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A path to net-zero carbon emissions at the W. M. Keck Observatory

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The 2019 carbon footprint of the W. M. Keck Observatory is estimated at 3.0 tonnes of CO_2 equivalent per science night and that figure will move towards net zero over the next decade or so by decarbonizing the Observatory's vehicle fleet, aviation footprint reductions and other measures.

With the release of the Intergovernmental Panel on Climate Change sixth assessment report[1], the crisis of climate change is irrefutable and the critical need for action to address it has gained broad support throughout the global community. The United Nations Secretary General's assessment of the November 2021 COP26 commitments was that they represent "an important step but not enough". It appears they are insufficient to meet the climate action targets of the Paris Accord without enhanced ambition. In this Comment we describe the approach used to measure the carbon footprint of the W. M. Keck Observatory (WMKO) in terms of greenhouse gas (GHG) emissions and how this has informed articulating an enhanced ambition to reduce the Observatory's carbon footprint in the decade ahead.

Baseline GHG inventory

For the initial carbon footprint estimate we elected to use 2019 as the baseline year since it was the most recent year that predates the COVID-19 pandemic, which had a significant impact on operations, on-site presence, and business travel. Several other observatories (ESO[2], CFHT[3], NOIRLab) have also chosen this same year and this choice could allow for some useful data comparisons.

The GHG Protocol Corporate Standard[4] provides standards and guidance for organizations preparing a GHG emissions inventory. It covers the accounting and reporting of the six greenhouse gases covered by the Kyoto Protocol. A key element of the GHG accounting protocol is the concept of scope. Scopes are used to account for direct and indirect emissions and to avoid double counting across organizations. They can also provide insights to inform mitigation strategies for maximum impact. The initial estimate for 2019 includes all direct emissions at WMKO facilities (scope 1), all indirect emissions from purchased power (scope 2) and a portion, described later, of the indirect emissions up and down the value chain as a consequence of WMKO activities (scope 3). Metric tonnes of CO_2 equivalent (tCO_2e) is the standard reporting unit. Other greenhouse gases, methane being the most significant, have different global warming impacts and half-lives in the Earth's atmosphere. Emissions of these gases are converted to the amount of CO_2 that would have equivalent global warming potential (GWP) over a 100-year period.

WMKO operates three facilities on Hawaiʻi Island: the twin 10-metre WMKO telescopes facility on Maunakea, the headquarters (HQ) facility in the town of Waimea, and the separately metered Visiting Scientist Quarters (VSQ) at the back of the main HQ campus. The WMKO employee headcount is around 125 full-time equivalents with most (70%) employees reporting to work at HQ and the remaining 30% working mostly on Maunakea. VSQ is purposed primarily for visiting astronomer use during their observing runs.

The scope 1 direct emissions for 2019 include those for gasoline consumed to operate the WMKO vehicle fleet, CO_2 for monthly cleaning of the telescope mirror segments, diesel fuel for the summit backup generator, propane for forklifts, and gasoline for HQ portable generators and power washers (Table 1).

The scope 2 indirect emissions from purchased electricity are the product of the total MWh purchased times the emissions rate in tCO_2e per MWh for the local island grid operated by Hawaiian Electric, a subsidiary of Hawaiian Electric Industries (HEI). All three separately metered WMKO facilities now have photovoltaic (PV) solar panels, however the PV at the Maunakea facility was not yet operational in 2019. Any excess solar power exported to the grid does not directly impact our scope 2 GHG calculations but does contribute to a greener grid for our local island community. Inspecting the monthly utility statements, we determined the total electricity delivered by the utility in 2019 to all three locations was 2,978 MWh. We convert this to tCO_2e by multiplying by the island-specific electricity emissions intensity (Table 2) to get 1,581 tCO_2e of scope 2 emissions.

