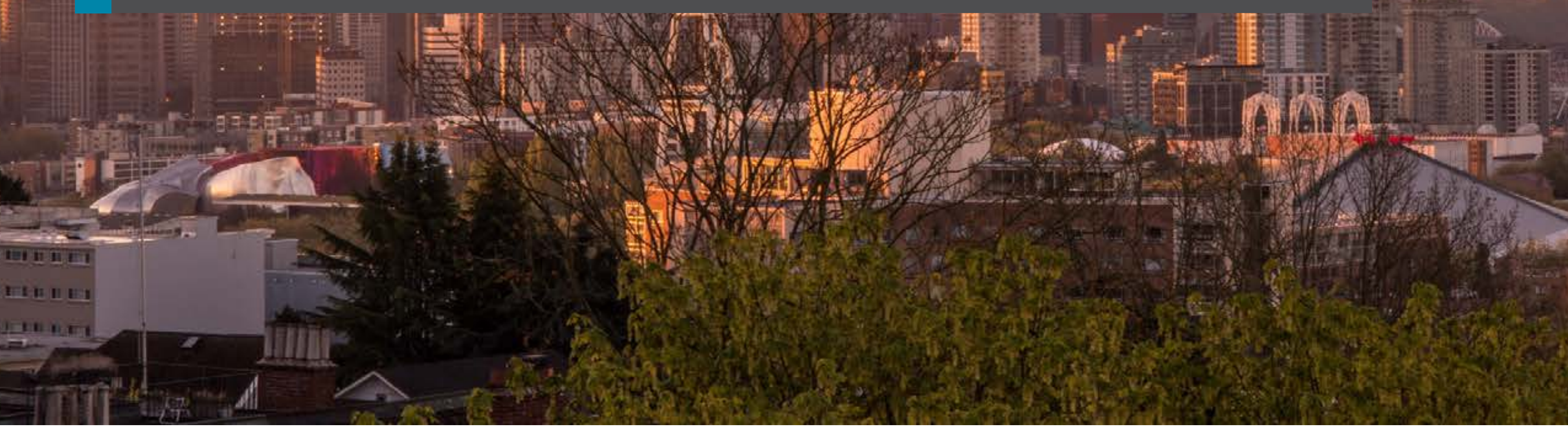
King County Communitywide Consumption-based GHG Emissions Inventory

Puget Sound Regional Emissions Analysis

EcoDataLab and Stockholm Environment Institute

FINAL REPORT

September 2022



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PART I:
CONSUMPTION-BASED EMISSIONS INVENTORY

Introduction

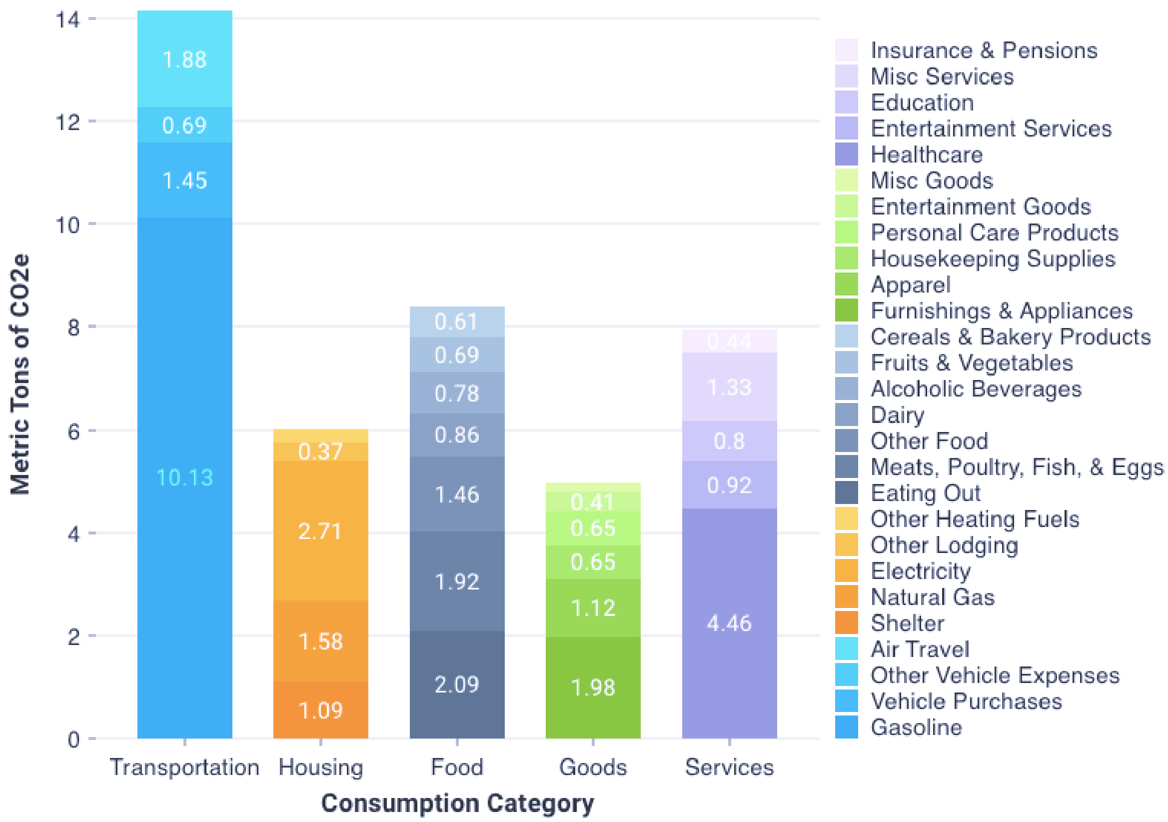
A consumption-based emissions inventory (or "CBEI") is an estimate of the greenhouse gas emissions associated with the activity of all residents of a geographic area. It's equivalent to a personal household carbon footprint estimate, except calculated for all households in a jurisdiction. Consumption-based emissions are modeled based on local variables such as income and vehicle ownership, and on scientific studies that tie these variables to changes in consumption-based emissions.

In King County in 2019, the typical household was responsible for 42 metric tons of CO_2e annually ($MTCO_2e$), or 17 $MTCO_2e$ per person. With 907,761 households in the county, this is a total of roughly 38 million $MTCO_2e$ for 2019 attributable to residents of King County.

These emissions are broken out into five areas: transportation, housing, food, goods, and services. Transportation was the single largest category of emissions, followed by services and housing. Gasoline was the single largest source of emissions overall, among all sub-categories.

The bar chart below provides an overview of the county's average per-household emissions. The actual emissions of any particular household, however, could vary significantly from this average. Differences in household size, spending, housing, travel, and other discretionary and non-discretionary factors will affect any individual household's emissions.

Figure 1. King County consumption-based inventory.



Consumption-Based Emissions Methodology

CBEIs differ from traditional greenhouse gas inventories. In traditional or "geographic" inventories, a county would look at all emissions that occur within the county's borders. In contrast, CBEIs consider emissions that may occur anywhere in the world, as long as they are directly or indirectly a result of the activities of the residents of the county.

Geographic and consumption-based approaches are complementary and partially overlapping. Both will look at resident's local, direct emissions (e.g., from driving or home heating). A geographic inventory will also consider the emissions from local businesses and visitors, but ignore anything outside the county's boundaries. Meanwhile, a consumption-based inventory will omit the local emissions from businesses and visitors, but instead account for emissions associated with resident's travel to other cities, as well as the emissions associated with producing the goods and services they purchase or consume. Those consumption-based emissions may occur anywhere in the world.

Because these emissions occur anywhere in the world, it’s virtually impossible to measure them directly. Instead, these consumption emissions are estimated using a model. This model takes into consideration six key household variables: household size, household income, vehicle ownership, home size, educational attainment, and home ownership.

These variables often have clear, direct effects on consumption. For instance, larger homes generally take more energy to heat or cool, while more people per household also means more food consumed per household.

Table 1 below compares the values of these household characteristics in King County with those of the US average:

Table 1. Household characteristics, King County vs United States.

Household Characteristic	King County	US
Average Income	$131,219	$88,783
Vehicle Ownership	1.71	1.82
Household Size	2.44	2.61
Home Size (rooms)	5.82	6.57
Home Ownership	56%	64%
Educational Attainment (college degree)	58%	35%

The emissions profile for King County is based on a "typical" household in 2019, using the average household characteristics for King County as shown above. Most actual households in the county differ in one or more ways; and households with different characteristics are expected to have different emissions profiles.

Major Categories

Among all categories, transportation, food, and services are the largest overall categories, accounting for 34%, 20%, and 19% of emissions, respectively. Together, these account for over 73% of total emissions. Within sub-categories, gasoline, healthcare, and electricity are the top three, accounting for 24%, 11%, and 7% of total emissions, respectively - a combined 42%.

Transportation

The transportation category includes gasoline usage, vehicle purchases & maintenance, and air travel. For an average household in King County, transportation accounts for 14.2 $MTCO_2e$ per year, per household. Much of this comes from gasoline, which accounts for 10.1 $MTCO_2e$, or 72% of the total transportation emissions.

Housing

Household energy use, home construction and maintenance (“shelter”), and water usage make up the Housing category. Overall, a typical household has 6.1 MTCO2e resulting from housing, with the largest single category being shelter. Shelter produced 1.1 MTCO_2e, or 18% of the total housing emissions.

Food

The Food category includes all food consumed by residents of King County, broken down by meat, dairy, fruits & vegetables, and other foods consumed at home, as well as eating out. Food accounts for 8.4 MTCO2e, and the single largest sub-category is eating out at 2.1, or 25% of total food emissions.

Goods

Goods includes all physical items purchased by the household (excluding items in other categories). Goods includes things like furniture, personal electronics, clothing, toys, and books. These goods account for 5 MTCO_2e per household per year. Of these goods, furnishings & equipment is the single largest source, making up 2 MTCO_2e, or 40%, of total goods.

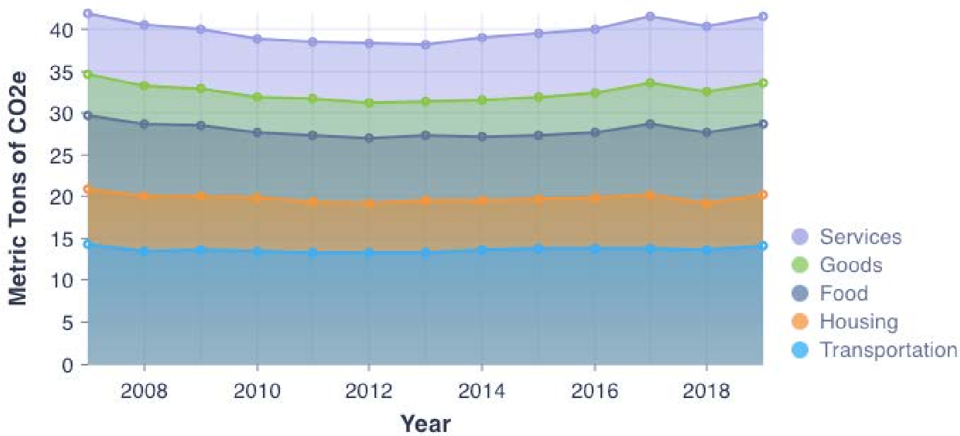
Services

Services includes the emissions associated with things like healthcare, education, insurance & finance, and entertainment experiences like concerts and museums. Services account for 8 MTCO_2e per household, and the single largest category is healthcare at 4.5 MTCO_2e, or 56%.

Historical Trends

Since 2007, per household CO2e emissions have decreased by 0.7%, or 0.3 $MTCO_2e$ per household, as shown in Figure 2. Historical CBEI trends.

Figure 2. Historical CBEI trends.

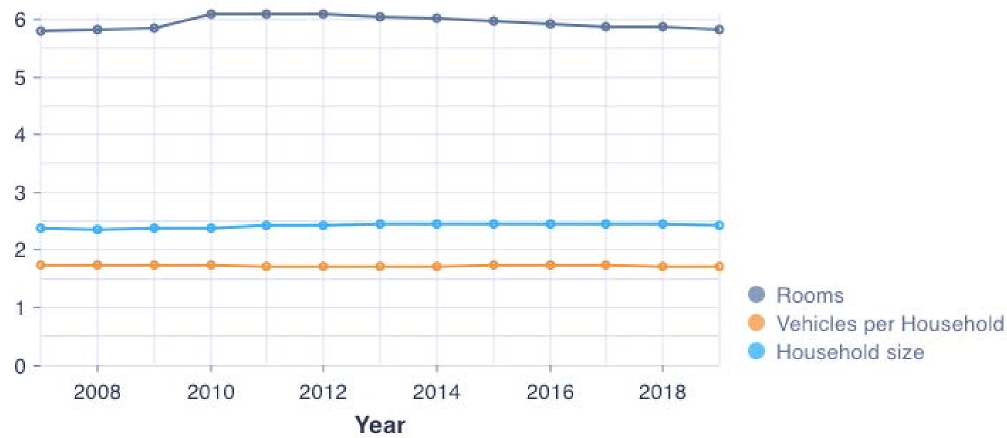


Services and Goods have seen the largest increases, of 9% and 1%, respectively.

At a national level, consumption-based emissions have declined by more than 12%. The electricity grid has been getting cleaner, vehicle fuel economy has been improving, and industries have generally been figuring out how to produce more with less emissions. However, King County has seen significant demographic changes over this same time period. Since 2007, household incomes have increased by over $44,000, or 51%. Even after adjusting for inflation, this is still an increase of 22%. The share of households with a college degree has also grown substantially, from 45% to 58%. Vehicle ownership and home ownership rates have declined slightly, but not enough to make a significant difference. As a result, overall, King County's changes in household characteristics – higher incomes and education – has almost entirely offset the national-level trends of lower emissions.

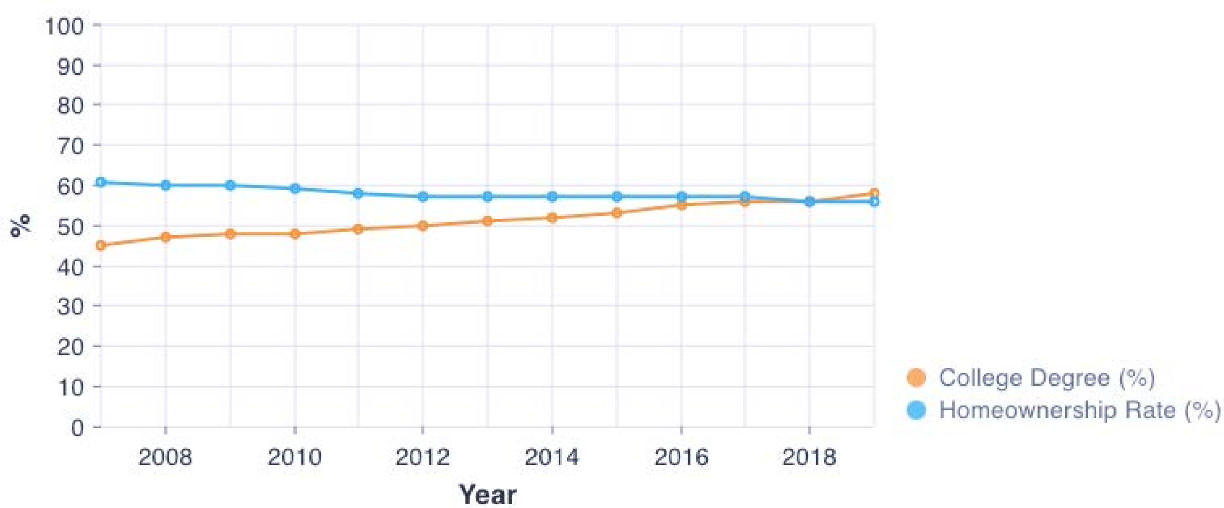
The charts below highlight the changes in these characteristics over time.

