-0, meaning no insulation present.

Using the results from the energy audit performed on 15 Albany homes, the most common type of foundation is vented crawlspace, and most attics are unconditioned. The ducts can be found in the vented crawlspace and are insulated, while the boiler pipes are not. In addition, most houses do not have weather-stripping and/or caulking to prevent air leakage. The roof has a wooden frame with an exterior covering of composite shingles and a medium colour. The walls have a wooden frame with a stucco finish. No Albany-specific data was available on doors, and therefore the pre-set values from the RECS data used by HES were modelled.

#### 4.2.3.5 Windows

The windows are chosen as the average from the Albany audit data. The average U-factor value used for modelling is 0.44 and the average solar heat gain coefficient (SHGC) is 0.56. U-factor values generally range from 0.25 to 1.25, with a lower U-factor signifying a better the window insulation. The SHGC is a measure of how well the window blocks heat caused by sunlight, typically from 0.25 to 0.80, with a lower value meaning less solar heat transmitted by the window [106]. From the homes with available data, the area of the windows was on average 23% of the house area. Therefore, this allotment is used for the three different home sizes, increasing the area of the windows with every increasing home area. It is assumed that the windows are equally divided on the four sides of the house, even if the house modelled is not perfectly square, but rectangular.

#### 4.2.3.6 Water Heating

Water heater are old and inefficient with default energy factor (EF) for storage tank heaters being 0.55, and tankless heaters being 0.8 in the Bay Area [105]. The most typical water heater type is storage tank water heater using natural gas. The water tank stores the hot water for space heating or domestic use up to several days depending on the insulation. The EF of 0.55 is used for modelling.

#### 4.2.3.7 Space Heating

As seen from audit data, most homes in Albany use central furnace heating using natural gas as fuel for burning. This is also in line with RECS data for the region. A central heating furnace distributes heat throughout the home using a duct system. 43% of heating systems in the Bay Area are beyond their 15-year expected life, meaning that most heating systems are outdated and inefficient and will be changed out soon [105]. The heating efficiency used for the average single-family household using central heating is 0.9.

#### 4.2.3.8 Space Cooling

Currently due to the climate zone of Albany, most homes don't have any kind of cooling equipment installed. Albany and the Bay Area are in climate zone 3, a zone where coastal influences result in year-round moderate temperatures with precipitation in the winter and fog likely from June through mid-August. Winters are moderately cold but with plenty of sunshine. Summers are warm and dry, but the nights are cool. There is a dominant need for heating and not cooling, but the climate is mild enough that energy consumption is relatively low [107]. No cooling is modelled for the typical single-family houses.

#### 4.2.3.9 Large Appliances

The inputs into the HES model are restrictive since not many parameters can be changed and it isn't possible to input custom efficiencies. The energy audits performed specifically on Albany, nor the audits performed on 100 houses in the Bay Area, don't give any information on the large appliances available in the homes. Therefore, the typical values are taken from RECS data for the region automatically integrated into the HES. The tool gives room to choose the fuel type for the large appliances. The baseline house modelled has one large-sized fridge with a top freezer from 2009. The stove and oven use natural gas, as it is the most common fuel for cooking in the area, respectively used for 1 hour per day and 2 hours per week. The home is also assumed to have a dishwasher used for 3 loads per week. It is assumed that the dishwasher isn't Energy STAR certified, meaning that it is not an efficient model. The average household modelled has a regular washing machine that is used on a weekly basis for 2 loads at a warm temperature and 3 loads at a cold temperature. The household has a natural gas fuelled clothes dryer that is used to dry the weekly 5 loads of clothes. No pools, spas, hot tubs, well pumps or sewage pumps are included for the modelling.

#### 4.2.3.10 Other

For other inputs, such as lighting and small appliances including entertainment, home office, miscellaneous kitchen appliances, and other small electric and gas appliances, no changes in the HES inputs are made, meaning that the model takes the RECS data averages for the area. They are assumed the same for the low, average and high area size single-family household.

#### 4.2.3.11 HES Input Summary for Typical Households

Table 15 summarizes the important inputs into the HES tool of which the methodology of acquisition were described in previous sub-chapters that make each case (low, average and high house area) of typical single-family households in Albany.

*Table 15: HES tool Input Summary of 3 cases of typical Single-Family Households in Albany*

| | Low Case | Average Case | High Case |
|---|---|---|---|
| Building Characteristics | | | |
| Zip Code | 94706 | 94706 | 94706 |
| Year Built | 1932 | 1932 | 1932 |
| Floor Area (sqft) | 900 | 1350 | 1800 |
| Shape | Rectangle | Rectangle | Rectangle |
| Orientation | North | North | North |
| Number of floors above ground | 1 | 1 | 1 |
| Floor to Ceiling Height (feet) | 8 | 8 | 8 |
| Building Design | | | |
| Air Sealing | No | No | No |
| Foundation Insulation | No | No | No |
| Foundation Type | Vented Crawlspace | Vented Crawlspace | Vented Crawlspace |
| Roof Insulation Level | R-0 | R-0 | R-0 |
| Roof Type | Unconditioned Attic | Unconditioned Attic | Unconditioned Attic |
| Roof Construction Type | Wood Frame | Wood Frame | Wood Frame |
| Roof Exterior Covering | Composition Shingles | Composition Shingles | Composition Shingles |
| Roof Color | Medium | Medium | Medium |
| Wall Insulation Level | R-0 | R-0 | R-0 |
| Wall Construction Type | Wood Frame | Wood Frame | Wood Frame |
| Wall Exterior Covering | Stucco Finish | Stucco Finish | Stucco Finish |
| Ceiling Insulation | R-0 | R-0 | R-0 |
| Duct Insulation | Yes | Yes | Yes |
| Duct Sealing | Yes | Yes | Yes |
| Duct Location | Vented Crawlspace | Vented Crawlspace | Vented Crawlspace |
| Windows | | | |
| Window Area (sqft/window) | 51.8 | 77.6 | 103.5 |
| Window U-value | 0.44 | 0.44 | 0.44 |
| Window SHGC | 0.56 | 0.56 | 0.56 |
| Water Heating | | | |
| Water Heater Type | Storage | Storage | Storage |
| Water Heater Fuel | Natural Gas | Natural Gas | Natural Gas |
| Water Heater EF | 0.55 | 0.55 | 0.55 |
| Space Heating & Cooling | | | |
| Heating Type | Central Furnace | Central Furnace | Central Furnace |
| Heating Fuel | Natural Gas | Natural Gas | Natural Gas |
| Heating Efficiency | 0.9 | 0.9 | 0.9 |
| Cooling Type | None | None | None |
| Large Appliances | | | |
| Stove Fuel | Natural Gas | Natural Gas | Natural Gas |
| Oven Fuel | Natural Gas | Natural Gas | Natural Gas |
| Clothes Dryer Fuel | Natural Gas | Natural Gas | Natural Gas |

### 4.2.4 Total Cost of Ownership

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 fuelled large appliances, the purchase cost, installation cost and maintenance cost are needed, as well as the energy usage for calculating fuel costs.

#### 4.2.4.1 Annualized costs

As different types of heating, cooling and large appliances have different lifetimes, it is not a fair comparison to simply compare the total cost of ownership, since those numbers don't reflect the different use times. Therefore, an annualized TCO is used, by applying Excel's payment (PMT) function on the net present value (NPV) function, accounting for a 7% discount rate. The results are presented as $/year and can be compared fairly.

#### 4.2.4.2 Fuel Costs

##### Energy Usage

The energy usage was obtained by using the HES tool to model the same single-family household, but with upgraded heaters and appliances. Since the fuel costs can largely vary between households depending on the number of people at home and how the energy is used, three cases of energy usage are presented: low, average and high energy usage.

The average energy usage is the one obtained from the HES tool for the typical household cases with the new heating equipment and large appliances, may they be natural gas or electricity fueled. The low case is 50% lower than the average case, and the high is 30% higher than the average case.

The HES tool is currently not built in a way to be able to model electric heat pumps for water heaters. Instead, the fuel type is set as electricity, and the EF is set at 1, which is the highest number the input accepts. The electricity usage output for water heating is divided by the EF of the heat pump (2.0 or 3.55). However, the tool can model heat pumps for space heating and accepts higher EFs for that.

It is assumed that the energy usage remains the same every year and doesn't change because of changing weather conditions or behavioral patterns after the first year in the TCO.

##### Fuel Price

The electricity price used is the July 2019 average for residential usage in the state of California at 19.96 cents/kWh [65]. The price of natural gas is also from the latest EIA data from July 2019 for residential use in California at 13.82 $/thousand Cubic Feet natural gas, which is approximately the same as 1.38 $/therms [108]. The annual increase for electricity price is assumed to be 0.6% per year, as it is the mid projection for the long-term electricity increase projected by the EIA [66]. Looking at the EIA's energy outlook reference case for the modelled natural gas prices between 2019 and 2040 for the Pacific U.S. region, the annual natural gas increase is 0.9% per year [109]. Since the longest lifetime of an appliance used in the TCO is 20 years, the natural gas trends of the next 20 years are used.

### 4.2.4.3 Initial and Maintenance costs

The initial costs that are made up of the purchase price and installation, as well as yearly maintenance costs were obtained from the latest EIA Technology Forecast updates using 2017 data [110]. The main cost and efficiency source was the Residential and Commercial Building Technologies Technology Forecast Update, which was crossed-checked on HomeWyse and with local architects in Berkeley and Albany to make sure that the cost estimates were in line with local averages and give a relevant TCO for the area. The efficiencies corresponding to the ENERGY STAR equipment of 2017 and higher efficiency equipment were used as inputs to the HES model, and the prices corresponding to these were used for the TCO.

## 4.3 Results

### 4.3.1 Water Heating

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). Two different energy factors are presented for each water heater type for the TCO.

Table 16 presents the hot water specific inputs to the HES tool. As previously explained in 4.2.4.2 Fuel Costs, the input to the HES tool for the HPWH requires setting the energy factor to 1, and dividing the output with the EFs desired.

*Table 16: Water Heater Relevant Inputs into the HES tool*

| | HPWH | NGWH | INGWH |
|---|---|---|---|
| Fuel Type | Electricity | Natural Gas | Natural Gas |
| Recovery Efficiency | 0.99 | 0.75 | 0.75 |
| Energy Factor | 1 | 0.66 or | 0.87 or |
| Rated Input (kW or BTU) | 4.5 | 34,000 | 34,000 |
| Tank Size (gallons) | 50 | 40 | 40 |
| Temperature Set Point | 120 | 120 | 120 |
| HW From Boiler | Separate | Separate | Tankless |

The water heating energy use is independent of house size and is the same for all three house area cases. No matter if the single-family house has low area (modelled as 900 sqft), average area (modelled as 1350 sqft) or high area (modelled as 1800 sqft), the outputs for water heating remains the same. Therefore, only one case is shown in the results for all area sizes, and it is the different cases of energy usage that changes the TCO. The water heating electricity or natural gas use for the three cases of energy usage are presented in Table 17, which are the energy usages used for fuel cost calculations.

*Table 17: Energy usage estimates from HES for different Water Heater types and energy use cases*

| Energy Use | HPWH, EF=2.0 (kWh/year) | HPWH, EF=3.55 (kWh/year) | NGWH, EF=0.66 (therms/year) | NGWH, EF=0.81 (therms/year) | INGWH, EF=0.87 (therms/year) | INGWH, EF=0.97 (therms/year) |
|---|---|---|---|---|---|---|
| Low | 552 | 311 | 59 | 43 | 39 | 32 |
| Average | 1,104 | 622 | 118 | 87 | 77 | 64 |
| High | 1,436 | 809 | 153 | 112 | 100 | 83 |

The inputs used for the TCO analysis for the three types of heaters, each with two different energy factors, are presented in Table 18. The fuel costs are shown for the first year and will be different from the yearly fuel cost in the TCO which is an annualized cost over the equipment's lifetime since the fuel prices are assumed to increase every year.

Table 18: Inputs for TCO analysis for different types of Water Heaters [1][110]

| | HPWH | | NGWH | | INGWH | |
|---|---|---|---|---|---|---|
| Energy Factor[1] | 2.00 | 3.55 | 0.66 | 0.81 | 0.87 | 0.97 |
| Purchase Price[1] ($) | 1,200 | 1,750 | 1,075 | 1,975 | 1,025 | 1,350 |
| Installation Cost[1] ($) | 1,900 | 2,475 | 2,025 | 3,075 | 2,300 | 2,450 |
| Maintenance Cost[1] ($/year) | 20 | 20 | 0 | 0 | 130 | 130 |
| Typical Capacity[1] (gallons or | 50 | 50 | 40 | 40 | 199 | 199 |
| Average life[1] (years) | 13 | 13 | 13 | 13 | 19 | 19 |
| Fuel Cost - Low ($/year) | 110 | 62 | 81 | 60 | 53 | 44 |
| Fuel Cost - Average ($/year) | 220 | 124 | 163 | 119 | 106 | 88 |
| Fuel Cost - High ($/year) | 287 | 161 | 212 | 155 | 138 | 114 |

In the case of vehicles, the comparison is straight forward one-on-one between electric and gas combustion vehicles for each category. However, in the case of heaters and appliances, there are more choices for comparison. Since most space heaters in the area have already surpassed their lifetime, it is safe to assume that many households will be facing the issue of getting a new water heating equipment in the near future. The baselines of households were modelled to have NGWH with an energy factor of 0.55, since it was the most common equipment and EF in Albany. If a household would experience their water heater to break, a common first reaction would be to purchase a new version of the same equipment. Therefore, when comparing TCO costs and ratios, the base of comparison is the new NGWH with the EF of 0.66. Other approaches to take were comparing the equipment to the cheapest option, the most efficient option, or the "greenest" option meaning lowest CO2 emissions. The approach of comparison to the new version of the existing equipment in the house was chosen because people tend to choose an equipment that they are familiar with, and a natural gas fuelled water heater is a good base for comparison. The base of comparison is also visible in Table 19 where the TCO difference is 0 and the TCO ratio is 1 for NGWH with EF of 0.66. Each fuel usage case is compared to the baseline of the same fuel usage, meaning that the TCO differences and ratios for the low energy cases of all heaters are compared to the low case of the NGWH with EF=0.66, and so forth with the average and high case.

