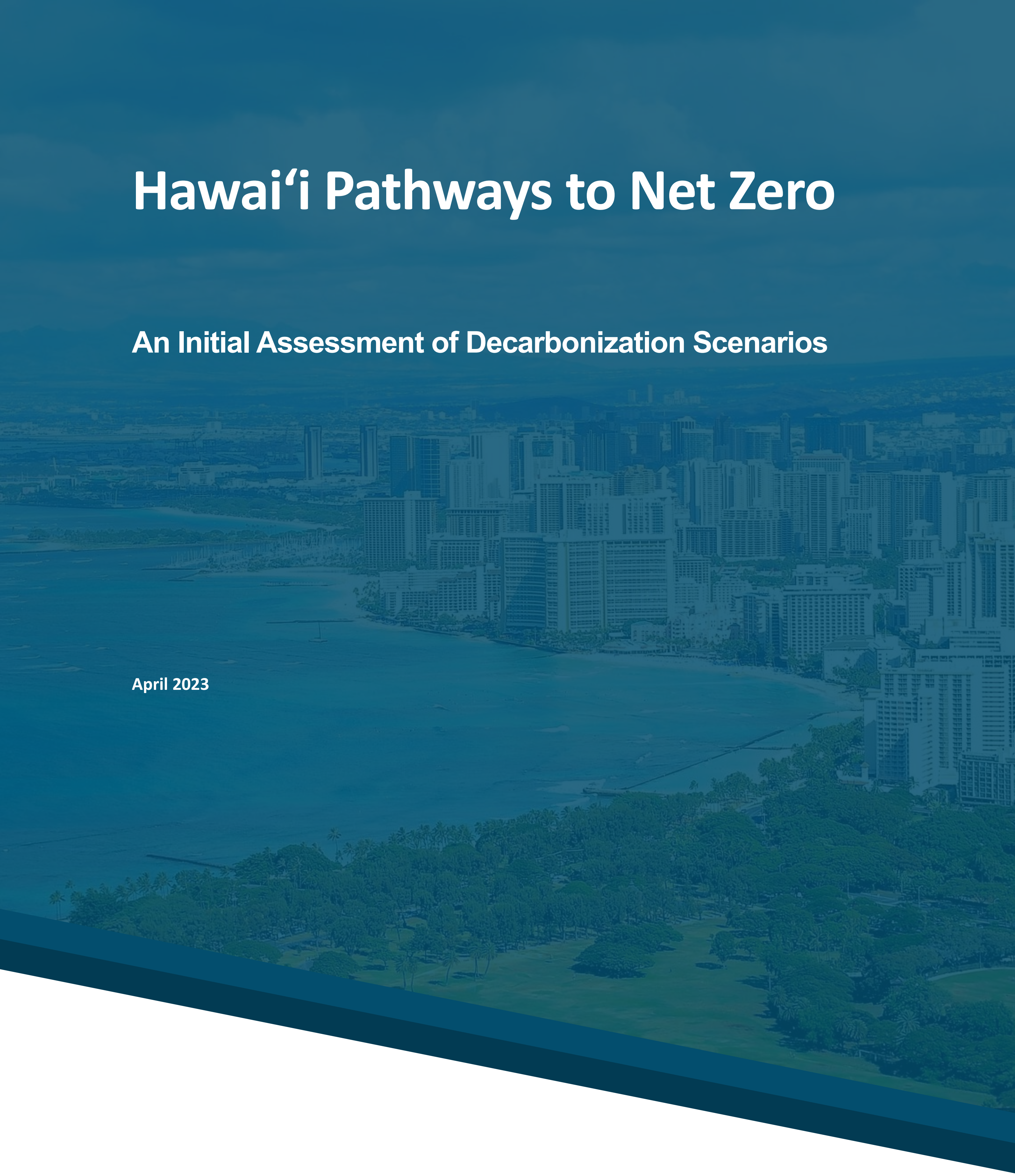

Hawaiʻi Pathways to Net Zero

An Initial Assessment of Decarbonization Scenarios

April 2023

Energy+Environmental Economics

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An Initial Assessment of Decarbonization Scenarios

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Table of Contents

List of Figures

List of Tables

Acronyms

Acronym	Description
AEO	(U.S. EIA) Annual Energy Outlook
AFOLU	Agriculture, Forestry, And Land Use
AIM	American Innovation and Manufacturing act
BAU	Business As Usual
CDR	Carbon Dioxide Removal
COP	Coefficient Of Performance
DAC	Direct Air Capture
DBEDT	Hawaiʻi Department of Business, Economic Development, and Tourism
EIA	(U.S.) Energy Information Administration
EPA	(U.S.) Environmental Protection Agency
EV	Electric Vehicle
GHG	Greenhouse Gas
HFC	Hydrofluorocarbon
IRP	Integrated Resource Planning
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Uses
LEAP	Long-range Energy Alternatives Planning System
LDV	Light-Duty Vehicle
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MHDV	Medium- and Heavy-Duty Vehicle
MMT	Million Metric Tonnes
NET	Negative Emissions Technology
PUC	Public Utilities Commission
RNG	Renewable Natural Gas
RPS	Renewable Portfolio Standard
SEC	(U.S.) Securities and Exchange Commission
SEDS	(U.S. EIA) State Energy Data System
USCA	United States Climate Alliance
VMT	Vehicle Miles Traveled
ZEV	Zero-Emission Vehicle

Executive Summary

Background

In 2018, Governor David Ige of Hawaiʻi signed Act 15, establishing one of the most ambitious economywide greenhouse gas (GHG) emissions targets in the country.[1] Act 15 requires the state of Hawaiʻi to reach net-zero GHG emissions "as quickly as practicable, but no later than 2045." In addition to this target, Hawaiʻi is a member of the United States Climate Alliance (USCA) and shares the voluntary Alliance-wide target of 50-52% reduction in GHG emissions below 2005 levels by 2030.[2] In July 2022, after the analysis for this study was already completed, Governor Ige signed Act 238, which sets a statewide greenhouse gas emissions limit of at least 50% below 2005 levels by 2030.[3]

These economywide emissions targets are informed by contemporary climate science. In 2018, the Intergovernmental Panel on Climate Change (IPCC) released the "Special Report on Global Warming of 1.5°C,"[4] finding that limiting warming to 1.5°C would require net carbon dioxide (CO_2) emissions to reach net zero between 2045-2055 alongside reductions in non-CO_2 GHG emissions. Along with Hawai'i, other US states have adopted similar targets for economywide net zero GHG emissions by midcentury through a mix of legislation and executive orders.[5]

In addition to the established economywide emissions targets for the state, Hawaiian Electric has instituted its own targets for emissions reductions from electricity generation.[6] These include a 70% reduction in GHG emissions below 2005 levels by 2030 and net-zero GHG emissions by 2045, in line with the state's economywide target.[7] These targets are voluntary commitments made by Hawaiian Electric and are in addition to legal requirements under the state's Renewable Portfolio Standard.

The Purpose of this Study

Hawaiian Electric asked E3 to develop long-term, economywide decarbonization scenarios that meet Hawaiʻi's 2045 target. Importantly, this study does not seek to define prescriptive approaches to achieving net zero in Hawaiʻi, but rather provides an initial exploration what might be needed to achieve this ambitious climate goal in terms of energy infrastructure, technology adoption and deployment, and supportive policies. This initial assessment of decarbonization scenarios does not include an evaluation of the potential costs and benefits of the energy transition, focusing instead on the scale of the energy transition and the types of technologies and fuels that would be needed to meet Hawaiʻi's 2045 target.

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[1] https://www.capitol.hawaii.gov/session2018/bills/GM1115_.PDF
[2] http://www.usclimatealliance.org/
[3] https://www.capitol.hawaii.gov/sessions/session2022/bills/GM1340_.PDF
[4] https://www.ipcc.ch/sr15/chapter/spm/
[5] https://www.c2es.org/content/state-climate-policy/
[6] https://www.hawaiianelectric.com/documents/about_us/our_vision_and_commitment/climate_change_action_flyer.pdf
[7] https://www.hawaiianelectric.com/about-us/our-vision-and-commitment/climate-change-action

The objectives of this study are:

- To **develop decarbonization pathways** for meeting Hawaiʻi's economywide net zero by 2045 target that **consider various options** for emissions reductions in each sector of the economy
- To **explore a range of potential electric loads** that are consistent with economywide decarbonization and to **compare these to Hawaiian Electric's current load forecasts**
- To **estimate the quantity of decarbonized fuels that may be needed** for end uses that are hard to electrify and to **consider the potential sources of decarbonized fuels**
- To **explore which sectors will require major policy or regulatory changes** to support decarbonization.

Key Findings

The broad lessons and key findings from this study are summarized below.

- **Renewable electricity generation is necessary but not sufficient to meeting Hawaiʻi's decarbonization goals.** Achieving electric-sector decarbonization goals may require an unprecedented scale-up in new generation capacity to serve both existing loads and new loads resulting from the electrification of transportation and buildings. However, decarbonization of electricity generation will not be sufficient to achieve Hawaiʻi's economywide net zero target.
- **Both electrification and decarbonized fuels will be required to decarbonize other sectors of the economy.** In some sectors, such as on-road transportation, electrification is likely to be the key driver of emissions reductions. However, in other sectors such as aviation and marine transportation, electrification is likely to play a smaller role and decarbonized fuels will be required to achieve emissions reductions.
- **Achieving the state's 2030 target of 50% economywide emissions reductions will be challenging due to long vehicle and equipment lifetimes, long siting and development timelines in the electric sector, and a lack of near-term decarbonization options for aviation.** The scenarios modeled in this study achieve 46-48% GHG reductions by 2030, reflecting ambitious effort across all sectors of the economy to meet the statutory 2045 target. However, these scenarios fall short of the 2030 target under Act 238, indicating that even more aggressive near-term action would be required to achieve 50% economywide emissions reductions by 2030.
- **Energy efficiency and conservation support achievement of the net zero goal** by reducing the total amount of zero-carbon electricity and fuels that must be procured, lessening the cost and land-use impacts of decarbonization.
- **By 2045, the level of electric loads aligned with achievement of economywide net zero are likely to be far above Hawaiian Electric's existing load forecasts, which will have major impacts on Hawaiian Electric's planning needs**. Even after accounting for higher levels of energy efficiency, the decarbonization scenarios evaluated in this report result in 2045 electric loads that are 25-56% higher than Hawaiian Electric's 2045 "base" load forecast. The level of electrification reached by different sectors will have important implications for the amount of zero-carbon generation and capacity that Hawaiian Electric will need to procure.

- **Decarbonization of aviation will require a large quantity of decarbonized fuels and is likely to be one of the major challenges for meeting Hawai'i's 2045 net zero goal.** The decarbonization scenarios evaluated in this report reflect 2045 decarbonized fuel demand of 82-99 TBtu/year, or 51-62% of 2018 demand for liquid (fossil) fuels in Hawai'i. By 2045, about 80% of the decarbonized fuel demand may be from aviation.[8] Depending on technological development, it may be possible to electrify short-haul inter-island flights among the Hawaiian Islands. However, most aviation fuel demands are for long-haul trans-Pacific flights to the US mainland and are likely to require decarbonized fuels. The future supply of decarbonized fuels is a significant risk to achieving carbon neutrality in Hawai'i, with potential concerns regarding availability, cost, and sustainability. Carbon dioxide removal may be required if adequate decarbonized fuel supplies cannot be procured.
- **Carbon dioxide removal will be required to achieve net zero in Hawai'i, either through increased natural carbon sinks or negative emissions technologies**. If GHG emissions from burning fossil fuels can be reduced to zero, the decarbonization scenarios still reflect 2045 totals of ~3 million metric tonnes per year of non-combustion GHG emissions. These non-combustion emissions, especially methane and nitrous oxide emissions from waste and agriculture, are challenging to abate and are not fully offset under a "business-as-usual" projection of the state's natural carbon sinks. Our interpretation of Act 15 is that any additional carbon sequestration will have to occur within the state of Hawai'i.[9] Thus, achieving the state's net zero target will likely require land-use measures to enhance Hawai'i's natural carbon sinks and/or in-state deployment of negative emissions technologies such as direct air capture (DAC).
- **Additional policies and regulations are needed to ensure the deployment of decarbonization strategies outside of the electric sector.** The electric generation sector has considerable policy and regulatory mechanisms in place to support decarbonization. However, other sectors of the economy do not yet have corresponding policies in place to ensure or support emissions reductions. Without additional sectoral policies, the state will not be on track to achieve the 2045 net zero target.

[8] Hawaii's emissions inventory includes jet fuel for domestic departures, *i.e.*, for inter-island flights and for departing flights to the US mainland. More details are provided below under Emissions by Sector.
[9] https://www.capitol.hawaii.gov/session2018/bills/GM1115_.PDF

Methodology

GHG Emissions Targets and Accounting

Act 15: Net Zero by 2045

Act 15 (2018) established a 2045 economywide net zero GHG emissions target for Hawai'i, which is aligned with limiting global warming to 1.5°C. The Act states:

"Considering both atmospheric carbon and greenhouse gas emissions as well as offsets from the local sequestration of atmospheric carbon and greenhouse gases through long-term sinks and reservoirs, a statewide target is hereby established to sequester more atmospheric carbon and greenhouse gases than emitted within the State as quickly as practicable, but no later than 2045."[1]

E3's interpretation of this language is that any carbon sequestration used to offset residual GHG emissions must occur within the state of Hawai'i. This requirement for local GHG sequestration is not unique among state net-zero targets (see New York's *Climate Leadership and Community Protection Act*),[10] but it does present unique challenges for Hawai'i given the state's limited land mass. Carbon sequestration may come from increasing carbon sinks in natural and working lands or through sequestration of carbon captured via negative emissions technologies (NETs).

2030 Climate Goal

As a member of the USCA, the State of Hawai'i has committed to achieving 50-52% emissions reductions below 2005 levels by 2030.[11] In July 2022, Act 238 established a statewide greenhouse gas emissions target of 50% below 2005 levels by 2030. The 2030 target was not yet established in statute when this Pathways study was developed, thus this study is focused on the 2045 net zero target under Act 15 and scenarios reflected here have not been designed to specifically meet the 2030 target. The 2030 target is discussed in more detail in the section on **Economywide Emissions**.

Emissions Accounting

While Act 15 does not specify the exact GHG accounting framework for evaluating the Act 15 target, E3 has calculated GHG emissions in Hawai'i using methodology aligned with the EPA's State Inventory Tool[12] and the Hawai'i Department of Health's *Hawai'i Greenhouse Gas Emissions Report for 2017.*[13] Consistent

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[10] https://nyassembly.gov/leg/?default_fld=&leg_video=&bn=A08429&term=2019&Summary=Y&Actions=Y&Text=Y
[11] http://www.usclimatealliance.org/
[12] https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool
[13] https://health.hawaii.gov/cab/files/2021/04/2017-Inventory_Final-Report_April-2021.pdf

with both of these sources, all GHG emissions are calculated using 100-year global warming potentials (GWP) from the *IPCC Fourth Assessment Report.*[14]

Although Hawaiʻi's previous GHG target, Act 234, excluded emissions from aviation, Act 15 does not specify any exclusion for aviation. As a result, aviation emissions in this analysis are accounted for in a manner consistent with the EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019*[15] and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*:[16] emissions are included from the combustion of fuel sold in Hawaiʻi for domestic flights (both inter-island and flights to the mainland). Emissions from fuel sold in Hawaiʻi for international flights are excluded. Emissions from out-of-state flights arriving in Hawaiʻi are also excluded. The same GHG accounting approach is used for emissions from residual fuel oil sold in Hawaiʻi for marine use.

