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Carbon Footprint of the MIT Kavli Institute

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ABSTRACT

We present a quantitative estimate of the total carbon footprint for the MIT Kavli Institute for Astrophysics and Space Research (MKI), based on a survey of travel and commuting patterns for our ~ 150 person workforce, and utility consumption in electricity, heat (steam + natural gas), and chilled water cooling of the physical plant. Each of these was independently evaluated over a one-year interval during 2018-2019 before the COVID-19 scaleback of campus research and teaching. Exact start and end dates varied for the different sources considered according to how data were collected. Our best estimate is that MKI produces 1826 metric tons of CO2 equivalent (MTCO2e) per year, or 12 MTCO2e per capita, per year. The largest contributor (40%) is from heating our physical plant, especially the Ronald McNair building which houses a majority of our staff. Air travel comprises 15% of the total carbon footprint; the largest total contribution comes from travel associated with professional development of our junior colleagues and support of current and future experiments, though the largest per capita contribution is from the faculty. Colloquium travel is a negligible contributor to the carbon footprint. MKI's computing cluster consumes both electricity and chilled water. While the total cooling load of the cluster is difficult to isolate accurately, if one uses standard ratios of total-to-computing power the implied footprint of cluster computing and cooling approaches 200 MTCO2e / year, similar to air travel and roughly 10% of MKI's total footprint. MKI has already realized a 20% net reduction in carbon footprint relative to 2014 levels, through MIT's purchase of offsets from a solar farm in North Carolina. To reach 2030 targets set by MIT (which meet or exceed the US Nationally Determined Contribution in the Paris Accord) a further reduction of 15% below present levels, or 220 MTCO2e per year, would be required. This goal could potentially be achieved by replacing the single-pane windows and their deteriorating wood frames on the Ronald McNair building's North facade, together with reduced emissions caused by pandemic-induced changes in commuting patterns and air travel.

Keywords: Operations

1. INTRODUCTION

The COVID-19 pandemic necessitated an abrupt stop to work-related travel in March 2020, which has lasted a year and still continues. Despite the major disruption to professional activities, many in our community have commented on its unanticipated salutary effects for the climate, in the form of reduced carbon emissions. Long-term reductions in air or commuter travel that would have been professionally unthinkable before 2020 may now be achievable when approached from below with a new steady state target in mind.

At the same time, carbon surveys from other astronomical institutes demonstrated that other, sometimes surprising research activities contribute substantially to greenhouse gas emissions. The electricity and cooling requirements associated with high performance computing in particular have been highlighted as an underappreciated source of carbon emissions (e.g. Stevens et al. 2020).

With these considerations in mind we are motivated to quantify the total carbon footprint of the MIT Kavli Institute. At the same time we wish to estimate the fractional contributions of various energy line items (e.g. commuting, colloquium travel, electricity, etc.) in the overall carbon budget so that we might identify and address any obvious worst offenders.

For this exercise we have evaluated each line item over a 12 month pre-pandemic period. Travel was analyzed between July 1, 2018 and June 30, 2019, corresponding to MIT's 2019 Fiscal Year, whereas utility usage and commuting were organized by calendar year according to MIT's reporting. Summing over a 1-year period offers a representative cycle of HVAC loads on the physical plant, and also accounts for seasonal trends in commuting and travel at MIT involving job searches, colloquia,