Figure 3. Rooms, vehicles per household, and household size trends over time.



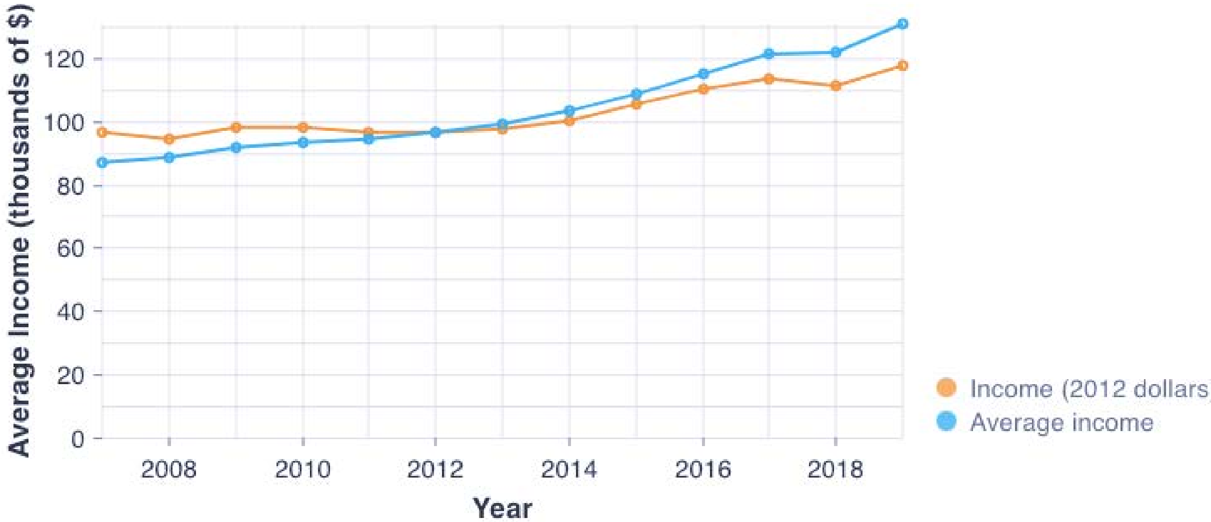
Since 2007, rooms per household, vehicles per household, and household size have remained largely constant.

Figure 4. Percent with college degree and homeownership rate trends.



The share of households with a college degree has increased substantially, from 45 to 56%, while the home ownership rate has decreased slightly.

Figure 5. Income over time.



The biggest change overall, however, has been in income. Since 2007, household incomes have increased by over $43,000, or 50%. After adjusting for inflation, this is an increase of 22%.

Growing household incomes – well outpacing inflation – have kept King County's consumption-based emissions from falling as much as the US average.

Category Breakdown

Some key sub-categories are of particular interest. These are detailed below.

Gasoline

Gasoline consumption is the #1 source of emissions in King County, responsible for over 10 $MTCO_2e$ per household. There are two key components that drive gasoline consumption: vehicle ownership, and the amount of driving per vehicle.

Nationwide, the US average is 1.82 vehicles per household. A typical vehicle is driven over 11,000 miles per year, and so the average American household drives roughly 20,514 miles per year.

Meanwhile, King County households have an average of 1.71 vehicles per household, and drive an estimated 21,172 miles per year. This works out to about 12,381 miles per vehicle, or 110% of average.

Lower vehicle ownership strongly corresponds to lower household vehicle miles traveled (VMT). However, despite reduced vehicle ownership, we still see above-average VMT in King County. This is not necessarily due to an unusually car-dependent lifestyle: 60% of people drove alone to get to work, with an average commute time of 28 minutes. Instead, the above-average household VMT is most likely attributable to the fact that King County's household income is substantially greater than the US average: at $131,219, vs $88,783 nationally. Greater incomes enable households to drive more for leisure or travel.

Examples of Individual Strategies for Reducing Gasoline Consumption

For households that aim to reduce their emissions from automobile usage, switching their primary commute vehicle to an electric vehicle is a common strategy. Depending on where they live, some households can purchase electric bicycles (e-bikes) to substitute for automobiles. E-bikes are bicycles that include an electric motor to assist pedaling, and can typically reach speeds of 20-28 mph. Some models include large cargo carriers capable of carrying kids, groceries, or even furniture. Between e-bikes, public transit, and the availability of car-sharing, rentals, or taxis (including Uber and Lyft), some households can achieve further reductions, or even eliminate their automobile use altogether. In King County, about 11% of households owned 0 vehicles.

Air Travel

For many individual households, air travel is a significant portion of emissions. However, for King County overall, air travel is only a small part of the county's consumption-based emissions, coming in at 1.9 $MTCO_2e$ per household on average (4.3% of total emissions). This varies significantly between households, however, largely due to income: air travel is a luxury for most Americans, and only the wealthiest households do substantial flying.

According to Gallup survey data, between 1999 and 2015, 48-60% of the US population did not fly in any given year. More recent data from Statista.com suggests that in 2019, 41% of the US had never traveled by air, and another 28% flew only about once per year.

Air travel in a mostly full aircraft is more fuel-efficient than driving alone, but the high-altitude pollution released is uniquely damaging to the environment and can make flying worse than driving. Most modern aircraft get roughly 70-100 miles per gallon per passenger seat; in comparison, the average fuel economy for new vehicles nationwide was 25.4 miles per gallon in 2020. However, due to additional climate forcing from high-altitude particulate matter, as well as lifecycle production of aviation fuels, air travel's overall emissions are roughly double what would be expected on a per gallon basis alone - making it more like driving a 35-50 mpg car. As a result, air travel may be more fuel-efficient than driving alone in an average vehicle, but usually not for two individuals traveling together.

Air travel also often results in significant emissions due to the long distances traveled. A two-person, one-vehicle household may only drive 10,000 miles per year, but could easily fly 24,000 person-miles with just two cross-country (3,000-mile) trips per year (3,000 miles each way on a two-way trip = 6,000 miles round trip per person, for two people = 12,000 miles round trip, twice = 24,000 miles).

Examples of Individual Strategies for Reducing Air Travel

Households that aim to reduce their air travel emissions typically avoid flying, take long-distance buses, or take Amtrak instead when available. In King County, Amtrak serves Seattle’s King Street Station with the *Coast Starlight*, which runs from Los Angeles, CA to Vancouver, BC; the *Empire Builder*, which runs east to Chicago; and the *Cascades*, a Pacific Northwest route running from Portland, OR to Vancouver, BC (the *Cascades* also stops in Tukwila).

Electricity

King County's electricity emissions derive from a combination of Puget Sound Energy (PSE) and Seattle City Light (SCL) data. Using the weighted average between these two utilities results in an average electricity usage of 8,740 kWh per household in the county and an average emissions factor of 310 grams per kWh.

However, there are significant differences between PSE and SCL. Firstly, in 2019 PSE derived 35% of its electricity from coal and another 31% from natural gas, two of the most carbon-intensive electricity sources available. Meanwhile, Seattle City Light derived 97% of its electricity from carbon-free sources. In addition, PSE and SCL customers used different amounts of electricity: PSE customers used an average of roughly 10,000 kWh, with an overall emissions of 531 grams of CO2 per kWh; while SCL customers used an average of 7,100 kWh at an emissions rate of only 19 gCO2 per kWh.

Roughly 51% of households in King County use electricity for heating.

Examples of Individual Strategies for Reducing Electricity Emissions

Some common strategies for households to reduce their electricity emissions include energy efficiency improvements and/or switching to 100% carbon-free or renewable electricity.

To improve energy efficiency, households can improve insulation and weatherization, replace old lightbulbs with LEDs and ensure new appliances are EnergySTAR-certified, and use a smart thermostat to ensure heating and air conditioning only run when needed.

For clean or renewable electricity, some utilities offer a carbon-free option, or a local power provider may be available to switch to with a clean power option. If neither of these options are available, individual consumers can also purchase renewable energy credits from a national provider.

Natural Gas

Natural gas is a common fuel for home heating, water heating, clothes drying, and cooking. The primary ingredient of natural gas is methane (CH_4), a potent greenhouse gas. The majority of GHG emissions associated with natural gas result from burning the gas to produce heat, which also emits CO_2. In addition, some methane is leaked into the atmosphere during the extraction, processing, and transport (piping) of natural gas into homes.

Burning natural gas in homes not only contributes to CO_2 emissions, but also to local (indoor and outdoor) air pollution. Natural gas combustion produces carbon monoxide, nitrogen dioxide, fine particulate matter ($PM_{2.5}$), and formaldehyde, among other pollutants. When burned in furnaces for heating or water heating, these fumes are vented into the surrounding neighborhood, where they generally disperse at low concentrations. However, when burned in a gas stove or oven, these fumes are emitted directly into residential living spaces, which are often not adequately vented. As a result, gas stoves can lead to dangerously elevated levels of indoor air pollution. Even moderately well-ventilated homes with gas stoves can have elevated levels of air pollutants that have increase the risk of asthma in children and exacerbate asthmatic symptoms in adults.

Methane extraction, transport, storage, and distribution systems nationwide typically have small leaks. Methane itself is a much more potent greenhouse gas than CO_2 - one ton of methane has the same warming impact as nearly 30 tons of CO_2 when considered over a 100-year time frame, and 80-90 tons of CO2 when considered over a 20-year time frame. As a result, even a small leakage rate of just 5% would mean that the leaked methane is a bigger contributor to climate change than the CO_2 from burning the other 95%. In 2019, the national average leakage rate throughout the entire natural gas supply chain was about 2.3%.

Nationally, the EPA estimates about half of all methane leaks occur in production, with another 25% occurring in transmission and storage. Distribution and post-meter leakage each contribute about 10% to the overall leakage rate. The consumption-based inventory uses the 2.3% overall leakage rate.

Natural gas usage for King County is estimated at 299 therms per household, resulting in 1.6 $MTCO_2e$. Roughly 43% of households in the county use gas for heating.

Examples of Individual Strategies for Reducing Natural Gas Use

Typically, the most effective ways for households to reduce their natural gas usage typically replace gas furnaces and water heaters with heat pumps, clothes dryers with electric alternatives, and gas cookstoves with induction cooktops. These replacement appliances can be expensive, however, so energy efficiency improvements in the interim can also help reduce natural gas usage. Some utilities allow customers to opt to purchase renewable natural gas to offset their household consumption.

Food

Globally, roughly 24% of greenhouse gas emissions are a result of agriculture, forestry, and other land use changes, with the majority of these emissions resulting from agriculture. In the US, agriculture resulted in roughly 623 million metric tons of greenhouse gas emissions in 2019, or about 10% of national emissions (according to the US EPA's most recent national inventory).

Emissions from agriculture are driven primarily by two sources. In the US, most agricultural emissions derive from nitrous oxide (N_2O), a greenhouse gas that is released from the breakdown of nitrogen-based fertilizers. N_2O accounts for roughly 55% of the US' agriculture greenhouse gas emissions.

The second-largest source of agricultural emissions is methane (CH_4), a potent greenhouse gas which is produced by certain animals like cows, sheep, and goats. These animals rely on microbes to break down the grass and other plants they eat, in a process known as enteric (intestinal) fermentation. This digestive fermentation produces methane as a byproduct (much in the same way that beer fermentation produces CO_2 as a byproduct). Methane from digestion is nearly 30% of the US GHG emissions from agriculture. The decomposition of animal manure (also into methane) contributes another 12% of agriculture emissions. Nitrous oxide and methane combined account for 97% of emissions directly associated with agriculture.

The consumption-based inventory includes these direct nitrous oxide and methane emissions from agriculture, emissions from fixed capital investments in agricultural equipment and facilities, as well as emissions associated with transport and sale of food. In the consumption-based inventory, direct emissions from agriculture are the vast majority of the emissions associate with food - generally around 67-80% of food emissions come directly from food production. For most foods, transportation comprises about 5% of the emissions, while wholesale and retail make up another 5-15%. Fixed capital investments (e.g. buildings and equipment) is estimated at typically around 13% of total emissions.

While nitrogen fertilizer is the single largest source of emissions nationally, meat & dairy are often the largest sources of at-home food emissions for households. In King County, meat, poultry, fish, eggs, and dairy combined account for 2.8 tons of emissions, while fruits & vegetables, cereals, and other foods account for another 2.8 $MTCO_2e$.

Despite being only a small fraction of overall calories, meat & dairy have an outsized impact on the typical household's emissions associated with food. This is because the emissions associated with meat consumption not only includes the direct methane emissions from the animals - it also includes the nitrous oxide emissions from growing all of the crops to feed those animals.

It takes a lot of feed crop - mostly corn - to produce one calorie of meat. In the case of beef, it can be as many as 33 calories of feed per calorie of beef. As a result, a quarter pound of beef (284 calories) could require over 9,000 calories of corn to produce.

Further compounding these food emissions is the fact that an estimated 30-40% of food goes to waste. Emissions from the production of wasted food is included in the overall emissions associated with food, driving up the emissions of all food consumption. While some of this loss occurs in production, storage, or transport, households are often also a significant source of food waste. According to the United Nations, US households purchase more calories per capita than any other country - nearly 3,800 calories per person per day in 2018. This includes all purchased food, whether consumed or otherwise.

Eating out also contributes to a portion of food emissions. For the typical King County household, eating out is associated with roughly 2.1 $MTCO_2e$ per year. However, this includes not only all the food consumed while eating out, but also the operational emissions from restaurants, including emissions from cooking, transportation, and construction of the building. In comparison, household emissions from cooking, transportation, and construction are allocated to the transportation and housing sectors. Overall, eating out is likely similar emissions per calorie as food prepared at home; however, restaurants across the US often also serve much larger portions than are typically consumed at home, which can lead to further food waste or excess.

Examples of Individual Strategies for Reducing Food Emissions

Households that aim to reduce emissions from food have two primary strategies they can use. First, avoiding food waste and only buying as much food as the household needs is one of the easiest - and most cost-effective - ways to avoid food emissions. Second, replacing meat and dairy with plant-based meat substitutes can lead to further large emissions reductions. Buying organic and locally grown food does not typically have much impact on emissions, but can provide other social and economic benefits.

Water

The average household in King County uses an estimated 36,613 gallons per year. This varies significantly between single-family and multi-family homes: a typical single-family household uses roughly 46,409 gallons per year, while a multi-family household uses an average of 26,001 gallons per year.

The emissions associated with average household water use in King County is estimated at 0.02 $MTCO_2e$, with an emission factor of roughly 0.5 grams CO_2e per gallon. 80% of emissions associated with water in King County occur in wastewater treatment; and within wastewater treatment, an estimated 80% of emissions occur as a result of methane leakage. Overall, water is a negligible contributor to household consumption-based emissions.

Waste

Overall, the average King County household generates 0.54 tons of waste per year. Household waste in King County is primarily composed of food waste, mixed materials, and construction materials, accounting for 62% of all residential waste. Based upon these materials and local recycling, composting, & landfill practices, the typical King County household is responsible for -0.06 $MTCO_2e$ emissions from waste every year. In other words, the materials discarded by King County residents may have a net effect of reducing GHG emissions, not causing them.