Scope 3 is an optional reporting category and represents all the indirect emissions from upstream and downstream activities not already included in scope 2. These emissions are hardest to measure and in general would be includable in the scope 1 or 2 emissions for other reporting entities. There is limited expectation for a full and accurate accounting for all categories up and down the value chain. Guidance from GHG Protocol is to include categories that are believed to have significant environmental impact especially when compared to the organization's scope 1 and 2 emissions. For many organizations, business travel can be a significant scope 3 GHG contribution. For WMKO on the island of Hawaiʻi, we suspected that the aviation component alone of business travel would be significant. For similar reasons, other observatories are prioritizing collecting data on business-travel-related GHG impact. The Astro2020 Decadal Survey[5] specifically identifies air travel as being a significant contributor to the astronomy profession's carbon footprint.

For the initial estimate the only scope 3 emissions included is the aviation component of business travel. We mined data from electronic records for all expense reports submitted for 2019 and found 212 reports that included air travel for WMKO staff. There are a plethora of tools available to calculate a carbon footprint for air travel between any two airports. We settled on using the travel footprint calculator tool released by D. Barret[6] to the science community in 2020. It combines

Table 1 | Estimated WMKO 2019 GHG emissions

Scope 1	Quantity	Units	$kgCO_2e$ per unit[a]	tCO_2e	% of scope 1	% of total GHG
Keck vehicle fleet (gasoline)	13,181.49	US gallons	8.887	117.14	99.06%	5.87%
CO_2 for primary mirrors	370	kg	1.000	0.37	0.31%	0.019%
Diesel for summit generator	47.5	US gallons	10.180	0.48	0.41%	0.024%
Propane for HQ forklifts	127.2	lbs	1.333	0.17	0.14%	0.009%
HQ generators & power washers	10	US gallons	8.887	0.09	0.08%	0.004%
Total scope 1 direct emissions				118.26	100.00%	5.93%

Scope 2 electricity	MWh	tCO_2e per MWh (ref. [10])	tCO_2e	% of scope 2	% of total GHG
Summit	2,404.2	0.531	1,276.63	80.72%	64.02%
HQ	556.88		295.70	18.70%	14.83%
VSQ	17.2		9.13	0.58%	0.46%
Total MWh	2,978.28				
Total scope 2 emissions			1,581.47	100.00%	79.30%

Scope 3 air travel only	Number of trips	Average tCO_2e per trip[b]	tCO_2e	% of scope 3	% of total GHG
US mainland	142	1.523	216.3	73.44%	10.84%
International	20	3.576	71.5	24.29%	3.59%
In-state trips	50	0.134	6.7	2.28%	0.34%
Total scope 3 air travel	212		294.5	100.00%	14.77%
Total scope 1 + 2 + 3 emissions			1,994.21		100.00%

Emissions include total scope 1 direct emissions by WMKO, plus total scope 2 electricity, plus partial scope 3 attributable to the aviation component of business travel. Scope 1 and 2 measurement uncertainties 3% and 1% respectively[7]; uncertainties for scope 3 considerably higher at ~50% due to model assumptions. Vehicle fleet, Maunakea facility electricity, and air travel to the US west coast are the three most significant in each scope, respectively, with electricity being the overall dominant (79%) source of 2019 emissions. Other categories of scope 3 merit further investigation such as employee commute, transporting of water up Maunakea and wastewater down, manufacture and transporting of other goods (including new instrumentation) to Hawai'i, and cloud computing infrastructure. [a]https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references; [b]https://travel-footprint-calculator.irap.omp.eu/home.html.

multiple selectable emission models. We chose the default model settings, which results in a middle-of-the-pack radiative forcing index of around 2.0. This tool with the same settings will also be used in a forthcoming estimate of the GHG emissions for NOIRLab, an observatory that manages a number of sites across the Americas, including Gemini North on Maunakea.

Estimated scope 1, scope 2, and the aviation component of scope 3 emissions for 2019 totalled 1,994 tCO_2e. With scope 3 only partially accounted for, further scope 3 investigation is merited. Measurements for scope 1 and 2 emissions are made with a high degree of confidence. More details on the data collection methods and sources of error and uncertainty are presented in ref. [7].