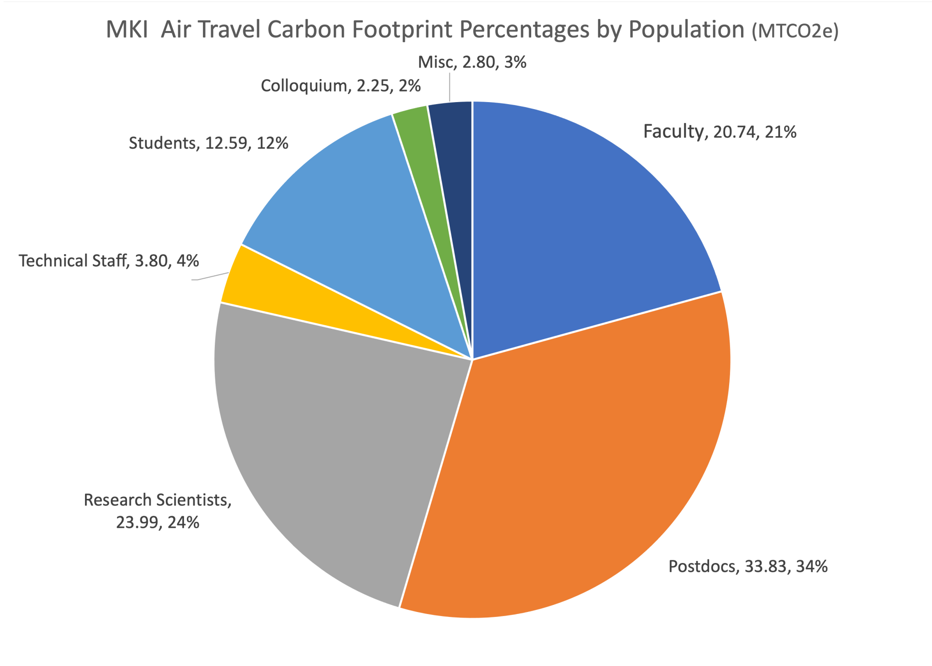

Figure 1. Breakdown of carbon production from air travel according to MKI constituency. The total budget is dominated by postdocs, research scientists, and faculty, in similar proportions. The contribution of air travel to MKI's total carbon footprint is roughly 15%.

meetings, and other activities that naturally follow the academic year.

While our study initially focused on travel, we soon discovered MIT's building-level data repository on energy usage in the Sustainability Data Pool, which can be accessed by any MIT employee with Touchstone credentials. Moreover MIT has collected relevant data on local travel patterns via the Commuter Survey, which a large number of MKI employees have completed. Commuter survey results may be queried at the level of individual Departments, Labs and Centers (DLCs), allowing for specific conclusions to be drawn about MKI (with some assumptions).

In the following sections we present individual accounting of the carbon footprint associated with (1) air travel, (2) commuting, (3) electricity usage, and (4) climate control, along with descriptions of the basis of estimate and possible shortcomings. These are followed by a rollup of the full budget, and a discussion of strategic areas for improvement in the context of goals set forth by the Paris Accord and MIT Sustainability Initiative, as well as progress already made by MIT through investment in solar farms to offset on-campus carbon consumption.

2. AIR TRAVEL

COVID-19 imposed an exogenous shock to our travel patterns which is unlikely to be replicated again, and has been conducive to collection of two-sample (before/after) data. It also created a window of availability for staff whose normal responsibilities for face-to-face interactions were reduced, but who still had still access to the travel database, to collect and analyze these patterns.

Using MIT's CONCUR travel expense reporting system, we pulled records for every trip taken by MKI staff members or visitors involving air transportation between the dates of July 1, 2018 and June 30, 2019 (i.e. FY2019). The travel records include airport codes, which may be used to estimate the carbon footprint of each individual trip. These trips include all travel paid for out of either MKI-managed sponsored research grants, or discretionary travel associated with

Table 1. MKI Carbon Production from Air Travel

Constituency	Metric tons CO2e	Percentage
Postdocs	86.1	34%
Research Scientists	61.0	24%
Faculty	52.7	20%
Students	32.0	13%
Technical Staff	9.7	4%
Miscellaneous	7.1	3%
Colloquium	5.7	2%
Total	254.3	

departmental accounts controlled by faculty (primarily Physics). We included travel associated with all inbound MKI colloquia, talks, and professional collaborations where the travel is sponsored by MIT. We did not include trips where MKI staff delivered talks at other institutions, and the travel was processed at those other institutions.

For each trip, we entered the airport codes for each leg into the online Carbon Emissions Calculator of the United Nations International Civil Aviation Office (ICAO)[1]. The calculator outputs an estimate of CO2 emissions per passenger, per leg. The ICAO methodology uses statistical data on the fleet of aircraft manifested for each route, passenger-to-cargo ratios, and load factors, assuming all seats are economy class (appropriate for MIT travel).

Wide variations exist between different calculators used in the literature. For example a Boston to London, Heathrow round trip was estimated 4× higher in CO2 emission by atmosfair (a carbon offset vendor used in Jahnke et al. 2020, who analyzed emissions from MPIA) than the ICAO used here. A comparison of calculators is beyond the scope of our analysis, but readers are cautioned to be mindful of these discrepancies.

Table 1 and Figure 1 display the aggregated CO2 footprint of each major MKI constituency, measured in metric tons of CO2 equivalent (often abbreviated as MTCO2e). The total footprint for MKI travel is approximately 250 MTCO2e, or approximately 1.7 metric tons per year, per MKI employee. Postdocs contribute the largest fraction of CO2 emissions, approximately one third of the total. Faculty and research scientists contribute roughly one fifth and one quarter of the total, respectively.

On a per capita basis however, faculty have the largest footprint (2.92 MTCO2e per year, per professor), followed by postdocs (2.32) and Research Scientists (1.60).

The Astrophysics Colloquium was the smallest contributor considered at only 2% of the total travel-related footprint. As will be shown below, when one also considers greenhouse gas emissions from our physical plant, the overall contribution from the colloquium is only 0.3% of MKI's total carbon budget.