Negative emissions occur when organic material (yard trimmings, paper, or food waste) is properly disposed of. In the landfill, this organic material can decompose to produce methane – normally a potent greenhouse gas, but in King County landfills, this biogenic methane is captured and sold to replace the use of fossil natural gas. Meanwhile, composted food waste turns into organic carbon stored in soil, supporting healthy soil practices for local farmers.

Goods & Services

Goods and services include all physical goods purchased for household use (including furniture, clothing, electronics, personal care products, and other various household furnishings), as well as services used by residents (including healthcare, entertainment, education, personal care services, financial services, and others).

Goods and services often have lower emissions per dollar than food or energy. Households with higher incomes tend to spend more money (as well as a greater fraction of their income) on these various goods and services. Households with an adult who has a college degree tend to have higher income, and as a result tend to spend more on entertainment services, financial services, personal care products & services, and education. Homeowners also tend to spend more on home furnishings and equipment.

The largest sources of emissions from goods comes from household furnishings and equipment (including miscellaneous household equipment, furniture, and appliances), as well as apparel (clothing). Healthcare dominates emissions from services, accounting for 4.5 $MTCO_2e$ in King County. Nationally, healthcare makes up roughly 18% of the US economy; in King County, healthcare emissions are about 11% of the typical household's carbon footprint. Healthcare emissions include emissions from hospitals and other medical facilities, pharmaceutical manufacturing, medical equipment, and more.

Other major categories of emissions include entertainment services (mostly fees & admissions to museums, concerts, etc.), education, financial services like insurance & pensions, and miscellaneous services (including personal care, household operations, etc.)

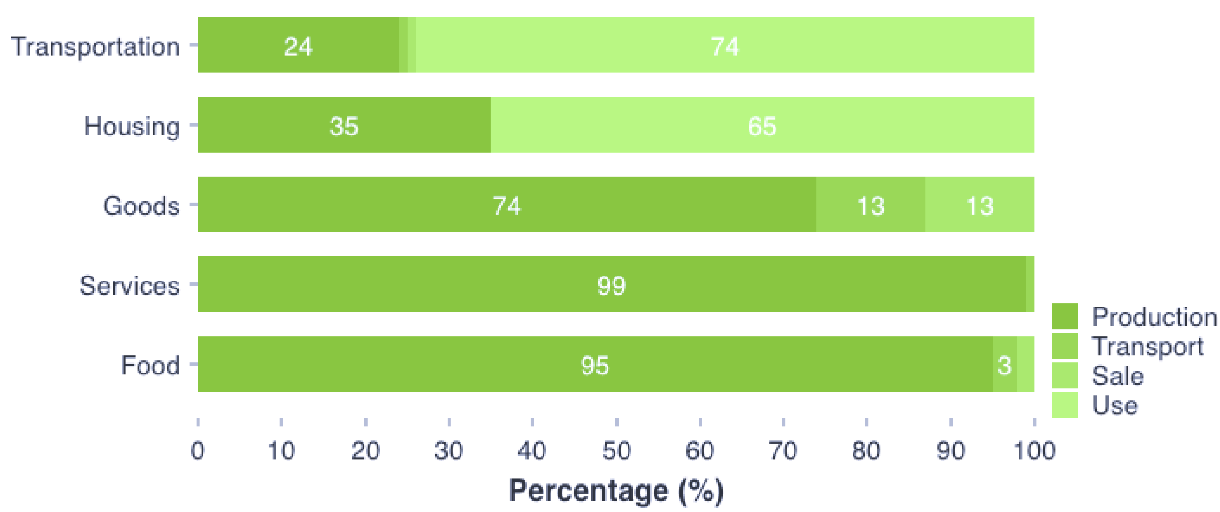
Emissions Breakdown by Supply Chain Stage

Consumption-based emissions occur at many points in the supply chain. Emissions are generated in production, during transport (by rail, sea, road, or air), in wholesale and retail, and use. In some cases, disposal also generates emissions; however, disposal also sometimes results in storing carbon that would otherwise be re-emitted. The chart below shows the share of emissions associated with production, transport, sale, and use for each overarching category of goods. (Because disposal emissions are sometimes negative, they are not included on this chart).

Household Emissions Breakdown by Supply Chain Stage - US Average

Below, Figure 6 shows what percentage of emissions are associated with each life-cycle phase (production, transport, sale, and use), for each category of consumption.

Figure 6. Household emissions breakdown by supply chain stage - US average.



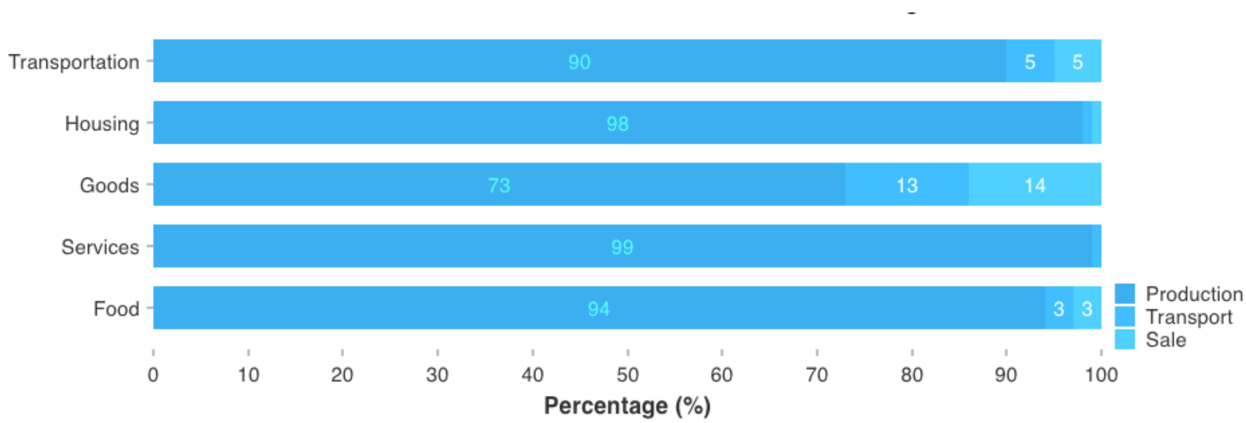
Overall, emissions from transportation and housing are dominated by "use phase" emissions - the burning of fossil fuels (such as gasoline or the methane in natural gas) for transportation or home heating energy. This "use phase" - primarily gasoline combustion - makes up nearly 74% of household transportation emissions. For housing emissions, "use phase" emissions (electricity and home heating fuels) make up 65%.

For food, goods, and services, however, use- phase emissions are practically zero. These categories have some transport and sale emissions, but are overwhelmingly dominated by production emissions. The chart below shows the pre-consumer (production, transport, and sale) breakdown of emissions by category.

Pre-Consumer Emissions Breakdown - US Average

Below, Figure 7 shows what percentage of emissions are associated with each life-cycle phase prior to use (production, transport, and sale), for each category of consumption. These are the emissions associated with the production of goods and services prior to households acquiring them.

Figure 7. Pre-consumer emissions breakdown - US average.



Pre-consumer emissions associated with Transportation (that is, prior to a consumer using a vehicle) are predominantly from production (90%). Roughly 50% of these emissions are associated with the production of fuel (oil extraction & refining); the remaining 50% are from the production of vehicles and vehicle parts. Most of the transport emissions in this section derive from the transport of used vehicles, while sales emissions mostly derive from the sale of gasoline and other transportation fuels.

For Housing, over 99% of pre-consumer emissions occur in production. This is dominated by the production of natural gas and the construction of homes, apartments, and other lodging (including hotels). The small portion of these emissions attributable to transport and sale are entirely due to the transport and sale of fossil fuels (and wood) used for home heating.

For Goods, only about 72% of emissions come from production. About 13% of emissions from goods comes from transportation, and 14% comes from retail. Transport emissions from goods disproportionately occur from truck travel, which make up over 90% of the total goods transport emissions (12% of goods total emissions). Similarly, over 90% of the emissions associated with the sale of goods comes from retail (13% of goods total emissions).

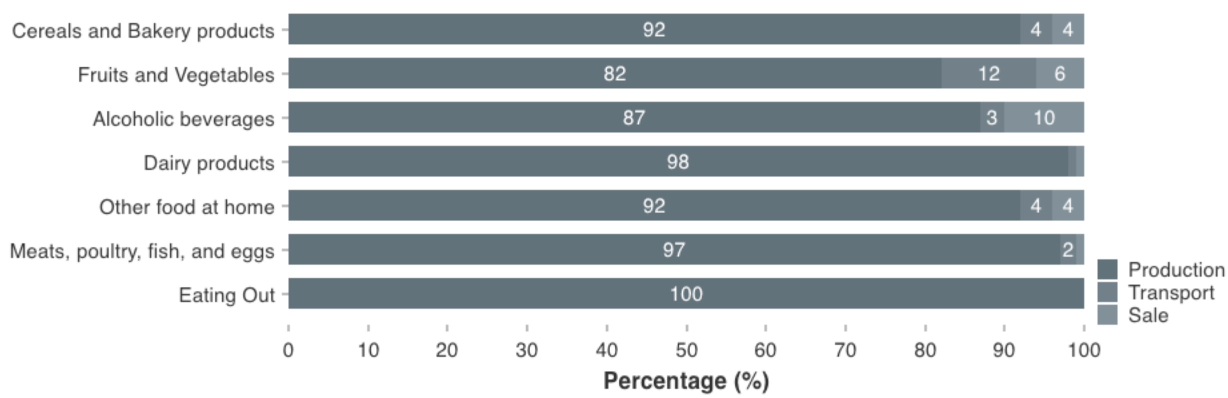
Like Housing, pre-consumer emissions from Services are overwhelmingly (99%+) from production. Services is primarily made up of activities like healthcare, education, entertainment, and various financial services; most of these involve little to no retail or transportation to provide these services.

Lastly, for Food, roughly 95% of emissions occur in production. As discussed in the Food category breakdown, food emissions primarily come from application of nitrogen fertilizers and enteric fermentation (methane released from digestion by cows and other livestock). These emissions significantly outweigh the emissions associated with transportation or sale of food. The following chart provides a detailed breakdown by sub-category within Food.

Pre-Consumer Food Emissions Breakdown - US Average

Below, Figure 8 shows what percentage of emissions are associated with production, transport, and sale, for each category of food.

Figure 8. Pre-consumer food emissions breakdown - US average.



For all food sub-categories, over 80% of emissions come from production. For fruits and vegetables, and alcoholic beverages, production emissions account for roughly 83% and 87% of pre-consumer emissions, respectively. Cereals and bakery products, as well as miscellaneous household food, have roughly 92% of their emissions from production. Meanwhile, meat and dairy products have over 97% of their emissions from production, while eating out has 99% of its emissions from production. Within all food sub-categories, transportation emissions are overwhelmingly dominated by truck transport.

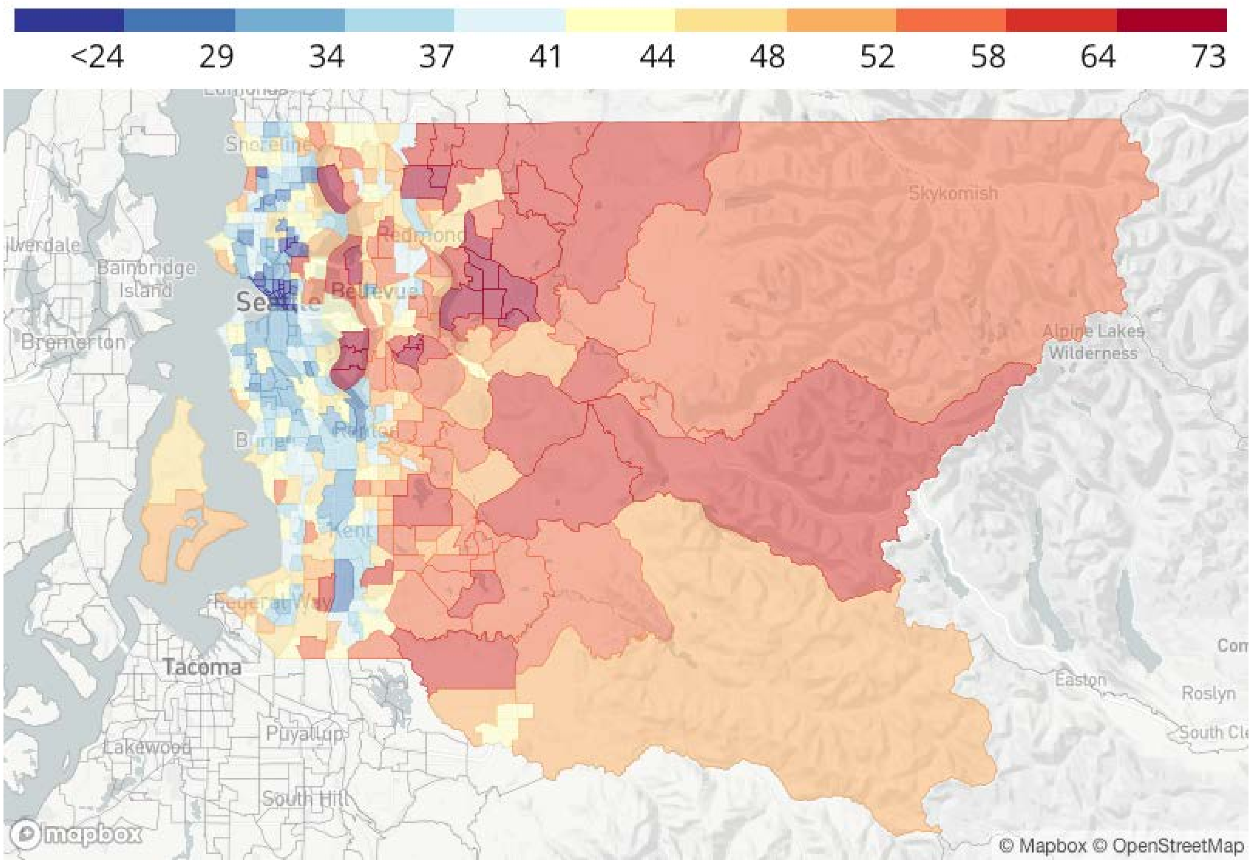
As discussed previously, meat and dairy products have significantly higher emissions (on either a per calorie or per dollar basis) than other foods. These extra emissions are virtually entirely in the production phase, which is why production is a higher-than-average share of emissions for meat and dairy.

Meanwhile, even fruits and vegetables have predominantly production-phase emissions because the transport of food is relatively efficient, even over longer distances. As a result, fruits and vegetables from local farmer's markets are not necessarily lower emissions than those at large supermarkets. Because farmers typically bring relatively small quantities to the farmer's market, the transport may be much less efficient, which could result in a higher overall footprint than food that may have been grown further away but transported more efficiently.