Path to net zero

WMKO is currently engaged with multiple stakeholders in developing a major update of its strategic plan looking out to 2035, with implementation beginning in early 2023. This is an excellent opportunity and horizon for articulating and adopting ambitious but attainable carbon footprint reduction goals for the Observatory as well as a high-level strategy to achieve them. WMKO leadership is considering adopting the following recommendations in the 2035 strategic plan for implementation in a WMKO climate action plan: (a) commit to net-zero emissions for scope 1 and 2 by 2035 and aspire to net zero by 2030; (b) strive for net-zero scope 3 emissions by 2035; and (c) get there by decarbonizing the WMKO vehicle fleet, efficiency improvements, a greener electricity grid, aviation footprint reductions, and carbon offsets to fill the gaps. In addition to reducing the Observatory's GHG emissions, we propose that WMKO's climate action plan strive to support reducing the carbon footprint of the broader astronomy community and in particular that associated with using WMKO telescope time.

Attainable goals. How realistic are the above commitments and aspirations? Taking each in turn, we start with the scope 1 emissions, which are dominated (> 99%) by the fuel consumed by the 25 vehicles in the WMKO fleet. At the historical replacement rate of 2 to 3 vehicles per year, it would take 10 years to decarbonize the fleet by replacing internal combustion engine vehicles with electric vehicles (EVs). A separate project[8] underway to operate the telescopes at night remotely from Waimea, without a presence on Maunakea, will result in a reduction of six vehicles in total fleet size. This makes the 2030 aspirational reduction goal for scope 1 realistically attainable. In June 2022, we installed our first EV charging station at WMKO HQ and in July took delivery of our first EV.

Turning to scope 2, which represents almost 80% of WMKO's estimated 2019 carbon footprint, the path to net zero is through further electricity savings and a greener local grid. Fig. 1 shows the downward trend in scope 2 electricity from 2006, when it peaked, to 2021, when

Table 2 | Hawaiian Electric GHG emissions

Source	2015 (baseline)	2019	2020	2021
Carbon dioxide (CO_2)				
CO_2 emissions (Mt)	7,057,212	6,721,656	6,070,284	5,979,756
CO_2 emissions intensity (Mt (net MWh)$^{-1}$)	0.700	0.648	0.616	0.594
Carbon dioxide equivalent (CO_2e)				
CO_2e emissions (Mt)	7,104,453	6,771,000	6,112,001	6,022,715
CO_2e emissions intensity (Mt (net MWh)$^{-1}$)	0.705	0.653	0.620	0.598
Carbon dioxide equivalent (CO_2e) intensity by island				
Hawai'i Island (Mt (net MWh)$^{-1}$)	0.439	0.531	0.511	0.423
O'ahu (Mt (net MWh)$^{-1}$)	0.782	0.698	0.663	0.651
Maui County (Mt (net MWh)$^{-1}$)	0.509	0.519	0.475	0.474

Island-specific emissions intensities going back to 2015 were first published in April 2022[10]. The data presented include total emissions from utility-owned generation, purchased power, transmission and distribution, and assumes zero emissions from customer-sited solar. Intensities in $MtCO_2e$ (net MWh)$^{-1}$ units are calculated by dividing emissions by net generation from utility-owned generation, purchased power and customer-sited solar. The differences between these emissions intensities and US Environmental Protections Agency (EPA) eGRID published emissions rates[14] are discussed in ref. [7]. Note that Hawai'i Island emission intensities for 2021 are now the lowest of the island chain after recovering from the negative impact of the Puna Geothermal Venture disruption due to volcanic activity in 2018.