Table 19 is showing the results from the TCO comparison for the different heater types and their EFs. The Low, Average and High cases are showing the result for different energy uses, keeping the initial and maintenance costs the same for the three cases, but varying the fuel costs. Depending on the heater type, the total TCO can vary up to 200 $/year from the low to high energy usage case.

The HPWHs are 11.2-16.5% more expensive than the low efficiency NGWH depending on the energy usage case. This range would be different if the high efficiency HPWH was compared to the high efficiency NGWH and not the low efficiency one. It was chosen to have one baseline for easy comparison, but if the HPWH with EF=3.55 was to be compared with the NGWH with EF=0.81, the TCO for the HPWH would have been cheaper by 73 to 76

$/year depending on energy usage scenario from low to high. If high efficiency was strictly to be compared with high efficiency and not the low efficiency baseline of NGWH, the HPWH with EF=3.55 would have had a TCO ratio lower than 1, resulting in the heat pump being 9-11% cheaper than the NGWH with EF=0.81.

The highest emissions savings are seen when choosing an electricity-fueled option compared to the NGWH with EF=0.66, with highest carbon savings ranging from 359 kg CO2/year in the low energy usage case to 934 kg CO2/year in the high energy usage case.

*Table 19: TCO Comparison Table for Water Heaters*

| | | Purchase Price ($/year) | Inst. Cost ($/year) | Maint. Cost ($/year) | Fuel Cost ($/year) | Total TCO ($/year) | Δ TCO ($/year) | TCO ratio | Emissions (kg CO2 /year) |
|---|---|---|---|---|---|---|---|---|---|
| HPWH, EF=2.0 | Low | 144 | 227 | 21 | 122 | 514 | 52 | 1.112 | 0 |
| | Average | 144 | 227 | 21 | 243 | 635 | 82 | 1.149 | 0 |
| | High | 144 | 227 | 21 | 316 | 708 | 100 | 1.165 | 0 |
| HPWH, EF=3.55 | Low | 209 | 296 | 21 | 69 | 595 | 133 | 1.288 | 0 |
| | Average | 209 | 296 | 21 | 137 | 664 | 111 | 1.200 | 0 |
| | High | 209 | 296 | 21 | 178 | 705 | 97 | 1.160 | 0 |
| NGWH, EF=0.66 | Low | 129 | 242 | 0 | 91 | 462 | 0 | 1 | 359 |
| | Average | 129 | 242 | 0 | 182 | 553 | 0 | 1 | 719 |
| | High | 129 | 242 | 0 | 237 | 608 | 0 | 1 | 934 |
| NGWH, EF=0.81 | Low | 236 | 368 | 0 | 67 | 671 | 209 | 1.452 | 264 |
| | Average | 236 | 368 | 0 | 134 | 738 | 185 | 1.334 | 527 |
| | High | 236 | 368 | 0 | 174 | 778 | 170 | 1.280 | 686 |
| INGWH, EF=0.87 | Low | 99 | 223 | 139 | 61 | 521 | 59 | 1.128 | 235 |
| | Average | 99 | 223 | 139 | 121 | 582 | 29 | 1.052 | 469 |
| | High | 99 | 223 | 139 | 158 | 619 | 11 | 1.017 | 610 |
| INGWH, EF=0.97 | Low | 131 | 237 | 139 | 50 | 557 | 95 | 1.205 | 194 |
| | Average | 131 | 237 | 139 | 100 | 607 | 54 | 1.097 | 388 |
| | High | 131 | 237 | 139 | 130 | 637 | 29 | 1.048 | 505 |

The TCO breakdown for the different water heating technologies and energy usage cases presented in Figure 28 show how the fuel costs change between the energy usage cases, as well as the share of purchase price, installation cost, maintenance cost and fuel cost in the TCO.

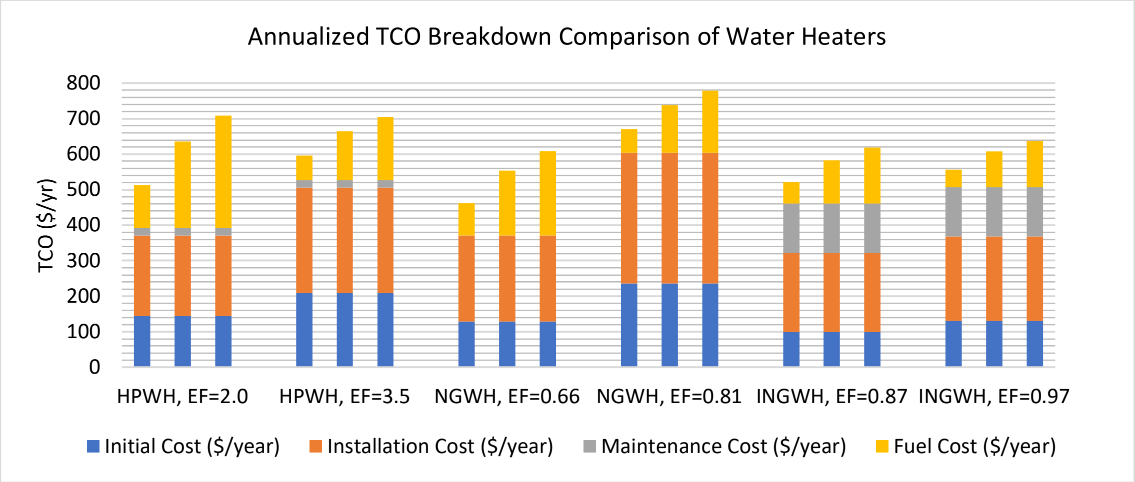


*Figure 28: Annualized TCO Breakdown Comparison of Water Heaters and Energy Usage Cases*

For storage tank natural gas water heaters, the maintenance costs are negligible [110]. There is a noticeable difference in the installation between typical and high efficiency products, seen in Figure 28 as a jump in purchase price and installation cost for an equipment of higher efficiency. Typical efficiency products are non-condensing, whereas the high efficiency products are condensing and require different installation [110]. NGWH with storage tank are very simple to operate, resulting in very low-cost repairs, while tankless water heaters are more complex and expensive to repair or replace [111].

In reality, the installation costs for both HPWH and INGWH can be higher because switching to tankless from a storage tank water heater is a difficult swap requiring a plumbing retrofit and a possible upgrade to gas lines to increase capacity, and HPWH can require an upgrade to the electric service. Since 90% of the water heater installation occur during an emergency when the existing heater suddenly breaks down, the switch in a tight timeline can increase contractor costs [112].

Figure 29 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. An interesting observation that goes against the energy efficiency efforts state policies are trying to achieve is that the higher efficiency equipment doesn't always pay off and can result in a higher total TCO. When comparing the HPWHs between each other, if the household has low or average energy usage, the higher efficiency heat pump is more costly than the lower efficiency. However, if the household has high consumption, a HPWH with EF=3.55 has a lower TCO than the HPWH with EF=2.0. This observation goes only for the HPWH, for the natural gas-fueled heaters, the lower efficiency heaters have a lower TCO in all three cases because the fuel cost savings don't balance out the higher initial costs. The gap between the two INGWHs is decreasing the more energy is used, but the INGWH with EF=0.97 doesn't become cheaper than the INGWH with EF=0.87.

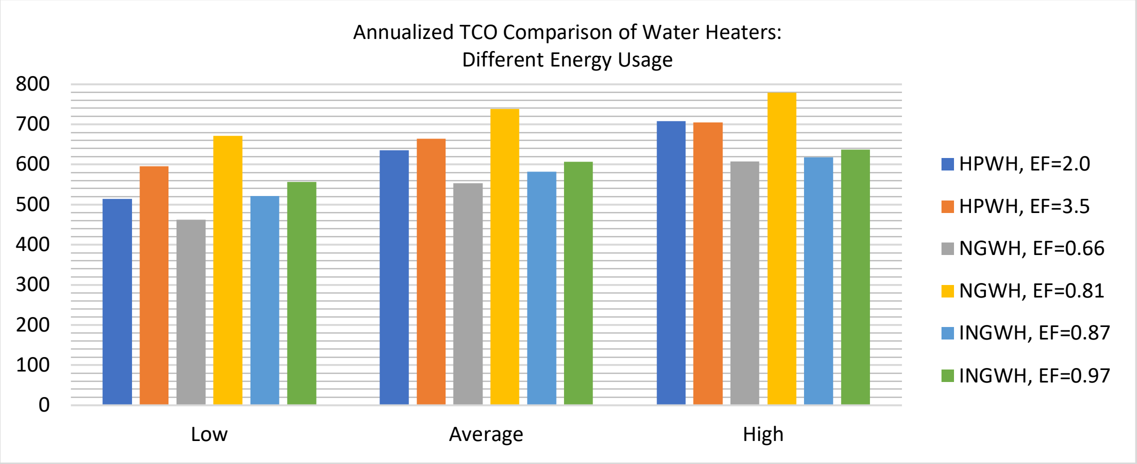


*Figure 29: TCO Comparison of Water Heaters for Low, Average and High Energy Usage*

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.

### 4.3.2 Space Heating

The space heating demand is largely dependent on the size of the home to be heated, and therefore is expected to differ for the three different sized typical single-family homes. 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.

Similarly to the methodology used for water heating, three energy use cases are used to reflect that the heating energy demand varies with the amount of people in the house, temperature settings and general habits. The average space heating energy use is taken from the HES tool (with a correction factor accounted for, as explained in Annex 2: Correction Factor for HES). The low energy use case is 50% less than the average energy use, and the high energy use case is 30% more than the average.

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. As mentioned in 4.2.3.8 Space Cooling, currently typical homes in Albany don't have cooling because of the low cooling demand, however, this can come to change due to a warming climate in the area. Therefore, a TCO comparison is done for both scenarios integrating room air-conditioning (AC) in the cooling scenario.

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. The specific inputs used for the HES tool are presented in Table 20. These inputs were run for the three different typical single-family house areas. The HPSC in the only heating scenario has a Heating Seasonal Performance Factor (HSPF) of 8.5 or 9.0, meaning that homeowners can choose between heat pumps of two different heating efficiencies. In the cooling scenario the HPSC with the lower heating efficiency also has a lower cooling efficiency, meaning that the heat pump with HSPF=8.5 has a Seasonal Energy Efficiency Ratio (SEER) of 15, and consequently the heat pump with HSPF=9.0 has a SEER=15. Two heating efficiencies are considered for NG-Furnaces, one with an Annual Fuel Utilization Efficiency (AFUE) of 90% and the other of 99%. When incorporating cooling, room ACs with a SEER=12 are bought separately, while for HPSCs cooling is readily available without having to purchase additional equipment.

*Table 20: Space Heating and Cooling Relevant Inputs into the HES tool*

| | HPSC | NG-Furnace |
|---|---|---|
| Heating | | |
| Fuel Type | Electricity | Natural Gas |
| Heating Type | Electric Heat Pump | Central Gas Furnace |
| Heating Capacity (btu/hr) | 36000 | 80000 |
| Heating Efficiency (HSPF or % AFUE) | 8.5 or 9.0 | 90 or 99 |
| Cooling | | |
| Fuel Type | Electricity | Electricity |
| Cooling Type | Electric Heat Pump | Room AC |
| Cooling Capacity (btu/hr) | 36000 | 36000 |
| Cooling Efficiency (SEER) | 15 or 19 | 12 |

#### 4.3.2.1 Heating Scenario

Space heating uses more fuel than water heating and is a significant contributor to the total energy use of a house. As the inputs for the HES tool were previously presented in Table 15 and Table 20, this chapter aims to present the energy usage outputs from the HES tool relevant to space heating, as well as the inputs used for the TCO analysis. The outputs of the HES tool for the modelled energy usage of space heating for different home sizes and different cases of energy usage intensity are summarized in Table 21. The results are shown with the integrated HES correction factor that makes the energy usage estimates match the average electricity and natural gas use for single-family homes in Albany in 2016. The electricity and natural gas usage estimates were used to calculate the fuel costs for the TCO analysis.

*Table 21: Energy Use outputs from HES for different Space Heating cases (No Cooling Scenario)*

| House Area | Energy Use | Fuel Type | HPSC (HSPF=8.5)* | HPSC (HSPF=9.0)* | NG-Furnace (AFUE=90%)* | NG-Furnace (AFUE=99%)* |
|---|---|---|---|---|---|---|
| Low | Low | Electricity | 497 | 464 | 47 | 47 |
| | | NG | 0 | 0 | 52 | 47 |
| | Average | Electricity | 994 | 929 | 94 | 94 |
| | | NG | 0 | 0 | 104 | 94 |
| | High | Electricity | 1293 | 1207 | 122 | 122 |
| | | NG | 0 | 0 | 135 | 122 |
| Average | Low | Electricity | 760 | 701 | 68 | 68 |
| | | NG | 0 | 0 | 83 | 77 |
| | Average | Electricity | 1519 | 1402 | 136 | 136 |
| | | NG | 0 | 0 | 167 | 155 |
| | High | Electricity | 1975 | 1823 | 177 | 177 |
| | | NG | 0 | 0 | 217 | 201 |
| High | Low | Electricity | 999 | 919 | 84 | 84 |
| | | NG | 0 | 0 | 109 | 99 |
| | Average | Electricity | 1998 | 1838 | 169 | 169 |
| | | NG | 0 | 0 | 219 | 199 |
| | High | Electricity | 2597 | 2390 | 220 | 220 |
| | | NG | 0 | 0 | 284 | 258 |

**The energy uses are displayed as kWh/year for electricity use and as therms/year for natural gas (NG) use.*

The inputs used for the TCO analysis for the two heating efficiencies of HPSCs and NG-Furnaces are presented in Table 22.

*Table 22: Inputs for TCO analysis for different types of Space Heater [1](EIA, 2018b)*

| | HPSC | | NG-Furnace | |
|---|---|---|---|---|
| Heating Efficiency[1] (HSPF or % AFUE) | 8.5 | 9.0 | 90 | 99 |
| Purchase Price[1] ($) | 3,500 | 4,550 | 1,150 | 1,620 |
| Installation Cost[1] ($) | 4,950 | 6,100 | 2,560 | 3,040 |
| Maintenance Cost[1] ($/year) | 73 | 73 | 40 | 40 |
| Typical Capacity[1] (Btu/hr) | 36,000 | 36,000 | 80,000 | 80,000 |
| Average life[1] (years) | 15.5 | 15.5 | 21.5 | 21.5 |
| Assumed lifetime in TCO (years) | 15 | 15 | 20 | 20 |

Typical single-family households in Albany have currently old NG central furnaces. It is assumed that these households are most likely to upgrade their space heaters to a new NG-furnace with a higher Annual Fuel Utilization Efficiency (AFUE), meaning that more heat can be obtained per unit of fuel. The baseline for comparison is a new, average efficiency NG-furnace with an AFUE of 90%. The difference in TCO ($/year) as well as TCO ratio is compared to this space heater.