3. COMMUTING

Commuting travel produces less carbon per trip, but is much more frequent and many of MKI's employees travel considerable distances daily to work. Every two years, MIT performs a Transportation Survey broken down by Department, Lab, and Center (DLC), with the most recent survey taking place in 2018. Although this does not strictly align with the same annual period considered for air travel, it still averages trends over an adjacent year. MKI's response rate was 58%; we assume commuting patterns of this group are representative of MKI as a whole. By a significant margin the largest two groups in the survey were Research Scientists and Postdocs; of these two the Research Scientists had a higher response rate. Because postdocs tend to commute shorter distances and use public transit or walk more than Research Scientists, the actual value of greenhouse gas (GHG) emissions may therefore be slightly lower than is estimated using that assumption.

Through contacts in the MIT Institutional Research office, we obtained anonymous Transportation Survey results for MKI employees, which include research staff, technical staff, postdocs and administrative staff. Unfortunately, data on students and faculty working at MKI are collected by their home academic departments, in a form that is impossible to disaggregate from other research divisions. We therefore needed to rely on the following (strong) assumptions to arrive at a commuting estimate.

- We assume all students either walk or commute on the MBTA
- We assume all MBTA commuting occurs on the Red Line
- We assume that commuting patterns are identical between faculty and research scientists.

Relevant survey results are highlighted in Table 2, with Column 2 presenting the primary survey result for MKI. Column 3 contains conversion factors of CO2 emissions per passenger mile with sources annotated. Because a large portion of MBTA commuters live in the Cambridge/Somerville area and Davis Square in particular, we chose 3 miles as the average Red Line commute. We further assumed that the average car commuter comes from a location near the I-95 loop.

The data in Table 2 may be combined as a weighted sum to produce an overall carbon footprint, assuming a total population of $N = 158$ employees. The resulting value is 78.6 MTCO2e per year (accounting for the fact that each round-trip commute traverses twice the average distance). However Column 2 in the table does not accurately reflect the commuting trends of faculty and students because their survey responses are tabulated in academic departments. This could skew the results because students tend to live closer to campus and walk or

[1] https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

Table 2. MKI Primary Commuting Methods, Assumed Distances and Conversion Factors

Method	% of MKI[a]	lb CO2 passenger^{-1} mile^{-1}	Avg. Distance (mi)	Comments
MBTA	55%	0.305[b,c]	3	Red Line, Kendall to Davis Sq.
Drive alone	15%	0.960[c]	11	MIT to Lexington, or I-95 loop
Carpool (×2)	2%	0.480[c]	11	Same as Drive Alone
Bicycle	11%	0.0	6	MIT to Arlington
Walk	18%	0.0	1	
Other	2%	0.0	11	Electric+solar; Commuter Rail

[a]Data from MKI responses to MIT Transportation Survey

[b]https://willbrownsberger.com/transit-energy-efficiency/

[c]https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/PublicTransportationsRoleInRespondingToClimateChange2010.pdf

Table 3. Commuting Assumptions by Constituency[a]

Constituency	*N*	Walk+Bike	MBTA	Drive	MTCO2e/year
Faculty	18	0.1	0.0	0.9	28.7
Research Scientists	38	0.2	0.6	0.2	27.6
Technical Staff	23	0.1	0.6	0.3	20.9
Postdocs	37	0.5	0.5	0.0	11.3
Admin Group	12	0.1	0.6	0.3	10.9
Students	30	0.5	0.5	0.0	9.2
TOTALS	158				108.6

[a]NB: These are *assumed* values used to adjust for the fact that faculty and students are not captured in survey data of Table 2. Proportions in this table for research scientists, technical staff, postdocs and administrators are constrained to match Column 2 of Table 2 but do not represent a unique solution.

ride public transit in higher proportions, whereas faculty more often live in the suburbs and commute by car.

To assess this effect and study commuting footprint by constituency, we generated Table 3, which we emphasize is *not* taken from survey data, but rather collects a large number of assumptions about different commuting patterns for various populations at MKI. These are almost certainly inaccurate in detail but provide an estimate of the size of correction required to account for students and faculty. Specifically the table assumes that all students and postdocs either walk to campus or commute by MBTA in equal proportion, and that most faculty drive, while other constituencies are more mixed. The listed proportions for the Research Scientists, Postdocs, Technical Staff and Admin Group are constrained to reproduce the Transportation Survey results in Column 2 of Table 2, although this particular solution is not unique.

The total commuting footprint calculated using this methodology is 108.6 MTCO2e, nearly 38% higher than the initial estimate. The primary reason for this is a higher contribution from the faculty.