One important uncertainty in emissions accounting relates to the treatment of imported synthetic fuels made from GHG-neutral carbon, such as CO_2 captured from the atmosphere. This study treats all biofuels and carbon-neutral synthetic fuels as having no contribution to net GHG emissions totals, regardless of whether produced in-state or imported. For biofuels, this treatment is consistent with emissions accounting conventions used by the IPCC[17] and with the current treatment of biofuels and ethanol in Hawaiʻi's inventory.[18] Of note, formal emissions accounting methodologies for carbon-neutral synthetic fuels have not yet been developed in Hawaiʻi.

Inventories may treat carbon-neutral synthetic fuels just like biofuels (*i.e.*, with zero contribution to net emissions totals); however, they could alternatively treat synthetic fuels as having negative emissions where produced and corresponding positive emissions where consumed. This latter convention would result in *imported* synthetic fuels having positive emissions under Act 15, as out-of-state carbon sequestration is not allowed. The net zero scenarios developed in this study rely on a large volume of decarbonized fuels, although the source of these fuels is not stipulated in the scenarios. More discussion is provided in the section on **Decarbonized Fuel Demand.** The future regulatory accounting of decarbonized fuels towards meeting Hawaii's climate goals represents an important source of uncertainty in this study.

PATHWAYS Model Overview

E3 used the PATHWAYS model to analyze decarbonization pathways for Hawaiʻi. The PATHWAYS model is an economywide representation of infrastructure, energy use, and emissions within a specified geography. The model allows comparison of user-defined scenarios of future energy demand and emissions to answer "what if" questions related to decarbonization. PATHWAYS can be used as a tool to explore the impacts and implications of potential climate and energy policies specified by the user, but it is not designed to produce scenarios that represent the "optimal" or "likeliest" pathways to meeting emissions targets, as future technology availability and costs are highly uncertain.

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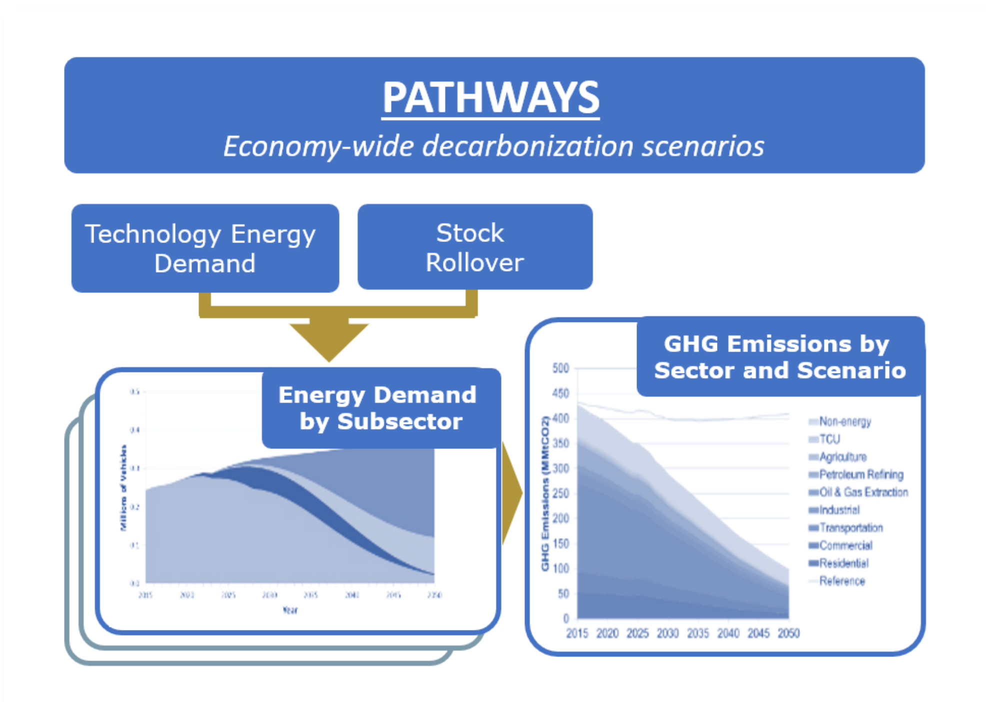
[14] https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html
[15] https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019
[16] https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
[17] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf,
[18] https://health.hawaii.gov/cab/files/2021/04/2017-Inventory_Final-Report_April-2021.pdf

E3 created the PATHWAYS model to help policymakers, businesses, and other stakeholders analyze trajectories to achieving deep decarbonization of the economy, and the model has since been improved over time in projects analyzing decarbonization at the utility service territory, state, and national level; recent examples include working with the California Energy Commission, the New York State Energy Research and Development Authority, and the Colorado Energy Office.

E3 built bottom-up island-level PATHWAYS models for Hawai'i using LEAP (Long-range Energy Alternatives Planning system),[19] a scenario-based modeling tool that tracks energy consumption and greenhouse gas emissions in all sectors of the economy. O'ahu, Hawai'i island, Kaua'i, Maui, Moloka'i, and Lāna'i were all modeled individually. At the state level, the base year model outputs were benchmarked to historical energy consumption from the EIA State Energy Data System[20] and non-energy related emissions from the EPA State Inventory Tool, with some adjustments made to align with the methodology used in the Hawai'i Department of Health *Hawai'i Greenhouse Gas Emissions Report for 2017*.

Figure 1: Illustration of E3 PATHWAYs model



A key feature of PATHWAYS is the characterization of stock rollover in major equipment categories (specifically in buildings and transportation fleets). The stock rollover approach tracks the retirement of vehicles and end-use equipment in buildings and their replacement with newer equipment that may have improved performance or may be powered by different fuels. This captures the time lag between changes in annual sales of new equipment and changes in the overall stock of equipment in the economy over

[19] LEAP is developed by the Stockholm Environment Institute. More information on the LEAP software can be found at www.energycommunity.org

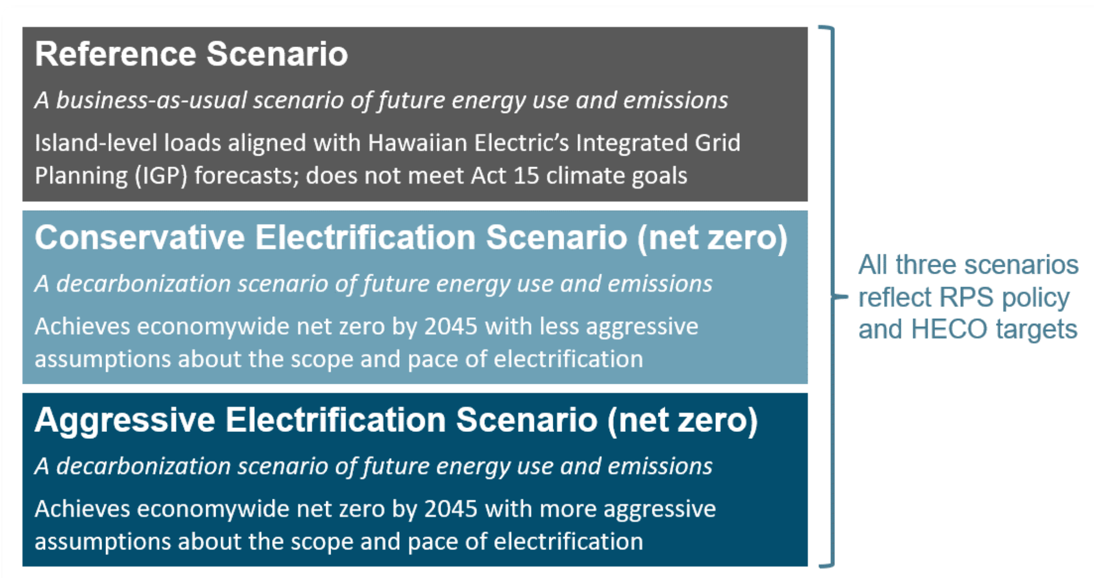
[20] https://www.eia.gov/state/seds/

time. This is important as different technologies will have different lifetimes; some technologies, such as lightbulbs, might have lifetimes of just a few years, while others, such as building shells, can have lifetimes on the order of decades. By accounting for this dynamic, a PATHWAYS scenario can determine the pace of technology deployment necessary to achieve economywide greenhouse gas emissions goals or policy targets. Figure 1 provides an illustration of the E3 PATHWAYS model.

Scenario Definitions

This study evaluates different pathways for achieving net zero economywide emissions and examines the range of electric load impacts on Hawaiian Electric's system in a future where the state achieves the emissions targets under Act 15. To meet these objectives, E3 examined three scenarios of future energy demand and emissions, as illustrated in Figure 2.

Figure 2: Three PATHWAYS scenarios modeled in this study



The Conservative Electrification and Aggressive Electrification scenarios are designed to represent lower and upper bounds of electricity demand resulting from deep decarbonization and are not meant to represent the "optimal" or "likeliest" pathways to achieving the state's 2045 GHG target. It is important to note that the Net Zero scenarios are not designed to achieve the 2030 goal of a 50% GHG reduction below 2005 levels. However, the results of these scenarios are useful in informing the level of ambition that would be required to achieve the 2030 goal.

Changes to underlying drivers of energy demand are included in the model and are common across all scenarios. These drivers include population growth, growth in vehicle miles traveled (VMT), aviation travel demand, growth of commercial building square footage, and energy demand for industry and refining. These were aligned with Hawaiʻi-specific data sources where possible, supplemented by national data from the EIA Annual Energy outlook where Hawaiʻi-specific data were not available. This study also modeled underlying assumptions for end-use efficiency improvements across all scenarios. The modeling also aligned efficiency trajectories for devices used in buildings with national results from the EIA Annual Energy Outlook.[21] It also aligned the fuel economy trajectory for EVs with forecast assumptions used by the Hawaiian Electric IGP Working Group.[22]

The Net Zero scenarios reflect decarbonization measures implemented across all sectors of the economy to achieve net zero economywide emissions by 2045. A summary of the measures modeled in all three scenarios is shown in Table 1, with narrative detail provided in the section **Emissions by Sector**.

Table 1: Key mitigation measures by sector and scenario. Colors are used to indicate where the two net zero scenarios differ.

Sector	Reference	Conservative Electrification	Aggressive Electrification
Electric Power	• 70% reduction in GHG emissions below 2005 levels by 2030; net zero GHG emissions by 2045[23]	• *Same as Reference*	• *Same as Reference*
Transportation: On-road	• Federal CAFE standards[24] • LDVs: ~80% EV sales by 2050 (Hawaiian Electric forecast)[25]	• LDVs: 100% EV sales by **2045** • MHDVs: **80%** EV sales by 2045 • 100% decarbonized gasoline and diesel by 2045	• LDVs: 100% EV sales by **2035** • MHDVs: **100%** EV sales by 2045 • 100% decarbonized gasoline and diesel by 2045
Transportation: Aviation	• 16% increase in fleetwide efficiency by 2045 (based on improvements from AEO21)[26]	• 16% increase in fleetwide efficiency by 2045 • 13% decarbonized fuel by 2030, 100% by 2045 • **No electrification of inter-island flights**	• 16% increase in fleetwide efficiency by 2045 • 13% decarbonized fuel by 2030, 100% by 2045 • **Electrification of inter-island flights by 2045**
Transportation: Other Off-road	• No energy efficiency, electrification, or decarbonized fuel blending for off-road transportation	• **No electrification of off-road diesel** • 100% decarbonized diesel and residual fuel oil by 2045	• **50% electrification of off-road diesel by 2045** • 100% decarbonized diesel and residual fuel oil by 2045

21 https://www.eia.gov/outlooks/archive/aeo20/

22 https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/working_groups/forecast_assumptions/PUC-HECO-IR-1_att_8_electric_vehicles.xlsx

23 https://www.hawaiianelectric.com/hawaiian-electric-sets-goal-of-70-percent-carbon-reduction-by-2030-envisions-zero-emissions-by-2045
Note: The mix of carbon-free electricity resources (e.g., wind, utility-scale solar, customer-sited solar, hydrogen combustion) used to achieve the electric sector emissions reductions was not specified as part of this analysis.

24 https://www.nhtsa.gov/press-releases/usdot-announces-new-vehicle-fuel-economy-standards-model-year-2024-2026

25 https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/working_groups/forecast_assumptions/PUC-HECO-IR-1_att_8_electric_vehicles.xlsx

26 https://www.eia.gov/outlooks/archive/aeo21/

Sector	Reference	Conservative Electrification	Aggressive Electrification
Buildings	• Energy efficiency: "Achievable Potential – BAU" levels from Hawaiʻi PUC Market Potential Study[27] • Solar water heating requirement for all new residential buildings[28]	• Energy efficiency: "Achievable Potential – **High**" levels from Hawaiʻi PUC Market Potential Study[27] • *Solar water heating same as Reference* • 100% sales of electrified devices for all end uses (water heating, cooking, etc.) by **2045** • 100% decarbonized gas replacing pipeline gas in 2030, by 2045 for LPG	• Energy efficiency: "Achievable Potential – **High**" levels from Hawaiʻi PUC Market Potential Study[27] • *Solar water heating same as Reference* • 100% sales of electrified devices for all end uses (water heating, cooking, etc.) by **2035** • 100% decarbonized gas replacing pipeline gas in 2030, by 2045 for LPG
Industry	• Phase out refinery production of fossil fuel products (along with associated energy demand and emissions) by 2030[29]	• *Refinery assumptions same as Reference* • Manufacturing, construction, and agriculture liquid fuels demand electrifies at same rate as MHDVs[30]	• *Refinery assumptions same as Reference* • Manufacturing, construction, and agriculture liquid fuels demand electrifies at same rate as MHDVs[30]
Non-Energy, Non-Combustion	• HFC emissions reduced per federal AIM Act requirements[31] • Non-combustion emissions from oil & gas sector eliminated by 2030[29]	• *HFC assumptions same as Reference* • *Non-combustion emissions from oil & gas sector same as Reference* • Max abatement available below \$100/tCO_2e from EPA Non-CO_2 report for agriculture and waste[32]	• *HFC assumptions same as Reference* • *Non-combustion emissions from oil & gas sector same as Reference* • Max abatement available below \$100/tCO_2e from EPA Non-CO2 report for agriculture and waste[32]
Carbon Dioxide Removal (CDR)	• Existing natural CO_2 sinks decline 18% through 2045[33]	• *Existing natural CO_2 sinks same as Reference* • Incremental 0.72 MMT/year of CDR needed through increased natural sinks or NETs	• *Existing natural CO_2 sinks same as Reference* • Incremental 0.72 MMT/year of CDR needed through increased natural sinks or NETs

[27] https://puc.hawaii.gov/wp-content/uploads/2021/02/Hawaii-2020-Market-Potential-Study-Final-Report.pdf
[28] https://programs.dsireusa.org/system/program/detail/2987
[29] Assumes that fossil petroleum refining ceases in 2030. See Industry Emissions below for details regarding this assumption.
[30] Gasoline and diesel demand in this sector is primarily from heavy-duty vehicles used in construction and agriculture.
[31] https://www.epa.gov/newsreleases/epa-moves-forward-phase-down-climate-damaging-hydrofluorocarbons
[32] https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections
[33] https://pubs.usgs.gov/pp/1834/a/pp1834.pdf

Emissions

Economywide Emissions

This section describes the greenhouse gas emissions trajectories for each of the scenarios described above, as well as a counterfactual scenario reflecting the Reference case without RPS policy or electric-sector greenhouse gas targets.