#### 4.3.2.2 Heating and Cooling Scenario

In this scenario, the idea of households integrating cooling options is explored. With global warming, global mean temperatures are increasing, but this hits differently on a local scale. In Albany, temperatures are projected to increase 1.1-2.2°C (2-4°F) by 2050, with daily maximum temperatures increasing by up to 5°C (9°F) [21]. As temperatures increase, extreme heat waves are also expected to become more frequent [113]. Historically, Albany had no days of extreme heat, meaning over 32.2°C (90°F), however 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, as seen in Figure 30 [21]. The hotter and significantly drier climate could lead to more people purchasing cooling equipment.

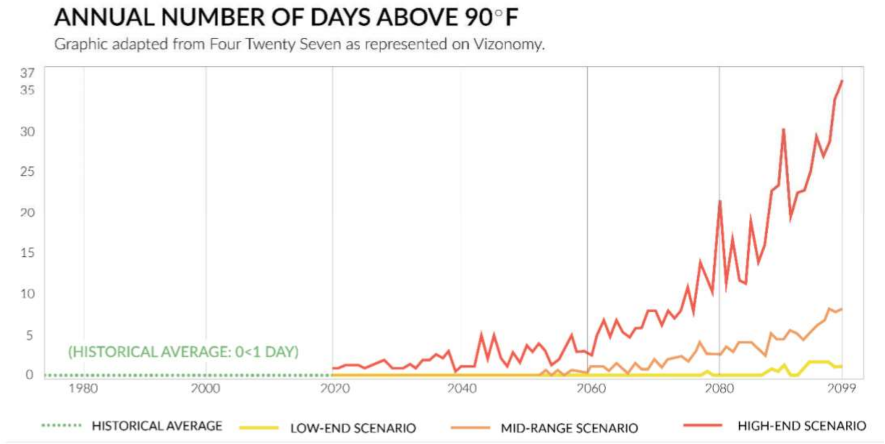


*Figure 30: Projected Extreme Heat Days in Albany* [21]

The outputs from the HES tool modelling the two different heating and cooling efficiency HPSCs, and the two different heating efficiency NG-Furnaces with room ACs are presented in Table 23. These results are higher than for the scenario without cooling because the cooling equipment (or cooling function of the heat pump) is adding on additional electricity usage.

*Table 23: Energy Use outputs from HES for different Space Heating cases (Cooling Scenario)*

| House Area | Energy Use | Fuel Type | HPSC (HSPF=8.5, SEER=15)* | HPSC (HSPF=9.0, SEER=19)* | NG-Furnace + AC (AFUE=90%, SEER=12)* | NG-Furnace + AC (AFUE=99%, SEER=12)* |
|---|---|---|---|---|---|---|
| Low | Low | Electricity | 561 | 512 | 94 | 94 |
| | | NG | 0 | 0 | 52 | 47 |
| | Average | Electricity | 1,121 | 1,025 | 189 | 189 |
| | | NG | 0 | 0 | 104 | 94 |
| | High | Electricity | 1,458 | 1,332 | 245 | 245 |
| | | NG | 0 | 0 | 135 | 122 |
| Average | Low | Electricity | 832 | 758 | 138 | 138 |
| | | NG | 0 | 0 | 83 | 77 |
| | Average | Electricity | 1,664 | 1,515 | 276 | 276 |
| | | NG | 0 | 0 | 167 | 155 |
| | High | Electricity | 2,163 | 1,970 | 359 | 359 |
| | | NG | 0 | 0 | 217 | 201 |
| High | Low | Electricity | 1,081 | 984 | 169 | 169 |
| | | NG | 0 | 0 | 109 | 99 |
| | Average | Electricity | 2,162 | 1,968 | 339 | 339 |
| | | NG | 0 | 0 | 219 | 199 |
| | High | Electricity | 2,810 | 2,559 | 441 | 441 |
| | | NG | 0 | 0 | 284 | 258 |

**The energy uses are displayed as kWh/year for electricity use and as therms/year for natural gas (NG) use.*

The inputs for the TCO analysis are presented in Table 24. The purchase price, installation and maintenance cost remain the same for the HPSC but changes significantly for the NG-Furnace. This is because three additional room ACs are purchased and installed with the NG-Furnace and added on to the total cost. Since the cooling capacity of one room AC is approximate a third of the HPSC cooling capacity (10,500 Btu/hr vs. 36,000 Btu/hr), for a fair comparison it is assumed that three ACs would be bought to be able to serve approximately the same amount of cooling. In reality, a single-family household might not choose to purchase three ACs with the small amount of extreme heat days, but presumably buy one or two that can be moved around the house. Another assumption is that three new room ACs for the same price will be purchased after 10 years and last until the end life of the NG-Furnace, incorporated in the annualized TCO.

*Table 24: Inputs for TCO analysis for different types of Space Heater [1]*[110]

| | HPSC (heating + cooling) | | Room AC | NG-Furnace + Room AC | |
|---|---|---|---|---|---|
| Heating Efficiency[1] (HSPF or % AFUE) | 8.5 | 9 | 0 | 90 | 99 |
| Cooling Efficiency[1] (SEER) | 15 | 19 | 12 | 12 | 12 |
| Purchase Price[1] ($) | 3,500 | 4,550 | 555 | 2,815 | 3,285 |
| Installation Cost[1] ($) | 4,950 | 6,100 | 640 | 4,480 | 4,960 |
| Maintenance Cost[1] ($/year) | 72.5 | 72.5 | 0 | 40 | 40 |
| Typical Heating Capacity[1] (Btu/hr) | 36,000 | 36,000 | 0 | 80,000 | 80,000 |
| Typical Cooling Capacity [1] (Btu/hr) | 36,000 | 36,000 | 10,500 | 31,500 | 31,500 |
| Average life [1] (years) | 15.5 | 15.5 | 9.5 | 21.5 | 21.5 |
| Assumed lifetime in TCO (years) | 15 | 15 | 10 | 20 | 20 |

The most important takeaway from Table 24 is that with the incorporation of room ACs, the purchase price and installation costs for NG-Furnaces are almost as high as for HPSCs. When seeing the purchase price and installation costs in Table 22 where no cooling is modelled, the big difference of initial costs between heat pumps and furnaces is apparent. When comparing the lower heating efficiency HPSC with the lower heating efficiency

NG-furnace, and the higher heating efficiency HSPC with the equivalent NG-furnace, the initial cost of the HPSC is 2.3 times as expensive as the NG-furnace. 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.

Since we are assuming that the baseline for comparison is the lower efficiency NG-Furnace, in the cooling case it will be the same NG-Furnace with the additional room ACs for TCO ratios and TCO differences. The TCO results are presented per home area case in the coming subchapters.

#### 4.3.2.3 Low Area Case

The results of the annualized TCO for different space heaters, for both the no cooling and cooling scenarios, are presented in Table 25. For small single-family houses, the big difference in initial cost between HPSCs and NG-Furnaces without cooling is not diminished by the yearly maintenance cost nor the variable fuel cost. The initial cost (purchase price and installation cost) is the biggest part of the HPSC TCO, accounting for 72-83% of the total annual cost depending on energy usage for the HPSC with HSPF=8.5, and 77-87% for the HPSC with HSPF=9.0. The fuel costs account for on average 15% of total costs for the HPSC and 27% for the NG-Furnaces. The maintenance costs are the smallest fraction for all energy uses and equipment.

*Table 25: Space Heater TCO Comparison for two scenarios for a small household with Low, Average and High Energy Uses*

| | | Purch. Price ($/yr) | Inst. Cost ($/yr) | Maint. Cost ($/yr) | Fuel Cost ($/yr) | Total TCO ($/yr) | Δ TCO ($/yr) | TCO ratio | Emissions (kg CO2 / yr) |
|---|---|---|---|---|---|---|---|---|---|
| Heating Scenario | | | | | | | | | |
| HPSC, HSPF=8.5 | Low | 384 | 543 | 78 | 110 | 1,115 | 630 | 2.298 | 0 |
| | Average | 384 | 543 | 78 | 220 | 1,225 | 647 | 2.120 | 0 |
| | High | 384 | 543 | 78 | 286 | 1,291 | 658 | 2.039 | 0 |
| HPSC, HSPF=9.0 | Low | 500 | 670 | 78 | 103 | 1,350 | 864 | 2.780 | 0 |
| | Average | 500 | 670 | 78 | 205 | 1,452 | 874 | 2.513 | 0 |
| | High | 500 | 670 | 78 | 267 | 1,514 | 881 | 2.390 | 0 |
| NG-Furnace, AFUE=90% | Low | 109 | 242 | 43 | 92 | 485 | 0 | 1 | 316 |
| | Average | 109 | 242 | 43 | 185 | 578 | 0 | 1 | 632 |
| | High | 109 | 242 | 43 | 240 | 633 | 0 | 1 | 822 |
| NG-Furnace, AFUE=99% | Low | 153 | 287 | 43 | 85 | 568 | 82 | 1.169 | 287 |
| | Average | 153 | 287 | 43 | 170 | 652 | 74 | 1.129 | 574 |
| | High | 153 | 287 | 43 | 221 | 703 | 70 | 1.110 | 746 |
| Heating + Cooling Scenario | | | | | | | | | |
| HPSC (HSPF=8.5, SEER=15) | Low | 384 | 543 | 78 | 138 | 1,143 | 125 | 1.123 | 0 |
| | Average | 384 | 543 | 78 | 276 | 1,281 | 160 | 1.143 | 0 |
| | High | 384 | 543 | 78 | 359 | 1,364 | 181 | 1.153 | 0 |
| HPSC (HSPF=9, SEER=19) | Low | 500 | 670 | 78 | 159 | 1,406 | 388 | 1.381 | 0 |
| | Average | 500 | 670 | 78 | 318 | 1,565 | 444 | 1.396 | 0 |
| | High | 500 | 670 | 78 | 414 | 1,661 | 478 | 1.404 | 0 |
| NG-Furnace + AC (AFUE=90%, SEER=12) | Low | 351 | 521 | 43 | 103 | 1,018 | 0 | 1 | 316 |
| | Average | 351 | 521 | 43 | 206 | 1,122 | 0 | 1 | 632 |
| | High | 351 | 521 | 43 | 268 | 1,183 | 0 | 1 | 822 |
| NG-Furnace + AC (AFUE=99%, SEER=12) | Low | 396 | 567 | 43 | 95 | 1,101 | 82 | 1.081 | 287 |
| | Average | 396 | 567 | 43 | 191 | 1,196 | 74 | 1.066 | 574 |
| | High | 396 | 567 | 43 | 248 | 1,253 | 70 | 1.059 | 746 |

In all categories the heat pump is more expensive for a small house, no matter the case of energy consumption patterns. In the no cooling case, the higher the energy use is, the smaller the TCO ratio is between the HPSCs and the NG-Furnace with AFUE=90%, which means that the cost of fuel for NG-furnace has a higher slope. However, still heat pumps are more than double the price of low efficiency NG-furnaces for all energy usage cases in the no cooling scenario. This translates into an additional 630-881 $/year for heat pump space heater users. The high efficiency NG-Furnace is more expensive for all energy use levels than the low efficiency one. When considering electrification options, it is the low efficiency HPSC for low energy use that is the cheapest when looking at the total TCO, but it is the high energy use case that has the lowest TCO ratio.

When including cooling as well, the ratios shift significantly. The HPSCs are still more expensive than the cheapest NG-Furnace combined with room ACs but are only 12-15% more expensive instead of being over the double. A HPSC with HSPF=8.5 could mean an additional 125-181 $/year compared to a NG-Furnace with AFUE=90% and three room ACs. The increase in competitiveness for HPSCs when cooling is taken into account is visible in Figure 31 where the gap between the HPSCs and NG-Furnaces becomes smaller in the cooling scenario. The different energy usage levels don't shift the hierarchy between the four different space conditioning options.

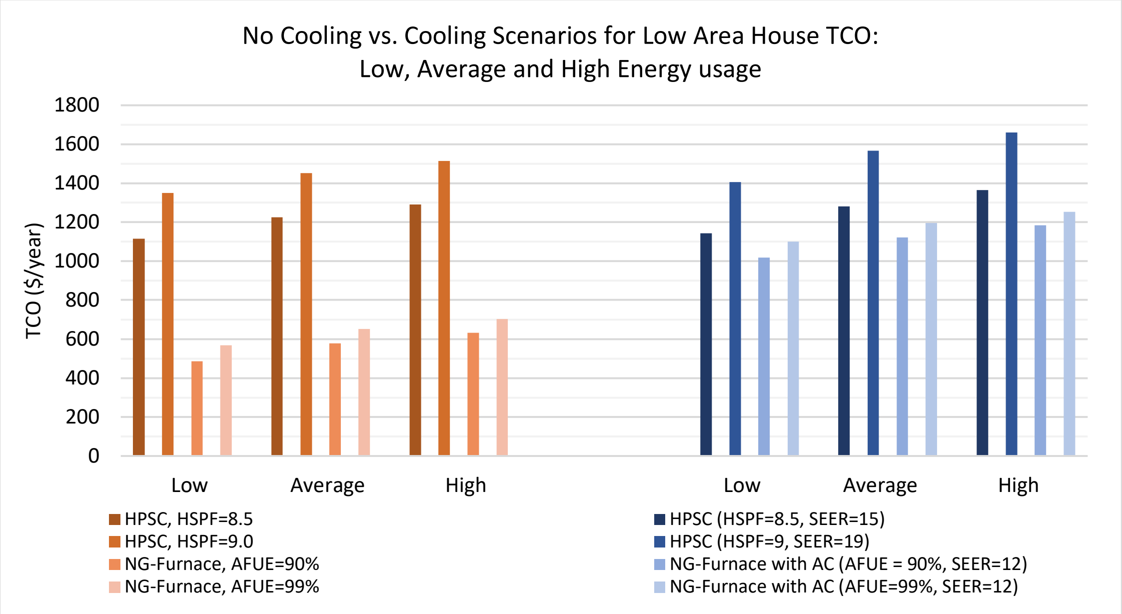


*Figure 31: TCO Results for Low Area House for different energy usage and cooling scenarios*

4.3.2.4 Average Area Case

For the average area case, meaning houses in the 1100-1700 square foot range that includes 47.4% of all Albany single-family households, the results broken down by low, average and high energy use show that NG-Furnaces are still the cheapest option for space heating.