The carbon footprint of MKI commuting is non-negligible and probably has the highest fractional uncertainty of any element of our total GHG budget. In accounting below we will use the value of 108.6 MTCO2e as a best estimate, though it is uncertain at the ±30% level. Allowing for uncertainty, this is still 2-3 times smaller than the annual air travel footprint, and smaller still than emissions associated with utilities from operation of our physical plant. This value should be reassessed regularly as a larger fraction of MKI moves toward commuting with electric vehicles.

It is worth noting that recent review studies (Hook et al. 2020) found that remote work has no or only minimal impacts on carbon emission when accounting for extra emission in people's homes and other mitigating

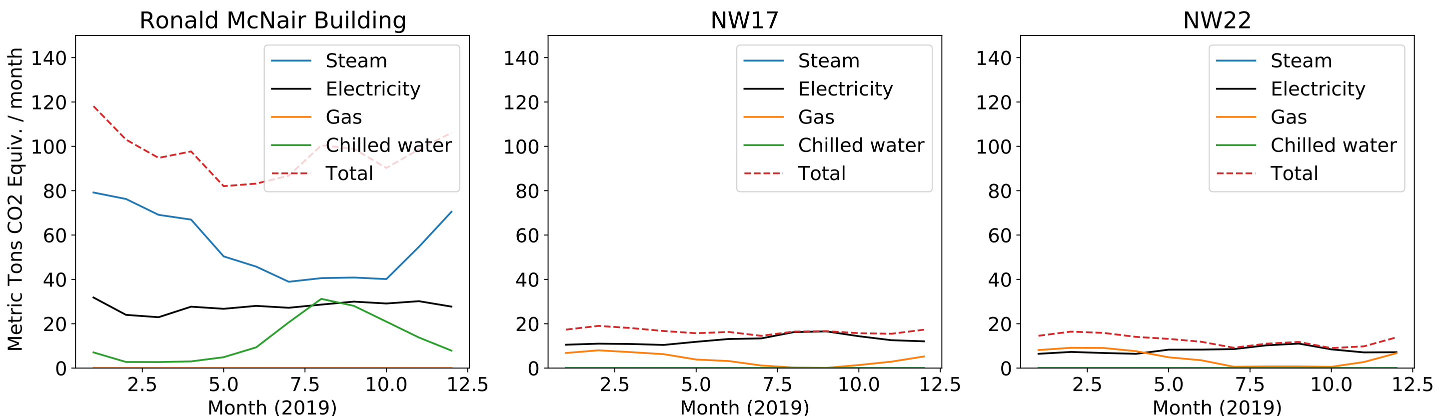

Figure 2. Utility consumption of 3 MKI buildings by month during the 2019 calendar year (January-December). Figures represent total metered building consumption scaled by the fraction of assignable space (i.e. square feet) in each building managed by MKI.

factors, for example, people who commute less often are willing to live further from their offices and select larger homes to live (and work) in.

4. UTILITIES AND THE MIT SUSTAINABILITY INITIATIVE DATA

The largest contribution to MKI's greenhouse emissions comes from utility usage in our buildings, namely, electricity, heat, and cooling. MIT generates a significant fraction of its own power at a cogeneration plant directly across Vassar St. from the McNair building, and purchases the rest from municipal utilities. An inventory of energy usage is maintained for each building on the campus by the MIT Sustainability Initiative [2].

We downloaded historical data for MKI's buildings from the sustainability data pool and used a small set of python scripts to extract MTCO2e estimates. We performed this exercise for the Ronald McNair Building (a.k.a. Building 37), NW-17, and NW-22. Our NE-83 complex is not included because it is leased, not owned by the institute, so data are not available. All of our buildings are shared with other DLCs and it is difficult to separate power consumption between individual departments in granular detail since metering is only performed at the building level. Instead we apportion emissions between DLCs according to the fraction of each building's total assignable square footage that is managed by Kavli, or other units. MKI manages 58% of space in the McNair Building, 34% of NW-17, and 33% of NW-22.

4.1. *MIT Cogeneration Plant*

The MIT Sustainability Data Pool tracks carbon *consumption* individually for electricity, heat (via steam), and chilled water at the point of service for each building. However the *production* of steam and electricity are linked within MIT's cogeneration plant, because a single unit of natural gas is burned to produce steam which turns turbine generators for electricity, and then is also routed to campus to heat buildings. For reporting purposes the plant calculates individual metrics to estimate GHG emissions per kWh of electricity consumed, or per unit of metered steam heat.

The GHG metrics are derived by performing a mass balance between fuel input to the process equipment (i.e. turbines) and captured plant output byproducts, with the difference assumed to be released directly to the atmosphere or oxidized and released as CO2. The cogen plant then calculates at the source what fraction of the output energy was converted to electricity, and what fraction was output as steam. These fractions are multiplied into the total mass released, to apportion GHG correctly between electricity and heat.