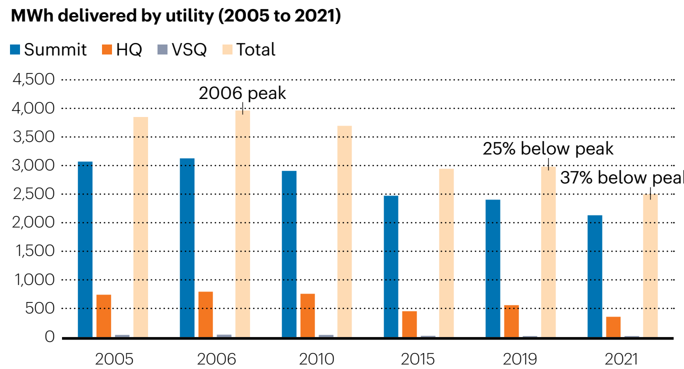

Fig. 1 | WMKO Electricity trends 2005 to 2021. Peak electricity delivered to WMKO by the utility occurred in 2006, when the Keck 2 liquid dye laser (70 kW energy hog) became fully operational. It has trended down ever since to 37% below peak in 2021. Contributing to this has been moving to solid-state lasers, multiple motor efficiency upgrades, lighting upgrades, solar PV at all three facilities and virtualization[15] of a significant portion of the computing infrastructure. The trend is expected to continue downward in the decade ahead as dozens of planned and not yet planned upgrades and efficiency improvements are implemented, for instance by replacing multiple aging cooling systems.

it dropped to 37% below peak. We see dozens of additional efficiency opportunities to continue a downward trend in the decade ahead. Planning is underway to realize 2023 reductions in energy for the dome exhaust fans and the hydrostatic bearing systems supporting the telescopes. These represent the four largest electricity consumers at the telescope facility.

The state of Hawai'i continues to raise the bar relative to US national goals for ambitious state climate action goals. These include state legislature bills directing the Public Utility Commission (PUC) to implement carrot-and-stick performance-based regulations that align with Hawai'i's economy-wide carbon neutrality by 2045. In November 2021, Hawaiian Electric announced[9] a 2030 Climate Action Plan with enhanced ambition including the following: "By 2030, Hawaiian Electric's renewable portfolio standard (RPS) is expected to exceed 70%, with renewable resources available to provide close to 100% of the electricity generated on Hawai'i Island and in Maui County." These ambitions are backed by published project plans[10] and incentives to get there (Fig. 2). How close to zero emissions intensity Hawaiian Electric gets for Hawai'i Island by 2030 or 2035 remains to be seen. It is reasonable to think, however, that any shortfall could be met by the Observatory purchasing carbon offsets until net zero is reached.

Between 2019 and 2021, energy efficiencies and additional solar PV implemented at WMKO (Fig. 1) combined with a greener Hawai'i Island Electric grid (Table 2) resulted in scope 2 GHG emissions reduction from 1,581 to 1,058 tCO_2e. Though unrealistic to continue the same steep trajectory, this 33% reduction in just two years is encouraging.

At roughly 2.5 times WMKO's scope 1 emissions, the aviation component alone of staff business travel (scope 3) is indeed significant and merits serious consideration towards reducing WMKO's overall environmental impact. Reducing the impact of aviation travel is one of the most challenging facing the global community in tackling climate change. There is no clear optimal single solution to this challenge. We believe addressing it[7] will take a combination of reduced air travel, increased traveller awareness and multiple emerging technologies and other measures within the aviation industry itself.

Broader astronomy community impact

Astronomers and their institutions that use observing time on the WMKO telescopes need to consider an allocation of WMKO's carbon footprint when calculating their scope 3 astronomy-related emissions. One approach to calculating this allocation is to divide the total WMKO annual carbon footprint by the annual number of science nights to arrive at a carbon footprint per allocated science night. Engineering nights used to maintain and advance the scientific capability of the telescopes are thus allocated across available science nights. With two telescopes and data for 2019 we have: 1,994 tCO_2e / (365 nights per telescope × 2 telescopes − 57.5 engineering nights) = 3.0 tCO_2e per 2019 science night. A 2020 paper by Stevens et al.[11] examining the carbon footprint of the Australian astronomy community includes an allocation of 35 tCO_2e for 10 nights of WMKO telescope time. The discrepancy (3.5 versus 3.0 tCO_2e per night) can be accounted for by how engineering nights are considered and the now outdated initial rough estimates provided for WMKO GHG emissions. Though we have not completed a full GHG inventory for 2021, the 33% scope 2 emissions reduction noted above and a significant reduction in staff business travel in 2021 taken together point to a drop in emissions per WMKO science night to around 2.0 tCO_2e for 2021 compared to 3.0 tCO_2e for 2019.