Neighborhood Variation

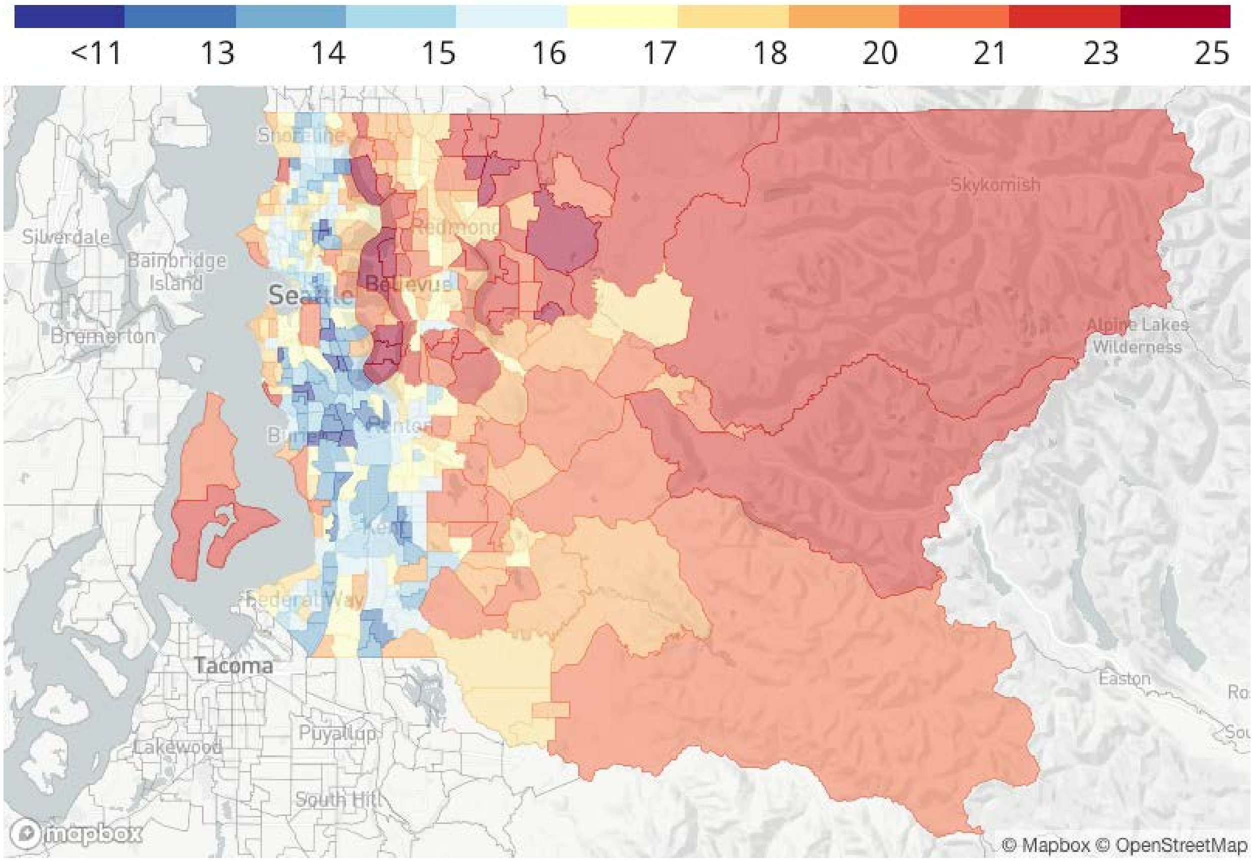
Among the 397 neighborhoods (census tracts) within the county, there is substantial variation in both emissions and the key driving demographic variables. The highest-emitting neighborhood has per-household emissions of 73 tons, while households in the lowest-emitting neighborhood have emissions of 17 tons - roughly a 4-fold difference.

Figure 9. Consumption-based emissions map ($MTCO_2e$ per household).



On a per-capita basis, these differences are similarly pronounced. King County's highest per-capita neighborhoods have emissions of 25 tons per person, while the lowest per-capita neighborhoods have emissions around 10 tons.

Figure 10. Consumption-based emissions map ($MTCO_2e$ per person).



The variation in emissions between neighborhoods is driven by a wide range of factors. In many locations, the history of local land use planning is a significant influence on the consumption-based emissions. Local jurisdictions adopt plans and regulations specifying what kinds of buildings can be built, under what conditions, and to what criteria. This has significant effects on where people choose to live, and what kind of lifestyles can be accommodated, with consequences for consumption-based emissions.

For instance, major city centers tend to have the lowest emissions per household. The land use plans and historical development in city centers have typically resulted in taller buildings, closer together, often with smaller homes which are typically available for rent. Because more people and destinations are closer together, city centers are often more walkable and have more public transit available, reducing vehicle ownership. Apartments mean lower home ownership; and smaller homes also means households tend to be smaller. Multi-unit dwellings also require substantially less energy to heat and cool each home. Smaller households living in smaller homes are also more likely to be younger, and to not earn as much as older generations, resulting in somewhat lower household income as well.

In contrast, suburban neighborhoods tend to have among the highest emissions per household. Suburban land use plans often encourage large, detached, single-family homes, with spacious yards and setbacks. Larger detached homes take more energy to heat or cool, and the extra space (and lack of nearby destinations) generally results in greater automobile usage. Larger homes also tend to be more expensive, making these suburban neighborhoods exclusive to wealthier households. Households that are drawn to suburban homes are also often looking to use the space to raise families, meaning larger household sizes.

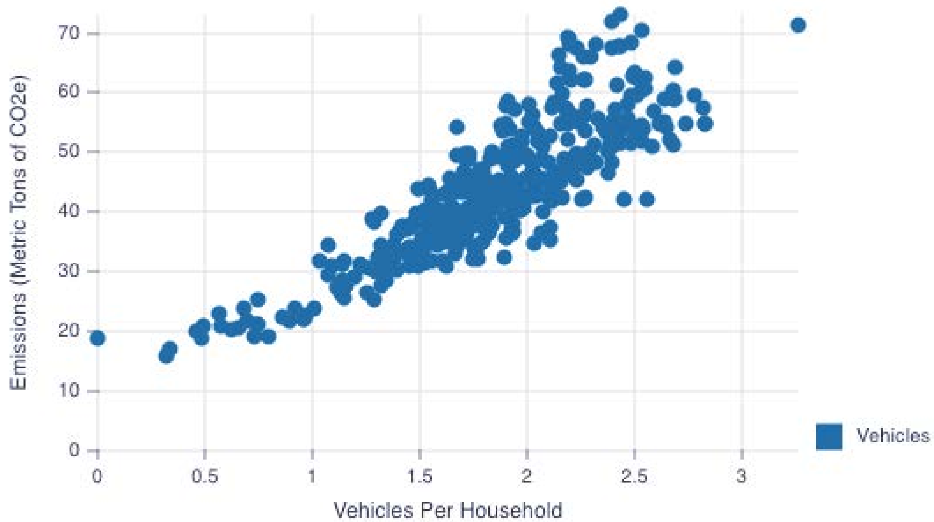
As a result, historical land use plans and the resulting built environment today are major drivers of consumption-based emissions, but also where people of different incomes are able to live. Because of historic discrimination and inequities, nonwhite Americans - particularly Black, Hispanic/Latino, and Native Americans - are less likely to be able to afford to buy a suburban single-family home. As a result, America's - and King County's - highest emission neighborhoods are also among the whitest and wealthiest.

The following charts provide some examples of how these neighborhood demographics correlate with per household emissions across the county. Each scatterplot shows census tracts in the county, with a demographic variable – such as income, vehicles per household, rooms per household, and home ownership rate – on the horizontal axis, while average per-household emissions for each tract are tracked on the vertical axis.

Figure 11. Household income vs emissions.

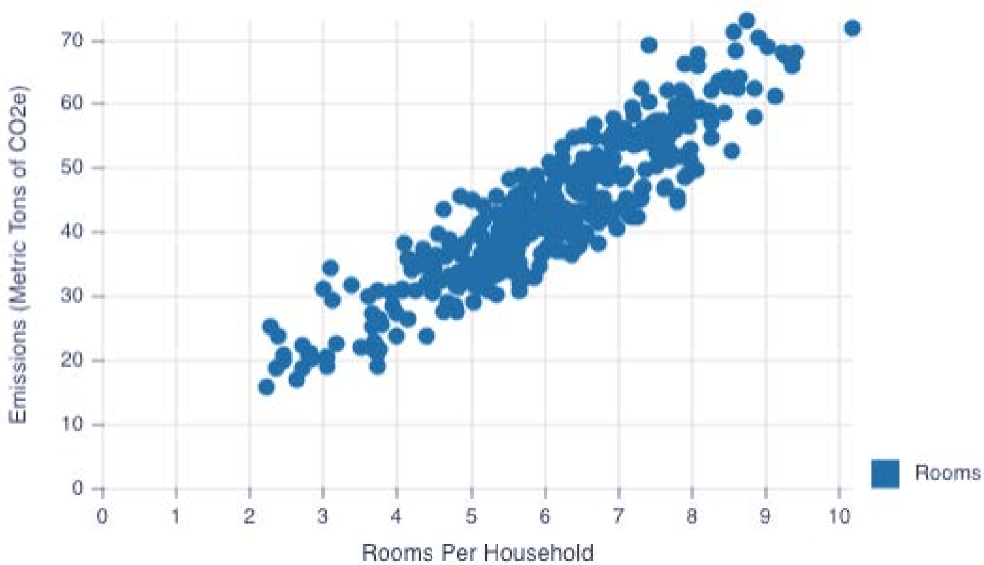
Higher incomes strongly correspond to greater consumption emissions. However, even at a given income level, different neighborhoods have different household emissions - sometimes by as much as a factor of 2. At the very highest incomes, neighborhoods tend to be clustered at the upper end of emissions, but middle-income (for the county) has a wider range of variation. Middle-income households often have the choice of either living in suburban, car-dependent communities or more walkable urban cores; those that live in areas with lower dependency on automobiles - as shown in the next chart - can have much lower emissions.

Figure 12. Vehicle ownership vs emissions.



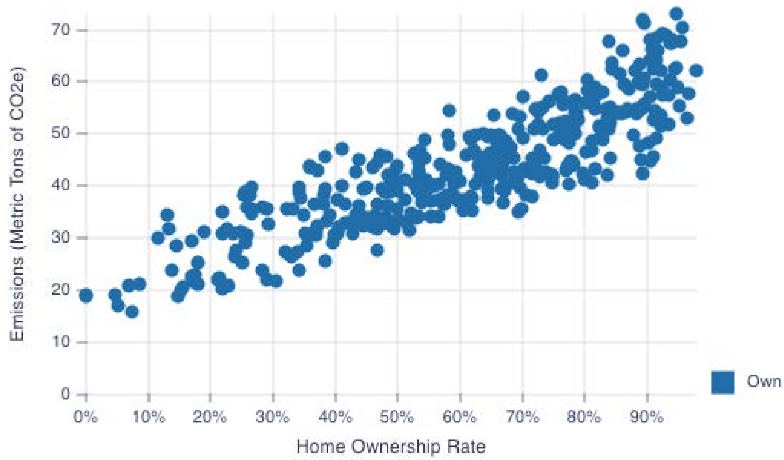
Greater vehicle ownership strongly corresponds to greater emissions, almost entirely due to the increased driving associated with the extra vehicle(s). Households with more vehicles may be wealthier, and thus able to afford the extra vehicle; but they may also be lower income and be unable to afford a transit-rich city center.

Figure 13. Rooms vs emissions.



More rooms per home strongly corresponds to greater emissions - homes with more rooms take more energy to heat or cool, and have more space to accommodate more purchases of furniture and other household goods.

Figure 14. Home ownership vs emissions.



Greater home ownership strongly corresponds to greater emissions. This is partly because home ownership correlates with income and household size, but it is also because home ownership on its own leads to more consumption of goods that are higher emissions - for instance, furniture and miscellaneous housewares.

Conclusion & Next Steps

Across King County, consumption-based household emissions range from 25 to 77 tons per household, with an average of 44 tons per household, or 18 tons per person. There is significant geographic variation, driven primarily by differences in income, household size, and vehicle ownership, reflective of different historical choices in local land use decisions and the availability of public transit.

Table 2 below compares consumption-based emissions between King, Pierce, Kitsap, and Snohomish Counties, as well as the City of Seattle. Unless otherwise stated, all emissions are on a per-household basis.

Table 2. Regional CBEI comparison.

Category	King	Pierce	Kitsap	Snohomish	Seattle	US AVG
Total Per Household Emissions	42	45	45	41	33	45
Total Per Capita Emissions	17	17	19	15	16	17
Transportation Emissions	14.2	15.6	15.6	16.2	10.2	10.8
Housing Emissions	6.0	9.2	9.5	3.5	3.1	9.5
Food Emissions	8.4	8.0	8.1	8.4	7.9	9.5
Goods Emissions	5.0	4.7	4.7	4.9	4.6	9.5
Services Emissions	7.9	7.9	7.5	7.9	7.3	5.9

King County's emissions are overall similar to those of the other counties in the Puget sound region. Seattle's low transportation emissions help to bring down King County's overall average, and both Seattle and Snohomish County benefit from 100% clean electricity, reducing their housing emissions significantly. The tract-level maps below show the household and per capita emissions across the four-county Puget Sound region.

Figure 15. Puget Sound neighborhood CBEI map ($MTCO_2e$ per household).