For this reason, MKI's GHG estimates reported in the Sustainability data pool for electricity and steam—based on meter readings at the building-level—already take into account that these two sources are produced by a shared fuel burn. Moreover they use a sophisticated approach to allocate carbon emissions among different process. From the perspective of the end user, electricity and steam may be treated as independent GHG sources, with the energy savings of cogeneration already factored in to the reported values.

Figure 2 shows the energy usage by month in each of the four categories tracked by MIT Utilities, for the three buildings where we have data. Several trends are evident.

[2] https://datapool.mit.edu/

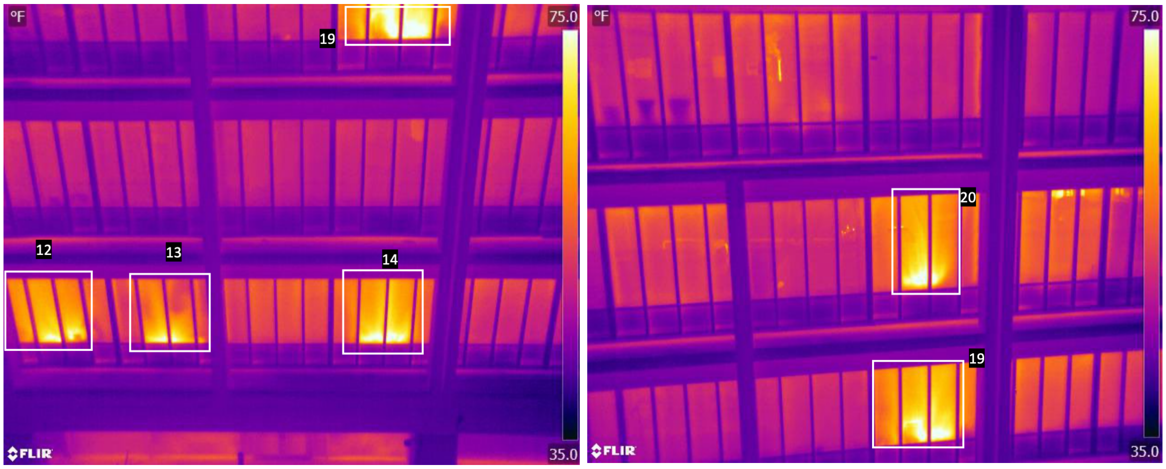

Figure 3. Thermal imaging detail from the North elevation of the McNair building, obtained 5:00 AM on March 16, 2022 when outdoor air temperatures was 19.6 degrees F (-7.2C). The average external temperature of windows is 49-50F (10C), with hot spots exceeding 75F (24C).

First, the McNair building accounts for a large majority of total utility usage. Electricity use in McNair is roughly level throughout the year, at 28-30 metric tons of CO2 per month. Metering of steam and chilled water are anticorrelated and track by season, since McNair uses steam and chilled water for building climate control including labs. Chilled water usage is relatively low except in summer months. Steam heat dominates McNair's carbon footprint in all months—especially in winter. However in August the reduced demand for steam and increased demand for chilled water brings all three sources into similar use. Because climate control is achieved through hot/cold water, there is almost no contribution from directly burned natural gas.

NW17 and NW22 (the locations of the LIGO Laboratory) consume much less energy than McNair, though an accurate assessment of LIGO's footprint may be found by summing these two figures. The LIGO buildings are not on the MIT steam tunnel/chilled water grid and therefore have zero contribution from these Physical Plant sources. Instead, climate control appears to be achieved by direct burning of natural gas in on-site boilers, and electrical air conditioning in summer months. Electricity is the dominant contributor to the overall carbon footprint of these buildings.

The total carbon footprint of our building operations (excluding NE-83) is 1463 Metric Tons of CO2 per year. Of this total, 46% is allocated toward steam heat of McNair, 40% meets the combined electricity demands of all buildings, 10% is allocated toward chilled water of McNair, and 4% is allocated to natural gas heating of LIGO's buildings.

4.2. *Thermal Imaging of the McNair Building and Window Performance*

Because heat load on McNair during the winter months is MKI's worst offender for energy usage, and McNair's original single-pane windows are suspected to be a major contributor, we contracted with a thermal imaging vendor (Eagle Hawk) to measure the exterior temperature of building windows during this period of the year. Drone footage was obtained on the morning of March 13, 2022, at 5:00 AM when the outside air temperature was 19.6F (-7.2C).

These measurements were performed on the South Elevation, which was renovated with double pane windows, and also on the North Elevation, which is still outfitted with the building's original single pane glass. Both sides of the building exhibited elevated average temperature (45-50F/7-10C, or 17C above ambient), subject to unknown uncertainties in the absolute calibration of Eagle Hawk's camera.