Until 1997, observers using WMKO telescope time travelled to the top of Maunakea to take their observations. For several years they have had options to take their observations from remote operations rooms at WMKO HQ in Waimea or similar setups replicated at institutions across

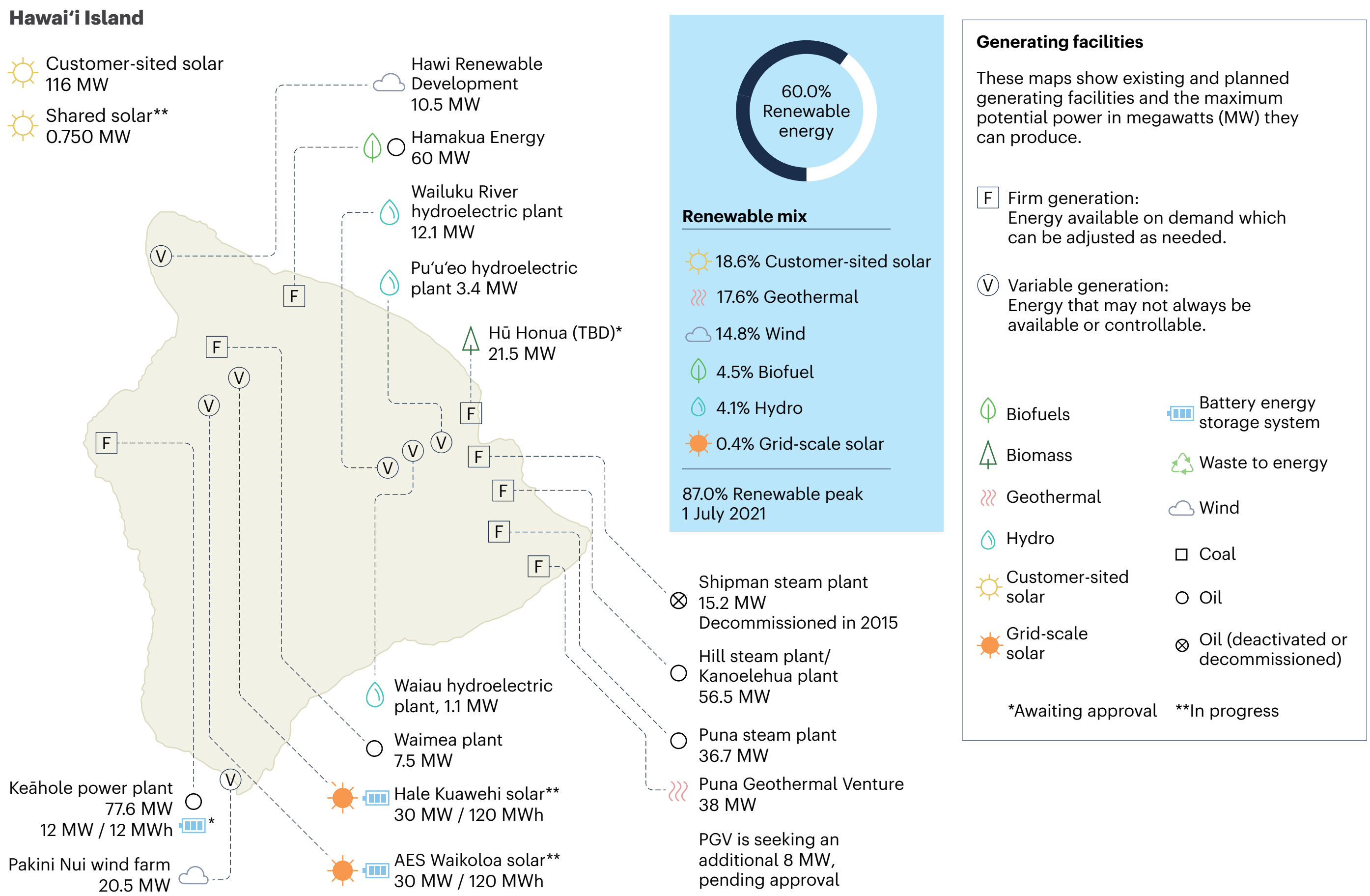

Fig. 2 | Hawai‘i Island existing and planned generation facilities on 2030 path to expected renewable resources to meet 100% of electricity generated. Hawai‘i Island achieved 60% renewable energy for 2021. 2022 will be the first full year of Puna Geothermal Venture generation back at full capacity after the disruptive volcanic activity in 2018. Expanded geothermal capacity is pending approval. Two large grid scale solar PV (covering 300 acres each) and battery storage plants are under construction and expected to come on line in 2023. Each is capable of delivering around 7% of the island's electricity needs. Figure adapted with permission from ref. [10], Hawaii Electric Industries.

the globe. These remote options saved observers costs and travel time. The carbon footprint associated with observer travel can be accounted for as scope 3 emissions business travel for the observer's institution. Our reading of the GHG Protocol technical guidance for scope 3[4,12] does not find this as includable within the WMKO boundaries for any of the scope 3 categories. Nevertheless, observer travel for WMKO science runs is something over which the Observatory can exert influence and take action with potential for significant impact in terms of reducing GHG emissions. Early in the pandemic lockdown phase, the travel restrictions and remote institution access limitations precipitated the need to extend the ability to conduct observations from astronomers' homes (also known as 'pyjama mode' observing) for WMKO to resume full science operations. A 2022 paper by Walawender et al.[13] discusses this in detail. Pre-pandemic observer air travel emissions alone were estimated at 1,120 $tCO_2e\ yr^{-1}$. This dropped to 40 tCO_2e for the year when full science operations resumed but access to WMKO HQ was restricted. In the 12 months through 27 June 2022, when travel and access restrictions were lifted it bounced back, but only to 330 $tCO_2e\ yr^{-1}$.