Figure 3: Economywide Hawaiʻi net GHG emissions by scenario

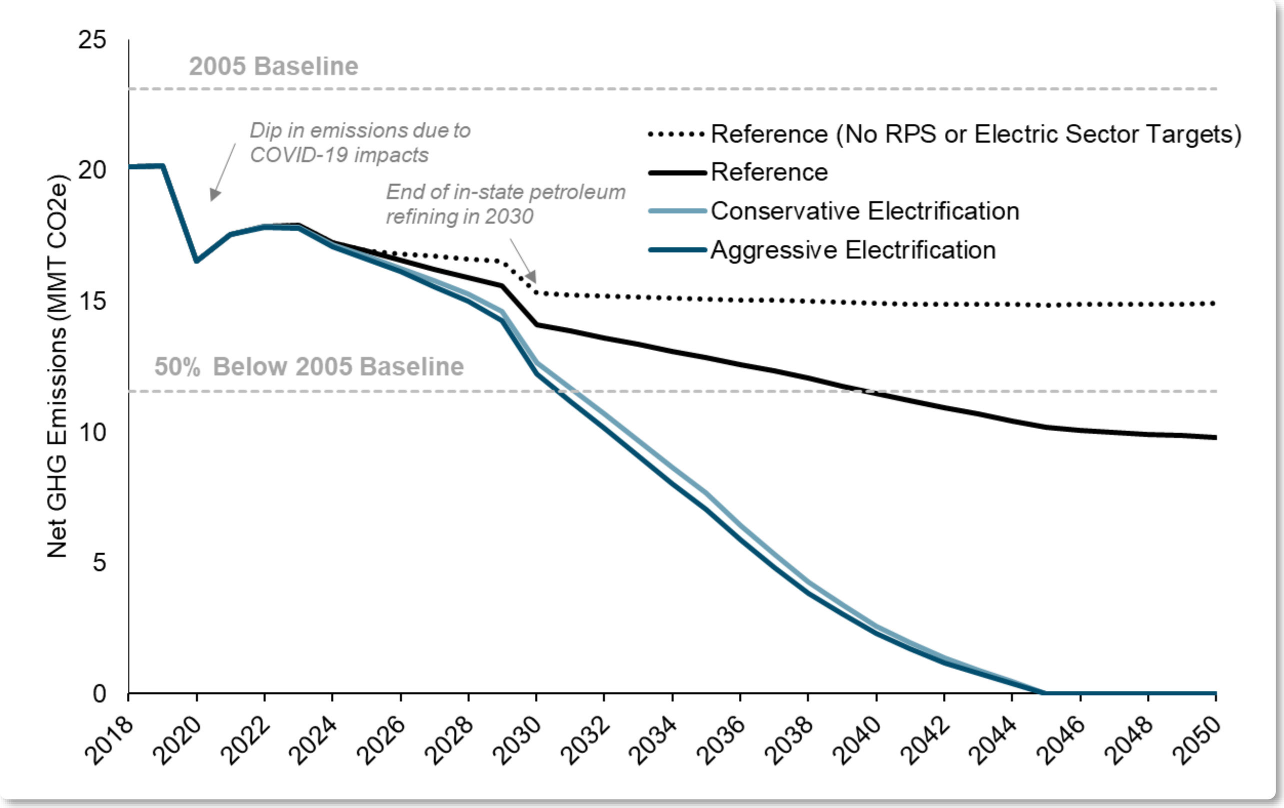


Figure 3 above shows net emissions (GHG emission sources net of carbon sinks) over time for three scenarios (solid lines) and a counterfactual (dotted lines). After a near-term increase in GHGs as the economy recovers from the impacts of the COVID-19 pandemic, economywide net GHG emissions decline by 2045 in all scenarios. Net emissions decline to 58% below 2005 levels by 2045 in the Reference scenario, while emissions reach net zero by 2045 in both the Conservative Electrification and Aggressive Electrification scenarios. Although the two net zero scenarios have similar emissions trajectories, they vary considerably in their demands for electricity and decarbonized fuels, as detailed in the corresponding sections below.

The first key takeaway from this figure is that electric-sector emissions reductions reflect a crucial step toward achieving the state's GHG reduction targets. The Reference scenario (black solid line) includes both the state's RPS policy as well as Hawaiian Electric's targets of 70% below 2005 levels by 2030 and net zero emissions by 2045 from electric generation, while the counterfactual scenario (black dotted line) does not include any electric-sector emissions reductions after 2024, reflecting only the procurement processes that are active today. The gap between these scenarios shows that electric-sector emissions reductions, including Hawaiian Electric's voluntary commitments, are a key part of economywide decarbonization.

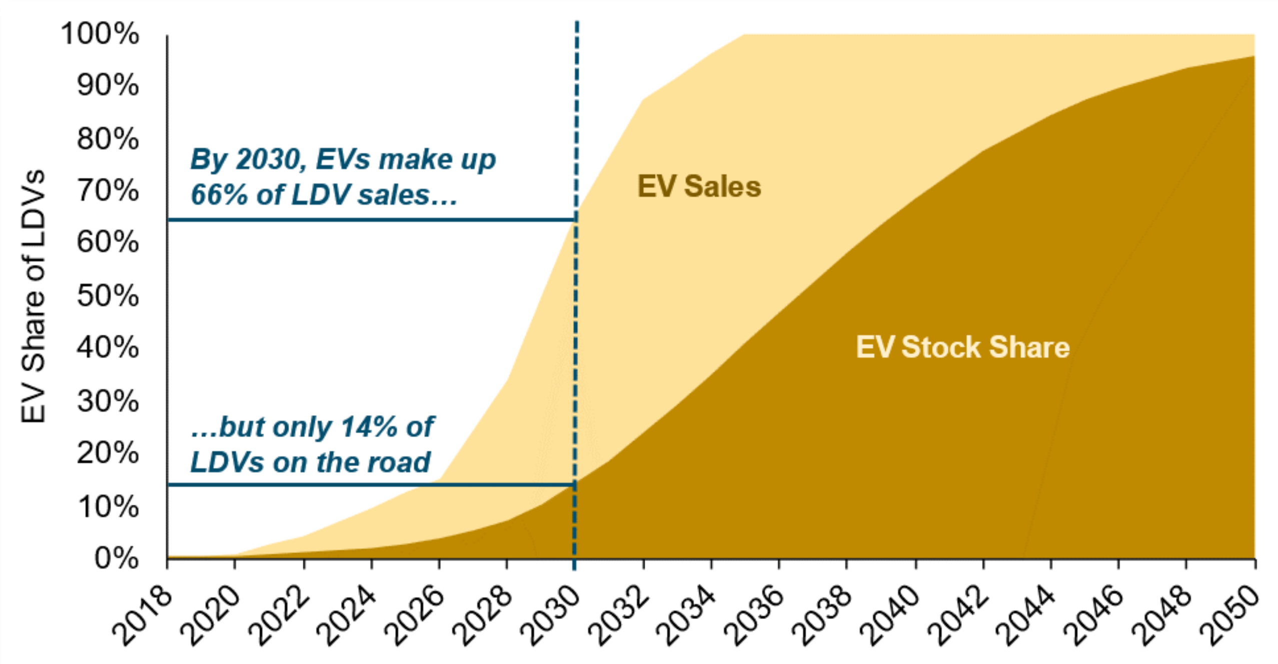
The second takeaway from this figure is that even aggressive electric-sector emissions reductions are not enough to achieve the state's 2045 net zero target on their own. The Reference scenario falls far short of net zero, only achieving 58% emissions reductions below 2005 levels by 2045. Achieving the state's net zero target will also require major emissions reductions across all other sectors of the economy. The Conservative Electrification and Aggressive Electrification scenarios achieve the net zero target by employing extensive decarbonization measures in all sectors, as described in the next section.

The third takeaway from this figure is the challenge of achieving deep emissions reductions by 2030. Even the significant decarbonization measures evaluated in the Conservative Electrification and Aggressive Electrification scenarios fall short of the USCA/Act 238 2030 target of 50% emissions reductions below 2005 levels, reaching 45% and 47% emissions reductions by 2030 respectively. Achieving deep emissions reductions by 2030 is challenging due to the long lifetimes of physical assets in the economy and the natural pace of asset replacement, as described below. In the net zero scenarios modeled here, a 2030 target of 50% GHG reductions could be achieved with deeper levels of electric-sector emissions reductions, requiring ~80% electric-sector emissions reductions below 2005 levels. This would necessitate a rapid build-out of zero-carbon generation with likely challenges for permitting, siting, and development. Further study is needed to evaluate the costs and implications of meeting a 50% GHG reduction target by 2030.

Figure 4 illustrates how the dynamic of gradual stock rollover is a challenge for achieving rapid decarbonization. In the Aggressive Electrification scenario, although electric vehicles (EV) make up 66% of new light-duty vehicle (LDV) sales by 2030, they only account for 14% of the actual on-road LDV fleet in that year. Similarly, by the time the scenario-imposed EV sales mandate reaches 100% in 2035, EVs only account for 40% of the on-road fleet. Even in 2045, after an EV sales mandate has been in place for 10 years, internal combustion engine vehicles still account for 13% of the on-road fleet.[34] This stock rollover dynamic highlights the critical importance of achieving high sales shares of electrified devices in the near-term, as decades are required for sales mandates to translate into high levels of electrification adoption among vehicles on the road and equipment in buildings.

[34] Survival curve assumptions for LDVs are based on survival rates from the EPA MOVES model (https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf) and reflect a mean LDV lifetime of 14 years and a relatively long tail with 12% of LDVs remaining in service after 20 years.

Figure 4: LDV EV sales share and stock share over time in the Aggressive Electrification scenario



Emissions by Sector

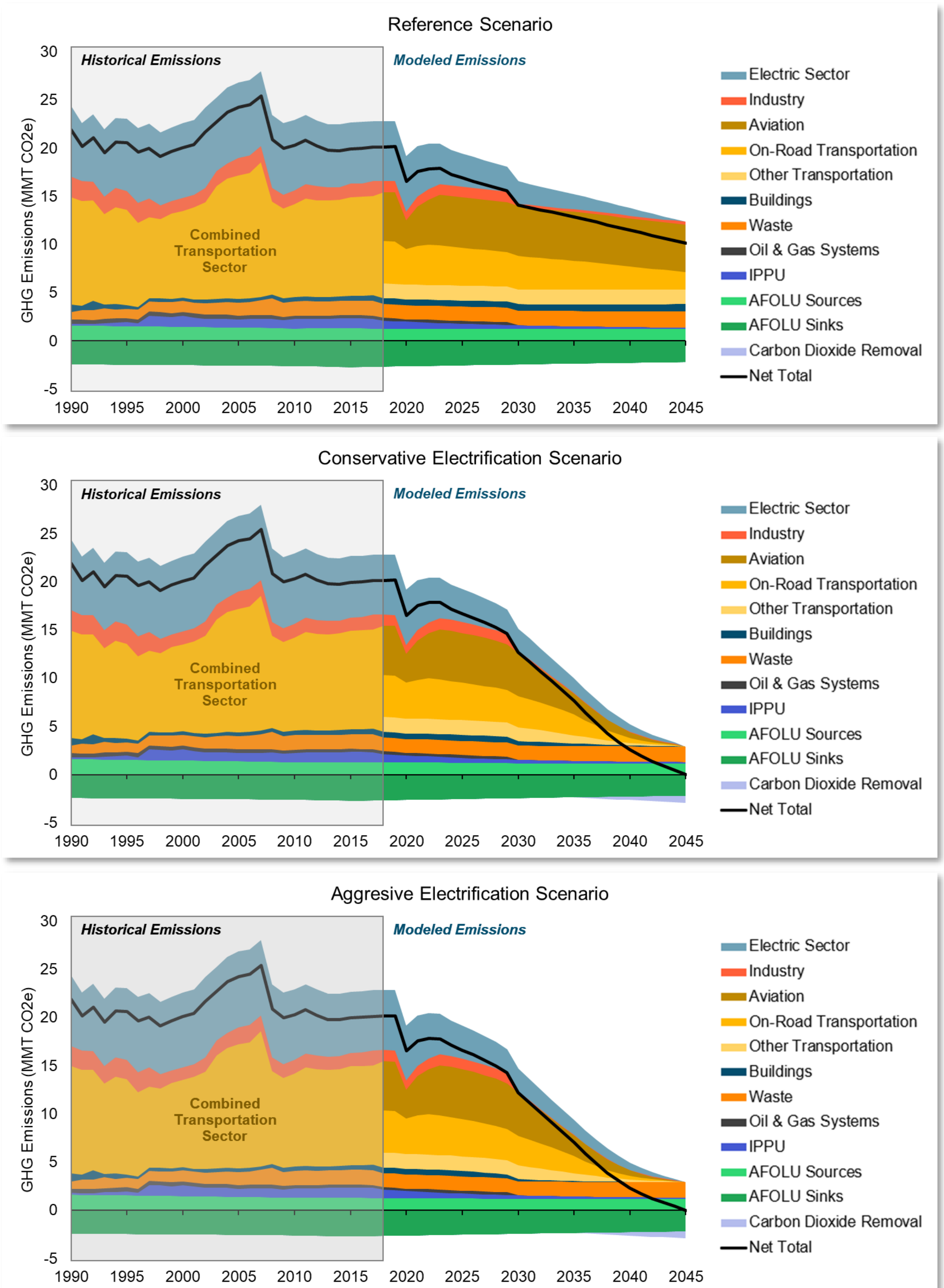
Figure 5 shows changes in GHG emissions by sector over time in each scenario. This figure shows historical emissions based on the EPA State Inventory Tool[35] and the Hawai‘i Department of Health's *Hawai'i Greenhouse Gas Emissions Report for 2017,*[36] as well as future emissions based on E3's PATHWAYS model. The figure shows gross emissions as areas above the x-axis, negative emissions as areas below the x-axis, and net emissions as a black line.

In the Reference scenario, emissions reductions largely come from two sources: the electric power sector achieving Hawaiian Electric's targets and reductions in on-road transportation emissions due to LDV electrification. Emissions reductions are also seen in industry due to the assumed phaseout of fossil petroleum refining at the Par Refinery on O‘ahu by 2030, as described in more detail below.

The two net zero scenarios see widespread reductions in combustion emissions across all sectors of the economy by 2045. Although non-combustion emissions are reduced, a small amount of net positive non-combustion emissions remain by 2045. This requires the deployment of carbon dioxide removal to reach net zero.

[35] https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool
[36] https://health.hawaii.gov/cab/files/2021/04/2017-Inventory_Final-Report_April-2021.pdf

Figure 5: GHG emissions by sector and scenario



Although both net zero scenarios have similar emissions, the distinct measures employed in the two scenarios lead to very different demands for electrictiy and decarbonized fuels. The rest of this section describes the measures that are modeled in the net zero scenarios to achieve the net zero GHG emissions by 2045 target. The following sections describe the impacts of these measures on demands for electricity and decarbonized fuels.

Energy Efficiency and Demand Reductions

The net zero scenarios include robust energy efficiency measures across multiple sectors, described in Table 1 and in the sections below under the sectors where they are implemented. These measures are important as they ultimately reduce the cost of emissions abatement through reducing demand for zero-carbon electricity, decarbonized fuels, or carbon dioxide removal. However, energy efficiency does not obviate the need for these decarbonization solutions. Thus, while energy efficiency measures may reflect no-regrets approaches to reducing the costs of economywide decarbonization, they should not be seen as substitutes for the decarbonization technologies and policies described below.

Other demand reductions, such as reductions in vehicle miles travelled (VMT) or in aviation demand, have not been modeled in the net zero scenarios. These kinds of demand reductions would be valuable for reducing near-term emissions as well as long-term costs. However, these kinds of demand reductions are challenging to achieve as they require changes in land use, work behaviors, leisure preferences, and/or other societal changes. Furthermore, while reducing VMT may be achievable without negative economic impacts, reducing aviation demand would likely have adverse economic impacts from reduced visitation to Hawaiʻi. In addition, other jurisdictions have struggled to achieve demand reductions in these areas. For example, the California Air Resource Board Draft 2022 Scoping Plan notes that California is "not on track to achieve the VMT reduction called for in the 2017 Scoping Plan."[37]

Electric Sector

Decarbonization of electric generation is essential to achieving the state's net zero climate goals. This study aims to build on Hawaiian Electric's GHG reduction targets for the electric sector by considering the measures needed to decarbonize other sectors and by exploring the electric load implications of achieving net zero economywide in Hawaiʻi.