Table 26 shows the TCO ratios and deltas of the heating equipment compared to the NG-Furnace with AFUE=90%. Getting a low-efficiency electric HPSC can cost 633-667 $ extra per year compared to the low-efficiency NG-Furnace, which is 1.9-2.2 times as expensive. What we see is that the total TCOs are higher for the average house size than a small house due to the increased energy use that gives higher energy bills, but the TCO ratios are slightly decreasing.

*Table 26: Space Heater TCO Comparison for two scenarios for an average household with Low, Average and High Energy Uses*

| | | Purch.Price ($/yr) | Inst. Cost ($/yr) | Maint. Cost ($/yr) | Fuel Cost ($/yr) | Total TCO ($/yr) | Δ TCO ($/yr) | TCO ratio | Emissions (kg CO2 / yr) |
|---|---|---|---|---|---|---|---|---|---|
| Heating Scenario | | | | | | | | | |
| HPSC, HSPF=8.5 | Low | 384 | 543 | 78 | 168 | 1,173 | 633 | 2.172 | 0 |
| | Average | 384 | 543 | 78 | 336 | 1,341 | 654 | 1.952 | 0 |
| | High | 384 | 543 | 78 | 437 | 1,442 | 667 | 1.860 | 0 |
| HPSC, HSPF=9.0 | Low | 500 | 670 | 78 | 155 | 1,402 | 862 | 2.596 | 0 |
| | Average | 500 | 670 | 78 | 310 | 1,557 | 870 | 2.266 | 0 |
| | High | 500 | 670 | 78 | 403 | 1,650 | 875 | 2.128 | 0 |
| NG-Furnace, AFUE=90% | Low | 109 | 242 | 43 | 147 | 540 | 0 | 1 | 509 |
| | Average | 109 | 242 | 43 | 294 | 687 | 0 | 1 | 1,018 |
| | High | 109 | 242 | 43 | 382 | 775 | 0 | 1 | 1,323 |
| NG-Furnace, AFUE=99% | Low | 153 | 287 | 43 | 138 | 620 | 80 | 1.148 | 472 |
| | Average | 153 | 287 | 43 | 275 | 758 | 71 | 1.103 | 945 |
| | High | 153 | 287 | 43 | 358 | 840 | 65 | 1.084 | 1,228 |
| Heating + Cooling Scenario | | | | | | | | | |
| HPSC (HSPF=8.5, SEER=15) | Low | 384 | 543 | 78 | 208 | 1,213 | 135 | 1.125 | 0 |
| | Average | 384 | 543 | 78 | 416 | 1,421 | 180 | 1.145 | 0 |
| | High | 384 | 543 | 78 | 541 | 1,546 | 207 | 1.154 | 0 |
| HPSC (HSPF=9, SEER=19) | Low | 500 | 670 | 78 | 241 | 1,488 | 410 | 1.380 | 0 |
| | Average | 500 | 670 | 78 | 482 | 1,729 | 488 | 1.393 | 0 |
| | High | 500 | 670 | 78 | 627 | 1,874 | 535 | 1.399 | 0 |
| NG-Furnace + AC (AFUE = 90%, SEER=12) | Low | 351 | 521 | 43 | 163 | 1,078 | 0 | 1 | 509 |
| | Average | 351 | 521 | 43 | 326 | 1,241 | 0 | 1 | 1,018 |
| | High | 351 | 521 | 43 | 424 | 1,339 | 0 | 1 | 1,323 |
| NG-Furnace + AC (AFUE=99%, SEER=12) | Low | 396 | 567 | 43 | 154 | 1,158 | 80 | 1.074 | 472 |
| | Average | 396 | 567 | 43 | 307 | 1,312 | 71 | 1.057 | 945 |
| | High | 396 | 567 | 43 | 399 | 1,404 | 65 | 1.049 | 1,228 |

The carbon savings remain the same for the heating only and the heating combined with cooling scenarios, since the additional cooling is electric, and the electricity in Albany is carbon free. When choosing a HPSC instead of the cheapest NG-Furnace option, the emission savings are between 0.5-1.3 ton of $CO_2$/year.

The results in Figure 32 are still showing that low efficiency NG-Furnaces are cheapest option and high efficiency HPSCs are the most expensive option for all energy use cases. As the TCO ratios are slightly decreasing for the HPSCs in the no cooling scenario for an average sized home compared to a small home, the relative gap between compared to NG-Furnaces is decreasing too. It means that it is better for an average sized house to get a HPSC than a small single-family house, however the big gap is still suggesting that households are unlikely to invest in heat pumps without subsidies. Especially if cooling is going to be used in the household, a higher efficiency furnace is only 5-7% more expensive than a lower efficiency furnace depending on the energy use and can save 8% emissions.

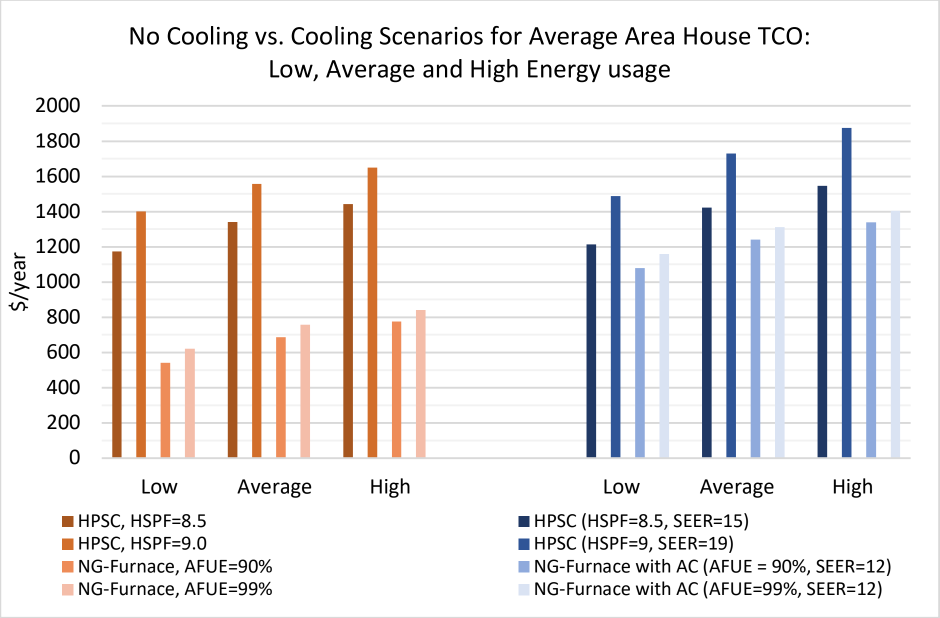


*Figure 32: TCO Results for Average Area House for different energy usage and cooling scenarios*

### 4.3.2.5 High Area Case

The results for a large Albany home (modelled as 1800 sqft) are shown in Table 27 and Figure 33. The results remain similar to the two smaller single-family home cases previously presented. Comparing all results, the lowest TCO ratio seen for a heat pump is for a large home with a high energy usage that is above average in which case the HPSC with HSPF=8.5 is 77.2% more expensive than the NG-Furnace with AFUE=90% for the same level of energy usage. The annualized TCO for a HPSC when including the cooling function barely changes, while it almost doubles for a NG-Furnace when ACs are added. This is showing the importance of planning ahead for the warmer weather in Albany and pushing the residents to invest in heat pumps that can satisfy all heating and cooling needs.

*Table 27: Space Heater TCO Comparison for two scenarios for a big household with Low, Average and High Energy Uses*

| | | Purch. Price ($/yr) | Inst. Cost ($/yr) | Maint. Cost ($/yr) | Fuel Cost ($/yr) | Total TCO ($/yr) | Δ TCO ($/yr) | TCO ratio | Emissions (kg CO2 /yr) |
|---|---|---|---|---|---|---|---|---|---|
| Heating Scenario | | | | | | | | | |
| HPSC, HSPF=8.5 | Low | 384 | 543 | 78 | 221 | 1,226 | 642 | 2.097 | 0 |
| | Average | 384 | 543 | 78 | 442 | 1,447 | 671 | 1.864 | 0 |
| | High | 384 | 543 | 78 | 574 | 1,580 | 688 | 1.772 | 0 |
| HPSC, HSPF=9.0 | Low | 500 | 670 | 78 | 203 | 1,450 | 865 | 2.480 | 0 |
| | Average | 500 | 670 | 78 | 406 | 1,653 | 877 | 2.130 | 0 |
| | High | 500 | 670 | 78 | 528 | 1,775 | 884 | 1.992 | 0 |
| NG-Furnace, AFUE=90% | Low | 109 | 242 | 43 | 192 | 585 | 0 | 1 | 667 |
| | Average | 109 | 242 | 43 | 383 | 776 | 0 | 1 | 1,333 |
| | High | 109 | 242 | 43 | 498 | 891 | 0 | 1 | 1,733 |
| NG-Furnace, AFUE=99% | Low | 153 | 287 | 43 | 176 | 659 | 74 | 1.127 | 606 |
| | Average | 153 | 287 | 43 | 352 | 835 | 58 | 1.075 | 1,212 |
| | High | 153 | 287 | 43 | 457 | 940 | 49 | 1.055 | 1,576 |
| Heating + Cooling Scenario | | | | | | | | | |
| HPSC (HSPF=8.5, SEER=15) | Low | 384 | 543 | 78 | 273 | 1,278 | 152 | 1.135 | 0 |
| | Average | 384 | 543 | 78 | 545 | 1,551 | 214 | 1.160 | 0 |
| | High | 384 | 543 | 78 | 709 | 1,714 | 251 | 1.172 | 0 |
| HPSC (HSPF=9, SEER=19) | Low | 500 | 670 | 78 | 320 | 1,567 | 441 | 1.391 | 0 |
| | Average | 500 | 670 | 78 | 640 | 1,886 | 550 | 1.411 | 0 |
| | High | 500 | 670 | 78 | 831 | 2,078 | 615 | 1.421 | 0 |
| NG-Furnace + AC (AFUE = 90%, SEER=12) | Low | 351 | 521 | 43 | 211 | 1,126 | 0 | 1 | 667 |
| | Average | 351 | 521 | 43 | 421 | 1,337 | 0 | 1 | 1,333 |
| | High | 351 | 521 | 43 | 548 | 1,463 | 0 | 1 | 1,733 |
| NG-Furnace + AC (AFUE=99%, SEER=12) | Low | 396 | 567 | 43 | 195 | 1,200 | 74 | 1.066 | 606 |
| | Average | 396 | 567 | 43 | 390 | 1,395 | 58 | 1.044 | 1,212 |
| | High | 396 | 567 | 43 | 507 | 1,512 | 49 | 1.033 | 1,576 |

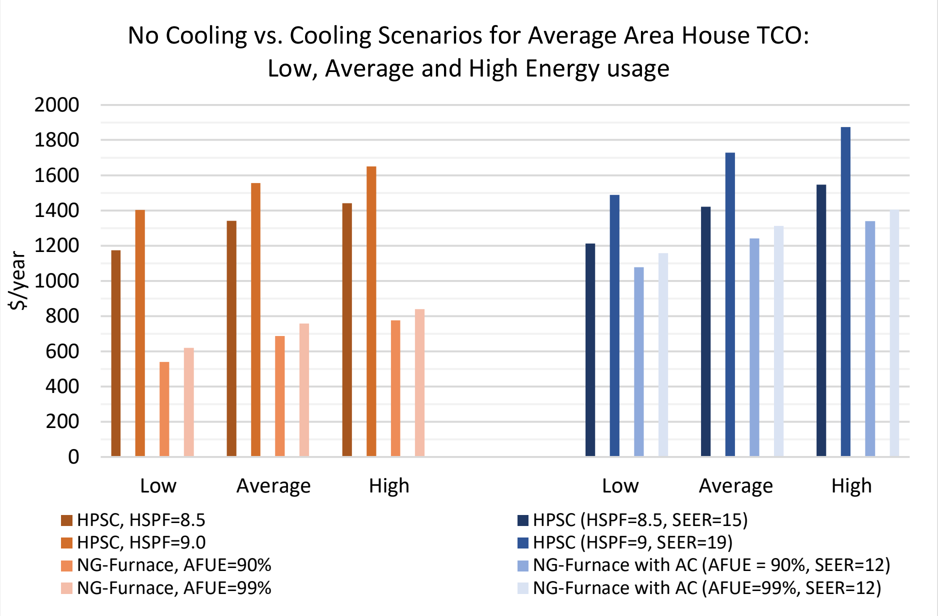


*Figure 33: TCO Results for Large Area House for different energy usage and cooling scenarios*

Unfortunately, heat pumps are not the cheapest options for any house size or energy usage, it is just a question of how much more expensive it is for a household depending on its characteristics and the residents' habits. Instead, another important takeaway from the results is TCO savings a household can have if using less energy. Going from high energy consumption to low energy consumption when having the cheapest NG-Furnace option can save a household can save over 300 $ per year, as well as over 1 ton of CO2 emissions per year. From an emissions standpoint, that is an even bigger saving that a household with low energy usage switching from natural gas to electricity as heating fuel, however, Albany is planning on achieving net zero carbon and for that reason households are expected to cut out their emissions by electrification.

As households can choose mild discomfort for the few extreme heat days over purchasing cooling equipment, the focus should stay on the no cooling scenario. The big annualized TCO gap between HPSCs and NG-Furnaces needs to be addressed and the subsidies are needed to lower the high initial costs of heat pumps.