The North Elevation single-pane windows also displayed many additional hot spots at the locations of operating indoor hot air blowers, which raise individual exterior window temperatures to 75F or higher (Figure 3).

These images may be used to produce a crude estimate of the thermal energy load shed to the ambient environment. For a vertically oriented window with temperature difference ΔT between the exterior (measured) window face and the ambient air, the convective heat loss is

$$Q(W) = h_o A \Delta T \quad (1)$$

where A is the total window area, and h_o is the heat transfer coefficient to the outside air. Engineering calculations commonly assume $h_0 = 34$ W$/m^2/K$, we use 30 in the calculations below. The exterior window area was estimated from campus floor plans, and assuming

80% of the facade on floors 2-6 are covered by single-pane windows. With a total assumed area of 750 m^2 for the North facade, and average exterior window temperature of 50F/10C quoted above, the estimated heat load on the morning of March 13, 2022 is 387 kW. This is comparable to the measured call for steam heat during the same period, but both estimates are subject to significant uncertainties; their similarity should not be interpreted as implying a detailed balance.

Because double-pane windows reduce heat loads by nearly a factor of 2 per unit area, this suggests a path to improve MKI's overall energy efficiency.

It is unlikely that McNair's steam load can be reduced by 2× through window replacement alone — some of the steam coming from physical plant must be used for utilities other than building heat, because there is a baseline call of $\sim$ 40 MTCO2e/month even in the hot summer months. Moreover anecdotal evidence suggests there are additional convective loads from poorly sealed seams in exterior walls which draft hot and cold air with the outdoors. If we subtract off this baseline of 40 MTCO2e per month and then allow that improved windows reduce half of the residual seasonal variation between 40 and 80, it would reduce MKI's carbon footprint by nearly 100 MTCO2e per year. If the same windows reduce the demand for chilled water in summer months by 30% it would save an additional 50 MTCO2e.

Though the exact thermal balance calculation is subject to uncertainty in the zero point of Eagle Hawk's calibration, the basic conclusions are supported that (a) that there are substantially elevated average surface temperatures and prominent hot spots on the building exterior, and (b) McNair sees high thermal load from antiquated windows, and uses steam and cold water without thermostatic controls in an inefficient climate control system.

4.3. *Comparing McNair building performance to modern standards*

The energy use intensity (EUI) of the McNair building (the sum of all energy inputs incl. electricity) is 260 kBTU/sqft/year. For a building containing labs, the energy use depends on the lab equipment run at that particular facility, so benchmarking is always difficult. The McNair building ranks above the median of comparable existing labs in the same climate zone in the I2SL benchmarking tool. However, the discussion above makes it clear that in the McNair building today the majority of the energy is used for space conditioning. For comparison, we look at the EUI that newly constructed buildings might achieve. Massachusetts is currently in the process of implementing the IECC 2021 (International Energy Conservation Code) into its building codes and is developing a specialized opt-in stretch code, that the city of Cambridge is likely to adopt in 2023. While the details are still under development and there are likely to be several compliance pathways, the current code proposal lists passive-house as one possible (and admittedly the strictest) pathway to permit a commercial building under the specialized opt-in stretch code. A PHI (Passive House Institute) compliant passive house building needs a heating and cooling load $<$ 4.8 kBTU/sqft/year; about a factor 20-30 below the current heating and cooling load in the McNair building. Outside of the US some office buildings in comparable climate zones have indeed reached this level in the last decade. Even adding in additional energy use by lab equipment, it is clear that the energy use intensity in the McNair building suffers from an inferior building envelope performance and outdated mechanical systems.

4.4. *High Performance Computing*

Recent studies of GHG emissions from the Australian astronomy community have emphasized the role of high-performance computing, finding that electricity use from computing clusters is the largest single contributor to their carbon footprint (Stevens et al. 2020). MKI maintains a modest high performance computing cluster ($\sim$ 1024 CPU cores plus a small GPU cluster, together with fileservers) split between the McNair Building and NE-83, allowing a more granular study of needs for our particular community.

The uninterruptable power supplies on MKI's racks measure instantaneous and average power consumption at the point of service, and can be used to infer the rate of carbon equivalent emissions. We took readings from all of these racks on two different days in 2020, finding results consistent at the few percent level. Total consumption was evenly split between the two buildings, with each drawing 19.4 kW of power for a total average power of 38.8 kW, which we convert into a carbon luminosity.