In addition to the state's 100% RPS target by 2045, Hawaiian Electric has set voluntary emissions targets for electricity generation of 70% reductions below 2005 levels by 2030 and net zero emissions by 2045. These electric-sector targets are assumed to be achieved in all scenarios including the Reference scenario. A small portion of electric-sector emissions come from Kauaʻi Island Utility Cooperative (KIUC), which is also committed to the state's 100% RPS target by 2045. This study has modeled KIUC as steadily reducing electric-sector emissions to net zero by 2045.

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[37] https://ww2.arb.ca.gov/sites/default/files/2022-05/2022-draft-sp.pdf

More discussion of electric loads is provided in the section on **Electricity Demand**. In subsequent work, these load scenarios could be used as inputs in electric-sector modeling to determine resource needs corresponding to economywide decarbonization.

Industry

Operations of the Par Refinery on Oʻahu currently account for over 80% of energy emissions from industry in the state of Hawaiʻi. (This does not include the downstream combustion of fuels produced at the refinery). While future refinery operations are uncertain, this study assumes that refining of fossil petroleum products at Par will cease by 2030 in all scenarios. This assumption is informed by the final report of the Hawaiʻi Refinery Task Force in 2014 that concluded that one or both of Hawaiʻi's two refineries would close by 2020 due to reduced profit margins, additional federal and state regulatory requirements, and decreased petroleum demand caused by energy efficiency and increased renewable electricity.[38] Since the Task Force report was published, one refinery ceased operations in 2019, while the Par Refinery continues to operate. The Par Refinery is configured to produce large amounts of fuel oil for electricity generation; however, Hawaiian Electric's decarbonization targets will lead to a steep decline in demand for fuel oil in all scenarios studied, which would have an adverse impact on the refinery's profits. In addition, the forecasted petroleum demand in all scenarios studied is much lower than what was assumed in the Task Force report. For these reasons, this study assumes that all fossil petroleum refining in the state of Hawaiʻi ceases by 2030.

If the Par Refinery ceases petroleum refining, it could convert to an import terminal for liquid fuels coming from overseas. Thus, although fuel prices may be impacted, liquid fuel supplies would still be available for transportation and electricity generation uses. However, most of the natural gas consumed in buildings on Oʻahu is produced from naphtha created as a byproduct at the refinery, and as a result, the cessation of on-island refining would reflect a major supply challenge for natural gas customers. Alternative gas supplies are currently under consideration in the Hawaiʻi Public Utility Commission's docket on Integrated Resource Planning for Hawaiʻi Gas.[39] In this study, unspecified fossil gas sources continue to serve Oʻahu buildings after 2030 in the Reference scenario. In the net zero scenarios, building electrification gradually reduces fuel demands in buildings and biogas is assumed to meet remaining gas needs after fossil petroleum refining ceases in 2030.

The Par Refinery may also transition to produce decarbonized liquid and/or gaseous fuels at the site, as these fuels will be necessary for any net zero future in Hawaiʻi and a local source of decarbonized fuels could be advantageous. Par Hawaii and Hawaiian Airlines recently announced plans to study the commercial viability of local production of sustainable aviation fuels, and Par Hawaii is considering converting some of the existing diesel refining capacity for the production of renewable diesel and renewable jet fuel.[40] In addition, because renewable naphtha is a natural byproduct of producing

[38] https://energy.hawaii.gov/wp-content/uploads/2011/08/HRTF_Final-Report_04-10-14.pdf
[39] https://dms.puc.hawaii.gov/dms/dockets?action=details&docketNumber=2022-0009
[40] https://newsroom.hawaiianairlines.com/releases/hawaiian-airlines-and-par-hawaii-announce-plan-to-jointly-explore-sustainable-aviation-fuel-in-hawai%E2%80%98i

renewable diesel, converting refinery capacity to renewable liquid fuels production would also create a source of feedstock for renewable natural gas production[41].

Outside of refinery operations, most remaining emissions in the Industry sector are from gasoline and diesel consumption for agriculture and construction vehicles and equipment.[42,43] This study assumes that decarbonization of these end uses will follow a similar trajectory to that of Medium and Heavy-Duty Vehicles (MHDVs). In both net zero scenarios, gasoline and diesel consumption in industry is electrified at the same pace as new EV sales for MHDVs. Decarbonized fuels are required to meet remaining gasoline and diesel demand in industry.

Aviation

Despite increasing air travel demand, aviation emissions decrease slightly over time in the Reference scenario due to fleetwide aviation efficiency improvements forecasted in EIA Annual Energy Outlook (AEO) 2021.[44] However, much more ambitious measures are required to achieve deep emissions reductions in the net zero scenarios. In both of those scenarios, the study assumes achievement of the Biden Administration target for sustainable aviation fuel production of 3 billion gallons per year by 2030,[45] which translates into a 13% blend of sustainable fuel based on AEO forecasts of national aviation fuel demand.

Beyond 2030, in the Aggressive Electrification scenario, the aviation sector is decarbonized through a combination of electrification and decarbonized fuels. Electric aircraft are expected to be limited to smaller aircraft and flight distances of less than 1,000 km by mid-century.[46] Thus, this study assumes that electric aircraft are used only for inter-island aviation, which is estimated to correspond to 12% of aviation energy demand. No change in efficiency is assumed for battery-electric vs. conventional aircraft.

Hydrogen-powered aircraft could be another option for short-haul inter-island flights, but they are unlikely to be an option for long-haul flights greater than 4,000 km, such as those from Hawaiʻi to the mainland United States.[47]

Decarbonized drop-in replacement fuels are used for all long-haul flights by 2045 in the Aggressive Electrification scenario and flights of all distances in the Conservative Electrification scenario. This results in an immense demand for decarbonized fuels, explored further in the **Decarbonized Fuel Demand** section below.

[41] https://www.spglobal.com/commodityinsights/en/market-insights/blogs/oil/060921-bionaphtha-market-biofuels-gasoline-petchems-plastics-clean-energy
[42] https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=87964
[43] https://www.eia.gov/energyexplained/diesel-fuel/use-of-diesel.php
[44] https://www.eia.gov/outlooks/aeo/data/browser/#/?id=7-AEO2021&region=0-0&cases=highmacro&start=2019&end=2050&f=A&linechart=highmacro-d113020a.39-7-AEO2021&ctype=linechart&sourcekey=0
[45] https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/
[46] https://www.iea.org/reports/aviation
[47] https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf

Since this study was completed, Hawaiian Airlines has announced details of its plan to achieve net zero GHG emissions by 2050, including commitments to specific milestones in the 2030s.[48] The Hawaiian Airlines net zero plan relies on two key measures that are also included in this study: efficiency improvements and the use of sustainable aviation fuel.

On-Road Transportation

All three scenarios show significant reductions in emissions from on-road transportation. The electrification of LDVs is a key contributor to these reductions, as all three scenarios assume increasing adoption of EVs to varying degrees. The Reference scenario assumes EV sales aligned with the Hawaiian Electric forecast, with EVs reaching ~80% of LDV sales by 2050. Both net zero scenarios assume that all LDVs will eventually be electrified, but with varying paces of EV adoption. The Conservative Electrification scenario assumes EVs reach 100% of LDV sales by 2045, while the Aggressive Electrification scenario assumes that EVs reach 100% of LDV sales by 2035. The accelerated pace of EV adoption in the Aggressive Electrification scenario results in deeper emissions reductions in earlier years compared to the Conservative Electrification scenario.

Both net zero scenarios also assume that there is significant electrification of MHDVs, with EVs reaching 80% and 100% of MHDV sales by 2045 in the Conservative Electrification and Aggressive Electrification scenarios respectively. This reflects a high level of electrification of heavy-duty trucks compared to prior decarbonization studies on the US mainland, where the options considered for long-haul trucking generally include hydrogen fuel cell vehicles and decarbonized fuels in addition to electrification.[49,50] However, trucking in Hawaiʻi reflects much shorter distances travelled than on the US mainland, leading to the assumption in this study that electrification is a feasible decarbonization strategy for heavy-duty trucks in Hawaiʻi.

Since the net zero scenarios do not reach 100% adoption of electric MHDVs by 2045, decarbonization relies on a supply of decarbonized diesel fuel for the remaining MHDVs. E3 assumed that the blend of decarbonized diesel steadily increases to 100% in 2045.

Other Transportation

Other off-road transportation currently accounts for 15% of emissions in the transportation sector. This subsector includes domestic marine transportation and military transportation (excluding aviation). This subsector likely includes a wide range of vehicle types, not all of which can be easily electrified. Given available data, the study estimated the electrification potential in this subsector based on fuel type.

Residual fuel oil in these subsectors is inferred to serve vehicle types that would be very difficult to electrify such as cargo ships and cruise ships. Thus, in both net zero scenarios, decarbonized fuel oil

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[48] https://newsroom.hawaiianairlines.com/releases/hawaiian-airlines-commits-to-new-milestones-on-path-to-net-zero-carbon-emissions

[49] https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf

[50] https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

supplies meet demands for residual fuel oil by 2045. Conversely, diesel demand in these subsectors is inferred to reflect vehicle types that could potentially be electrified given technological progress. In the Aggressive Electrification scenario, 50% of off-road diesel use is electrified, whereas in the Conservative Electrification scenario, E3 assumes that there is no electrification of off-road diesel use. In both scenarios, remaining diesel use in these sectors is met by decarbonized diesel fuel by 2045.

Buildings

Direct emissions from buildings represents a relatively small share of Hawaiʻi's emissions compared to the US average. There are two key differences between Hawaiʻi and the mainland that explain this difference. First, buildings in Hawaiʻi have very little space heating demand due to Hawaiʻi's mild climate, whereas fuel consumption for space heating reflects a large share of building emissions on the mainland. Second, relatively few customers in Hawaiʻi receive natural gas service, with remaining customers relying on more expensive fuels such as propane (a.k.a. LPG, liquified petroleum gas; or HGL, hydrocarbon gas liquids) to serve building fuel needs.

The Energy Information Administration's State Energy Data System (SEDS) provides information on fuel use by sector in Hawaiʻi, indicating that nearly 85% of gas and propane are used in non-residential buildings.[51] Regarding specific end uses, state-level data on end-use fuel consumption are not available for Hawaiʻi. On the US mainland, fuel combustion in residential and commercial buildings is primarily to serve space heating and water heating needs, with additional fuel combustion for cooking, clothes drying, and other end uses. Given the very small space heating demands in Hawaiʻi, this study infers that the majority of direct building emissions from fuel consumption in Hawaiʻi reflect gas and propane used for non-residential water heating.

All scenarios include growth in the building sector as well as energy efficiency improvements based on the Hawaiʻi PUC's market potential study,[52] with the Reference scenario using the "Achievable Potential – BAU" energy efficiency case and the net zero scenarios using "Achievable Potential – High."

The net zero scenarios also include additional decarbonization measures in buildings. Both scenarios include building electrification sales mandates, with 100% sales of electrified devices for all end uses by 2045 in the Conservative Electrification scenario and by 2030 in the Aggressive Electrification scenario. For remaining fuel demands, both scenarios include a switch from fossil natural gas to biogas in 2030, coinciding with the modeled phaseout of fossil petroleum refining at the Par refinery, as well as a conversion from fossil propane gas to decarbonized propane by 2045.

Non-Combustion Emissions

The agriculture, waste, and industrial processes and product uses (IPPU) sectors produce most of Hawai'i's non-combustion emissions. The Reference scenario is aligned with national projections for these sources from the 2019 EPA report on non-CO_2 emissions,[53] reflecting that agriculture emissions stay relatively flat

[51] https://www.eia.gov/state/seds/seds-data-complete.php?sid=HI#Consumption
[52] https://puc.hawaii.gov/wp-content/uploads/2021/02/Hawaii-2020-Market-Potential-Study-Final-Report.pdf
[53] https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections

while emissions from waste grow over time. IPPU emissions are projected to decline over time in the Reference scenario, as most IPPU emissions in Hawaiʻi are from hydrofluorocarbons (HFCs) commonly used as refrigerants in HVAC systems and refrigerators, and the recently passed federal AIM Act mandates the phaseout of these refrigerants.

Non-combustion GHG emissions from oil and natural gas systems in Hawaiʻi are dominated by refinery operations. As a result, these emissions would be avoided with the phaseout of fossil petroleum refining and drop to zero in 2030 in all scenarios. Although there could be fugitive emissions from gas distribution after 2030, their magnitude is small relative the size of existing process emissions from the refinery, thus emissions from gas distribution leaks were not analyzed in this study.

In the net zero scenarios, mitigation potential for non-CO_2 emissions from the agriculture and waste sectors was estimated using the 2019 EPA report described above, which provides a supply curve of emissions reductions available at various cost levels.[53] Although decarbonization costs are not explicitly examined in this study, we chose to implement mitigation measures costing less than \$100/tCO_2e. While the EPA report evaluates additional emissions reductions available between \$100 to \$500/tCO_2e, these relatively expensive measures would only reduce an additional 0.03 MMT CO_2e and were thus excluded.

The waste sector remains the largest source of emissions by mid-century in the net-zero scenarios, accounting for over 50% of gross emissions in 2045. In the net zero scenarios, waste emissions are modeled to increase relative to 2018 levels due to underlying population growth, although they are reduced 5% relative to the business-as-usual growth in the Reference scenario. Around 90% of waste emissions in Hawaiʻi are from landfills, a source for which EPA national estimates show relatively little potential for emissions abatement by 2045. While this analysis only used national mitigation potential estimates for non-energy, non-combustion emissions, additional state-level analysis of Hawaiʻi's landfills could show greater potential for cost-effective reductions. Waste diversion or waste combustion measures could reduce the growth in waste that would contribute to additional future landfill emissions but would not address methane emissions from existing landfills.

Natural Sinks

All three scenarios reflect natural carbon sinks declining 18% by 2045 based on a business-as-usual forecast of changes projected by the US Geological Survey.[54] While the State of Hawaiʻi has pledged that one hundred million trees will be "conserved, restored, or grown" by 2030,[55] the impact of achieving this pledge on net carbon sequestration in the state has not been analyzed and would likely vary significantly based on the relative amounts of conservation, reforestation, or afforestation.

A 2020 study by Conservation International and the State of Hawaiʻi Office of Planning evaluated carbon sequestration solutions on lands currently used for agriculture, agroforestry, aquaculture, forestry, ranching, and urban forestry.[56] The annual GHG sequestration potential from solutions identified as "High" and "Medium" priority by the study ranges from less than 100 thousand to 5 million metric tons of CO2e

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[54] https://pubs.usgs.gov/pp/1834/a/pp1834.pdf

[55] https://governor.hawaii.gov/newsroom/dlnr-news-release-state-pledges-one-hundred-million-trees-to-be-conserved-restored-or-grown-by-2030/

[56] https://planning.hawaii.gov/wp-content/uploads/Conservation-International-FINAL-Report_GHG-4.30.2020.pdf

per year. While the individual potentials of these solutions are not perfectly additive (some solutions overlap in terms of land where they could be implemented), this range suggests that application of at least some of these measures could feasibly offset the remaining 0.72 MMT of gross emissions not offset by existing land sinks in Hawaiʻi by 2045.

Negative Emissions Technologies

Negative emissions technologies reflect another option for carbon dioxide removal that may be deployed in addition to or instead of enhanced natural carbon sequestration. In this study, the negative emissions required to achieve net zero emissions economywide in 2045 in the Aggressive Electrification and Conservative Electrification scenarios were modeled through the use of Direct Air Capture (DAC) to provide an estimate for the electric load requirements. This study assumes that DAC systems are sited on Hawaiʻi Island, as recent studies have indicated that the basaltic formations of the island are likely a suitable location for carbon sequestration.[57,58]

While there are a range of DAC systems currently under development, E3 chose to model a solid sorbent system based on the Climeworks DAC system.[59] The main reason for this choice is that the Climeworks DAC process requires a relatively low amount of heat and thus the entire process can be powered by electricity.[60] Other liquid solvent-based DAC systems require high temperature heat that is more feasibly achieved through fuel combustion, often modeled as natural gas, which is not available on Hawaiʻi Island.