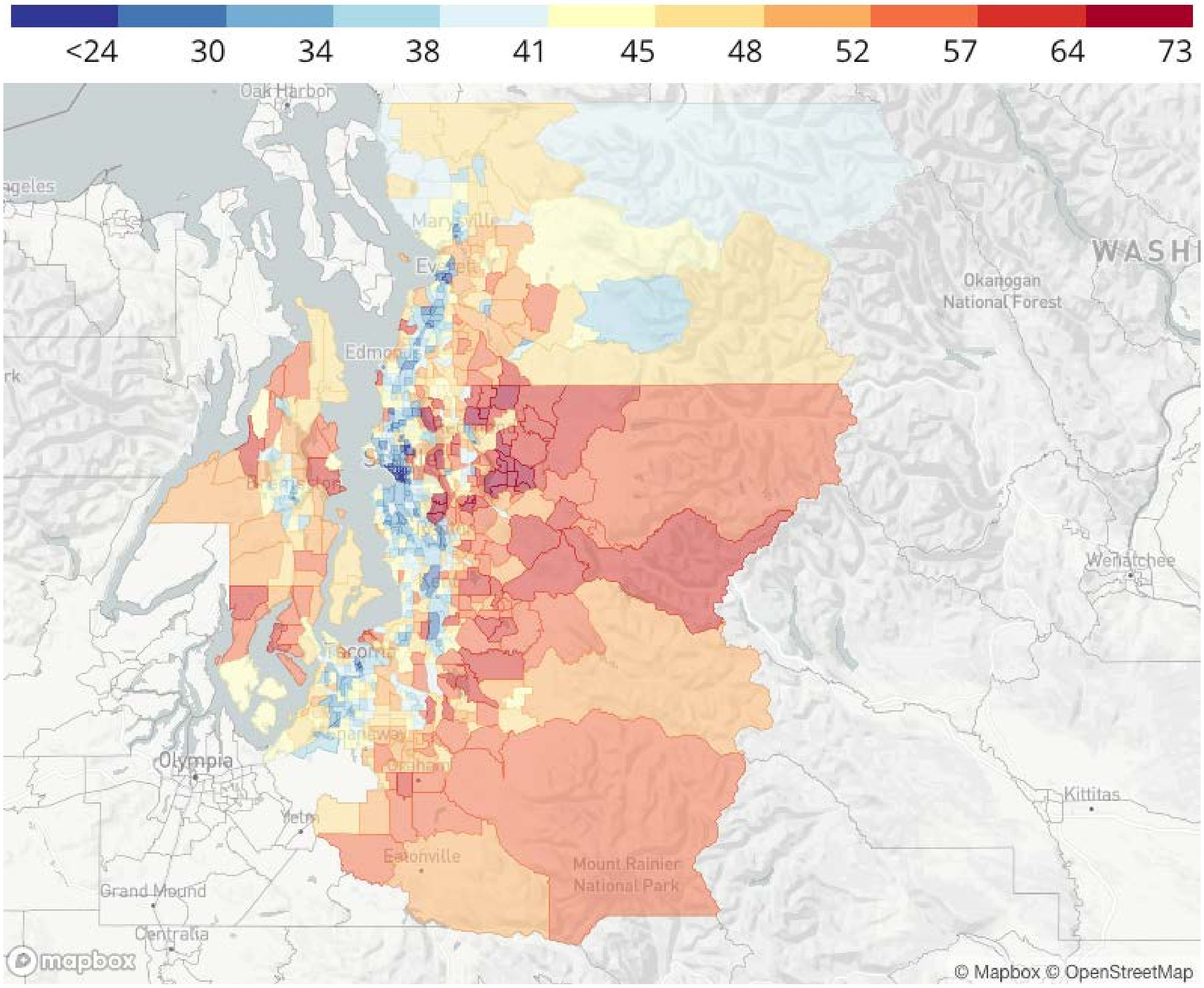
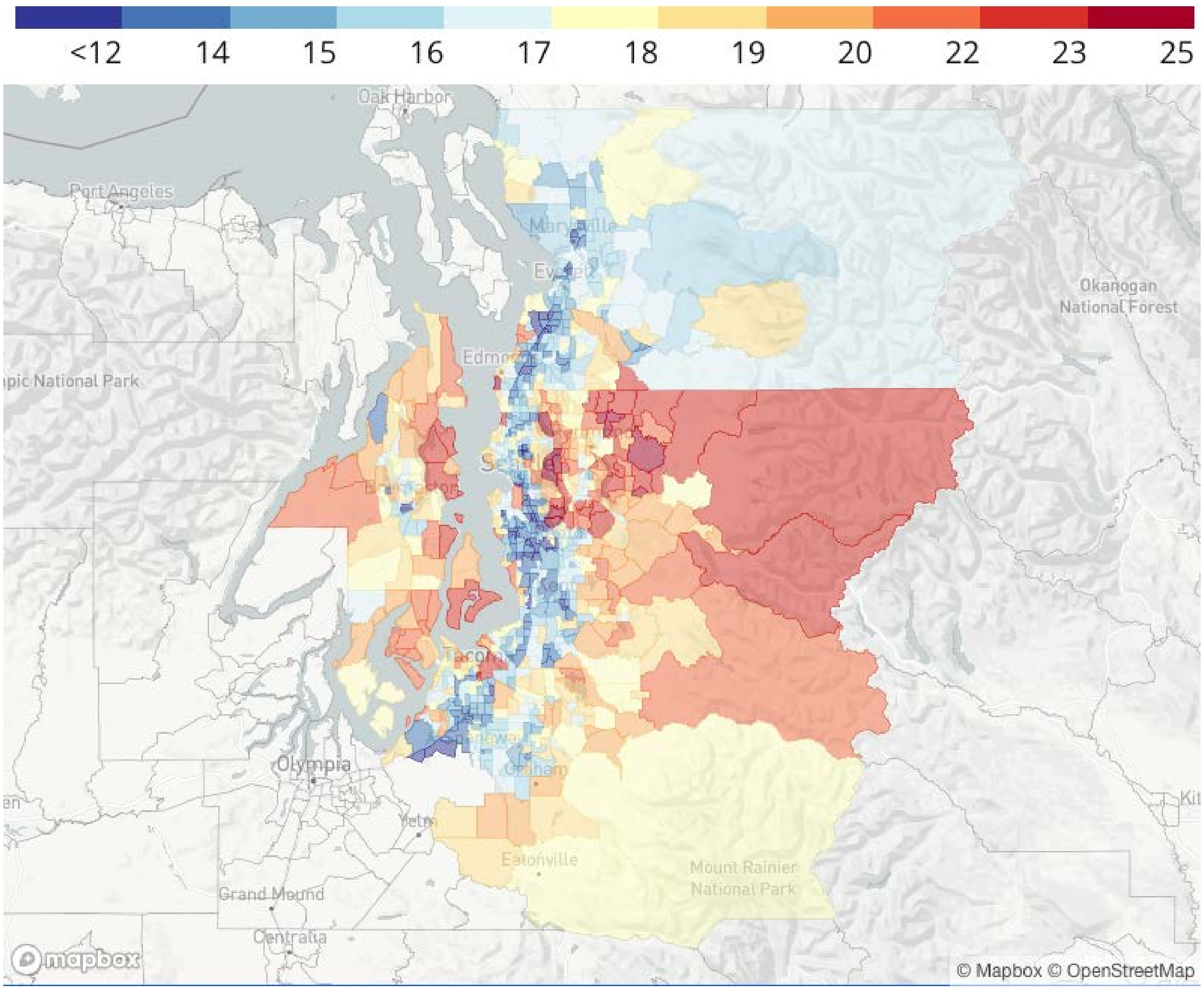


Figure 16. Puget Sound neighborhood CBEI map ($MTCO_2e$ per person).



King County's total countywide consumption-based emissions of over 38 million metric $MTCO_2e$ are roughly 40% larger than the geographic inventory of 27 million metric tons occurring within County limits. Previous research suggests that King County exports goods and services with associated emissions equivalent to about 5% of the County's total consumption emissions, or around 1.9 million metric tons.

King County's largest categories of consumption-based emissions include gasoline usage, electricity, healthcare, eating out, meat, and air travel. Growth in household income has been the largest demographic change since 2007, driving up consumption-based emissions for King County households. With gasoline and meat being the highest emissions per dollar categories of consumption, much of this growth in income has gone towards areas of consumption that are relatively lower in emissions on a per-dollar basis, such as most goods and services.

King County has multiple paths available to reducing consumption-based emissions. More housing in transit-rich areas of the county, and expanding alternative transportation to more areas, can reduce vehicle ownership and gasoline consumption (the #1 source of emissions for the typical household). Switching to renewable energy can eliminate emissions from electricity, while also reducing emissions associated with goods and services across the board by helping to reduce production emissions. Moving off of fossil natural gas will similarly reduce emissions from housing, goods, services, and eating out. Encouraging a dietary shift away from red meat, along with strategies to reduce food waste, can help bring down food emissions.

For a more detailed breakdown of strategies to reduce consumption emissions, see King County's Consumption-based Wedge Analysis.

Appendix A: Methodology

EcoDataLab CBEI Modeling Approach

The consumption-based emissions inventory (CBEI) is not a direct measurement of individual resident's consumption or behavior. Instead, EcoDataLab uses a model (a series of complex calculations) to estimate consumption and emissions, using a combination of real-world consumption or emissions data where available, along with predictions based upon household characteristics, as well as regional and national averages.

This model is based upon an approach first developed by the CoolClimate Network at the University of California, Berkeley, and published extensively in multiple scientific journals.

The overall model has a number of sub-models, but each one follows the same general formula:

1) Select a survey

We select a nation-wide survey, conducted by the US federal government, that focuses on an important element of the inventory. The US sub-models are built using the Consumer Expenditures Survey (CEX), the National Household Travel Survey (NHTS), and the Residential Energy Consumption Survey (RECS).

These surveys are used to build the full suite of models. CEX provides data used to model all categories of consumption except for gasoline and home energy use. NHTS provides data for the vehicle miles traveled model (which translates into gasoline usage), and RECS provides data for the home energy use models (including electricity, natural gas, and other heating fuels).

2) Identify key household characteristics

Next, we look at the household characteristics available from the survey, and identify data for which we can get nationwide data from the US census and other data sources. These data include variables like household size, income, vehicle ownership, etc. We also include geography, climate, and other relevant data where applicable.

3) Build a predictive model

Using the nation-wide survey and selected household and geographic characteristics, we run a computer program that identifies how strongly each of those household characteristics correlates with the survey results. This technique is called multiple linear regression, and is a type of machine learning - the computer sees many input data (the household and geographic characteristics) and learns how to predict what the outcome will be (the survey result). The computer then gives us an equation that takes each of those household and geographic characteristics and produces an estimated result.

A single linear regression might take this form:

$$y = mx + b$$

where y is the survey result (dependent variable), x is the household and geographic characteristics (independent variable), m is the computer's predicted correlation between x and y (slope), and b is a fixed value that adjusts for any underlying base discrepancy between x and y when x is equal to 0 (intercept).

In multiple linear regression, the equation takes on a more complex form:

$$y = m_1x_1 + m_2x_2 + m_3x_3 + ... + b$$

where in this case, each x (x_1, x_2, x_3, etc.) is a different household or geographic characteristic, with its own unique correlation (m_1, m_2, m_3, etc.) that together add up to make the overall result. The number of x variables depends on the sub-model and available data. All EcoDataLab sub-models use at least six variables (…x_6), with some using a dozen or more to get the most accurate prediction possible.

In addition, many of the values we are considering do not scale linearly. Instead, the models often look more like this:

$$\ln(y) = m_1x_1 + m_2*\ln(x_2) + m_3x_3 + ... + b$$

where the survey result might actually be scaled as a natural log (ln) variable, and some of the household and geographic characteristics are also calculated using its natural log (or sometimes both its ordinary and natural log values). This generally occurs in cases where there are nonlinear effects from household characteristics, and smaller values have different implications than larger values. For example, a household of 2 is typically two adults, whereas a household of 3 typically includes a child, which can significantly change consumption patterns. Similarly, consumption patterns based on income change significantly once basic needs are met and "luxury goods" start being consumed.

4) Run the model using local data

With these multiple linear regression models built (see above), we then collect over 200 points of local data - mostly census and climate data, from federal sources including the US Census Bureau, the National Oceanic and Atmospheric Administration (NOAA), but also things like energy prices, inflation rates, fuel economy, and emission factors from sources including the Energy Information Agency (EIA), the Bureau of Labor Statistics (BLS), the Department of Energy, and the Environmental Protection Agency (EPA). Those values are transformed to fit the required inputs to the model, and then the model is run with that local data as the independent (x) variables in the model.

5) Make final adjustments to consumption estimates

While the multiple linear regression model helps us estimate consumption, the model doesn't perfectly resemble reality. We adjust for these discrepancies by comparing the model's predicted results with real-world data wherever available, and scaling the model outputs accordingly where real-world data isn't available.

To achieve this, we compare the model results with the actual results for the most granular level of data available. This can be national-level data (in the case of surveys), state-level data (in the case of transportation), or locality-level data (in the case of energy or water consumption). For cases where real-world data is available at the geographic scale of interest, we use the real-world data in place of the modeled data; otherwise, we run the model at a geographic level at which data is available and use that to create a scaling factor, which we use to correct the locally modeled data. For example, the standard approach to energy modeling is to compare modeled state-level energy use with real-world state-level energy data, and then use that scaling factor to adjust a city or county's modeled energy use.

6) Calculate emissions

After calculating consumption using the models, we then calculate emissions. Most consumption emissions are calculated using the US EPA's USEEIO Model, which bridges the gap between consumption (dollars) and emissions ($MTCO_2e$). This model includes data on emissions by sector and supply chain stage, allowing us to differentiating between emissions associated with production, transport, wholesale, and retail, for all US emissions. Emissions associated with fixed capital investments (e.g. buildings & infrastructure construction, excluding residential construction) are also incorporated across all sectors.

For electricity emissions, we use EIA's eGrid emission factors, detailed at the zip code level and then scaled to any geography. For all other direct consumption of fuels (natural gas / methane, gasoline, etc.), we use the latest IPCC GWP values and best available academic literature to estimate life-cycle emissions. This includes fugitive and non-CO_2 GHG emissions, as well as any radiative forcing effects from other emissions (such as particulate matter or contrails).

When working with local jurisdictions, we always replace these national or grid average emission factors with the best available local data. We contact state agencies to procure detailed vehicle registration data, which we combine with US DOE fuel economy data to get the most granular and accurate estimate for fuel economy of local residents' vehicles. We work with local jurisdictions to identify local utilities and their geographic coverage, and their local emission factors for electricity, water & wastewater, or methane leakage rates. For waste emissions analyses, we use local household waste data where available, and either local emission factors or the US EPA WARM model.

Model Input Variables

The consumption models use the following six variables: household size, average income, vehicle ownership, home ownership, share of households respondents with a bachelor's degree or higher (educational attainment), and number of rooms (home size).

The vehicle miles traveled model uses household size, average income, vehicle ownership, home ownership, and educational attainment, along with commute time to work, drive alone to work, number of homes per square mile, number of employed people per square mile, employed people per household, family status, children per household, youth per household, adults per household, and Census region. The race of households (white, Hispanic or Latino, or neither) also proved to be statistically significant and was included.

The home energy models use household size, average income, home ownership, and home size as well as detached home status, heating and cooling degree days, statewide average price of electricity, statewide average price of natural gas, and census division.

Appendix B: Government Emissions

In the consumption-based inventory, government agencies are considered final demand the same way households are, and so government emissions are not attributed directly to households. These emissions are not insignificant – based on GDP data and the same USEEIO emission factors discussed in Appendix A, federal, state, and local governments across the US had emissions totaling over 660 million $MTCO_2e$. Of this total, roughly 69% came from state & local governments, with the remaining 31% from the federal government split between defense (24%) and non-defense sectors (7%).

Like households, government emissions include transportation, buildings, food, and procurement of goods & services. Transportation emissions include the use of government vehicles, aircraft, trains and buses, police and firefighting vehicles, ambulances, and more. (Because public transit is heavily subsidized in the US and associated emissions are not directly related to consumer spending, these emissions are allocated to government instead).

Government emissions from buildings include natural gas used for heating and water heating, as well as electricity use associated with the operation of the building. Government buildings include agency or department offices, legislatures, public colleges and universities, local schools, ports and airports, courts and prisons, post offices, military bases, some museums, research laboratories, libraries, water treatment plants, some hospitals, and more.

Embodied emissions from construction, including infrastructure, are also included. Roads, highways, and bridges all have large emissions associated with their construction. Governments also build and maintain local water supplies and resources, as well as some railway and public transit infrastructure, with additional emissions associated. Lastly, other purchases of food, goods and supplies, and services all have emissions associated with them as well.

Government consumption, and associated emissions, are not linked to particular household characteristics or activities in readily traceable ways. While some government activities can be linked to certain households – such as direct cash transfers for unemployment insurance or social security; and healthcare coverage through Medicare, Medicaid, or veteran's benefits – other government activities, like infrastructure construction and maintenance, national defense and public safety (police & fire), R&D spending, and parks maintenance cannot be readily and systematically assigned to households based on any discernable characteristics.

As a result, these emissions can only be effectively allocated to households on a flat average basis. If these emissions were allocated to households, it would be an average of 5.5 $MTCO_2e$ per household. For King County, this would work out to an additional 5 million $MTCO_2e$ countywide. These "hidden" emissions are not otherwise captured in the consumption-based emissions inventory, but still contribute to overall emissions nationally and globally.

Government agencies often have their own internal plans for reducing their emissions, with strategies that include switching to 100% renewable energy, purchasing electric vehicles, and retrofitting buildings to eliminate natural gas usage.