By examining the ratio of metered electricity consumption to reported MTCO2e in the Sustainability Database tables, we inferred that the cogeneration plant converted fuel to electricity in 2019 at a rate of 0.3 kg CO2e per kWh. This compares favorably with typical US electricity conversion of gas-fired plants ($\sim$ 0.45 kg CO2 / kWh), though the most efficient regions of the US reach 0.2 kg / kWh, and MIT's Green Computing Center in Holyoke achieves a much more favorable rate of 0.023 kg CO2e / kWh —nearly 10× more efficient— through extensive use of hydroelectric power and renewables.

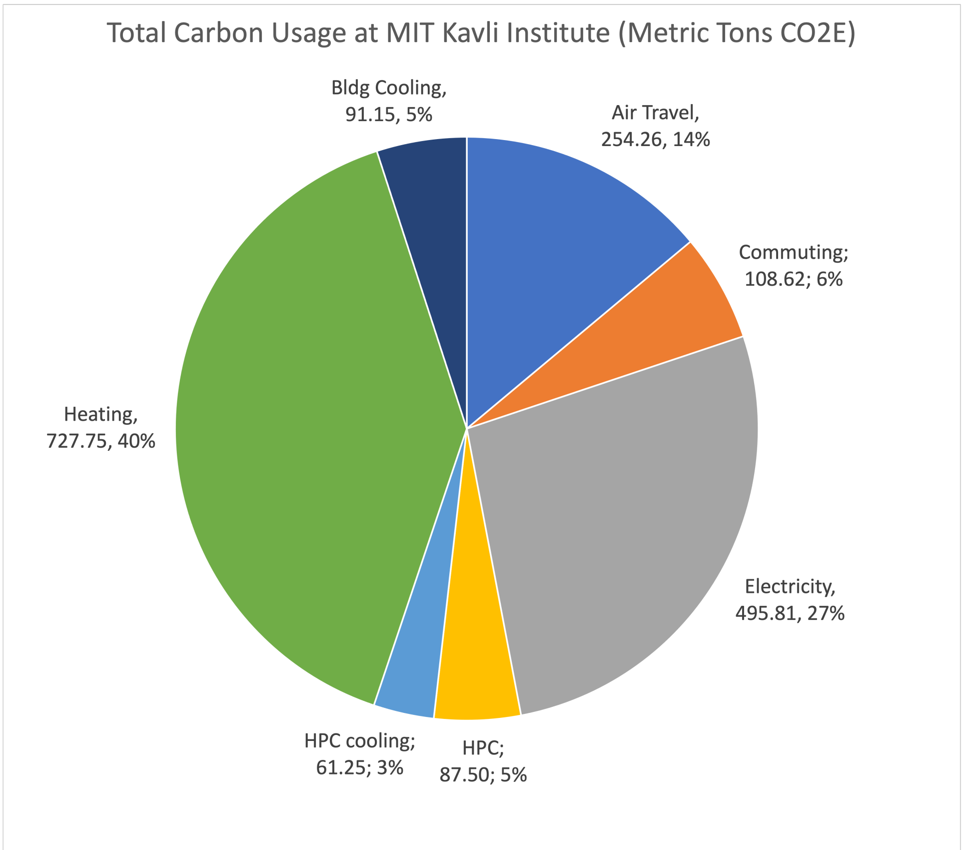

Figure 4. Breakdown of carbon consumption at MKI, into utilities (steam, electricity, chilled water) and travel (air and commuting). Electricity and cooling in support of MKI's high-performance computing cluster is called out separately. This chart already accounts for the energy savings achieved by MIT's cogeneration plant, which burns a single fuel mass to produce both electricity and steam heating service.

At 38.8 kW load for one year, MKI's computing cluster would consume 340 MWh of electricity, producing approximately 100 MTCO2e greenhouse gas emissions. In McNair, the monthly rate was 4.5 metric tons per month, or about 15% of the total electricity use. This is similar to our footprint from commuting, and a factor of 2.5 smaller than the contribution of air travel to the overall budget.

The above analysis does not account for the power required to cool high density computing racks. In MKI's server rooms cooling is achieved via air blowers serviced by the building chilled water loop. For industry-standard computing centers, the ratio of total facility power to CPU power is ~ 1.7, so the total footprint from computing plus cooling may be closer to 200 MTCO2e. Considered this way, high performance computing at MKI may account for as much as 10% of the overall carbon footprint, via calls on the electricity and chilled water terms in Figures 2 and 4. While computing does not presently dominate carbon pollution at MKI, its contribution cannot be neglected. Moreover it is a rapidly growing area that seems poised to increase in prominence within our enterprise in the coming years.

For this reason, MKI has already begun moving Research Computing resources to the Holyoke MGHPCC facility, including a new 4096-core cluster and Pb fileserver, as well as project-specific cluster nodes that make heavy use of power-hungry GPUs. Situating these new resources in green facilities and sunsetting older hardware in legacy data centers offers a path to lower gross carbon emissions.