To explore a range of potential loads for DAC, the heat required for the DAC process was met with different electric technologies in the two net zero scenarios. In the Conservative Electrification scenario, the heat is supplied by industrial heat pumps with an overall coefficient of performance (COP) of 2.2 to represent the lower bound of loads (COP reflects heat output divided by electricity input),[61] while in the Aggressive Electrification scenario, the heat is supplied by less efficient electric resistance heating to represent the upper bound of loads. As a result, the annual load required to power a DAC system capturing 0.72 MMT of CO_2 per year ranges from 810 to 1,400 GWh. These electric loads are shown below in Figure 6. Note that DAC systems may be sited off-grid with dedicated renewables and battery storage and may not need transmission interconnection to the bulk grid.

In addition to the electricity requirements, DAC systems would also have impacts on land and water use. Using land-use figures from an analysis of renewable resource potential in Hawaiʻi performed by the National Renewable Energy Laboratory (NREL), supplying the electricity to abate 0.72 MMT of CO_2/year via DAC would require building solar generation that impacts 11 to 19 square kilometers.[62] In addition to the energy required for capturing CO_2 from the atmosphere, water is required for injecting the captured CO_2 into geologic storage reservoirs. At an existing CO_2 capture and storage facility in Iceland, around 27

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57 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
58 https://doi.org/10.1016/j.ijggc.2021.103396
59 https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full
60 https://iopscience.iop.org/article/10.1088/2516-1083/abf1ce/pdf
61 https://www.sciencedirect.com/science/article/abs/pii/S0360544218305759
62 https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/stakeholder_council/20200818_sc_heco_tech_potential_final_report.pdf

metric tons of pure water (7,128 gallons) are required to dissolve each metric ton of CO_2.[63] However, the rapid mineralization of CO_2 in the basaltic reservoirs removes dissolved CO_2 from water within months, which may offer the potential for recycling water for continued CO_2 injection.[64]

63 https://www.sciencedirect.com/science/article/abs/pii/S1750583617309593?fr=RR-2&ref=pdf_download&rr=70cd8cc9ae9c595b

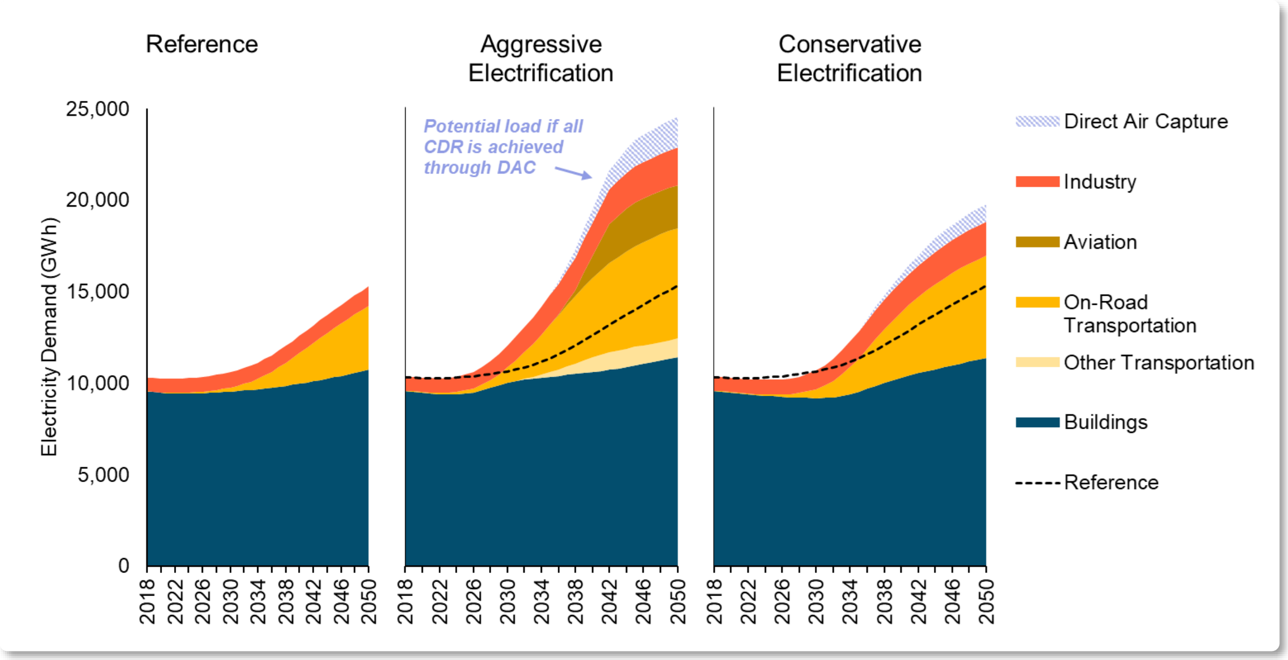
64 https://www.frontiersin.org/articles/10.3389/fclim.2019.00009/full

Electricity Demand

Electric Loads: Summary

As shown in Figure 6, electricity demand increases in all scenarios, largely driven by electrification of end-uses currently powered by fossil fuels.

Figure 6: Final electricity demand by sector and scenario (statewide)



Electrification in the Reference scenario is largely limited to electrification of LDVs within on-road transportation. LDV electrification combined with some growth in building electricity demands leads to an almost 40% increase in total electric loads by 2045.

The Conservative Electrification scenario delays electrification sales mandates for LDVs and building equipment to 2045 and includes no electrification of aviation or off-road transportation. In this scenario, final electricity demand grows 75% by 2045. In the Aggressive Electrification scenario, aggressive sales mandates require all new building equipment, LDVs, and MHDVs to be electric by 2035, 2035, and 2045, respectively. In addition, inter-island aviation and some off-road transportation are electrified by 2045. This more than doubles final electricity demand by 2045.

If all carbon dioxide removal (CDR) necessary to achieve net zero emissions by 2045 was achieved through DAC, these systems would require between 800-1,400 GWh of electricity. However, this is an upper bound that assumes all CDR is achieved through DAC, and this could be reduced by CDR achieved through increased natural sequestration. Furthermore, DAC systems do not necessarily require grid interconnection and could be served by off-grid renewables and storage.

While both net zero scenarios see dramatic increases in electricity demand in the long-term, it is notable that neither sees a major increase in load by 2030 despite rapid near-term deployment of electrification in buildings, transportation, and industry. As described above, this is due to the long lifetimes of energy-consuming assets throughout the economy.

Electric Loads: Implications

By 2045, both net zero scenarios see considerably higher loads than the Reference scenario, as shown in Table 2. The Reference scenario reflects Hawaiian Electric's forecast of load growth given existing technologies and policies along with projections of customer economics-driven adoption decisions.[65] In contrast, the net zero scenarios are better described as "back-casts:" these scenarios were engineered to meet the state's 2045 decarbonization target, in many instances reflecting policy measures that are not in place and technologies that are not commercialized today.

Table 2: 2045 Hawaiian Electric service territory load by scenario (excluding off-grid DAC).

	Reference	Conservative Electrification	Aggressive Electrification
2045 Load (GWh)	13,300	17,300	21,800
% Above Reference	-	30%	64%

The significant differences in load among these scenarios would have major impacts on long-term electric system planning. In the Integrated Grid Planning process, Hawaiian Electric is developing resource plans that meet the utility's 2030 and 2045 targets, which essentially reflect caps on GHG emissions from electricity generation. Any load growth above forecasts would need to be met by 100% decarbonized electricity to prevent the emissions limits from being exceeded. Thus, the high electric loads in both net zero scenarios would require a dramatic increase in the amount of zero-carbon generation and capacity procured by the utility relative to resource plans designed to meet Reference scenario loads.

This study should not be construed as a criticism of Hawaiian Electric's load forecasts (*i.e.,* the Reference scenario). Absent major policy changes and technological developments, the Reference scenario may be a more predictive load forecast than either of the net zero scenarios. In that regard, the Reference scenario may be an appropriate load forecast to use in system planning, especially for determining near-term resource procurement needs.

However, within the resource planning process, it would be prudent to evaluate sensitivities with much higher load growth corresponding to economywide net zero scenarios, as illustrated in this study. If new policies and new technologies drive very high levels of electrification and/or negative emissions

[65] Note: Reference scenario load growth for Kauai is not benchmarked to any forecast from KIUC and is instead based on the growth drivers used for Maui in this study

technologies in support of an economywide net zero target, the resulting loads would require a much larger scale of generation resource buildout than currently modeled. Planners, regulators, and stakeholders may want to consider the implications as part of the resource planning process.

Initial Electric System Modeling for Oʻahu

The net zero scenarios developed in this study identify much higher electric load levels beyond 2030 than scenarios currently modeled in Hawaiian Electric's Integrated Grid Planning (IGP) process. This will have major impacts on long-term electric resource needs. To understand these impacts, E3 performed initial modeling to evaluate Oʻahu's electric resource needs if the island experienced load growth aligned with the Aggressive Electrification scenario.

Generation Needs

Under the Aggressive Electrification scenario, electric loads on Oʻahu reach 14,500 GWh/year by 2045, which is roughly double today's electric loads and is 45% higher than 2045 loads in the IGP Reference case. Initial modeling indicates that solar and wind energy would be the core zero-carbon generation resources and would serve over 90% of loads by 2045. This includes distributed solar, utility-scale solar, land-based wind, and offshore wind. In addition, battery storage would be needed to shift energy into high-load hours on a daily basis.

Initial modeling suggests that the shift from fossil fuel-based generation to renewable generation may lower the cost of electricity generation by reducing purchases of imported fuels. However, this transition would require a massive buildout of new generation and transmission infrastructure. Although distributed resources can play a key role, they would not be sufficient to serve customer loads. Modeling from the National Renewable Energy Laboratory finds that, even if distributed solar were built on every roof in Oʻahu, it would generate 6,400 GWh/year, or less than half of annual loads.[66] Thus, large-scale resources including utility-scale solar, land-based wind, and offshore wind will be needed, along with associated electric transmission to connect these resources to the grid. Although the development of this infrastructure will have significant land use impacts, there are not currently alternative generation resources that are zero-carbon, cost-effective, and can achieve the scale needed.

Reliability Needs

By 2045, initial modeling indicates that renewables could reliably serve over 90% of annual load, with solar generation serving all of Oʻahu loads during solar hours, wind contributing intermittently, and batteries storing excess generation from renewables and shifting energy into periods with low renewable generation. However, without additional firm resources, a high-renewable system would face reliability risks during periods of low renewable output, specifically during cloudy or stormy periods with prolonged low solar output, which are most likely during winter months.

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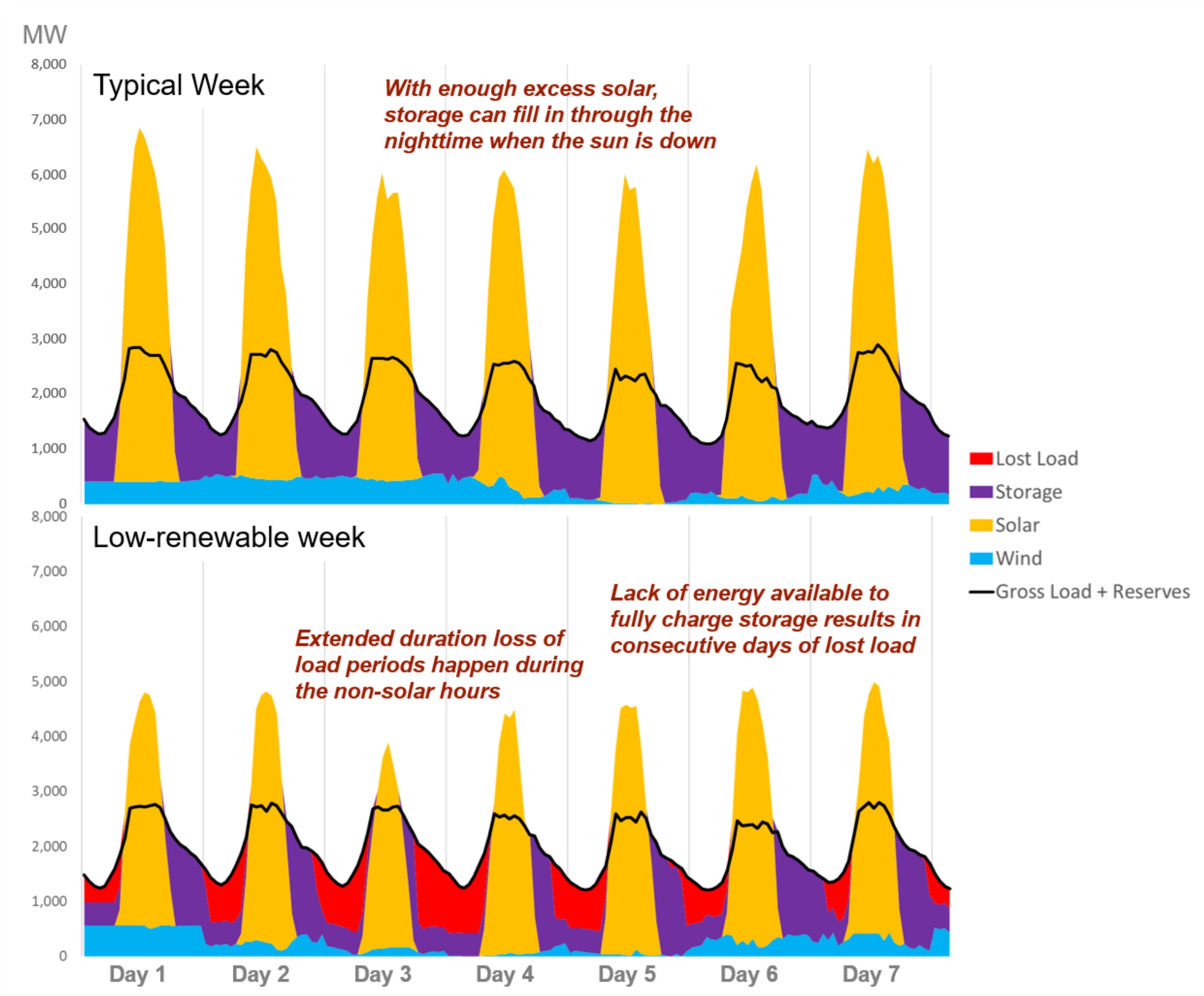
[66] https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/stakeholder_council/20210730_sc_heco_tech_potential_final_report.pdf

Figure 7 shows operations on a high-renewable Oʻahu grid during a typical week (top) and a low-renewable week (bottom). During a typical week, renewables and battery storage could reliably meet system load. However, during a low-renewable week, absent firm generation, Oʻahu customers could experience extended power outages over multiple days. Approximately 1 GW of firm capacity resources would be needed to reliably serve Oʻahu during the week shown below.

Figure 7: Example of a typical week (top) and low-renewable week (bottom) on a high-renewable Oʻahu grid



There are a number of different firm resource options that could be pursued, although each of these options has one or more implementation risks. Table 3 lists potential firm resource options and identifies implementation risks for these options.

Table 3: Potential firm resource options and implementation risks

Firm resource option	Implementation Risk(s)
Multi-day battery storage	A
Advanced / enhanced geothermal systems (EGS) on Oʻahu	A
Imported zero-carbon liquid fuels	A, B
Diesel with carbon capture and sequestration (CCS)	A, B, C
Diesel offset with direct air capture (DAC)	A, B, C
Conventional geothermal on Hawaiʻi Island delivered via subsea transmission	D

A. These options reflect developing technologies that are unproven at scale
B. These options have risks associated with availability and price volatility of imported fuels
C. These options may not be eligible under Hawaii's Renewable Portfolio Standard (RPS)[67]
D. Inter-island high-voltage electric transmission would be a large-scale infrastructure project with highly uncertain cost and timing

Although all these options have implementation risk, some amount of firm resources will be needed in order to maintain reliability. These and other options should be considered and the development of novel firm technologies should be closely tracked.