PART II: CONSUMPTION-BASED EMISSIONS ABATEMENT ANALYSIS

Assessing Consumption-Based Emissions Abatement Potential

The Puget Sound Regional Emissions Analysis (PSREA) project is providing a comprehensive update of the region's greenhouse gas (GHG) emissions, looking at *geographic* emissions produced within the Puget Sound region (and from electricity consumed within the region) as well as *consumption-based* emissions. As noted in Part I, consumption-based emissions may occur anywhere in the world, as long as they are directly or indirectly the result of activities of Puget Sound residents. These emissions may overlap with geographic emissions – such as emissions produced when residents burn gasoline for local car trips – but also include a large quantity of emissions associated with the production, manufacture, transportation, and sale of energy, food, products, and services consumed by residents. These "embedded" emissions can form a large part of a community's total carbon footprint.

Climate policies typically focus on reducing geographic emissions, in part because these are the emissions over which governments, businesses, and individuals have the most direct control and influence. Recognizing that Puget Sound residents' household consumption is responsible for producing emissions around the country and throughout the world, however, the PSREA is examining how these emissions could be reduced as well.

Consumption-based emissions will be reduced and eliminated if people around the world take action to phase out fossil fuels and reduce GHG emissions globally, in line with the goals of the Paris Agreement. This will be a major undertaking, however, and its success will depend on transforming not just how energy, food, goods, and services are produced, but also how – and in what proportions – they are consumed. By reducing overall consumption – using energy more efficiently, avoiding energy- and emissions-intensive forms of transportation (like flying), and consuming fewer goods and more services – Puget Sound households can play an important role in aiding the transition to global net zero emissions.

The Household Consumption-Based Emissions Abatement Analysis Tool

The PSREA Consumption-Based Emissions Abatement Analysis (CBEA) tool, developed by the Stockholm Environment Institute, shows how a combination of existing policies, household consumption changes, and broader economy-wide decarbonization efforts could lower the total carbon footprint of Puget Sound households. The tool allows exploration of different kinds of abatement *wedges*, i.e., reductions in consumption-based emissions from discrete measures that, when added together, could move the region towards its goals. These are illustrated in a *wedge diagram* showing the contribution of different measures to total greenhouse gas abatement (Figure 1).

In the CBEA tool, all emission reductions are measured against a *reference case*, indicated by the dotted black line in Figure 1. As in the PSREA territorial abatement wedge analysis, the reference case is a projection of how emissions in the Puget Sound region will grow along with population growth, assuming *no other changes* in the consumption behavior or carbon footprints of area households. This is a simplification. Under a true "business as usual" scenario with no abatement measures, for example, consumption-based emissions per household are likely to change, due to changes in household consumption patterns (e.g., arising from changes in income and the relative prices of goods and services) and the economy (e.g., switching to different production methods as technologies evolve). Like the geographic wedge analysis, the CBEA tool is meant to illustrate the *relative magnitude* of different abatement wedges over time, compared to today's consumption and technologies, not estimate absolute emission reductions against a true "business as usual" forecast.

The following sections describe the main elements of the CBEA tool and how it models different kinds of abatement wedges.

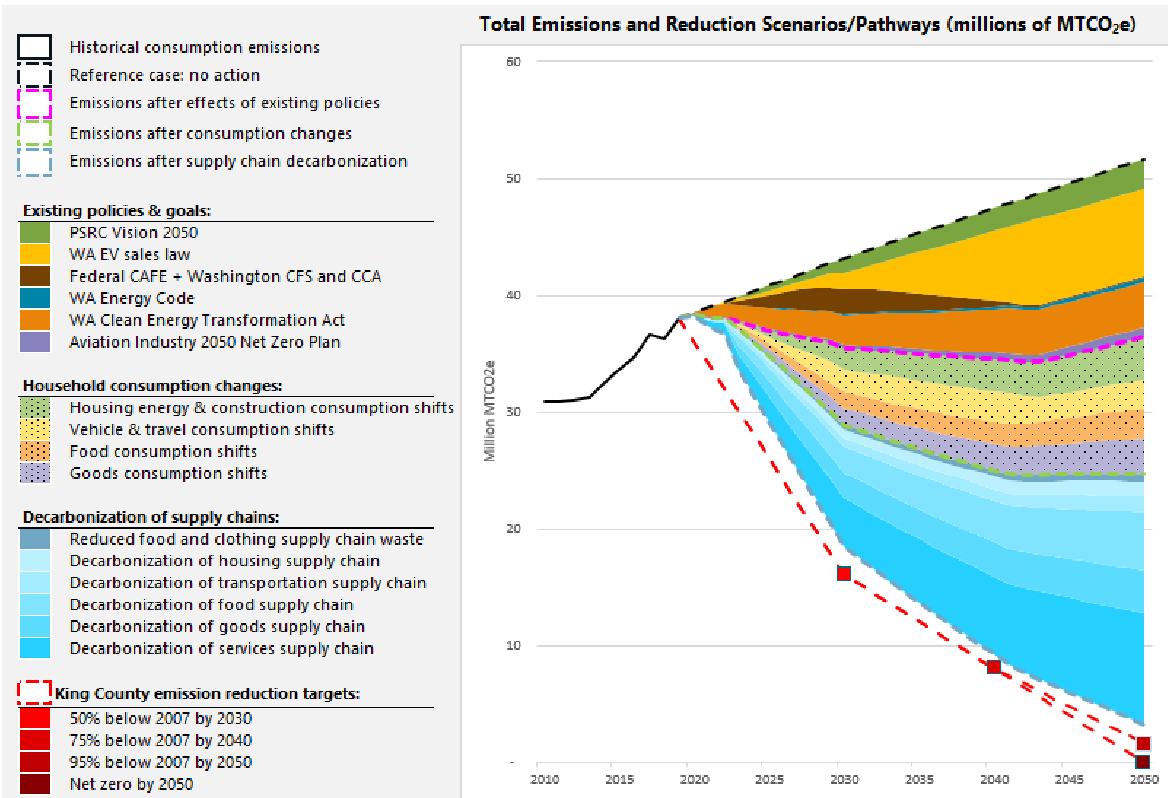


Figure 17. CBEA wedge diagram showing the contribution of different abatement measures for King County

How Consumption-Based Emissions Can Be Reduced

In general terms, there are three ways to reduce consumption-based emissions:

- **Consuming less**. Simply reducing household consumption will reduce consumption-based emissions. Although reducing consumption is often associated with self-denial, it can be achieved by reducing waste (e.g., throwing away less food so less needs to be produced); greater efficiency (e.g., using energy-efficient cars and appliances); sharing or renting goods, like tools, cars, or gardening equipment; and purchasing goods with greater reusability and durability (e.g., avoiding "fast fashion" clothing). These kinds of changes can be encouraged through "circular economy" measures that, for example, incentivize more durable and reusable product designs and promote more sustainable consumption habits (Haigh et al. 2021).

- **Consuming lower-carbon alternatives**. Consumption-based emissions can also be reduced by shifting consumption to lower-carbon alternatives. Eating more vegetables and less meat, for example, could significantly reduce the carbon footprint of many households. Likewise, using lower-carbon cement blends in housing construction can lower the carbon intensity of housing.
- **Lowering the carbon intensity of supply chains.** Although consumption changes can significantly reduce emissions, they will ultimately need to be complemented by measures that reduce emissions associated with the production, provision, and/or delivery of energy, transportation, food, goods, and services. A wide range of interventions are possible here, including measures to reduce *supply chain* waste (before delivery to households) and to decarbonize production methods. Since these kinds of measures cannot be directly undertaken by local households (or achieved through local policies), they are reflected as aggregate wedges in the CBEA tool (see further discussion, below).

The CBEA tool defines multiple abatement wedges related to all three of these general strategies. In the tool's summary wedge diagram (illustrated in Figure 1), abatement wedges are grouped into three kinds of interventions:

- *Existing policies and goals*. These wedges are shown between the reference case and the pink dotted line in Figure 1.
- *Household consumption changes.* These wedges are shown between the pink and green dotted lines in Figure 1.
- *Decarbonizing supply chains.* These wedges are shown between the green and grey dotted lines in Figure 1.

Each of these is explained further below. Details on individual wedges and the assumption behind them are provided further below (see "Abatement wedge details").

Existing Policies and Goals

A range of existing policies and goals – at local, state, national, and international levels – can be expected to reduce Puget Sound household consumption-based emissions relative to the reference case. These include many of the same policies whose effects are estimated in the PSREA geographic wedge analysis. For the consumption-based analysis, they include:

- Federal vehicle fuel efficiency (CAFE) standards
- Washington State clean energy, clean fuel, energy efficiency, electric vehicle, and carbon pricing policies
- Puget Sound Regional Council plans for reducing average household passenger car travel
- International aviation industry goals for reducing air travel greenhouse gas emissions

Under the CBEA tool's default assumptions, existing policies and goals are estimated to reduce King County household consumption-based emissions by 30% in 2050, relative to the reference case.

Reducing Household Consumption

Although existing policies will help to reduce consumption-based emissions, there is much more that local households can do to change their consumption of energy, housing, transportation, food, and goods in ways that would substantially reduce their carbon footprints. These include steps to reduce waste, use goods and energy more efficiently, and shift consumption. New local policies could help encourage these shifts, but realizing their full potential will require Puget Sound residents to voluntarily change their consumption habits by, for example, consuming less meat, flying less, purchasing fewer carbon-intensive goods, and shifting their spending to low-carbon alternatives like services and entertainment.

Key wedges here include:

- Choosing smaller, more efficient housing that uses fewer, and less carbon-intensive, materials
- Using alternative transportation options and accelerating the shift to electric vehicles
- Reducing household food waste, and consuming less meat and dairy
- Consuming fewer, more durable household goods an apparel

Under the CBEA tool's default assumptions, these additional shifts in consumption could reduce King County household carbon footprints by an additional 23% in 2050, relative to the reference case.

Decarbonizing National and Global Supply Chains

When it comes to reducing consumption-based emissions, Puget Sound residents will not be able to do the job alone. Locally consumed goods and services depend on supply chains that extend well beyond the region, to other states and around the world. To achieve the Paris Agreement's goal of keeping global warming "well below 2ºC," the world will need to fully "decarbonize." That is, goods and services will need to be produced and transported using carbon-free energy sources; chemicals, plastics, and pharmaceuticals will need to be derived from fossil fuel alternatives; fossil carbon emissions will need to be captured and stored in geologic reservoirs where they cannot be avoided; and other greenhouse gas emissions will need to be dramatically reduced, including methane and nitrous oxide in the agriculture sector.

The task of decarbonizing the economy will require systemic transformations in how energy, goods, and services are produced, including wholesale adoption of carbon-free energy sources, but also dramatic improvements in energy efficiency and more efficient use of materials in the production of things like housing and consumer goods. The tool highlights a couple of areas where reducing *supply chain* waste could significantly reduce consumption-based emissions: for food and clothing (see Figure 1, grey wedge). For other goods and services, economy-wide efforts to decarbonize energy, improve energy efficiency, and use materials more efficiently are represented as "supply chain decarbonization" wedges. As a default, these wedges indicate how much the Puget Sound's consumption-based emissions would be reduced if the *rest of the world* were to decarbonize in line with Washington State's greenhouse gas reduction targets. Legislative targets established in 2020 require economy-wide emission reductions of 45% below 1990 levels by 2030, 70% below 1990 levels by 2040, and net zero emissions by 2050 (Washington State Department of Commerce 2020). Though ambitious, these targets are in line with what is needed globally to avoid more than 1.5ºC of warming.

The tool also allows the selection of alternative scenarios based on modeling by the International Energy Agency (IEA 2021):

- **IEA Net Zero**. Expected decarbonization of energy, goods, and services in line with the IEA's roadmap for achieving "net zero" energy-sector emissions worldwide by 2050. This scenario is similar to the pathway reflected in Washington State's greenhouse gas targets.
- **Current policies (US)**. Expected decarbonization of energy, goods, and services in line with the IEA's modeling of the effects of current US climate and energy policies. This reflects the emission reductions that could be expected if one assumes (most) goods and services consumed in the Puget Sound region are produced in the United States.
- **Current Policies (Global)**. Expected decarbonization of energy, goods, and services in line with the IEA's modeling of the effects of current climate and energy policies around the world. This reflects the emission reductions that could be expected if one assumes (most) goods and services consumed in the Puget Sound region are produced in other countries. Although this is not the case, the scenario

Finally, getting to net zero globally will also require reducing greenhouse gas emissions from land use and agriculture. These are an important component of consumption-based emissions for food and, to a lesser extent, clothing and textiles. The tool addresses these emissions in separate wedges associated with: (1) halving nitrous oxide emissions from the application of fertilizer, and (2) substantially reducing methane emissions from livestock. (In the summary wedge diagram at the top of the tool – Figure 1 – these wedges are not shown separately, but instead are included under the "supply chain decarbonization" wedges for food and goods.)

Under the CBEA tool's default assumptions, supply chain decarbonization measures are assumed to follow Washington State greenhouse gas reduction targets, and could reduce King County household carbon footprints by an additional 41% in 2050, relative to the reference case.

Note that if all assumed abatement wedges are applied, emissions are projected to be 95% lower in 2050 than they would be in the reference case. The remaining 5% of emissions come primarily from unabated emissions in the agriculture and aviation sectors.

How Abatement Wedges Are Sequenced

The sequence in which abatement wedges are applied can affect their apparent impact. For example, if the tool were to estimate emission reductions from decarbonizing electricity *before* estimating the impact of improving household energy efficiency, the latter would appear to have no impact on reducing emissions. Similarly, if supply chain decarbonization wedges were applied first, many other measures would appear to have little or no impact on emissions, especially in later years (reducing consumption of a good with zero embedded emissions will not further reduce emissions). To highlight the benefits of household consumption changes in helping to reach GHG goals, the CBEA tool applies these wedges before wedges associated with decarbonizing energy and supply chains. This is true irrespective of whether the wedges are associated with existing policies or additional household consumption changes. For transportation emissions, for example, wedges associated with reducing vehicle-miles traveled (from both the PSRC regional transportation plan and additional efforts assumed locally) are sequenced before any assumed shift to electric vehicle ownership.

The CBEA tool's summary wedge diagram (Figure 1, at the top of the page) groups wedges according to the three categories described above: policies, household consumption changes, and supply chain decarbonization. **The actual order in which wedges are applied, however, is indicated in more detailed wedge diagrams for each sector of household consumption (housing, transportation, food, and goods), which are found further down on the same page of the tool.**

Reduced Consumption and the Rebound Effect

One challenge with trying to reduce GHG emissions by reducing consumption is that doing so typically frees up household income that can be spent on other goods or services. These other goods and services will themselves have embedded emissions, so the total net reduction in emissions from shifting consumption depends on their relative carbon intensity. The increase in emissions associated with shifting to alternative types of consumption is called a "rebound effect." Ideally, the rebound effect will be lower than the emission reduction associated with reducing consumption of other goods or energy, but this depends on what consumers actually shift their consumption to. The CBEA tool assumes that households deliberately seek to lower emissions, by using any freed-up income to consume a generic basket of low-carbon services (following the PSREA consumption-based GHG inventory, these include a mix of healthcare, entertainment services, education, financial services, and others).

Over time, as supply chains are decarbonized, the carbon intensity of any rebound consumption will decrease along with all other goods and services (and ideally at a faster rate). The significance of any rebound therefore depends on what is assumed about general decarbonization efforts. As a default, the CBEA tool indicates the degree to which rebound emissions would be reduced by national and global decarbonization in line with Washington State GHG targets.