### 4.3.3 Large Appliances

The energy usage of large appliance is assumed to be independent of the house size, and therefore one set of results are presented for the three house cases, broken down into low, average and high energy use. The TCO analysis is a one-on-one comparison of a large appliance using electricity or natural gas (NG) as a fuel. Only one efficiency is used per fuel type of each large appliance since the HES tool does not allow to change the energy efficiencies, only the type of fuel and in some cases the year of purchase of the large appliance. The analysis is solemnly on large appliances that typical current Albany homes have and are NG-fuelled, it does not take into consideration appliances that only work on electricity and whether or not they need an energy efficiency upgrade (such as washing machines, dishwashers, fridges and freezers). 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.

*Table 28: HES tool energy use outputs for large appliances*

| | Low Energy Use | Average Energy Use | High Energy Use |
|---|---|---|---|
| Electric Dryer (kWh/year) | 378 | 756 | 983 |
| NG Dryer (therms/year) | 16 | 32 | 42 |
| Electric Stove (kWh/year) | 164 | 329 | 427 |
| NG Stove (therms/year) | 15 | 30 | 39 |
| Electric Oven (kWh/year) | 108 | 215 | 280 |
| NG Oven (therms/year) | 5 | 10 | 13 |

The energy use outputs shown in Table 28 are once again used as inputs into the TCO calculations, together with price estimates on purchase price and installation costs. Maintenance costs are negligible for all large appliances. The same lifetime of 12 years is assumed for all appliances [104]. The inputs used for the TCO are summarized in Table 29.

*Table 29: Inputs into TCO analysis for Large Appliances [1][104] [2][114]*

| | Electric Dryer | NG Dryer | Electric Stove | NG Stove | Electric Oven | NG Oven |
|---|---|---|---|---|---|---|
| Purchase Price[1,2] ($) | 430 | 500 | 557 | 260 | 915 | 560 |
| Installation cost[1,2] ($) | 540 | 660 | 229 | 370 | 228 | 680 |
| Maintenance [1] cost ($/year) | 0 | 0 | 0 | 0 | 0 | 0 |
| Average life [1] (years) | 12 | 12 | 12 | 12 | 12 | 12 |

The results of the TCO analysis are shown in Table 30, as an annualized cost of ownership during for the duration of their lifetime. For the TCO difference and TCO ratio, each electric appliance is compared to its NG version, and each energy use case is compared to the same energy use, meaning that the low energy use for an electric dryer is compared to the low energy use for a NG dryer for example.

From the TCO ratios of above 1, it is seen 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 monetary difference between 4-127 $/year. This TCO difference is low in comparison to water heaters and space heaters. NG dryers emit the most CO2 per year, with stoves following closely behind. It is also these two appliances that have the least affordable electric versions in comparison to the gas fueled one.

*Table 30: Large Appliances TCO Comparison for Low, Average and High Energy Use Cases*

| | | Purchase Price ($/year) | Installation Cost ($/year) | Fuel Cost ($/year) | Total TCO ($/year) | Δ TCO ($/year) | TCO ratio | Emissions (kg CO2 / year) |
|---|---|---|---|---|---|---|---|---|
| Electric Dryer | Low | 54 | 68 | 83 | 205 | 34 | 1.200 | 0 |
| | Average | 54 | 68 | 166 | 288 | 92 | 1.470 | 0 |
| | High | 54 | 68 | 216 | 338 | 127 | 1.602 | 0 |
| NG Dryer | Low | 63 | 83 | 25 | 171 | 0 | 1 | 99 |
| | Average | 63 | 83 | 50 | 196 | 0 | 1 | 198 |
| | High | 63 | 83 | 65 | 211 | 0 | 1 | 257 |
| Electric Stove | Low | 70 | 29 | 36 | 135 | 33 | 1.322 | 0 |
| | Average | 70 | 29 | 72 | 171 | 46 | 1.368 | 0 |
| | High | 70 | 29 | 94 | 193 | 54 | 1.388 | 0 |
| NG Stove | Low | 33 | 47 | 23 | 102 | 0 | 1 | 91 |
| | Average | 33 | 47 | 46 | 125 | 0 | 1 | 181 |
| | High | 33 | 47 | 60 | 139 | 0 | 1 | 236 |
| Electric Oven | Low | 115 | 29 | 24 | 168 | 4 | 1.023 | 0 |
| | Average | 115 | 29 | 47 | 191 | 20 | 1.116 | 0 |
| | High | 115 | 29 | 61 | 205 | 29 | 1.167 | 0 |
| NG Oven | Low | 71 | 86 | 8 | 164 | 0 | 1 | 30 |
| | Average | 71 | 86 | 15 | 171 | 0 | 1 | 60 |
| | High | 71 | 86 | 20 | 176 | 0 | 1 | 79 |

The higher the energy usage level, the higher the TCO ratio. This is observed because the fuel costs are higher for the electrical large appliances. The breakdown of the TCO can be visualized in Figure 34, which shows clearly how the fuel costs for the electrical appliances are higher than for gas appliances, with the fuel costs of the electrical dryer being more than double the purchase price and installation cost for average or high energy usage. The installation costs for natural gas appliances is more expensive than for electrical ones.

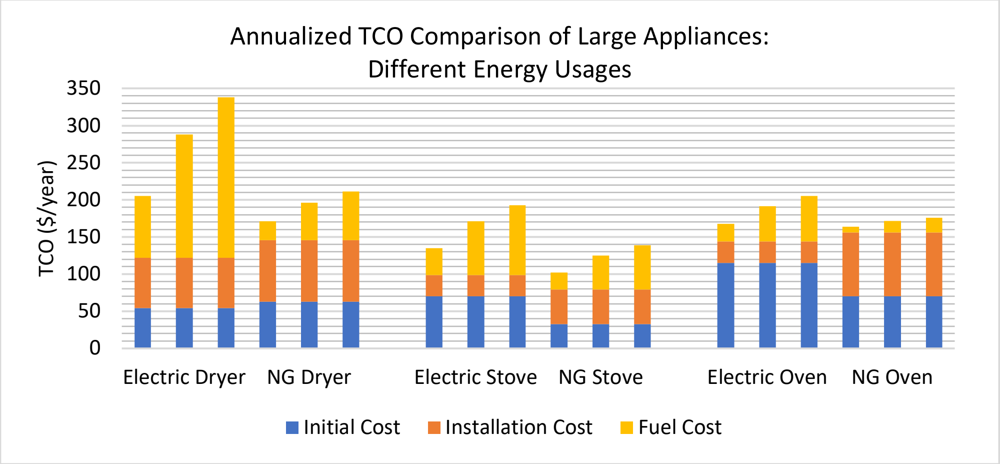


*Figure 34: TCO Comparison of Large Appliances for Low, Average and High Energy Usage*

The results show that large NG appliances are still the cheapest options for households independent of the energy usage cases. Even though the emissions are relatively small compared to other emitters in the household, it is still important to encourage electrification. Especially the switching of gas stoves to electrical stoves has a slow momentum due to people being used to a certain way of cooking. If there is already a push against electrical stoves, it is important to prove financial benefits of kitchen electrification and therefore subsidies for stoves could swing households in Albany to electrify.

### 4.3.4 Additional reasons of relevance for Household Electrification

Even though in many cases the NG alternative to water heating, space heating and large appliances was a cheaper option and doesn't by itself motivate households to fully electrify, there are other important reasons why electrification is relevant today and should be done.

Not only are NG leaks bad for the environment, but they have major negative health effects. Immediate gas leaking can cause carbon monoxide poisoning, the cause of death of almost 500 people per year in the U.S. [115]. Gas stoves for cooking or heating are burning fossil fuels inside homes and emit pollutants that lead to respiratory illnesses, such as increased risk of asthma, wheeze and reduced lung function, especially when exposed as children. This has been a well-researched topic for a long time [116–120]. Using NG inside homes can result in having $NO_2$ levels 4-7 times higher than in homes with electric stoves [119]. Chronic obstructive pulmonary diseases (COPDs), partly caused by air pollutants at home from heating fuels, affected 4.6% of California residents in 2011 [121].

The natural gas pipelines are also a major security issue where aging pipeline infrastructure are causing substantial leaks, overpressure and explosions. The National Transportation Safety Board (NTSB) and the Pipeline and Hazardous Materials Safety Administration (PHMSA) have been warning gas utilities to change the aging pipelines, but it isn't happening at a needed rate since it is very expensive to replace the infrastructure and it isn't required by law [122]. Even though accidents happening at the gas distribution to consumers only account for 17% of all pipeline related accidents, it causes the most injuries (79%), deaths (73%), evacuees (62%), fires (71%), and explosions (78%) [123]. Data from the PHMSA shows that on average, a pipeline catches fire every 4 days, resulting in an explosion every 11 days, an injury every 5 days, and a fatality every 26 days in the U.S. [123]. The devastation of natural gas infrastructure is familiar for Californians, with five of the 10 most destructive fires in California since 2015 being linked to PG&E's electrical network. In 2018, the most destructive wildfire in California, killing 85 people and destroying 14,000 homes, started with a live wire breaking free of a PG&E tower that was 25 years older than its considered useful life [124]. A 2010 explosion of a PG&E gas pipeline in the city of San Bruno killed eight people due to the inadequate quality assurance by the utility [125].

As wildfire risks due to weather conditions are peaking, PG&E recently in an unprecedented move shut off powers to 800 000 customers across Northern California up to a week to avoid winds damaging power equipment [126]. This is a big disruption in people's lives and is predicted to happen more often due to the increase in projected heatwaves, which is another reason to lower the dependence on natural gas [98]. As the pipelines are aging and restoration work is needed, even PG&E can come to support electrification of existing building stock. In addition, as more and more houses are electrifying, the ones that don't can come to pay higher costs for maintaining the existing pipeline system, which is another incentive to jump on the electrification train and not invest in new NG equipment.

# 5. The Big Picture

## 5.1 Household-level

This final chapter aims to assemble all the puzzle pieces previously presented to answer the main objective of this thesis: highlighting the real cost of reaching net zero carbon on a household level through a multi-sectoral analysis, identifying which households are to benefit the least and most from this measure and calculate the carbon savings on a city level. The results summarized the costs of buying an EV instead of an ICE for four different vehicle categories and three different yearly mileages, the costs to electrify a household's water heating system, space heating system and large appliances versus replacing the old NG equipment into a newer NG equipment, shown for three different house sizes and three different levels of energy use. The variety of cases was used to capture the habits of a large share of single-family households in Albany for the analysis to hopefully be of high value for citizens and the city council.

Presenting a large set of data and results from all the chapters is challenging due to the high number of combinations a household can have. There are 972 different possible combinations of all the results presented for a single-family household including the choices for vehicles. The results are first presented in a summary table of all electrification measures, the annualized total cost of ownership, the difference of TCO between the decarbonization measure and the upgraded baseline equipment, the TCO ratio and the carbon emissions saved compared to the new version of the original gas-fueled equipment. Each category is compared to the so-called upgraded baseline, meaning a new version with higher efficiency of what was modelled in a current Albany home. For vehicles, EVs are compared to their ICE version in each vehicle model category. For household electrification, heat pump water heaters are compared to a storage tank natural gas water heater with EF=0.66, space conditioners in the no cooling case are compared to a natural gas furnace with AFUE=90% and in the cooling case to the same furnace with an additional three room ACs with SEER =12. Lastly, the electric versions of each large appliance are compared to the same gas-fueled version of the appliance. For each category, the electric version is compared to the gas version for the same energy use or mileage case and the $CO_2$ emissions savings are compared in the same way.

A positive delta TCO signifies the amount by which new electric equipment is more expensive than its natural gas comparison per year, and a negative delta TCO means that the electrification means money saved. The TCO ratio shows the ratio of electric equipment to gas equipment (or EV/ICE ratio for vehicles). A TCO ratio below 1 is desired meaning that the electric version is cheaper than its counterpart for that equipment category and usage case.

As the vehicle usage, water heater and large appliances are mostly independent of the house area, only one set of results is shown with the use cases varied between low, average and high energy use or annual vehicle miles travelled. Space heating is largely dependent of the home size, and therefore the three different house area sizes are presented as different cases. In addition, whether a household chooses to incorporate cooling or not is a choice presented in the results table.

A summary of electrification TCO and emissions results are presented in Table 31.