[67] https://www.capitol.hawaii.gov/hrscurrent/vol05_ch0261-0319/hrs0269/hrs_0269-0092.htm

Decarbonized Fuel Demand

Decarbonized Fuels Overview

While electrification is key to reducing energy emissions from buildings, transportation, and industry, not all end uses can easily be electrified. For these remaining end uses, decarbonized fuels that serve as drop-in replacements for existing fossil fuels will be an important strategy for mitigating emissions, especially in sectors like aviation and marine transportation. Both net zero scenarios reflect the need for a large quantity of decarbonized fuels by 2045, as shown in Table 4. Fuels consumed for electricity generation are not reflected here, so any decarbonized fuel needs for the electric sector would be incremental to these amounts.

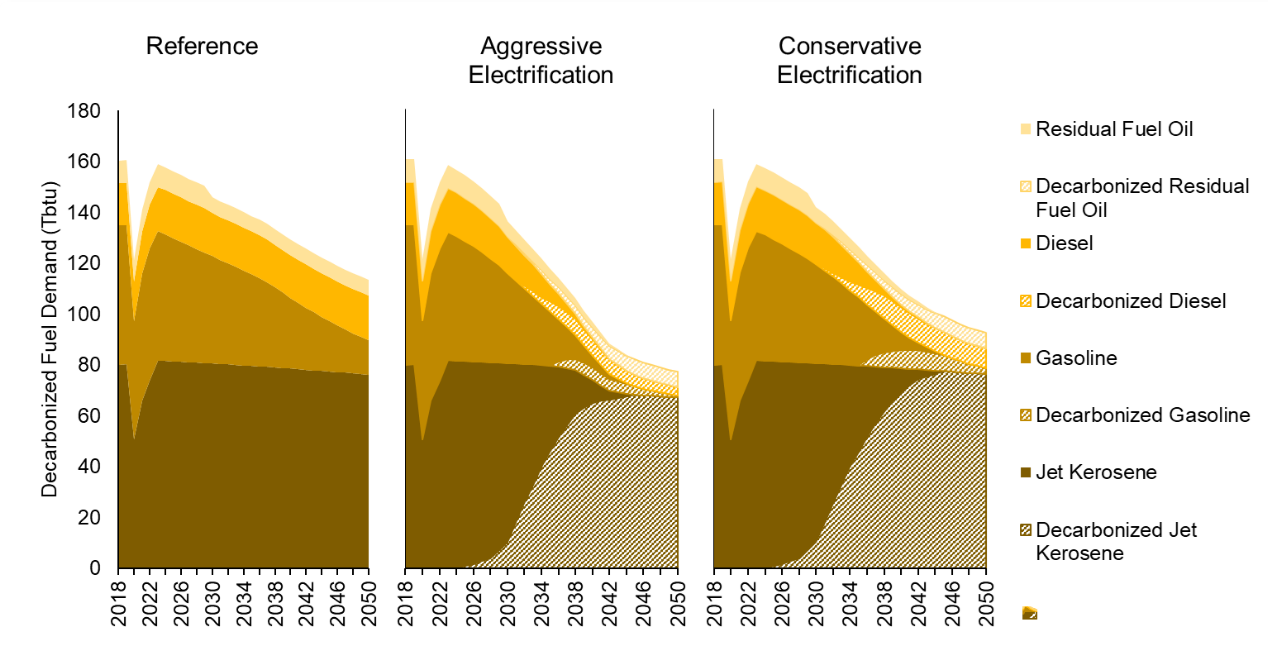
Table 4: 2045 decarbonized liquid fuel demands in the net zero scenarios and comparison to present-day liquid fuel demands (excludes fuel consumed for electricity generation)

	Historical 2018 Fossil Fuels	**Con. Electrification** 2045 Decarbonized Fuels	**Agg. Electrification** 2045 Decarbonized Fuels
Jet Kerosene	80 TBtu	77 TBtu	68 TBtu
Gasoline, Diesel, & Residual Fuel Oil*	81 TBtu	22 TBtu	14 TBtu
Total Liquid Fuel Demand	161 TBtu	99 TBtu	82 TBtu
Total % of 2018	N/A	61%	51%

**Final energy demand only, excludes fuel consumption for electricity generation*

Figure 8 shows the final demand for liquid petroleum fuels and decarbonized fuels over time. The demand for liquid petroleum fuels declines over time in all scenarios. In the Reference scenario, this decline is driven mainly by LDV electrification and fuel efficiency standards reducing demand for gasoline, with efficiency improvements from aviation also leading to a slight reduction in jet kerosene consumption despite increasing travel demand. In the Aggressive Electrification and Conservative Electrification scenarios, more rapid electrification of LDVs and MHDVs leads to a faster decline in gasoline and diesel consumption, while an increasing quantity of decarbonized fuels are used to meet demand for transportation end-uses that are difficult to electrify. In the Aggressive Electrification scenario, E3 assumed that inter-island aviation and some other off-road transportation end-uses could be electrified, while in the Conservative Electrification scenario, these end-uses rely entirely on decarbonized fuels. Despite this distinction, both scenarios require very large quantities of decarbonized fuel to meet the economywide net zero target by 2045.

Figure 8: Final demand for petroleum fuels and decarbonized replacement fuels by scenario (excludes fuel consumed for electricity generation)



While detailed modeling of decarbonized fuel production is not included in this analysis, there are different options for how these fuels could be supplied. These can broadly be categorized by feedstock type (biofuels or synthetic fuels) and geographic source (on-island or imported). A brief description of each decarbonized fuel option and potential benefits and risks of each is provided in Table 5, with details below.

Table 5: Benefits and risks of different decarbonized fuel options

Decarbonized Fuel Option	Benefits	Risks
In-state Biofuels	• No reliance on international markets • Local economic development	• Biomass residues have very limited potential • Purpose-grown crops have major land-use concerns
In-state Synthetic Fuels	• No reliance on international markets	• High cost, high load impacts • Significant land-use requirements
Imported Biofuels	• No local land-use changes	• Sustainability concerns are outsourced • Market development out of Hawaiʻi's control
Imported Synthetic Fuels	• Produced in areas with abundant renewable energy	• High cost • May not be considered carbon-neutral under Act 15

Decarbonized Fuel Options

In-state Biofuels

A 2010 report published by the Hawaiʻi Department of Business, Economic Development, and Tourism (DBEDT) estimated that the maximum theoretical biofuel production potential in the state of Hawaiʻi was 109 TBtu per year if all feedstocks were allocated to decarbonized jet fuel.[68] This amount is larger than the 77 TBtu of decarbonized jet fuel demand remaining in 2045 in the Conservative Electrification scenario, and, although the efficiency of biofuel production varies by final fuel type, it is likely enough to meet all 99 TBtu of decarbonized liquid fuel demands in 2045 in the Conservative Electrification scenario (including the needs for decarbonized diesel, residual fuel oil, and gasoline).

Decarbonized fuels could be locally produced in the State of Hawaiʻi from a variety of biogenic feedstocks. The two general categories of feedstocks are 1) biomass residues from agricultural, forestry, and municipal waste; and 2) dedicated energy crops. Of the technical potential described above, only 7% is from biomass residues. Residues are generally considered to have much lower sustainability concerns than dedicated energy crops as there is no risk of displacing farming, grazing, or other productive uses of agricultural lands. However, there may be significant competition for biomass residues, which can also be used to power electric generation or can be converted into biogas to serve retail customers via pipeline.

The other 93% of the technical potential reflects dedicated energy crops grown on prime irrigated lands or nonprime rainfed agricultural lands, with the majority coming from prime irrigated lands. While local production of biofuels could provide economic benefits, these purpose-grown crops would have major land use impacts in Hawaiʻi due to economic competition for agricultural lands as well as competition with

[68] https://energy.hawaii.gov/wp-content/uploads/2011/10/Hawaii-Biofuels-Assessment-Report.pdf

land that could be used for natural carbon sequestration. Thus, it is unlikely that Hawaiʻi could meet all decarbonized fuel demands in the future without drastic changes to land use and agricultural practices in the state.

In-state Synthetic Fuels

Decarbonized synthetic fuels are drop-in replacement fuels created through the combination of carbon and hydrogen from climate-neutral sources. The source for carbon is often modeled as CO_2 captured from the atmosphere via direct air capture (DAC), while the source for hydrogen is usually green hydrogen produced via electrolysis powered by zero-carbon electricity. Both carbon capture via DAC and hydrogen electrolysis require significant amounts of electricity; thus, the round trip efficiency of synthetic fuels produced in this manner is fairly low. Internal E3 modeling estimates the efficiency to be around 45% by 2045. As a result, meeting the 99 TBtu of decarbonized fuel demand in 2045 in the Conservative Electrification scenario through synthetic fuels produced from DAC and electrolysis would require almost 71,000 GWh of electricity, a seven-fold increase over 2018 electricity consumption in the State of Hawaiʻi. Due to the extremely high electric load impacts, on-island synthetic fuels are unlikely to meet a significant portion of the demand for decarbonized fuels in the state.

Imported Biofuels and Synthetic Fuels

The decarbonized fuels necessary to achieve net zero emissions in Hawaiʻi could potentially be imported from the mainland United States or from global markets. There are existing domestic and global biofuels markets that are projected to see continued growth in the future.[69] While carbon-neutral synthetic fuels are pre-commercial today, they are included in many deep decarbonization pathways for the United States as a critical tool for hard-to-electrify end-uses.[70] While DAC is an emerging technology with few pilot plants built to date,[71] the other needs for synthetic fuels are both mature: the International Energy Agency considers hydrogen electrolysis to be a relatively mature technology[72] and the Fischer-Tropsch plants necessary for making synthetic liquid fuel from CO_2 and hydrogen have been operated for decades.[73]

Both imported biofuels and synthetic fuels have relative merits and drawbacks. While advanced biofuels are closer to commercialization today and may be available at a lower cost than synthetic fuels, there are sustainability concerns both in terms of lifecycle GHG emissions and direct environmental impacts from land use changes associated with biofuels production.[74] Importing from a global market would make it more challenging to verify the sustainability of biofuels than for local production.

Imported carbon-neutral synthetic fuels would benefit from production in locations with abundant renewable energy supply and fewer land constraints such as desert regions with plentiful solar energy or

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[69] https://www.eia.gov/todayinenergy/detail.php?id=51778
[70] https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf
[71] https://www.weforum.org/agenda/2021/09/worlds-biggest-carbon-machine-iceland
[72] https://www.iea.org/articles/etp-clean-energy-technology-guide
[73] https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/sasol
[74] https://royalsocietypublishing.org/doi/10.1098/rspa.2020.0351

plains regions with high wind energy potential, meaning production costs would be lower than in Hawaiʻi. However, even with cheap electricity powering both DAC and hydrogen electrolysis, the capital costs of these systems mean that synthetic fuels are likely to remain a more expensive option than biofuels. Another concern is that imported synthetic fuels may not be viewed as zero-emissions under Act 15. As discussed above under **Emissions Accounting**, accounting methodologies have not yet been developed for carbon-neutral synthetic fuels, as they are pre-commercial. Since the CO_2 removal corresponding with producing these fuels would occur out-of-state, they may not be treated as zero-carbon under Act 15.

Decarbonized Fuels vs. Negative Emissions Technologies

Given the uncertainty regarding cost and availability of decarbonized fuels, it is important to recognize that negative emissions technologies (NETs) represent an alternative emissions abatement strategy for end uses that are difficult to electrify. In this approach, NETs such as DAC with carbon sequestration would be deployed to offset remaining fossil fuel use in aviation and other forms of transportation that are not electrified nor served by a limited supply of decarbonized fuels. This approach may be less expensive than producing carbon-neutral synthetic fuels, which are modeled to require both CO_2 captured from the atmosphere via DAC as well as hydrogen produced via electrolysis powered by zero-carbon electricity. Table 6 describes the infrastructure, electricity, and land needs corresponding to using DAC vs. synthetic fuels to abate emissions from 77 TBtu/year of fuel demand. This level of fuel demand reflects 2045 aviation fuel demand in the Conservative Electrification scenario or nearly all 2045 liquid fuel demand in the Aggressive Electrification scenario. In this table, the electricity needs are assumed to be met by solar generation, although other zero-carbon resources could alternatively provide the electricity.

Table 6: Comparison of two options to abate emissions from 77 TBtu/year of fuel demand in 2045 if decarbonized fuels cannot be procured

Description[75]	Unit	Option A: Fossil Fuel + DAC	Option B: In-state Synthetic Fuel
Infrastructure Needs	N/A	• DAC with geologic CO_2 sequestration	• DAC, carbon used for synthetic fuel production (no sequestration) • Hydrogen electrolyzer • Synfuel plant
Fuel Demand	TBtu/year	77 (imported fossil fuel)	77 (in-state synthetic fuel)
Electric Load	GWh/year	6,300	50,200
Solar to Meet Load	MW	2,700	21,200
Land Need for Solar	km^2	80	660

There are two important conclusions from this table. The first conclusion is that relying on either DAC or in-state synthetic fuels to abate a substantial portion of emissions from liquid fuels would have significant infrastructure needs, electric load impacts, and land-use impacts. The second conclusion is that the synthetic fuels option has load impacts that are nearly 8x larger than using fossil fuels plus DAC, as electricity would be needed not just to capture carbon from the atmosphere but also to provide the energy content for the fuels while incurring efficiency losses from synthetic fuel production. Due to the very high electricity needs, in-state synthetic fuels are unlikely to be a competitive option for abating fuel emissions unless either the price of fossil jet fuel were extremely high or carbon sequestration in Hawaiʻi were deemed infeasible.

[75] Assumptions:

- DAC load requirement: 1125 GWh/MMT CO_2
- Synfuel process overall efficiency (electricity to synfuel): 45%
- Solar capacity factor: 27%
- Solar land need: 32 MW / km^2 Table 3, page 15. NREL. Nick Grue, Katy Waechter, Travis Williams, Jane Lockshin, "Assessment of Wind and Photovoltaic Technical Potential for the Hawaiian Electric Company," Oct. 2020: https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/stakeholder_council/20200818_sc_heco_tech_potential_final_report.pdf

Discussion of Sectoral Policies

This study has illustrated that achieving net-zero economywide emissions by 2045 will require robust near-term and sustained action across all sectors of the economy. Over the past two decades, the electricity generation sector has been the focus of decarbonization policy in Hawaiʻi. These policies and associated regulations have achieved significant emissions reductions and have put the electric sector on a path to net zero by 2045. However, other sectors of the economy have not seen the same degree of policy support for decarbonization. Figure 9 shows Reference scenario emissions in 2018 and 2045. Although emissions decline substantially, the Reference scenario modeled here is far from meeting the state's 2045 emissions goals. To achieve Hawaiʻi's 2045 net zero target, new policies, targets, and regulations are needed to support emissions reductions outside the electric sector.