It remains to be seen to what level observer travel settles out to once the pandemic is well in the rear-view mirror, however this clearly shows the potential for emissions reduction with remote observing in line with recommendations from Astro2020[5]. It also illustrates the value in organizations' understanding of potential scope 3 opportunities up and down the value chain, even those outside an organization's scope 3 GHG reporting boundaries, to uncover actions and decisions potentially more impactful than emission reductions more directly within an organization's control.

Sharing knowledge is key to carbon footprint reduction

The efforts described in this Comment were informed by and benefited from carbon footprint assessment efforts at other astronomical observatories. Though not specifically compared in this article we believe WMKO emission data compare very favourably with published and not yet published emission intensity data we are seeing emerging from other observatories on Maunakea and elsewhere. Since we all share the same common atmosphere, it is in all our common interests to compound our collective efforts towards net zero by sharing data and lessons learned to build momentum as we work to accelerate the reduction of astronomy's carbon footprint. Articles such as this can play a role, as well as other venues for exchange of ideas and collaboration. For example, we look forward to working with other Maunakea observatories to understand and address some of the Hawaiʻi Island local logistical challenges around fleet decarbonization, such as EV charging. The local electric utility's emission rate trajectory is of direct common interest across all of Hawaiʻi Island organizations as we work to reduce scope 2 emissions. Energy efficiency improvements provide multiple targeted opportunities for sharing approaches across geographies. With scope 3 emissions being the more complex to understand and assess but with potential opportunity for big impact, we believe it could be particularly valuable to share insights on scope 3 strategy and individual use cases.

The emission reduction goals, aspirations, and strategy outlined here articulate an enhanced ambition which, especially if shared by other Maunakea observatories, can play a role in accelerating Hawaiʻi's transition to a green economy and contribute to propelling astronomy to a greener future.

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Competing interests

The authors declare no competing interests.