The rebound effect is not shown in any of the CBEA wedge diagrams (this would require displaying "negative" rebound wedges.) Instead, estimated rebound effects are displayed in separate charts showing the contribution of each wedge to reducing emissions in a single year, or cumulatively across all years (Figure 2). Specifically, these "waterfall" charts show:

- Total reference case emissions to the left (black bar)
- The successive contribution of each wedge to reducing emissions (interim segments)
- The level of abated emissions after abatement wedges are applied, but before any rebound effect (light grey bar)
- Estimated rebound effects from measures that reduce consumption (red dotted segment)
- The *reduction* in rebound emissions assuming this consumption is decarbonized in line with wider supply chain decarbonization efforts (yellow dotted segment)
- The final level of net emissions abatement, accounting for rebound effects and their decarbonization (dark grey bar)

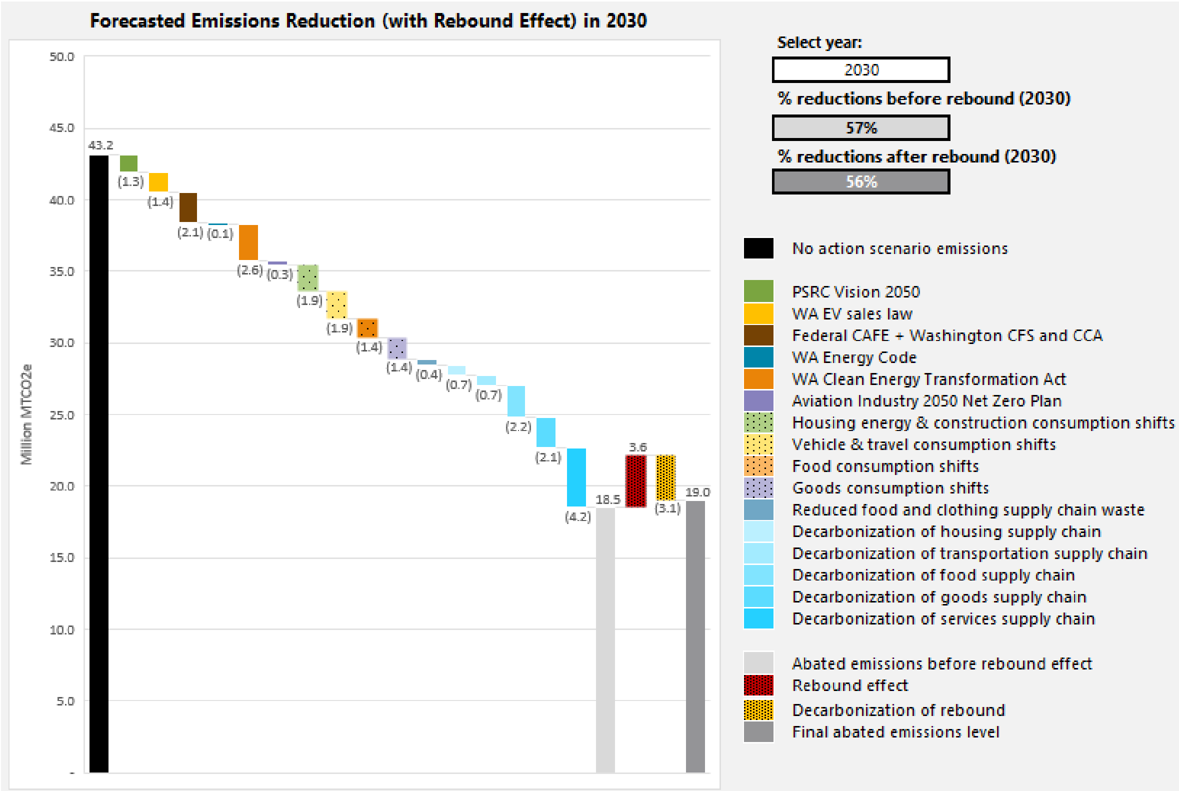


Figure 18. "Waterfall" chart showing the relative contribution of wedges to emission reductions, along with rebound effects, for King County in 2030

Abatement wedges for which a rebound effect is assumed include:

- Washington State energy code (improving energy efficiency in new buildings)
- Reduced demand for new construction
- Existing building energy efficiency
- PSRC Vision 2050 (reducing travel demand)
- Reduced vehicle travel (beyond PSRC Vision 2050)
- Reduced vehicle purchases (fewer vehicles + extending vehicle lifetimes)
- Reduced air travel
- Federal CAFE standards (improving fuel economy)
- Reduced household food waste
- Healthy calorie intake (avoiding overconsumption of food)
- Reduced good consumption (all types)

Note: the CBEA tool currently assumes no rebound effect associated with switching from conventional to electric vehicles. In reality, electric vehicles have somewhat higher manufacturing emissions than conventional gasoline-powered vehicles (https://www.epa.gov/greenvehicles/electric-vehicle-myths#Myth5). This may be reflected in a future update to the tool.

Abatement Wedge Details

The following tables provide short descriptions of, and summarize the analytical assumptions behind, each of the abatement wedges included in the tool.

Wedges associated with existing policies and goals are modeled using the same assumptions used in the PSREA wedge analysis tool for *geographic* greenhouse gas emissions, but in this case applied to consumption-based emissions. Consumption-based emissions reflect both direct and "upstream" emissions from consuming energy, goods, and services, and are derived from the PSREA consumption-based emissions inventory. For example, in the geographic wedge analysis, federal CAFE standards are expected to improve the fuel economy of internal combustion vehicles by 33% by 2050. This results in an expected 33% reduction in direct emissions from burning gasoline in car engines in 2050. In the consumption-based analysis, this wedge shows a 33% reduction in 2050 in both direct combustion emissions *as well as* upstream greenhouse gas emissions associated with extracting and refining petroleum and delivering it to gas stations.

Wedges associated with changing household consumption apply different assumptions depending on the type of consumption involved. In all cases, the wedges are configured using the same basic parameters:

- Either one or two **target years**, indicating when a particular target for reducing or shifting consumption is reached. In the default scenario, these target years are typically 2030 and 2050.
- The **target** for reducing consumption in each target year. In most cases, targets are expressed as a percentage reduction in consumption activity or waste *per household*, relative to base year (2019) inventory levels.
- The **percentage of households** achieving the target. This allows exploration of the emission reductions that would result if all households in the selected jurisdiction, or only a subset, achieve the configured target for reducing or shifting consumption.

Finally, the supply chain decarbonization wedges indicate the expected reduction in consumption-based emissions due to assumed economy-wide improvements in the emissions intensity of production and transportation of energy, goods, and services (as described above).

All parameters have default settings reflecting the CBEA tool's default scenario for deeply reducing consumption-based emissions. Details on these default settings, and the basis for their values, are provided below. For all wedges other than existing policies and goals, users of the tool can also choose manual settings to explore alternative scenarios and approaches (e.g., assuming more or less aggressive uptake of various consumption changes, and/or alternative scenarios for decarbonizing supply chains).

Housing Consumption Wedges

Existing policies and goals

Wedge	Description	Key assumptions
Washington Energy Code (SB 5854)	SB 5854 requires residential and nonresidential construction permitted under the 2031 state energy code to achieve a 70% reduction in annual net energy consumption (compared to a 2006 baseline). State energy codes will be adopted from 2013-2031 to incrementally move towards achieving the 70% reduction by 2031.	Following assumptions used for the geographic wedge analysis, this wedge is modeled as a straight-line reduction in the energy consumption rate in *new residential buildings* from 2019 to 2031 to achieve the 70% reduction from baseline. The tool assumes that any additional energy consumption under BAU compared to 2019 is from new residential buildings.
Washington Clean Energy Transformation Act (CETA)	CETA applies to all electric utilities serving retail customers in Washington and sets specific milestones: By 2025, utilities must eliminate coal-fired electricity from their state portfolios; By 2030, utilities must be greenhouse gas neutral, with flexibility to use limited amounts of electricity from natural gas if it is offset by other actions; By 2045, utilities must supply Washington customers with electricity that is 100% renewable or non-emitting, with no provision for offsets.	Following assumptions used for the geographic wedge analysis, this wedge assumes electricity will be GHG neutral (electricity emissions factor equals zero) in 2030 and beyond with a straight-line emissions factor reduction from 2019 to 2030. For utilities that rely on coal for electricity generation, the tool assumes a straight-line reduction to 0% coal by 12/31/2025, with the assumption that coal is replaced by renewables. This action impacts electricity emissions factors (reduces emissions per unit of energy consumed) – with emissions impacts identical to those in the geographic analysis, but for residential electricity consumption only.
Washington Climate Commitment Act	The Climate Commitment Act (known as Cap and Invest) places an economy-wide cap on carbon to meet state GHG reduction targets and remain consistent with best available science, while minimizing the use of offsets to meet those targets. Every polluting facility covered under the program needs to hold one allowance for every ton of greenhouse gas that it emits. Based on an environmental justice review, 35-40% of	Following assumptions used for the geographic wedge analysis, this wedge applies a straight-line -10% emission factor adjustment to natural gas (assuming increase in hydrogen or RNG in fuel mix) to 2030.

	investments must be made in overburdened communities to reduce health disparities and create environmental benefits, with an additional 10% allocated for tribal programs and projects.	

Household consumption changes

Wedge	**Description**	**Key assumptions**
Reduced demand for new construction	This wedge models emission reductions that would result from reduced demand for new housing construction, assuming population growth remains unchanged from the reference case. Reduced demand could result from a combination of: • More intensive use of existing residential buildings (avoiding new construction) • Reducing the average size of new homes, apartments, and dwelling units **Note:** Smaller average home size is correlated with reduced household consumption in aggregate, which can substantially reduce consumption-based emissions (Oregon Department of Environmental Quality 2010; Dubois et al. 2019). However, these "knock-on" effects for consumption are not modeled as part of this wedge (they are assumed as part of other wedges related to goods and transportation).	Prior studies suggest that enhanced use of building space and smaller new home sizes (relative to business as usual) could result in an overall reduction of about 10% in demand for new construction within 10-15 years, compared to the reference case (Erickson et al. 2012; C40 Cities et al. 2019b). This wedge is therefore modeled as a straight-line reduction to 10% below reference case by 2030 for (1) consumption-based emissions in all new building construction and (2) energy use emissions in all new buildings.
Material efficiency and reuse in new construction	This wedge models reductions in emissions that could result from greater material efficiency in new residential construction (especially cement) and reuse of building components, e.g., applying	C40 Cities estimates that greater material efficiency and reductions in virgin material use could reduce construction-related emissions by a total of over 20% in an "aggressive" scenario. Achieving this level of

	"circular economy" approaches to the construction sector, especially for steel and petrochemical-based materials.	reduction would require actively fostering new markets for reused building materials (C40 Cities et al. 2019b; C40 Cities et al. 2019c). This wedge is therefore modeled (in the default scenario) as a 10% reduction in new residential housing construction emissions by 2030, and a 20% reduction by 2050.
Use of low-carbon concrete	Use of low-carbon cement and concrete blends can reduce the carbon intensity of concrete used in residential construction by around 12%. If carbon capture and storage and other technologies are adopted in cement production, the overall carbon intensity of cement could be reduced by 95% or more by midcentury (MPA UK Concrete 2020). Consumers can aid this transition by actively choosing low-carbon cements and concretes for new housing construction. This could have a substantial impact, especially for houses with concrete basements (Irving 2021).	This wedge is modeled as a straight-line 12% reduction in concrete-related emissions for all new housing by 2030, and a 95% reduction by 2050, assuming cement and concrete production are largely decarbonized by midcentury (driven in part by consumer demand). For houses with basements, around 55% of total material intensity is associated with concrete. The tool uses 25% intensity on average, as a midpoint assumption for average new housing (with and without basements).
Existing building energy efficiency	Aggressive efforts to improve energy use efficiency in existing residential buildings could substantially reduce household energy-related emissions, including upstream emissions from use of natural gas and other household fuels.	This wedge is identical to "reduce energy use in existing buildings" wedge in the geographic abatement wedge analysis, but estimates emission reductions based on the total lifecycle emissions of fossil fuels. For the default scenario, it assumes a 25% reduction in energy use in existing buildings by 2030 (all households) and a 45% reduction by 2050.
New building electrification	Using electricity to meet household energy needs will be a critical measure for achieving net zero emissions, especially as electricity generation is decarbonized. This wedge is specific to electrification of new buildings.	This wedge is identical to the "electrify new buildings" wedge in the geographic abatement wedge analysis, but estimates emission reductions based on the total lifecycle emissions of displaced fossil fuels (primarily natural gas). For the default scenario, it assumes a full electrification of all new buildings by 2030 (assuming straight-line progress towards this goal).

Existing building electrification	Using electricity to meet household energy needs will be a critical measure for achieving net zero emissions, especially as electricity generation is decarbonized. This wedge is specific to retrofitting and electrifying existing buildings (including "new" buildings that are not electrified under the new building electrification wedge).	This wedge is identical to the "electrify existing buildings" wedge in the geographic abatement wedge analysis, but estimates emission reductions based on the total lifecycle emissions of displaced fossil fuels. For the default scenario, it assumes a full electrification of *half* of all existing buildings by 2030 (assuming straight-line progress towards this goal), and full electrification of *all* existing buildings by 2050.

Supply chain decarbonization

Wedge	**Description**	**Key assumptions**
Decarbonization of housing supply chain	This wedge shows remaining emission reductions that could be expected – after all other housing sector abatement wedges are achieved – if supply chains for housing construction and other housing-related consumption (including "other lodging," such as hotels) were decarbonized in line with efforts to decarbonize the wider economy.	As describe above, the default scenario assumes all supply chain emissions (nationally and globally) are decarbonized in line with Washington State greenhouse gas emission reductions targets (ca. 50% by 2030, 75% by 2040, and 100% by 2050).