Figure 9: Reference scenario emissions in 2018 and 2045, indicating the need for policies in many sectors to achieve further decarbonization

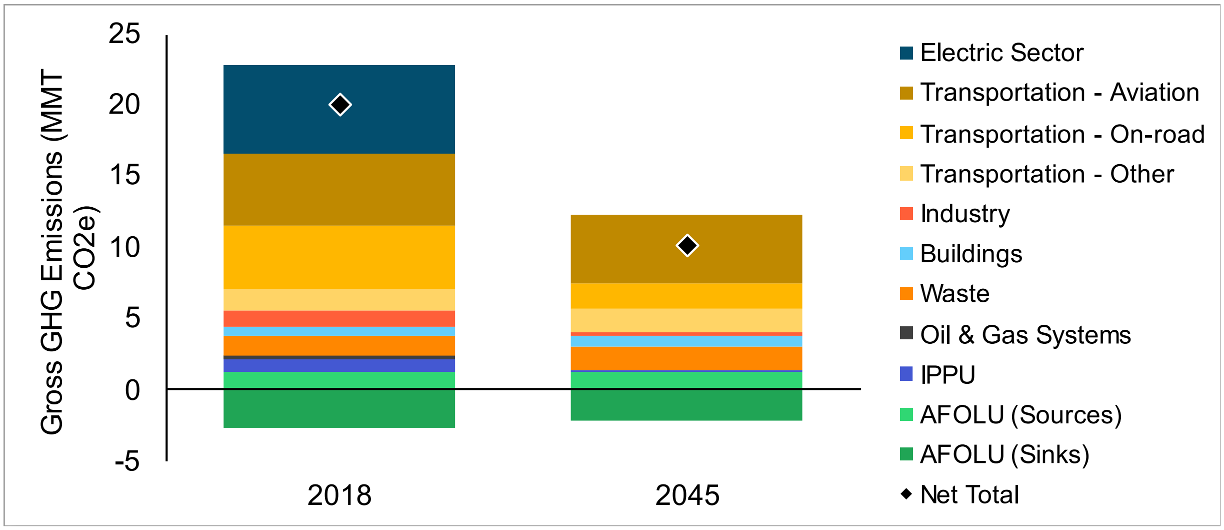

Table 7, on the following page, describes existing and example policies, targets, and regulations to support the decarbonization strategies modeled for each sector of the economy.

Table 7: Example existing decarbonization policies by sector and jurisdiction

Sector	Strategy	Region	Example Policies to Achieve Decarbonization Strategy
Electricity	Clean electricity standard	Many	21 states, D.C., Puerto Rico and many utilities call for 100% renewables or 100% zero carbon electricity by 2040 or 2050; though the details differ between jurisdictions.
On-Road Transportation	Light-duty zero-emission vehicles	CA	**Advanced Clean Cars II Program**: Zero-Emission Vehicle (ZEV) sales requirement for manufacturers increasing to 100% sales requirement for battery-electric vehicles, hydrogen fuel cell electric vehicles, and plug-in hybrid electric-vehicles by 2035[A]
		NY	**Senate Bill S2758**: Requirement that 100% of in-state sales of new passenger cars and trucks shall be zero-emissions by 2035[B]
		WA	**House Bill 1287**: Requirement that all light duty vehicles of model year 2030 or later that are sold, purchased, or registered in-state must be battery-electric or hydrogen fuel cell vehicles, pending passage of road usage charge[C]
	Medium- and heavy-duty zero-emission vehicles	CA	**Advanced Clean Trucks Program**: ZEV sales requirement for manufacturers for 2024-2035. Final year ZEV sales percentages vary by vehicle type, ranging from 40% for Class 7-8 tractors to 75% for Class 4-8 trucks[D] (also adopted by OR, WA, NY, NJ, and MA)
	Vehicle fuel efficiency standards	US	**Updated Federal CAFÉ Standards** recently announced by the US Department of Transportation[E]
	Reductions in vehicle miles traveled (VMT)	HI	**HCEI Road Map 2011 target of 10% reduction in total statewide VMT by 2030 relative to 2030.[F]** Numerous other states and local governments have VMT reduction targets[G] *(Note: VMT reductions were not modeled in these scenarios)*
Aviation	Aviation electrification (short-haul flights)	N/A	**No existing state or federal level regulations** to require aviation electrification, although Hawaiʻi SB3311 targets achieving zero emissions for interisland and international transportation "as soon as practically possible"[H]
	Decarbonized drop-in fuels	N/A	**No existing state or federal level regulations** that require decarbonized aviation fuel, but the Biden administration has set a target of achieving 20% reduction in aviation emissions by 2030 through the use of sustainable fuels and has promised $4.3 billion in new and ongoing funding for sustainable aviation fuel projects and fuel producers[I]
Other Transportation	Off-road vehicles electrification	N/A	**No existing state or federal level regulations** that require electrification of off-road vehicles, although Hawaiʻi SB3311 targets achieving zero emissions for interisland and international transportation "as soon as practically possible"[J] and California Executive

Sector	Strategy	Region	Example Policies to Achieve Decarbonization Strategy
(e.g., marine, military)			Order N-79-20 targets "100% zero-emission from off-road vehicles and equipment operations in the state by 2035"[K] with no developed plan for implementation.
	Decarbonized drop-in fuels	N/A	**No existing state or federal level regulations** require decarbonized fuel. (Existing low carbon fuel standard programs like those in CA, OR, and WA target on-road transportation fuels)
Buildings	Building electrification	CA	**Newly adopted statewide building code** strongly incentivizes electrification in new homes and buildings[L]
		WA	**Newly adopted statewide building code** requires most new commercial buildings and large multi-family buildings to install electric heat pumps[M]
		Local	**Several local government gas bans and building codes** requiring all-electric new construction[N]
	Decarbonized drop-in fuels	CA	**Biomethane procurement requirements for gas utilities**, includes a medium-term target of around 12% of gas usage by 2030[O]
	Building codes	HI	**Statewide adoption of 2018 International Energy Conservation Code (IECC)** for residential and commercial buildings,[P] and solar **water heater requirement** for all new single-family dwellings[Q]
	Appliance standards	US	**Federal appliance and equipment standards**[R]
		HI	**State appliance and equipment standards** that exceed federal regulations for certain products[S]
	Energy efficiency programs	HI	**Multiple statewide programs to provide incentives, rebates, and financing** for energy efficiency upgrades[T]
	Distributed resources and demand-side management	HI	**Customer solar and battery storage programs** that reduce electricity demand on the grid and/or provide electricity back to the grid[U]
Industry	Off-road vehicles and equipment (ag. and construction)	N/A	**No existing state or federal level regulations** require electrification of off-road vehicles, although California Executive Order N-79-20 targets "100% zero-emission from off-road vehicles and equipment operations in the state by 2035"[F]

Sector	Strategy	Region	Example Policies to Achieve Decarbonization Strategy
Non-energy, Non-combustion	Phase-out of HFCs with high global warming potential	US	**EPA proposed rule to reduce production and consumption of HFCs** in the United States by 85% over the next 15 years[V]
		CA	**State prohibition on high global warming potential HFCs** to achieve a 40% reduction in HFC emissions by 2030[W]
Carbon Dioxide Removal	Negative emissions technology deployment	US	**Section 45Q tax credit for carbon sequestration**, set to reach $50 per metric ton of geologically sequestered CO_2 by 2026 (inflation-adjusted)[X]

[A] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii
[B] https://www.nysenate.gov/legislation/bills/2021/s2758?intent=support
[C] https://lawfilesext.leg.wa.gov/biennium/2021-22/Pdf/Bills/Session%20Laws/House/1287-S2.SL.pdf#page=1
[D] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/fro2.pdf
[E] https://www.nhtsa.gov/press-releases/usdot-announces-new-vehicle-fuel-economy-standards-model-year-2024-2026
[F] https://energy.hawaii.gov/wp-content/uploads/2011/09/Final_TransEnergyAnalysis_8.19.15.pdf
[G] https://database.aceee.org/state/transportation-system-efficiency
[H] https://www.capitol.hawaii.gov/session2022/bills/SB3311_HD2_.pdf
[I] https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/
[J] https://www.capitol.hawaii.gov/session2022/bills/SB3311_HD2_.pdf
[K] https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf
[L] https://www.nrdc.org/media/2021/210811-0
[M] https://sbcc.wa.gov/sites/default/files/2022-01/WSR_22_02_076_Full_WSEC_C_CR102.pdf
[N] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/gas-ban-monitor-building-electrification-evolves-as-19-states-prohibit-bans-65518738
[O] https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-sets-biomethane-targets-for-utilities
[P] https://energy.hawaii.gov/hawaii-energy-building-code/2018-iecc-update
[Q] https://programs.dsireusa.org/system/program/detail/2987
[R] https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program
[S] https://energy.hawaii.gov/appliance-standards
[T] https://energy.hawaii.gov/efficiency-rebates-solar-initiatives
[U] https://www.hawaiianelectric.com/products-and-services/customer-renewable-programs/rooftop-solar
[V] https://www.epa.gov/climate-hfcs-reduction/proposed-rule-phasedown-hydrofluorocarbons-establishing-allowance-allocation
[W] https://ww2.arb.ca.gov/resources/fact-sheets/hydrofluorocarbon-hfc-prohibitions-california
[X] https://sgp.fas.org/crs/misc/IF11455.pdf

The following sections provide more detail on policy considerations for each sector.

Carbon Pricing

The policy discussion in this report is primarily focused on policies to support the decarbonization of specific sectors of the economy. However, this subsection provides a brief discussion of carbon pricing, which is a cross-cutting policy option that can support decarbonization across many or all sectors. Carbon pricing describes a policy that captures external costs of greenhouse gas emissions and ties them to their source.[76] Carbon pricing can be implemented either through a carbon tax or through a market for emissions allowances ("cap and trade").

Pricing carbon emissions appeals to many economists because it improves the cost-effectiveness of decarbonization technologies in a technology neutral way. Some policymakers see benefits in carbon pricing as a mechanism to increase state revenues. These revenues can be used to support decarbonization objectives through investments that support emissions reductions, or to support progressive distributional outcomes via cash payments to households. While carbon pricing can be an effective lever to reduce emissions, it should not be thought of as a silver bullet to the climate challenge.

A research team from UHERO has studied carbon pricing in Hawaiʻi, developing a study in 2021[77] and recently publishing a peer-reviewed research article in the journal *Climate Policy*.[78] The article in *Climate Policy* evaluates a carbon tax set at the federal social cost of carbon ($56-$79/tonne over the study timeline of 2025-2045). The article finds that returning the revenues from a carbon tax via equal-share household dividend payments would result in progressive outcomes across income groups as well as welfare gains for all income groups, in part due to the large visitor contribution to carbon tax revenues. However, the carbon pricing policy would only reduce 2045 GHG emissions by 13% relative to a baseline. Thus, pricing carbon at these levels may be valuable policy, but would not be enough to meet the Act 15 requirements.

The 2021 UHERO report[77] also evaluated pricing carbon at a much higher level ($1000/tonne). The report found this policy would have substantial negative impacts on household welfare and still would not fully achieve the state's climate goals. UHERO's analyses support the view that specific sectoral policies will be needed in Hawaiʻi regardless of whether carbon pricing is implemented.

Energy Efficiency and Demand Reductions

Energy efficiency and demand reductions are discussed together here rather than in the following sections that cover each sector independently. Both energy efficiency and demand reductions are crucial to achieving short- and medium-term emission reductions by reducing demand for fossil fuels and electricity. Even in a future where energy supply is fully decarbonized through zero carbon electricity and

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[76] https://carbonpricingdashboard.worldbank.org/what-carbon-pricing

[77] https://energy.hawaii.gov/wp-content/uploads/2021/04/HawaiiCarbonPricingStudy_Final_Apr2021.pdf

[78] https://uhero.hawaii.edu/wp-content/uploads/2022/04/Coffman-La-Croix-et-al.-Impact-Carbon-Tax-Hawai-Emissions-and-Economy-CLIMATE-POLICY-2022.pdf

decarbonized fuels, energy efficiency and demand reductions help reduce the land use impacts of decarbonization, and help reduce total costs from electric generation and decarbonized fuels.

In the on-road transportation sector, the most impactful energy efficiency measure modeled in this study is the recently updated federal fuel economy standards.[79] These standards will lead to an estimated average improvement in fuel economy of 10 miles per gallon for model year 2026 passenger vehicles relative to model year 2021 vehicles.

In addition to fuel economy improvements, reductions in vehicle miles travelled (VMT) are often targeted as a way to reduce fuel demand, GHG emissions, and local air pollution. Hawaiʻi has a long-term statewide VMT target established in the Hawaiʻi Clean Energy Initiative (HCEI) of 10% below 2010 levels by 2030. Currently, there are few binding mechanisms to achieve VMT reductions, and the state has had challenges achieving interim targets also established as part of HCEI.[80] This is not unusual among states, as both California and Washington have also established VMT reduction targets that have proven difficult to achieve through existing policies and programs. While not modeled in these scenarios, policies and mechanisms to reduce VMT in Hawaiʻi would help reduce total electricity demand in an electrified future and represents a promising area for further research as a means to reduce both cost and land use impacts from decarbonizing the state.

Energy efficiency is also applicable to aviation and off-road transportation. The 2021 EIA Annual Energy Outlook forecasts a 16% improvement in aviation efficiency by 2045.[81] These improvements align with historically observed trends in aviation efficiency,[82] which has improved at a similar rate to passenger vehicle fuel economy since the introduction of CAFE standards, despite not being directly regulated.[83] There are currently no local, state, or federal policies that regulate aviation fuel economy and any regulations would likely be challenging to successfully implement without international coordination given the nature of the aviation industry. Airlines already have a strong incentive to improve efficiency as jet fuel accounts for a significant share of operating costs.[84] Thus, it is reasonable to expect that this incentive would become even stronger if policies were implemented requiring the use of more expensive decarbonized fuels, as is assumed in these scenarios, or through the purchase of verifiable carbon offsets.

The buildings sector has significant potential for energy efficiency and conservation, as well as several policies and programs in place to support energy efficiency. The energy efficiency improvements modeled in the net zero scenarios lead to a 17% and 28% reduction in electricity demand relative to reference by 2030 and 2040, respectively. These measures are aligned with the "Achievable Potential – High" scenario from the State of Hawaiʻi Market Potential Study 2020, which assumes high adoption of cost-effective energy efficiency measures through expanded programs, new state and federal codes and standards, future market effects, and other future interventions.[85] Some of the most impactful measures included in

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[79] https://www.nhtsa.gov/press-releases/usdot-announces-new-vehicle-fuel-economy-standards-model-year-2024-2026
[80] https://energy.hawaii.gov/wp-content/uploads/2011/09/Final_TransEnergyAnalysis_8.19.15.pdf
[81] https://www.eia.gov/outlooks/archive/aeo21/
[82] https://theicct.org/sites/default/files/publications/Airline-fuel-efficiency-standard-2020.pdf
[83] https://www.bts.gov/content/average-fuel-efficiency-us-light-duty-vehicles
[84] https://www.transportation.gov/administrations/assistant-secretary-research-and-technology/what-cost-airline-fuel-means-you
[85] https://puc.hawaii.gov/wp-content/uploads/2021/02/Hawaii-2020-Market-Potential-Study-Final-Report.pdf

the net zero scenarios are the replacement of electric resistance water heaters with solar water heaters, air conditioner efficiency improvements, and LED lighting.

Reducing or reversing recent trends towards greater use of air conditioning in buildings, by taking advantage of natural ventilation in Hawaiʻi's tropical climate is an important step towards reducing total electricity demand. The 2015 Hawaiʻi Energy Code created a Tropical Energy Code compliance pathway that encourages the use of natural ventilation and provides greater energy savings than the standard building code.[86] The Tropical Energy Code has recently gone into effect and represents an important step forward, but is only applicable to residential new construction, and to the renovation of homes that use air conditioning for less than 50% of the applicable space. Applying similar standards to commercial construction could be an area for future energy efficiency savings.

The Market Potential Study also included an "Economic Potential" scenario that achieves a 30% and 46% reduction in building electricity demand relative to reference by 2030 and 2040, respectively, indicating that there is even greater potential for cost-effective energy efficiency in buildings than what was modeled for this analysis. Often the greatest barriers to customer adoption of energy efficiency measures include the upfront investment costs, a lack of customer knowledge or contractor training, as well as the "hassle factor" associated with retrofits of existing buildings. Finding innovative ways to unlock the energy savings in the "Economic Potential" scenario would lead to lifecycle cost savings and reduce land use impacts from higher electric loads.