*Table 31: Summary of Electrification TCO and emissions results*

| | Total TCO ($/year) | | | Δ TCO compared to Upgraded Baseline ($/year) | | | TCO ratio compared to Upgraded Baseline | | | CO2 Emissions Saved (kg CO2/year) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | Average | High | Low | Average | High | Low | Average | High | Low | Average | High |
| Vehicles: | | | | | | | | | | | | |
| Subcompact | 7,319 | 7,428 | 7,550 | 1,842 | 1,563 | 1,250 | 1.336 | 1.266 | 1.198 | 2,160 | 3,051 | 4,050 |
| Compact | 6,404 | 6,508 | 6,626 | 206 | -89 | -420 | 1.033 | 0.986 | 0.940 | 2,228 | 3,146 | 4,177 |
| Midsize | 6,867 | 6,967 | 7,079 | -44 | -332 | -654 | 0.994 | 0.955 | 0.915 | 2,160 | 3,051 | 4,050 |
| Full-size | 15,537 | 15,654 | 15,784 | -1,470 | -2,106 | -2,820 | 0.914 | 0.881 | 0.848 | 4,193 | 5,923 | 7,862 |
| Water Heater: | | | | | | | | | | | | |
| HP EF=2.0 | 514 | 635 | 708 | 52 | 82 | 100 | 1.112 | 1.149 | 1.165 | 359 | 719 | 934 |
| HP EF=3.5 | 595 | 664 | 705 | 133 | 111 | 97 | 1.288 | 1.200 | 1.160 | 359 | 719 | 934 |
| Space Heater: | | | | | | | | | | | | |
| Low Area | | | | | | | | | | | | |
| No Cooling: HPSC (HSPF = 8.5) | 1,115 | 1,225 | 1,291 | 630 | 647 | 658 | 2.298 | 2.120 | 2.039 | 316 | 632 | 822 |
| No Cooling: HPSC (HSPF = 9.0) | 1,350 | 1,452 | 1,514 | 864 | 874 | 881 | 2.780 | 2.513 | 2.390 | 316 | 632 | 822 |
| Cooling: HPSC (HSPF = 8.5, SEER = 15) | 1,143 | 1,281 | 1,364 | 125 | 160 | 181 | 1.123 | 1.143 | 1.153 | 316 | 632 | 822 |
| Cooling: HPSC (HSPF = 9, SEER = 19) | 1,406 | 1,565 | 1,661 | 388 | 444 | 478 | 1.381 | 1.396 | 1.404 | 316 | 632 | 822 |
| Average Area | | | | | | | | | | | | |
| No Cooling: HPSC (HSPF = 8.5) | 1,173 | 1,341 | 1,442 | 633 | 654 | 667 | 2.172 | 1.952 | 1.860 | 509 | 1,018 | 1,323 |
| No Cooling: HPSC (HSPF = 9.0) | 1,402 | 1,557 | 1,650 | 862 | 870 | 875 | 2.596 | 2.266 | 2.128 | 509 | 1,018 | 1,323 |
| Cooling: HPSC (HSPF = 8.5, SEER = 15) | 1,213 | 1,421 | 1,546 | 135 | 180 | 207 | 1.125 | 1.145 | 1.155 | 509 | 1,018 | 1,323 |
| Cooling: HPSC (HSPF = 9, SEER = 19) | 1,488 | 1,729 | 1,874 | 410 | 488 | 535 | 1.380 | 1.394 | 1.400 | 509 | 1,018 | 1,323 |
| High Area | | | | | | | | | | | | |
| No Cooling: HPSC (HSPF = 8.5) | 1,226 | 1,447 | 1,580 | 642 | 671 | 688 | 2.097 | 1.864 | 1.772 | 667 | 1,333 | 1,733 |
| No Cooling: HPSC (HSPF = 9.0) | 1,450 | 1,653 | 1,775 | 865 | 877 | 884 | 2.480 | 2.130 | 1.992 | 667 | 1,333 | 1,733 |
| Cooling: HPSC (HSPF = 8.5, SEER = 15) | 1,278 | 1,551 | 1,714 | 152 | 214 | 251 | 1.135 | 1.160 | 1.172 | 667 | 1,333 | 1,733 |
| Cooling: HPSC (HSPF = 9, SEER = 19) | 1,567 | 1,886 | 2,078 | 441 | 550 | 615 | 1.391 | 1.411 | 1.421 | 667 | 1,333 | 1,733 |
| Large Appliances: | | | | | | | | | | | | |
| Electric Dryer | 205 | 288 | 338 | 34 | 92 | 127 | 1.200 | 1.470 | 1.602 | 99 | 198 | 257 |
| Electric Stove | 135 | 171 | 193 | 33 | 46 | 54 | 1.322 | 1.368 | 1.388 | 91 | 181 | 236 |
| Electric Oven | 168 | 191 | 205 | 4 | 20 | 29 | 1.023 | 1.116 | 1.167 | 30 | 60 | 79 |

The results can be interpreted in a number of ways and serve as a matrix where a household can easily combine their habits together for their individual outcome. One approach is for a household to see the cost of decarbonizing their current habits, for instance knowing that they will drive a compact vehicle for a low annual VMT, have an average sized single-family home and have a high energy use for all household related end-uses. Adding the TCOs together gives the total annualized cost for total decarbonization for a household, while the total delta TCO shows how much more expensive the decarbonization option is compared to upgrading the current on average outdated gas-fueled vehicles and equipment to a newer gas option.

It is the TCO ratio that is considered when determining which scenario is the most beneficial for a household to electrify. As the TCO will be higher with a higher fuel use, it is not conclusive to say that households with the lowest fuel use would get to electrify for the cheapest price, even though they would pay the least on an annual basis. Instead, the electric and gas alternatives are compared to each other for low, average and high fuel use cases and the lowest TCO ratio of these cases signify the most favorable electrification option. The lowest TCO means the biggest saving (or smallest additional cost) of an electric vehicle or equipment compared to its gas-fueled counterpart.

Focusing on EVs, the cheapest TCO of all models and usages is a compact EV driven at low yearly mileage (8,000 miles/year) costing 6,404 $/year. Even though it is the lowest TCO of all options, the TCO ratio is over 1 and the TCO difference is 206 $/year, meaning that for a compact EV with low VMT, the ICE option is cheaper and therefore the household is not financially benefitting from getting an EV. Instead, the lowest TCO ratio for compact EVs is for a high VMT (15 000 miles/year) where the buyer saves 420 $/year. The lowest EV/ICE TCO ratio overall is 0.848 for the full-size EV driven at high VMT, which means the most savings compared to an ICE in the same category driven the same mileage. However, the full-size vehicles are luxury vehicles due to the lack of full-size EVs in other price categories and are not representative of the choices a typical Albany resident would make when investing in a vehicle. Disregarding the luxury full-size vehicle, the midsize EV has the lowest TCO ratio for all three mileages. It is therefore buying a midsize EV that gives the biggest savings compared to buying a midsized ICE. Even though the midsize EV has the lowest TCO ratio, it might be a trade-off situation between the midsize and compact EV when purchasing, since the savings are smaller for a compact EV compared to a compact ICE, but the total costs are also lower by over 450$/year. What is clear from the results is that it is not economically viable currently to get a sub-compact EV instead of a sub-compact ICE and that a household should instead opt for a compact EV that is cheaper and has a longer range. The high TCO for sub-compacts is due to the weak market presence of EVs in that model category and the few existing EVs have a much higher purchase price than sub-compact ICEs that can be very cheap, when following the DOE’s definition of vehicle model categories.

For vehicles, the vehicle model is of high importance due to family size, functionality and habit, and the choice of vehicle won’t be purely made on the most beneficial option in comparison to the annual mileage driven. However, for heating equipment and large appliances, the energy use is the most important property to consider since people are indifferent to what type of heat pump should be installed as long as it is the most favorable choice. For home-related decarbonization, one can look for the lowest TCO ratio based on their energy use level.

Regarding these choices, no TCO ratio is below 1 and the lowest TCO ratio means the smallest additional cost compared to getting a NG-fueled equipment.

Analyzing per energy use case, for a low energy use (50% lower than average), a heat pump water heater with EF=2.0 has the lowest TCO ratio at 1.112 translating into an additional 52 $/year compared to a low-efficiency NG storage tank. The same low efficiency HPWH is more favorable for an average energy use, however, for a high energy use, the heat pump water heater with EF=3.55 has a lower TCO ratio (1.160 vs. 1.165). What is interesting is that if a household has a high hot water energy use, it can be beneficial to change consumption habits to decrease the energy use to average which would result in the lower efficiency HP to be cheaper to install. Instead of the fuel cost savings occurring in the TCO when jumping from high to average energy use for the HPWH with EF=3.55, saving 41 $/year, the jump could be to the average energy use TCO for the HPWH with EF=2.0, increasing the savings by 71% to 70 $/year instead. Once a HPWH with EF=2.0 has been bought, the lowest TCO ratio occurs at the lowest energy use, but the opposite is seen for a HPWH with EF=3.55 since the cheaper fuel costs for the heat pump will level out the higher initial costs compared to the NGWH.

For space heating, the results behave in a similar way for all three house area sizes, except the fuel prices effect the total TCO and TCO ratio to different extents. The main focus is on the no cooling case because it is the most relevant for the current situation in Albany, and the cooling case is to highlight the possible TCO ratio improvement and cost competitiveness of HPSCs if cooling will be integrated in more and more homes. Concentrating on solely heating, the bigger the house, the lower the TCO ratios, meaning that there is more incentive to invest in a HPSC for a bigger house than a smaller house. This is because the more energy used, the more the fuel cost savings lower the TCO ratio for an electric heat pump compared to a NG-Furnace, which is also reflected in the results table with the lowest TCO ratios occurring for the high energy use case. Independent of the energy use case, the lower efficiency HPSC is more promising. Decarbonizing space heating is very costly for a household because the HPSCs are not currently cost competitive with cheap NG-Furnaces, leading to an additional yearly cost of 630-688 $ compared to the gas-fueled option. This high delta TCO is counterbalancing any savings that could have been done with picking the most optimal EV in the non-luxury range. The introduction of cooling equipment costs incorporated with the NG-Furnace can lower the TCO ratio and delta TCO substantially for HPSCs, but the ratios remain above 1 in all cases.

Lastly, the large appliances are compared on a one on one basis. The TCO ratios grow with growing energy use, meaning that the fuel costs for electric appliances have a larger inclination and increase at a higher rate than the NG fuel costs. It is most beneficial to get electric large appliances with a low energy use.

Focusing on the carbon emissions saved, it is clear that the higher the energy usage or VMT, the more carbon is saved since it is the amount of $CO_2$ that would have been emitted from natural gas or gasoline that is accounted for. Household vehicles are the largest carbon emitters, followed by space heating, water heating and large appliances. The emissions of the space heating vary largely, between 0.3-1.7 tons of $CO_2$ per year due to the large dependence on house size and fuel use. Nonetheless, for average and large homes, these are important carbon savings. The highest possible avoided emission totals at over 11 tons of $CO_2$ per year, when choosing electric options for a full-size vehicle with high mileage and heating and appliances with a high energy use for a large home.

The analysis for comparison is on the basis that the current heating equipment and vehicles have a high average age and are reaching their end of life. Therefore, changing these items will be necessary in the near future in any case. Regulations should aim to lower the costs of electrification options to prevent the purchase of new NG-fueled heating options and appliances that will continue to pollute for the next 10-20 years. This is equally important for new gasoline-powered vehicles and their potential to pollute during their 10 year ownership time, but usually much longer in use lifetime. Gottfredson and O'Keeffe (2019) concluded for the analysis for EV tipping point that while commercial vehicle fleets are likely to switch to EVs when the TCO is the same or lower than ICEs, but for individuals the purchase price needs to be matching or be cheaper than ICEs for an acquisition to occur. This is showing that individuals have more difficulties integrating the concept of TCO into their purchase strategy and that up-front costs are of high importance. This concept can also be transferred to heat pumps which have a much higher initial cost than their NG counterparts which results in a higher TCO as well. Thus, incentives are needed to lower initial costs to make EVs and heat pumps appealing and competitive with a lower purchase price.

## 5.2 City-level

This work was conducted with a household perspective for costs and emissions on the individual level and was not a city-level aggregated modelling. However, an objective is to quantify the total costs and carbon savings the decarbonization of the residential transport and residential energy sector would entail for the city of Albany.

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 behavior 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.

As there are currently not enough variety of affordable sub-compact and full-size EVs on the market, a very small share of Albany households will opt for this option. Instead, it is assumed that families wanting originally a sub-compact will get a compact EV, and families wanting a full-size vehicle will choose a mid-size EV instead. Therefore, the vehicle choices are boiled down to compact and mid-size EVs as these are the most affordable and cost competitive compared to their ICE 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. Although the range of sub-compact to full-size vehicles does not represent all residential vehicles due to the national popularity of SUVs and pickup trucks, many households have more than one car (a household has on average 1.48 cars in Albany). Thus, the household decarbonization here includes the purchase of one EV per household, meaning that a household can buy a compact or mid-size EV and keep an SUV or pickup truck for the times they might be needed.

When translating the household-level results into aggregated city-level data, a what-if analysis approach is taken, presenting what the decarbonization of households and household vehicles would mean for Albany if all single-family households were to do this right now. This is, of course, not a realistic approach for several reasons. Firstly, due to the natural turnover rates of vehicles, heating appliances and large appliances, there will be a percentage of single-family homes that have relatively new natural gas appliances or a new gas-fuelled vehicle and will not decarbonize until these items reach their end of life. Secondly, some households will find the vehicle model of high importance and need an affordable full-size vehicle, SUV or pick-up truck due to habits or specific circumstances. These households may wait a few years until EVs are introduced to these vehicle categories as well, or until they are forced to change habits due to increasingly severe ICE regulations. Lastly, electrification and the purchase of new vehicles and appliances is very costly for a household, and many households will simply not afford to make these changes as almost 10% (9.6%) of Albany population live below the poverty line [128]. However, a what-if analysis has a high importance to understand the total costs decarbonization actions would entail, as well as the emissions reductions if all single-family households had the incentives and means to do it, since Albany is aiming to achieve net zero carbon economy-wide by 2050.

The results for the combinations are presented in two tables broken down by vehicle type, Table 32 showing the household combinations with a compact EV and

Table 33 with a midsized EV (presented on a separate page). The tables show a simplification of possible combinations and an estimation of the percentage of single-family households that each combination represents. From the tables it is possible to see the costs incurred by different households, and how it changes depending on home size, energy use, vehicle type and vehicle miles travelled. The highest and lowest TCO-related numbers and emission savings are highlighted with red and green colors for each column, showing which household combination is the least and most favorable for full electrification.