Transportation Consumption Wedges

Existing policies and goals

Wedge	Description	Key assumptions
PSRC Vision 2050	The Regional Transportation Plan (RTP) is a long-term transportation plan for the central Puget Sound region and is designed to implement the region's growth plan, VISION 2050, outlining investments the region is making in transit, rail, ferry, streets and highways, freight, bicycle and pedestrian facilities, and other systems.	Following assumptions used for the geographic wedge analysis, this wedge assumes future passenger vehicle VMT reductions will reflect estimations from the RTP model (note that this does not apply to Kitsap County). Emission reductions reflect avoided emissions from direct combustion of gasoline plus avoided upstream emissions.
Washington EV sales target	Washington's internal combustion engine ban (SB 5974) establishes a target that, "all publicly owned and privately owned passenger and light duty vehicles of model year 2030 or later that are sold, purchased, or registered in Washington state be electric vehicles."	Following assumptions used for the geographic wedge analysis, this wedge is modeled by assuming the following schedule for the percentage of new vehicle sales that are electric vehicles (EVs): - 25% by 2026 - 65% by 2030 - 100% by 2035 - Maintained by 100% thereafter Emission reductions are calculated as the difference between lifecycle gasoline emissions avoided and emissions from new EV electricity consumption ***prior to*** any reduction in electricity emissions intensity due to CETA (see below). Note that this wedge assumes EVs will be driven the same number of miles as the conventional vehicles they displace. This may be inaccurate in the near term (e.g., if households purchase EVs as second cars), but

		is likely a valid simplifying assumption over the long run as conventional vehicles are fully displaced.
Washington Clean Energy Transformation Act (CETA)	CETA applies to all electric utilities serving retail customers in Washington and sets specific milestones: By 2025, utilities must eliminate coal-fired electricity from their state portfolios; By 2030, utilities must be greenhouse gas neutral, with flexibility to use limited amounts of electricity from natural gas if it is offset by other actions; By 2045, utilities must supply Washington customers with electricity that is 100% renewable or non-emitting, with no provision for offsets.	Following assumptions used for the geographic wedge analysis, this wedge assumes electricity will be GHG neutral (electricity emissions factor equals zero) in 2030 and beyond with a straight-line emissions factor reduction from 2019 to 2030. For utilities that rely on coal for electricity generation, the tool assumes a straight-line reduction to 0% coal by 12/31/2025, with the assumption that coal is replaced by renewables. This action impacts electricity emissions factors (reduces emissions per unit of energy consumed) – with emissions impacts identical to those in the geographic analysis, but for residential electricity consumption only (in this case related to EV operation).
Federal CAFE + Washington CFS and CCA	This wedge shows the combined effect of three policies affecting passenger vehicle emissions: (1) federal corporate average fuel economy (CAFE) standards; (2) the Washington Clean Fuel Standard (CFS); and (3) the Washington Climate Commitment Act (CCA). Federal CAFE standards require continuous improvement in the fuel economy of internal combustion engine vehicle over time. The CFS requires a 20% reduction in the carbon intensity of transportation fuels by 2038, compared to a 2017 baseline level. Reductions in carbon intensity may be achieved through cleaner fuels or by purchasing clean fuel credits from cleaner producers such as those providing electricity as fuel.	Following assumptions used for the geographic wedge analysis, this wedge assumes the following: - CAFE standards will result in a 33% reduction in passenger vehicle emissions by 2050 (modeled as a straight-line improvement from 2019). - The CFS will drive greater EV penetration as well as a reduction in the lifecycle carbon intensity of gasoline used in passenger vehicles of 3.5% by 2030; 10% by 2040; maintained at 10% through 2050. - The CCA will drive a reduction in gasoline lifecycle carbon intensity of 23.5% by 2030 and 30% by 2040 The effect of each of these policies over time is relatively small because they all affect conventional vehicle emissions, which are assumed to be phased

	The CCA established an economy-wide cap-and-trade system in Washington, as described above in the housing sector wedge descriptions.	out rapidly under Washington's EV sales target. In practice, the assumed effects of the CFS are subsumed by the EV sales target and the CCA's effect on fuel carbon intensity. Therefore, this wedge primarily reflects the effects of CAFE standards and the CCA.
Aviation industry 2050 Net Zero Plan	This wedge is based on the Air Transport Action Group (ATAG) 2050 Plan (ATAG 2021). ATAG is made up of representatives of the world's major aviation industry associations and largest aircraft and engine makers. In 2021, ATAG committed to a goal of net zero by 2050 for global civil aviation operations. This will be supported by accelerated efficiency measures, energy transition and innovation across the aviation sector and in partnership with Governments around the world.	Following assumptions used for the geographic wedge analysis, this wedge assumes the following for the default scenario: - 10% reduction of 2050 BAU emissions from technology advancements - 9% reduction of 2050 BAU emissions from operations and infrastructure improvements - 31% reduction of 2050 BAU emissions from sustainable aviation fuels - Total reduction = 50% of 2050 BAU emissions Note that this is based on the ATAG's scenario for (optimistically) high use of sustainable aviation fuels ("BAU High SAF"), without any use of carbon offsets. The tool also allows selection of a low SAF scenario, as well as the ATAG's net zero target for 2050, which effectively assumes zero net carbon intensity for household aviation trips (based on use of carbon offsets).

Household consumption changes

Wedge	Description	Key assumptions
Reduced vehicle travel (beyond PSRC Vision 2050)	Households may be able to reduce their use of passenger vehicles beyond the amounts envisioned by the Puget Sound Regional Council's Regional Transportation Plann(RTP). This could be achieved, for example, through even greater use of transit or active transportation modes, increased carpooling, and/or increased urban density that reduces the need for automobile travel.	This wedge parallels the "reduce passenger vehicle travel" wedge in the geographic abatement analysis. In the consumption-based wedge analysis tool, the default scenario assumes local households can achieve a 15% reduction in passenger vehicle-miles traveled (VMT) by 2030 (all households) and a 25% reduction by 2050 (with straight-line progress towards these targets in interim years). These targets exceed the VMT reductions assumed in the Regional Transportation Plan, and therefore provide additional emission reductions. Note that it is possible to manually choose different targets in the tool. If targets are set at a level that is less than the VMT reductions envisioned in the RTP, this wedge will not appear (it will not produce any additional emission reductions).
Accelerated EV adoption (beyond state targets)	Local households may choose to purchase EVs at a rate that exceeds statewide rates expected under Washington's EV sales target. This could result in additional emissions reductions associated with avoiding the use of conventional vehicles assumed in the reference case.	This wedge parallels the "electrify passenger vehicles" wedge in the geographic abatement analysis. In the consumption-based wedge analysis tool, the default scenario assumes 85% of all new vehicles purchased by local households will be EVs by 2030. Between now and 2030, this would mean the rate of EV adoption exceeds the statewide average, yielding additional local emission reductions. Note that this wedge assumes EVs will be driven the same number of miles as the conventional vehicles they displace. This may be inaccurate in the near term

		(e.g., if households purchase EVs as second cars), but is likely a valid simplifying assumption over the long run as conventional vehicles are fully displaced.
Reduced vehicle purchases	In conjunction with – or in addition to – reducing the number of vehicle-miles traveled, households could decide to purchase fewer cars. This could significantly reduce household carbon footprints by avoiding emissions associated with vehicle manufacturing. Today, households in King County own around 1.7 cars on average. Households could also reduce car purchases by holding onto vehicles longer and extending their average lifetime.	There are two components to this abatement wedge, one related to average household vehicle ownership and one concerning average vehicle lifetimes. In the default scenario, the tool assumes local households could reduce average vehicle ownership to 1.25 by 2030, and to 1 vehicle per household by 2050, reflecting a lower need for cars as passenger vehicle miles are reduced. The default scenario also assumes average vehicle lifetimes could be extended by 33% by 2030 and 50% by 2050, based on modeling assumptions adopted by Erickson et al. and C40 Cities (Erickson et al. 2012; C40 Cities et al. 2019b, p.40).
Reduced air travel	Air travel is one of the single greatest contributors to household carbon footprints. Because of technological challenges in decarbonizing air travel, reaching global net zero goals will likely require absolute reductions in the amount that people fly (IEA 2021). Local households can do their part by choosing to fly less.	This wedge parallels the "reduce air travel & increase efficiency" wedge in the geographic abatement wedge analysis, but estimates emission reductions based on the total lifecycle emissions of fossil fuels used for aviation. In the default scenario, the tool assumes all households could reduce their average air travel by 20% by 2030 and 25% by 2050. This follows assumptions used in the geographic wedge analysis, but is also corroborated by an assessment by C40 Cities (C40 Cities et al. 2019b, p.40).

Supply chain decarbonization

Wedge	Description	Key assumptions
Decarbonization of vehicle supply chains	This wedge shows remaining emission reductions that could be achieved if supply chains for passenger vehicles – including vehicle maintenance services and vehicle manufacturing – were decarbonized in line with efforts to decarbonize the wider economy.	As describe above, the default scenario assumes all supply chain emissions (nationally and globally) are decarbonized in line with Washington State greenhouse gas emission reductions targets (ca. 50% by 2030, 75% by 2040, and 100% by 2050).

Food Consumption Wedges

Household consumption changes

Wedge	Description	Key assumptions
Reduced household food waste	The USDA estimates that a large percentage of food produced for human consumption in the United States goes uneaten (Buzby et al. 2014). At the household level, around 21 percent of purchased food is wasted. Reducing household food waste could significantly reduce greenhouse gas emissions in the agriculture sector associated with food production.	C40 Cities estimates that household food waste could be reduced by 50% by 2030, and in an aggressive scenario completely eliminated (C40 Cities et al. 2019b; C40 Cities et al. 2019a). The CBEA tool's default scenario assumes that 90% of Puget Sound households could reduce waste by 50% by 2030, and by 100% by 2050.
Healthy calorie intake	Numerous studies suggest that Americans consume more calories than is necessary for a healthy diet. Optimizing calorie intake (and in conjunction consuming healthier foods) could reduce overall food consumption and thereby reduce emissions from food production.	Multiple studies suggest that aligning US diets with health recommendations could result in an average reduction in food consumption of around 6% (Erickson et al. 2012; C40 Cities et al. 2019a). The CBEA tool's default scenario assumes that 75% of Puget Sound households could adopt optimal diets by 2030 (and maintain this thereafter).
Reduced meat and dairy consumption	Livestock production is highly greenhouse gas-intensive compared to other forms of agriculture. Not only do livestock produce methane emissions directly, but around 65% of emissions from crop production are attributable to animal-based products (e.g., to produce animal feed) (C40 Cities et al. 2019a). Reducing consumption of meat and dairy products – especially from cattle – and adopting more vegetarian diets could dramatically reduce emissions associated with household food consumption.	Research by the EAT Lancet Commission suggests that per-person meat consumption of around 300g per week, and dairy consumption equivalent to 250g of milk per day, would be optimal for health and global sustainable development goals (EAT Lancet Commission 2019). For typical US households, these amounts would constitute a reduction of over 70% in meat consumption, and a 15% reduction in dairy (C40 Cities et al. 2019a). Figures in this range are corroborated by other studies (Erickson et al. 2012; Institute for Global Environmental Strategies et al. 2019).

		The CBEA tool's default scenario assumes that half of Puget Sound households could achieve these reductions (switching consumption to lower carbon calories) by 2030, and 80% of all households could do so by 2050.

Supply chain reductions and decarbonization

Wedge	Description	Key assumptions
Reduced supply chain food waste	The USDA estimates that around 10% of food produced in the United States is wasted before it reaches consumers (e.g., it is damaged in transport, or discarded by grocery stores) (Buzby et al. 2014). This adds to the total greenhouse gas footprint of agricultural production. Reducing food supply chain waste is therefore another way to significantly reduce overall consumption-based emissions. Note that households could directly contribute to this wedge by opting to purchase "imperfect" food products (e.g., with cosmetic blemishes) and/or consuming food past its "sell by" date (but safely still edible) – especially if encouraged to by retailers (Liu 2022).	Based on assumption used by C40 Cities (C40 Cities et al. 2019a) – as well as US food loss and waste reduction goals (US EPA 2016) – the CBEA tool's default scenario assumes that half of all supply chain food waste could be reduced by 2030, and 75% by 2050.
Decarbonization of food production supply chains	This wedge shows emission reductions that could be achieved if food supply chains – including land-based fossil carbon emissions associated with	As describe above, the default scenario assumes all supply chain emissions (nationally and globally) are decarbonized in line with Washington State

	agricultural production – were decarbonized in line with efforts to decarbonize the wider economy.	greenhouse gas emission reductions targets (ca. 50% by 2030, 75% by 2040, and 100% by 2050).
Reduced livestock methane emissions	One reason livestock production is greenhouse gas-intensive is because ruminant livestock produce significant volumes of methane. Methane from enteric fermentation in livestock (especially dairy cattle) produces over one quarter of total US methane emissions (U.S. EPA 2022). Manure management contributes another 9% to US methane emissions and is also a significant contributor to N_2O emissions. The most direct way to reduce these emissions would be to reduce meat and dairy consumption. However, through optimizing feed and other interventions, livestock methane emissions could be directly reduced. Alternative manure management systems, including collection and destruction of methane from biodigesters, could also significantly reduce methane emissions.	Based on a study by Smith et al., the CBEA tool's default scenario assumes that enteric fermentation emissions in the United States could be reduced by 25% by 2030 (Smith et al. 2008). The tool additionally assumes that manure management emissions could be reduced up to 90% by 2030 through aerobic disposal and/or methane capture and destruction at manure lagoons.
Reduced N_2O emissions from agriculture	Over half of all greenhouse gas emissions from US agriculture (on a CO_2-equivalent basis) are in the form of nitrous oxide emissions associated with soil management: use of synthetic fertilizers, irrigation, drainage, cultivation and tillage, shifts in land use, and application and/or deposition of livestock manure and other organic materials on cropland and other farmland soils (CRS 2022). More efficient synthetic and organic fertilizer application could reduce these emissions significantly (though not eliminate them entirely).	Based on a study by Davidson, the CBEA tool's default scenario assumes that agricultural N_2O emissions could be reduced by half by 2050 through improved efficiency (Davidson 2012).

Goods Consumption Wedges

Household consumption changes

Wedge	Description	Key assumptions
Reduced clothing and textile consumption	The PSREA consumption-based emissions inventories suggest that apparel consumption is a significant contributor to household carbon footprints – around 25% of all emissions from the consumption of goods. Furthermore, reducing apparel consumption could be relatively easy – especially if consumers choose to buy more durable clothing (and textiles) and use them for longer.	Analysis by C40 Cities suggests that urban households could feasibly reduce clothing and textile purchases by up to 65% (C40 Cities et al. 2019b). Following this analysis, the CBEA tool's default scenario assumes household apparel and textile purchases in the Puget Sound region could be reduced by 45% by 2030, and 65% by 2050.
Reduced consumption of other major goods	Other major contributors to consumption-based emissions from goods include furniture, home supplies, appliances, entertainment goods, and personal care items. By seeking out more durable goods in these categories, promoting "sharing economies" for them, and using them for longer, Puget Sound households could significantly reduce their consumption. See, for example: https://sustainableconsumption.usdn.org/	Following analysis by C40 Cities, the CBEA tool's default scenario assumes that half of Puget Sound households could reduce consumption of goods in all these categories by 50% by 2030, and all households could do so by 2050 (C40 Cities et al. 2019b). (Note that the same assumptions are applied to all goods in the default scenario; however, the tool allows manual configuration of different assumptions for each good represented in this wedge.)

Supply chain reductions and decarbonization

Wedge	Description	Key assumptions
Reduced clothing supply chain waste	By some estimates, up to 25% of all materials produced for making apparel end up wasted before they reach store shelves (Cosgrove 2019; Davies 2020). Reducing this waste would be an important step in reducing the overall carbon footprint of apparel consumption.	Following analysis by C40 Cities, the CBEA tool's default scenario assumes that textile supply chain waste could be reduced by 50% by 2030, and 75% by 2050 (C40 Cities et al. 2019b).
Decarbonization of food production supply chains	This wedge shows emission reductions that could be achieved if product supply chains – including land-based fossil carbon emissions associated with textile and apparel production – were decarbonized in line with efforts to decarbonize the wider economy.	As describe above, the default scenario assumes all supply chain emissions (nationally and globally) are decarbonized in line with Washington State greenhouse gas emission reductions targets (ca. 50% by 2030, 75% by 2040, and 100% by 2050).
Reduced N_2O emissions from agriculture (textiles)	This wedge is identical to the one for food production, but is applied to fiber crop production only (e.g., cotton). The percentage of agricultural N_2O emissions associated with fiber crop production is derived from analysis by C40 Cities (C40 Cities et al. 2019b).	Based on a study by Davidson, the CBEA tool's default scenario assumes that agricultural N_2O emissions could be reduced by half by 2050 through improved efficiency (Davidson 2012).

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