Electric Sector

This study assumes that the electric sector succeeds in achieving zero GHG emissions by 2045. Although more research is needed to understand the approaches and costs for achieving this target, the electric sector has a strong set of policies, regulations, and targets in place to support emissions reduction through 2045. Regarding state policy, Hawaiʻi was the first US state to adopt a 100% Renewable Portfolio Standard (RPS). Although the RPS policy aims to fully decarbonize the electric sector, legislators have recognized that the existing policy language may not achieve complete electric-sector decarbonization. House Bill 2089 to update the language in the RPS to definitively require 100% renewable generation by 2045 passed the legislature and was sent to the Governor in April 2022.[87]

In addition to requirements under statute, Hawaiian Electric is a regulated public utility with resource planning and procurement activities all subject to oversight from the Hawaiʻi Public Utilities Commission, which ensures that these activities are aligned with the state's climate goals. Finally, Hawaiian Electric has announced emissions targets for electricity generation of 70% emissions reductions by 2030 (relative to 2005) and net zero emissions by 2045, providing a timeline for decarbonization over the next two decades.

Although there is still a large amount of work needed to plan and transform the infrastructure of the electric system, the existing set of policy, regulation, and target-setting provides a strong foundation for electric-sector decarbonization and has put the electric sector on a pathway to net zero. However, even with ambitious decarbonization underway for the electric sector, achieving Hawaiʻi's economywide net

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86 https://hawaiienergy.com/files/resources/codes/ResidentialTropicalKeyChanges.pdf

87 https://www.capitol.hawaii.gov/measure_indiv.aspx?billtype=HB&billnumber=2089&year=2022

zero target will require new policies and regulations to address other sectors that currently lack a foundation to support decarbonization.

Transportation Sector

The transportation sector is the largest source of emissions in the State of Hawaiʻi. The Reference scenario reflects a significant level of emissions reductions from transportation coming from the economic adoption of light-duty EVs. To some extent, this reflects the fact that light-duty vehicles are the only transportation end use with substantial policy support for decarbonization, including the federal EV tax credit and Hawaiian Electric programs and incentives to support EVs and EV charging infrastructure. However, these policies fall short of the level of support needed to fully decarbonize light-duty vehicles in Hawaiʻi. In addition, other transportation end uses lack the policies and targets necessary to achieve the state's goals.

Several other states have established regulatory programs and/or issued executive orders mandating the sale of zero-emission vehicles (ZEVs) for both LDVs and MHDVs at a level of ambition commensurate with achieving net-zero emissions by midcentury. These reflect model policies that will likely be increasingly adopted by states with net zero emissions goals. Table 8 describes the ZEV sales mandate policies by state.

Table 8: State policies mandating ZEV adoption

State	Policy	Policy Type	Policy Requirement
CA	Advanced Clean Cars II[88]	Regulatory Program	100% ZEV sales requirement for LDVs by 2035
CA (Also adopted by NJ, NY, MA, OR, and WA)[89]	Advanced Clean Trucks[90]	Regulatory Program	Manufacturer sales requirement for ZEV MHDVs from 2024-2035 Final year ZEV sales percentages vary by vehicle type: Class 2b-3: 55% Class 4-8: 75% Class 7-8 Tractors: 40%
NY	Senate Bill S2758[91]	Legislation	100% ZEV sales for LDVs by 2035
WA	ESS House Bill 1287[92]	Legislation	100% ZEV requirement for all LDV registrations model year 2030 and later by 2030 (pending implementation of a road usage charge)

Despite numerous examples of ambitious state policies for on-road transportation decarbonization, there are few examples of policies requiring deep decarbonization in off-road transportation and aviation. While Hawaii's SB3311 targets achieving zero emissions for interisland and international transportation "as soon as practically possible" there is no clear mechanism in place to oversee or implement this target as sales of off-road vehicles and equipment are regulated differently than sales of on-road vehicles.

The absence of example policies from other states targeting off-road transportation and aviation emissions may reflect the fact that there are fewer decarbonized technology options available today than for on-road transportation. However, these sectors represent an especially large share of emissions in Hawai'i. Hawai'i could work with other states, for example through the USCA, to develop specific policies to support the development of electric technologies and/or sustainable fuels in these sectors. Examples include expanded research support for decarbonized aviation fuel and electric short-haul aviation, research support for sustainable marine fuels, and incentives for electric recreational and fishing craft.

88 https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii
89 https://www.ttnews.com/articles/six-states-adopt-clean-truck-rule
90 https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/fro2.pdf
91 https://www.nysenate.gov/legislation/bills/2021/s2758?intent=support
92 https://lawfilesext.leg.wa.gov/biennium/2021-22/Pdf/Bills/Session%20Laws/House/1287-S2.SL.pdf#page=1

Buildings Sector

Direct emissions from buildings (*i.e.,* fossil fuel combustion in buildings) reflect a relatively small share of emissions in Hawai'i. However, policies are still needed to ensure building decarbonization. See the section above on **Energy Efficiency and** for a discussion of the assumptions and options in buildings.

Both mitigation scenarios assume significant adoption of solar water heating and building electrification by 2045, with the majority of emissions reductions via the adoption of heat pump water heating in commercial buildings. Given Hawaii's mild climate and relatively high saturation of electric resistance water heating, solar water heating represents an important opportunity to reduce electricity demand in the near-term in the residential sector. In the commercial sector, including in hotels, electrification of gas use in buildings is a key measure to support decarbonization by replacing fuel combustion with an increasingly decarbonized electricity supply. In addition, building electrification represents an opportunity to mitigate potential gas supply constraints associated with the potential phaseout of fossil petroleum refining at the Par Refinery, which supplies gas to buildings on O'ahu.

The electrification of new buildings has seen increasing policy support across the US. Several municipalities across California have adopted all-electric building codes for new buildings, with wide variation in applicability to different building types and end uses.[93] State-level policies are also increasingly encouraging all-electric new buildings. For example, the California Energy Commission's 2022 Energy Code strongly encourages electric heat pumps[94] and legislators in New York have recently proposed a state-wide all-electric mandate for new buildings.[95]

However, the pace of new construction is relatively slow, and buildings that exist today will still make up most of Hawaii's building stock by 2045. Thus, electrification of existing buildings will also be needed in Hawai'i. The retrofit installation of heat pump water heaters in existing commercial buildings may see substantial upfront costs, including both the costs of new equipment as well as costs for engineering and design to support new systems that may require a larger footprint. New policy measures for retrofits may be needed to support market transformation via customer incentive programs and contractor training and education.

Both net zero scenarios also include the decarbonization of remaining fuels consumed in buildings. Within Hawai'i, the greatest policy movement in this direction has come from the Hawai'i PUC, which has opened a proceeding to investigate Integrated Resource Planning (IRP) for Hawai'i Gas. The IRP process has numerous goals, including to "(1) address and further State policies including emissions reductions and decarbonization goals; (2) establish a pathway to increase the proportion of renewable resources in Hawai'i Gas' fuel mix; (3) assess supply chain reliability and resilience for Hawai'i and (4) ensure customer energy affordability."[96]

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[93] https://www.buildingdecarb.org/active-code-efforts.html

[94] https://www.energy.ca.gov/news/2021-08/energy-commission-adopts-updated-building-standards-improve-efficiency-reduce-0

[95] https://www.nysenate.gov/legislation/bills/2021/S6843

[96] Order No. 38189 instituting the Hawaii Gas IRP proceeding. https://dms.puc.hawaii.gov/dms/DocumentViewer?pid=A1001001A22A20A85615F00512

Much of the fuel consumed in Hawaiian buildings is provided by the Hawaiʻi Gas company. A description of Hawaiʻi Gas's business is provided in the SEC filings of their former parent company, Macquarie:[97]

> Hawaii Gas' utility business includes the processing, distribution, and sale of synthetic natural gas (SNG) and renewable natural gas (RNG) and the distribution and sale of regasified liquefied natural gas (LNG) on the island of Oahu, as well as the distribution and sale of LPG via pipeline on all of the main islands. Hawaii Gas' unregulated business distributes LPG by truck to individual tanks located on customer sites or distributes LPG in cylinders filled at central locations to customers on all the main islands.

The Hawaiʻi Gas IRP reflects an important step toward the decarbonization of buildings in Hawaiʻi. However, there is no analogue to the RPS policy to guide the PUC in their determination of whether Hawaiʻi Gas's plans are aligned with state decarbonization goals. Example policies to support building decarbonization could include declining emissions targets for Hawaiʻi Gas or a decarbonized gas standard that would require an increasing share of the gas blend to be decarbonized over time.

In addition, a key gap in the scope of the IRP is that only a portion of Hawaiʻi Gas's business is subject to Hawaiʻi PUC regulation. The distribution of propane via truck or in propane cylinders, by Hawaiʻi Gas and/or by other suppliers, is considered a competitive and unregulated business. Thus, other policies implemented via means aside from PUC regulation will be needed to support the decarbonization of propane.

Industry Sector

Operations at the Par Refinery on Oʻahu are responsible for over 80% of energy emissions from the industry sector (including agriculture and construction). As described by the Hawaiʻi Refinery Task Force in 2014, economic factors such as a decline in demand for fuel oil may lead to the refinery's eventual closure.[98] Although a phaseout of fossil petroleum refining would reduce emissions from the industry and agriculture sectors, it may have adverse impacts on consumers including price shocks for liquid fuels and supply shortages for gas. The Hawaiʻi PUC is considering the latter concern through the Hawaiʻi Gas IRP. However, it may be valuable for the state's Refinery Task Force to reconvene to consider the future of petroleum refining in Hawaiʻi and plan for potential changes to refinery operations.

Other emissions in industry are primarily from construction and agricultural vehicles. Policy options for decarbonizing these end uses could include incentives for electric alternatives and policy support for decarbonized fuel pilots.

Non-energy, Non-combustion Emissions

Non-energy, non-combustion emissions from waste, oil and gas systems, IPPU, and agriculture account for around 17% of gross emissions in Hawaiʻi. While non-combustion emissions from oil and gas systems and IPPU in Hawaiʻi are likely to decline in the future due to changes in economic activity and existing

[97] https://sec.report/Document/0001628280-21-002304/mic-20201231.htm
[98] https://energy.hawaii.gov/wp-content/uploads/2011/08/HRTF_Final-Report_04-10-14.pdf

regulations, emissions from waste and agriculture are unlikely to be reduced without additional policy action.

The most meaningful existing policy for reducing non-energy, non-combustion emissions is the federal AIM Act directing EPA to phase out production and consumption of HFCs in the US by 85% over the next 15 years,[99] in line with the schedule outlined in the Kigali Amendment to the Montreal Protocol.[100] Because virtually all IPPU emissions in Hawaiʻi are from HFCs, this study reflects significant reductions in the sector due to this policy.

While not an explicit policy goal, the phaseout of fossil petroleum refining on Oʻahu would eliminate the vast majority of non-combustion emissions from the oil and gas sector in Hawaiʻi in addition to the fuel combustion emissions that would be avoided.

Many of the remaining non-combustion emission sources from agriculture and waste are impacted by state and local policies that may not be primarily focused on GHG emissions reductions (e.g., soil conservation programs, waste diversion targets). These sectors have traditionally been less of a focus in terms of state policies directly targeting emissions reductions when compared to energy production and energy consumption sectors.

Natural Emissions Sinks

While the USGS predicts that carbon sequestration in the terrestrial ecosystems of Hawaiʻi will decline through mid-century due to land use and climatic changes, the state is projected to remain a net carbon sink over this period.[101] Moreover, the state Office of Planning and Sustainable Development and the Greenhouse Gas Sequestration Task Force have already completed numerous studies and pilot projects investigating the potential for increased natural sequestration of carbon in Hawaiʻi.[102] In particular, the 2020 study completed by Conservation International identified multiple strategies that could increase sequestration in Hawaiʻi on the order of millions of metric tons of CO2e per year.[103]

The magnitude of this potential suggests that the state could achieve the required CDR identified in this analysis through increases in natural carbon sequestration. However, the strategies for achieving natural carbon sequestration will compete for land with agricultural uses, residential and commercial development, and renewable energy deployment. Coordinated planning efforts may be needed to identify natural sequestration projects with minimal land use conflicts or where natural sequestration can be combined with other land uses.

[99] https://www.epa.gov/climate-hfcs-reduction/proposed-rule-phasedown-hydrofluorocarbons-establishing-allowance-allocation
[100] https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en
[101] https://pubs.usgs.gov/pp/1834/a/pp1834.pdf
[102] https://planning.hawaii.gov/ghgstf/projects/
[103] https://planning.hawaii.gov/wp-content/uploads/Conservation-International-FINAL-Report_GHG-4.30.2020.pdf

Negative Emissions Technologies

This study has illustrated that some level of negative emissions technologies could be needed to achieve the State of Hawaiʻi's net zero emissions target. Although a number of different NETs are under development, DAC is the most technologically advanced. Policy support for negative emissions technologies could include research funding to further investigate the potential for in-state carbon sequestration or the development of a pilot project to demonstrate the viability of DAC in Hawaiʻi.

Another important policy consideration is that negative emissions may be considerably less expensive outside of Hawaiʻi. Today, the markets for carbon emissions offsets face challenges in validation and verification, even within a single state such as California.[104] Thus, Act 15's requirement that negative emissions occur in-state may reflect reasonable skepticism regarding the veracity of emissions offsets purchased from external markets. However, locations with better renewable resource quality and lower construction costs may be able to develop DAC systems at a much lower cost than in Hawaiʻi. If, in the future, more robust validation protocols for negative emissions are developed, policymakers may reevaluate the in-state requirement for negative emissions technologies under Act 15.

[104] https://carbonplan.org/research/forest-offsets-explainer

Conclusions and Next Steps

This study has illustrated two potential pathways for Hawai'i to achieve carbon neutrality by 2045; both pathways rely on significant investments in **energy efficiency and conservation, electrification, zero-carbon electricity, decarbonized fuels, reductions in non-energy emissions, and carbon dioxide sinks or removal.** Despite the clear scientific imperative of addressing climate change, this will not be a simple transition to accomplish.

The findings of this pathways analysis underscore the fact that meeting Hawai'i's ambitious net zero goal will require transformations from all sectors of the economy. While zero-carbon electricity is a necessary step to supporting the transition to net zero, it is not sufficient.

In Hawai'i, achieving a net zero future will require a particular focus on the aviation and marine sectors, which represent a larger share of total GHG emissions in Hawai'i than in the rest of the country. However, much like the rest of the country, Hawai'i will also need to accelerate the adoption energy efficiency and electrification in industry and buildings, renewable and zero-carbon electric generation technologies, and light-duty electric vehicles – transitions which can take time and are largely driven by consumer purchasing decisions and the natural replacement cycles of equipment.

Key questions remain around how the decarbonization solutions in Hawai'i will intersect with the islands' land-use constraints. Both of the decarbonization pathways illustrated in this study highlight the potential for significant increases in electricity demand, due primarily to electrification of the transportation sector. However, demand for decarbonized fuels and carbon dioxide removal technologies could also significantly increase demands for zero-carbon electricity, putting further pressure on costs and land availability.

Finding innovative solutions to **reduce total energy demand** in Hawai'i will become even more essential to alleviate the constraints of a net-zero future, even as current trends are pointing towards higher energy demands with a growing population, increased air conditioner saturation, and growing transportation demands. Moving away from electric resistance and gas hot water heating towards a greater reliance on solar water heating, reducing reliance on air conditioning through greater adoption of natural ventilation and passive cooling techniques in both residential and commercial buildings, encouraging the use of natural daylight to reduce daytime lighting needs, and investing in shared and public transit options all appear to be energy efficiency solutions worthy of increased attention.

This study focuses on an initial look at economywide solutions to net zero by 2045, but also highlights some of the steps needed to cut GHG emissions in half by 2030, relative to 2005 levels. A valuable next step would be to perform a deeper dive on the near-term actions and policies needed to achieve the state's 2030 goal, as called for in Act 238. Additional next steps would also be to evaluate customer costs and benefits, as well as societal costs and benefits, of pathways to 2030.

With less than seven years to accomplish such an ambitious and important goal, time is of the essence.