*Table 32: TCO and emission saving results of household combinations with a compact EV including estimated fraction of single-family households in each combination.*

| Area | Energy Use | EV Model | VMT | Est. Fraction | | | Total TCO($/year) | ΔTCO ($/year) | TCO ratio | Emissions saved (kg CO2/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | Low | Compact | Low | 30.3% | 7.6% | 1.9% | 8,541 | 959 | 1.126 | 3,123 |
| Low | Low | Compact | Avg. | | | 3.8% | 8,645 | 663 | 1.083 | 4,041 |
| Low | Low | Compact | High | | | 1.9% | 8,763 | 332 | 1.039 | 5,072 |
| Low | Avg. | Compact | Low | | 15.2% | 3.8% | 8,915 | 1,094 | 1.140 | 4,018 |
| Low | Avg. | Compact | Avg. | | | 7.6% | 9,020 | 798 | 1.097 | 4,937 |
| Low | Avg. | Compact | High | | | 3.8% | 9,137 | 467 | 1.054 | 5,967 |
| Low | High | Compact | Low | | 7.6% | 1.9% | 9,136 | 1,171 | 1.147 | 4,555 |
| Low | High | Compact | Avg. | | | 3.8% | 9,241 | 876 | 1.105 | 5,474 |
| Low | High | Compact | High | | | 1.9% | 9,358 | 545 | 1.062 | 6,504 |
| Avg. | Low | Compact | Low | 47.4% | 11.9% | 3.0% | 8,599 | 962 | 1.126 | 3,315 |
| Avg. | Low | Compact | Avg. | | | 5.9% | 8,703 | 667 | 1.083 | 4,234 |
| Avg. | Low | Compact | High | | | 3.0% | 8,821 | 335 | 1.040 | 5,264 |
| Avg. | Avg. | Compact | Low | | 23.7% | 5.9% | 9,031 | 1,100 | 1.139 | 4,403 |
| Avg. | Avg. | Compact | Avg. | | | 11.9% | 9,136 | 805 | 1.097 | 5,322 |
| Avg. | Avg. | Compact | High | | | 5.9% | 9,253 | 474 | 1.054 | 6,352 |
| Avg. | High | Compact | Low | | 11.9% | 3.0% | 9,287 | 1,180 | 1.146 | 5,056 |
| Avg. | High | Compact | Avg. | | | 5.9% | 9,392 | 885 | 1.104 | 5,975 |
| Avg. | High | Compact | High | | | 3.0% | 9,509 | 554 | 1.062 | 7,005 |
| High | Low | Compact | Low | 22.3% | 5.6% | 1.4% | 8,652 | 970 | 1.126 | 3,473 |
| High | Low | Compact | Avg. | | | 2.8% | 8,756 | 675 | 1.084 | 4,392 |
| High | Low | Compact | High | | | 1.4% | 8,874 | 344 | 1.040 | 5,422 |
| High | Avg. | Compact | Low | | 11.2% | 2.8% | 9,137 | 1,117 | 1.139 | 4,718 |
| High | Avg. | Compact | Avg. | | | 5.6% | 9,241 | 822 | 1.098 | 5,637 |
| High | Avg. | Compact | High | | | 2.8% | 9,359 | 491 | 1.055 | 6,668 |
| High | High | Compact | Low | | 5.6% | 1.4% | 9,425 | 1,202 | 1.146 | 5,466 |
| High | High | Compact | Avg. | | | 2.8% | 9,529 | 906 | 1.105 | 6,385 |
| High | High | Compact | High | | | 1.4% | 9,647 | 575 | 1.063 | 7,415 |

*Table 33: TCO and emission saving results of household combinations with a midsized EV, including estimated fraction of single-family households in each combination.*

| Area | Energy Use | EV Model | VMT | Est. Fraction | | | Total TCO | Δ TCO ($/year) | TCO ratio | Emissions saved (kg CO2/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | Low | Midsize | Low | 30.3% | 7.6% | 1.9% | 9,004 | 709 | 1.085 | 3,055 |
| Low | Low | Midsize | Avg. | | | 3.8% | 9,104 | 421 | 1.048 | 3,946 |
| Low | Low | Midsize | High | | | 1.9% | 9,216 | 98 | 1.011 | 4,945 |
| Low | Avg. | Midsize | Low | | 15.2% | 3.8% | 9,378 | 844 | 1.099 | 3,950 |
| Low | Avg. | Midsize | Avg. | | | 7.6% | 9,478 | 556 | 1.062 | 4,841 |
| Low | Avg. | Midsize | High | | | 3.8% | 9,590 | 233 | 1.025 | 5,840 |
| Low | High | Midsize | Low | | 7.6% | 1.9% | 9,599 | 922 | 1.106 | 4,487 |
| Low | High | Midsize | Avg. | | | 3.8% | 9,699 | 634 | 1.070 | 5,378 |
| Low | High | Midsize | High | | | 1.9% | 9,811 | 311 | 1.033 | 6,377 |
| Avg. | Low | Midsize | Low | 47.4% | 11.9% | 3.0% | 9,062 | 712 | 1.085 | 3,248 |
| Avg. | Low | Midsize | Avg. | | | 5.9% | 9,162 | 424 | 1.049 | 4,139 |
| Avg. | Low | Midsize | High | | | 3.0% | 9,274 | 101 | 1.011 | 5,138 |
| Avg. | Avg. | Midsize | Low | | 23.7% | 5.9% | 9,494 | 851 | 1.098 | 4,336 |
| Avg. | Avg. | Midsize | Avg. | | | 11.9% | 9,594 | 563 | 1.062 | 5,227 |
| Avg. | Avg. | Midsize | High | | | 5.9% | 9,706 | 240 | 1.025 | 6,226 |
| Avg. | High | Midsize | Low | | 11.9% | 3.0% | 9,750 | 930 | 1.105 | 4,988 |
| Avg. | High | Midsize | Avg. | | | 5.9% | 9,850 | 642 | 1.070 | 5,879 |
| Avg. | High | Midsize | High | | | 3.0% | 9,962 | 320 | 1.033 | 6,878 |
| High | Low | Midsize | Low | 22.3% | 5.6% | 1.4% | 9,115 | 721 | 1.086 | 3,405 |
| High | Low | Midsize | Avg. | | | 2.8% | 9,215 | 433 | 1.049 | 4,296 |
| High | Low | Midsize | High | | | 1.4% | 9,327 | 110 | 1.012 | 5,295 |
| High | Avg. | Midsize | Low | | 11.2% | 2.8% | 9,600 | 867 | 1.099 | 4,651 |
| High | Avg. | Midsize | Avg. | | | 5.6% | 9,700 | 579 | 1.064 | 5,542 |
| High | Avg. | Midsize | High | | | 2.8% | 9,812 | 257 | 1.027 | 6,541 |
| High | High | Midsize | Low | | 5.6% | 1.4% | 9,888 | 952 | 1.107 | 5,398 |
| High | High | Midsize | Avg. | | | 2.8% | 9,988 | 664 | 1.071 | 6,289 |
| High | High | Midsize | High | | | 1.4% | 10,100 | 341 | 1.035 | 7,288 |

,

Table 34 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.

*Table 34: 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 |

The lowest annualized total cost is for the smallest house, with the lowest energy usage and VMT, for the smallest car of the two options. It is also in this case that the smallest emission savings occur, since it would generate the least amount of emissions if the electrification was not implemented. The highest TCO and emission savings are on the opposite end of the spectrum for the largest house, with the highest energy usage and highest VMT travelled by the midsized EV, which can save 7.4 tons of $CO_2$ per year. These results are intuitive since the costs for purchasing the appliances and vehicle remain similar in both cases (except the difference in purchase price for the compact vs. midsized EV and the difference for water heating where a higher efficiency HPWH is bought for high energy use), and it is the fuel usage that determines the TCO. In the combination where all cases are set to "low", the lowest fuel costs are seen and therefore the lowest TCO. The range of the TCO for single-family Albany households is 8,541 to 10,100 $/year, which is 10-12% of the median yearly household income of $87,694. This is an annualized TCO that adds together the TCO of each electrification component which is broken down into a yearly cost constituting of initial, maintenance and fuel costs considering the useful lifetime. However, it is important to remember that there are high up-front investment costs that the TCO doesn't reflect by itself. For a sense of order of magnitude, for an average sized home with average energy usage opting for the cheaper compact EV, the initial costs add up to over $40,000, even though it wouldn't be payed upfront but through a loan.

The lowest delta TCO signifies the lowest additional costs to electrify compared to purchasing the cheapest gasoline of natural gas fueled alternatives. This occurs for a household purchasing a midsized EV, driving a high yearly mileage, while owning a small home using low energy for heating and appliances. For this household combination, decarbonization adds a yearly cost of $98 compared to the NG and ICE options. It is also the household with the lowest TCO ratio of 1.011, which signifies that the decarbonization measures are only 1.1% more expensive than the comparison case. The same low TCO ratio is seen for an average house size with the same traits (low energy use, midsized EV and high VMT). The most expensive additional annual cost of 1,202 $/year, which is 14.6% more expensive than the gas options, occurs for a large home with high energy usage, purchasing a compact car that is driven at a low VMT. The highest TCO ratio of 1.147 is seen for a small home with high energy usage, with a compact car driven at a low VMT. 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 households with the most and least favorable characteristics have been identified with the help of the combination tables above.

Each combination table represents a 100% of the single-family households in Albany, but the aggregated city-level results in Table 35 combine the two results equally, meaning that 50% of the single-family households are assumed to buy a compact EV and 50% are assumed to buy a midsize EV. The results show the TCO of the cheapest way to fully decarbonize household related energy use and residential vehicles connected to households, since with different efficiencies of equipment, it is possible to decarbonize at a higher cost. The total TCO is presented, as well as the delta TCO compared to the upgrade of all equipment and vehicles to a gas-fueled version, and the carbon emissions saved. As each case is attributed a share of the total single-family households, the total costs for going net zero carbon for single-family households from the city's perspective can be estimated, as well as how much carbon this saves from Albany's total carbon emissions from the categories of transportation and residential energy use (see Table 35).

*Table 35: Decarbonization TCO and emission saving estimates for single-family homes on a city-wide level for Albany*

| | | | |
|---|---|---|---|
| Total TCO ($/year) | 34,932,898 | Emissions Saved from Transport (MTCO2/year) | 11,726 |
| Δ TCO ($/year) | 2,482,952 | Emissions Saved from Housing (MTCO2/year) | 7,587 |
| TCO ratio | 1.077 | Total Emissions Saved (MTCO2/year) | 19,313 |

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-fuelled 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. Considering that 25% of homes with high energy usage buying a higher efficiency HPWH and the share of households buying a compact or midsized EV, the average initial cost (including purchase prices, installation costs, taxes, registration fees, tax credit and EV charging station) lands at over $41,000 for a single-family household in Albany. Of course, most people take out loans especially when purchasing a vehicle and don't pay upfront, but it the up-front cost of decarbonizing on a household-level needs to be highlighted. This translated into an initial cost of over $157 million for all the single-family households in Albany.

The delta TCO from Table 35 could be seen as the cost for the city to achieve net zero carbon for single-family households because of the assumption that households are bound to upgrade their cars, heating equipment and large appliances. If incentives were to cover the cost difference of approximately $2.5 million per year, the electrification package would have the same TCO as a natural gas or gasoline-based package, which could lead to households shifting faster to become all-electric. This 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.

The emission reductions on a city level from the 2018 emissions estimate (the first year electricity became carbon-free) if all single-family households were to decarbonize their homes and one of their residential vehicles is presented in Figure 35. The results show that emissions from transportation would reduce by 40% and the emissions from the residential sector by 62%. These numbers are reasonable, since vehicles owned by single-family households make up 45% of all light-duty vehicles (which in turn makes up 99.3% of all vehicles). Therefore, the switching to EVs for single-family household-owned vehicles could lead to 40% emissions reduction in the transportation. Half of all households are formed by single-family households. A single-family home uses more energy than a multi-family home, and therefore the electrification of 50% of the building stock could lead to an emission reduction of the residential sector by 62%.

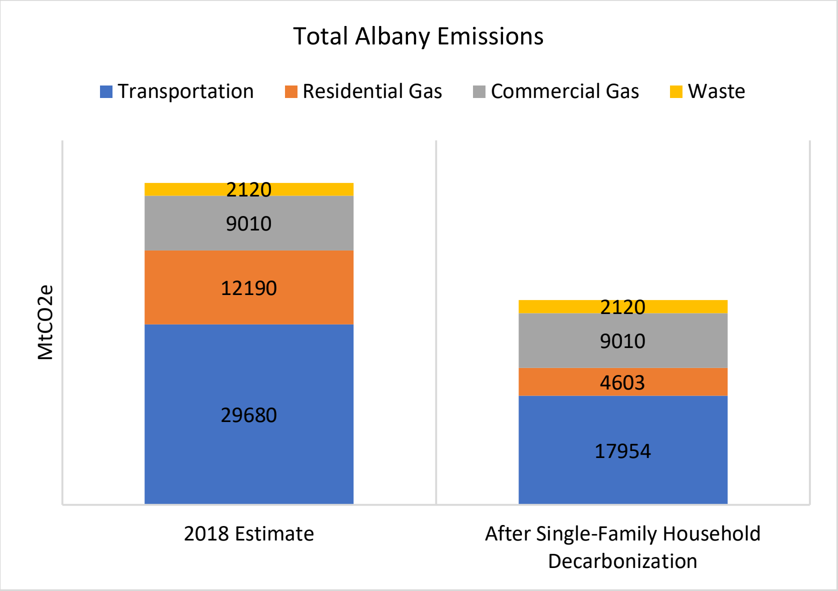


*Figure 35: Emissions reduction after decarbonization of single-family households compared to 2018 emissions in Albany*

This emissions reduction due to the electrification of single-family homes and their vehicles would also shift the share of emissions each sector is responsible for. Since the emissions from waste and commercial gas are unchanged but the total emissions are lower, their share increases, and commercial gas becomes the second largest emitter in Albany. Even though emissions from transportation would be reduced by 40%, the transport sector would remain the most important emitter responsible for 53% of all emissions. This shows that decarbonising the vehicle fleet needs to remain a priority for the city.

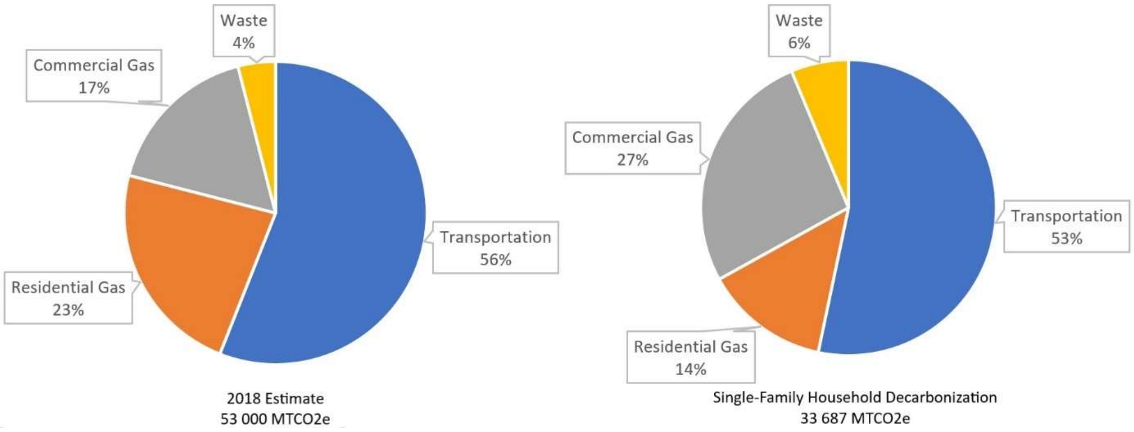


*Figure 36: Albany's share of emission by sector after single-family household electrification compared to 2018 estimate*

This thesis focused on single-family households, but the knowledge from several sections can be transferred to multi-family households or even the commercial sector. The TCO analysis of vehicles can be used for any citizen in Albany, and the state of California, and is not bound to single-family households. The HES tool has limitations to modelling multi-family homes or commercial buildings but could be used as a first estimate of energy usage for different end-uses, combined with the cost components found for heat pumps and large appliances. Showing the large emissions reductions and the price incurred on a household and city-level, this work can inspire similar studies focusing on the rest of the residential sector and the commercial sector, which will be crucial for the city of Albany to reach net zero carbon.

# 6. Conclusions

## 6.1 Thesis objective related conclusions

This thesis was one of the first of its kind to take a multi-sectoral household-perspective on the issue of decarbonization in order to reach net zero carbon on a city level. The objectives set out in the beginning of the work were fulfilled. This work presented a methodology for how to create typical household packages based on city-data used to model the energy uses and create a TCO analysis per end-use and for the combination of measures. 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 most advantageous and disadvantageous household combinations in regards of total electrifications were highlighted, which the city can use to identify which households need subsidies the most.

The TCO analysis resulted in several insights. Firstly, midsize and luxury full-size EVs are cost competitive with ICEs for all VMT cases. Compact EVs are cost competitive for average and high annual mileages. Following the DOE's vehicle model classification, there are currently not many cheap sub-compact or full-size EVs to choose from. It is a good time to purchase an EV because the $7,500 tax credits for EVs are being phased out and without manufacturers adjusting the purchase price to counterbalance the loss of the tax credit, compact and midsized EVs could lose their price-competitive edge over ICEs.

Heat pumps, both for water heating and space heating, have much higher initial costs than NG-fuelled heating options which can't be evened out by lower fuel prices and lead to higher TCO ratios. 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. 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 conclusions answering the objectives can be summarized as the following:

- The annualized total cost of ownership for a single-family Albany household result in an additional cost of 98-1202 $/year.
- 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.
- 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 lower energy use corresponds to lower TCO ratio, which could incentivize households to decrease energy use habits before electrifying homes. The higher mileage driven, the more it pays off to get an EV, however, generally less vehicle use (more walking, biking and public transportation) is encouraged in the city which would increase the TCO ratio.
- The emissions saved going net zero carbon on a household level is in the range of 3.1-7.4 $MtCO_2$ / year when focusing on compact and mid-sized household vehicles.
- Accounting for the estimated share of households in each house size, energy use, vehicle type and VMT combinations, the total costs of decarbonizing 3 751 single-family households in Albany adds up to over $35 million per year, which is $2.5 million more expensive than the gas alternative combinations.
- 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%.

## 6.2 Further work

Due to the large scope that a multi-sectoral analysis entails, some restrictions had to be made to fit the timeframe of the thesis. A range of improvements and further ideas can be implemented.

The weakness of any TCO analysis lies in the fact that it can easily lose relevance with prices shifting on a yearly basis. It is therefore important to point out that this analysis has a high relevance at the time of composition, especially while being in parallel to Albany updating its Climate Action and Adaption Plan that sets the direction of the city's development, with more and more discussion on natural gas bans and how to get gasoline vehicles off the streets. However, the TCO is to be regularly updated as heat pump purchase prices and installation costs fall, and as new EV models enter the market.

The current analysis could be further improved by refining the purchase price, installation costs and maintenance costs of heat pumps by contacting more companies in the area to give price estimates and not relying on EIA data, with a sensitivity analysis conducted on the influence of initial costs on the TCO.

The TCO was done with current pricing assuming that all households would decarbonize right now. However, since there is a natural turnover of vehicles and appliances as they reach their end of useful life which would happen for all households in the next 20 years at maximum, the analysis could be further enriched by doing a TCO for future years as well to estimate how the TCO could drop.

In addition, the electrification concept could be connected with energy efficiency measures, calculating the costs and benefits of energy efficiency upgrades (such as insulation) on a house to see if it could lead to the need of smaller and cheaper equipment. This could add another layer to the reality of options a household is faced with when considering retrofits. The results could show whether it makes sense for the city to incentivize energy efficiency upgrades of a home or if all efforts and incentives should be put into making decarbonization cheaper.

Lastly, further work could be put into presenting the result tables in a more comprehensible way for Albany residents. The results relevant on a household-level are presented as a matrix where the traits can be combined to calculate total costs and emission savings. These results could be made into an easy-to-use tool, webpage or app where residents could select their inputs of low, average or high house area, energy use, annual mileage and vehicle size of preference to get the total costs and emissions reductions. This could lead to more public awareness and citizen involvement which is crucial for the city's goal of economy-wide net zero carbon.

Personal further work will be done together with Max Wei and the Lawrence Berkeley National Laboratory to publish a research paper on this topic and to present the outcomes of this thesis to the city council of Albany.

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# Annexes

## Annex 1: Albany Energy Use Tables

*Table 36: Electricity usage and emissions for Albany 2005-2016*

| | | Electricity | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Residential | | | | Commercial | | | | Total | | | |
| Year | EF [tCO2 /MWh] | Usage [MWh] | % Δ against 2005 | Emissions [t CO2e] | % Δ against 2005 | Usage [MWh] | % Δ against 2005 | Emissions [t CO2e] | % Δ against 2005 | Usage [kWh] | % Δ against 2005 | Emissions [t CO2e] | % Δ against 2005 |
| 2005 | 0.222 | 26,757 | | 5,934 | | 40,461 | | 8,973 | | 67,218 | | 14,907 | |
| 2006 | 0.207 | 27,219 | 1.7% | 5,629 | -5.1% | 40,574 | 0.3% | 8,391 | -6.5% | 67,793 | 0.9% | 14,020 | -6.0% |
| 2007 | 0.288 | 26,793 | 0.1% | 7,728 | 30.2% | 40,673 | 0.5% | 11,731 | 30.7% | 67,466 | 0.4% | 19,460 | 30.5% |
| 2008 | 0.291 | 26,385 | -1.4% | 7,670 | 29.3% | 39,622 | -2.1% | 11,518 | 28.4% | 66,007 | -1.8% | 19,188 | 28.7% |
| 2009 | 0.261 | 26,450 | -1.1% | 6,897 | 16.2% | 38,943 | -3.8% | 10,155 | 13.2% | 65,393 | -2.7% | 17,052 | 14.4% |
| 2010 | 0.202 | 26,610 | -0.5% | 5,370 | -9.5% | 38,752 | -4.2% | 7,821 | -12.8% | 65,362 | -2.8% | 13,191 | -11.5% |
| 2011 | 0.178 | 26,420 | -1.3% | 4,709 | -20.6% | 38,752 | -4.2% | 6,907 | -23.0% | 65,173 | -3.0% | 11,616 | -22.1% |
| 2012 | 0.202 | 25,647 | -4.1% | 5,176 | -12.8% | 38,098 | -5.8% | 7,689 | -14.3% | 63,745 | -5.2% | 12,865 | -13.7% |
| 2013 | 0.194 | 25,202 | -5.8% | 4,880 | -17.8% | 38,457 | -5.0% | 7,447 | -17.0% | 63,660 | -5.3% | 12,328 | -17.3% |
| 2014 | 0.197 | 23,499 | -12.2% | 4,636 | -21.9% | 36,886 | -8.8% | 7,277 | -18.9% | 60,385 | -10.2% | 11,913 | -20.1% |
| 2015 | 0.184 | 22,992 | -14.1% | 4,223 | -28.8% | 36,590 | -9.6% | 6,721 | -25.1% | 59,582 | -11.4% | 10,944 | -26.6% |
| 2016 | 0.133 | 23,260 | -13.1% | 3,098 | -47.8% | 39,606 | -2.1% | 5,275 | -41.2% | 62,866 | -6.5% | 8,373 | -43.8% |

*Table 37: Natural gas usage and emissions for Albany 2005-2016*

| | | Natural Gas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Residential | | | Commercial | | | Total | | |
| Year | EF [kg/ therm] | Usage [thousand therms] | Emissions [t CO2e] | % Δ against 2005 | Usage [thousand therms] | Emissions [t CO2e] | % Δ against 2005 | Usage [thousand therms] | Emissions [t CO2e] | % Δ against 2005 |
| 2005 | 5.31 | 2,634 | 13,977 | | 1,670 | 4.02 | | 4,304 | 13,981 | |
| 2006 | 5.31 | 2,708 | 14,371 | 2.8% | 1,889 | 4.55 | 13.1% | 4,597 | 14,375 | 2.8% |
| 2007 | 5.31 | 2,671 | 14,174 | 1.4% | 2,047 | 4.93 | 22.6% | 4,718 | 14,179 | 1.4% |
| 2008 | 5.31 | 2,665 | 14,141 | 1.2% | 1,889 | 4.55 | 13.1% | 4,554 | 14,145 | 1.2% |
| 2009 | 5.31 | 2,655 | 14,088 | 0.8% | 1,872 | 4.51 | 12.1% | 4,527 | 14,092 | 0.8% |
| 2010 | 5.31 | 2,695 | 14,301 | 2.3% | 1,789 | 4.31 | 7.2% | 4,484 | 14,305 | 2.3% |
| 2011 | 5.31 | 2,802 | 14,866 | 6.4% | 1,818 | 4.37 | 8.9% | 4,619 | 14,870 | 6.4% |
| 2012 | 5.31 | 2,611 | 13,853 | -0.9% | 1,807 | 4.35 | 8.3% | 4,418 | 13,857 | -0.9% |
| 2013 | 5.31 | 2,613 | 13,864 | -0.8% | 1,833 | 4.41 | 9.8% | 4,445 | 13,868 | -0.8% |
| 2014 | 5.31 | 2,061 | 10,936 | -21.8% | 1,422 | 3.42 | -14.8% | 3,483 | 10,940 | -21.8% |
| 2015 | 5.31 | 2,093 | 11,104 | -20.6% | 1,459 | 3.51 | -12.6% | 3,552 | 11,108 | -20.6% |
| 2016 | 5.31 | 2,198 | 11,664 | -16.5% | 1,528 | 3.68 | -8.5% | 3,726 | 11,668 | -16.5% |

## Annex 2: Correction Factor for HES

When comparing similar occupied houses, it is not unusual to see energy usage differences in the order of up to factor 5 for due to occupancy differences (Rainer, L., e-mail communication, Aug 28, 2019). With mild climates like Albany, the temperature set point can have a large effect on heating energy use. The other gas appliances (stove, dryer) can also make a difference.

The outputs of the HES tool for an average sized home with average energy usage were compared to typical energy usage values from RASS for the area to make sure the modelling was consistent with another source. Additional data points for comparison were the 2016 average natural gas and electricity usage for single-family households in Albany obtained from PG&E, and audit data showing total natural gas and electricity usage for 15 single-family households in Albany. The audit data is based on the Home Energy Scoring Tool, performed by DOE-trained Home Energy Score Assessors that provide the home with a Home Energy Score within an energy audit, home inspection package, or as a standalone product to get directly comparable and credible information about a home's energy use [129]. The RASS was the only source that showed energy usage broken down per end-use the same way as the HES tool.

When juxtaposing the HES outputs with the other sources, it became clear that a series of correction factors were needed to be introduced to match the model outputs to empirical data.

Firstly, a correction factor for the HES tool space heating overestimation of 2.5 was introduced to the space heating natural gas and electricity consumption in order to match the RASS data for space heating, as well as the estimations from the audit data. While the natural gas usage from water heating and large appliances matched approximately the 2009 RASS data, the space heating was 1.9-3.1 times as much as the average Zone 5 home (which is the RASS Forecasting Climate Zone that Albany belongs to) or the average single-family home. The electricity usage for the space heating for furnaces was also 1.2-2.5 times as much [130]. Once this correction factor was incorporated, the HES model is in line with the RASS and audit numbers. However, an interesting phenomenon was discovered, where the HES outputs, RASS data and audit outcomes were all higher than the 2016 PG&E average electricity and natural gas usage for Albany.

This could be explained by several reasons. Firstly, the building simulation program DOE-2 used in HES does the simulations using TMY3 weather data from the National Solar Radiation Data Base, that is a typical meteorological year put together using monthly data from the years 1991 to 2005 [131]. The years used are cooler than present years and can impact the results, especially space heating. We have aggregated residential electricity and natural gas use for the city of Albany obtained from PG&E from 2005 to 2016. If we assume that the TMY3 modelled data is like 2005 weather (and not 1991-2005 due to lack of data), and compare how the weather impacts the energy usage, we can assume a weather correction factor. The 2016 PG&E average is much lower than the other data because it was a relatively warm year that diminished the heating needs. When there was an extremely warm year in 2014, the heating demand days dropped and so did the residential natural gas and electricity use from 2013 to 2014. The 2016 data is still from a relatively warm year but is cooler than 2014. The residential NG dropped 16.7% from 2005 to 2016, and the residential electricity dropped 13.1%. Although the drop of energy usage can't be fully contributed to the weather, a strong correlation is seen. Therefore, a weather correction factor is assumed for the weather change between the HES output and the PG&E 2016 data, with a 5% energy reduction for water heaters and 20% reduction in space heating energy demand.

Another reason for a difference between the Albany average single-family energy usage and the RASS data is the fact that there have been equipment efficiency improvements since the 2009 California residential appliance saturation study. As typically heating equipment and large appliances have useful lifetimes of approximately 10-20 years, most equipment has been changed out in the last 10 years since the release of the RASS data. As the HES tool takes into account the efficiencies of water and space heating equipment, but not the energy efficiency improvements in large appliances, a final correction factor of 10% reduction in the energy use of large appliances is introduced accounting for the efficiency improvement.

The three correction factors introduced to the outputs of the HES model, summarized in Table 38, are an important assumption in the methodology which impacts the results. The correction factors were adopted to give results that are relevant to the households of Albany, and an over-estimation of the natural gas and electricity usage could have shifted the TCO outcomes in a way that doesn't mirror the reality when estimating average households. In addition, inputting the natural gas usage without the correction factor would have grossly over-estimated the $CO_2$ emissions saved on a household and city level. The results presented of the energy usage and fuel prices for the TCO are already including the correction factor and are reflecting the case of Albany as close as it can.

*Table 38: Summary of correction factors implemented on HES outputs*

| | | |
|---|---|---|
| Correction 1 | HES Space Heating Overestimation | Factor 2.5 reduction |
| Correction 2 | Warmer Weather in 2016 compared to 2005 | 5% reduction for Water Heating<br>20% reduction for Space Heating |
| Correction 3 | Efficiency Improvements for Large Appliances | 10% reduction |