5. UNACCOUNTED SOURCES

The calculations presented here do not account for the footprint associated with off-campus facilities connected with MKI. These include operations of the Magellan and LIGO observatories, our association with HERA and CHIME, or GHG from launch and operations of spacecraft including TESS (for reference, a Falcon 9 generates 387 MTCO2e per launch, more than 1 year of all MKI's air travel), Chandra, NICER, or Voyager. Magellan does offset some fraction of its carbon consumption through participation in a large solar farm located along the observatory access road in the Chilean Atacama desert. Likewise the LIGO Hanford Observatory runs on renewable energy from hydroelectric power. In general however, offsite research labs are outside the scope of this analysis and would need to be addressed in a future revision.

6. TOTAL CARBON FOOTPRINT

In the 2018-2019 time frame, MKI produced a total of 1826 metric tons CO2 equivalent emission per year, combining the contributions of heating, cooling, electricity, air travel, and commuting, estimated according to the methods described above. Figure 4 displays the breakdown of these contributions, with the heating contribution as a sum of steam (used to heat McNair) and natural gas (used to heat NW17 and NW22).

These total emissions amount to 11.5 tons CO2 per capita, per year. This may be compared to the World Bank estimate of 14.7 metric tons *total* per capita annual emissions in the United States[3]. MKI's work-related footprint significantly exceeds the total (work + non-work) per capita value from many similarly industrialized countries such as Austria, Germany, France or Spain.

The largest single contributor is heating of our buildings at 40% of total CO2 emissions. This is followed closely by electricity, at 32%. All remaining sources total to slightly over 25% of the total carbon budget.

7. NATIONAL AND MIT TARGETS FOR GHG REDUCTIONS

When evaluating possible paths to reduce MKI's carbon footprint, it is helpful to reference targets established by external experts in connecting between GHG emissions and climate change. The US has recently rejoined the Paris Accord climate agreement, in which each country communicated an intended "Nationally Determined Contribution" to overall emissions reduction.

The US is revising its 2030 targets for resubmission in 2021, but according to its most recent statement, the country "intends to achieve an economy-wide target of reducing its greenhouse gas emissions by 26-28 per cent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%."

Separately, in 2017 MIT announced a *Plan for Action on Climate Change* [4] which included a commitment to reduce GHG emissions by a minimum of 32% from baseline 2014 levels by 2030.

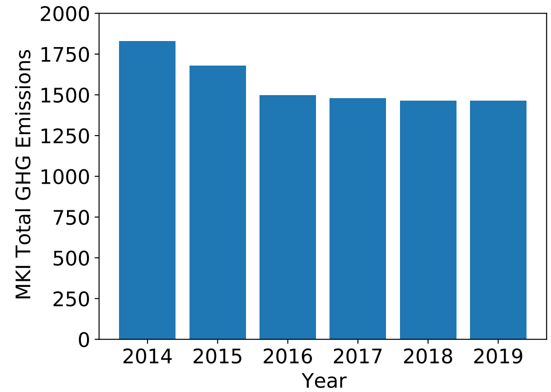

Figure 5. Net utility consumption of MKI buildings (exclusive of NE83) by calendar year. Gross utility consumption has remained roughly constant, but over 2014-2016 MIT purchased energy offsets in solar farms to reduce net emissions, resulting in a net 20% overall reduction for MKI. An additional 15% reduction (220 MTCO2e / year) is needed to meet MIT's 2030 emissions target.

As of 2020 MIT has already achieved a campus-wide 24% net reduction in emissions relative to 2014. A portion of this was achieved by renovation of the cogeneration plant and aging buildings on campus, though the gross emissions have remained nearly flat or seen only incremental improvement because of increases in demand.

However a significant net reduction was realized in 2016 when MIT entered a Power Purchase Agreement that led to the construction of Summit Farms—a 60-Megawatt solar electricity producer in North Carolina. This 25-year agreement generates annual offsets to on-campus carbon consumption. Successful commissioning of the 650-acre solar farm led in part to decommissioning of a nearby coal-fired power plant in North Carolina. Evidently MIT continues to be a heavy consumer of power, and with an aging physical plant we are challenged to meet aggressive reduction goals in our campus buildings without incurring very large renovation costs. The most successful strategy has been to invest in off campus solar production that reduces the carbon footprint of *other* users on the consumer market, a strategy which has been cost effective in the short term and achieved real net savings for MIT and MKI.

Looking more carefully at the yearly evolution of MKI's utilities GHG emissions (accounting for MIT's solar purchase), one sees a 20% decrease in net emissions over the 2014-2016 time frame, after which emissions are constant (Figure 5). To achieve MIT's goal of a 32% reduction, MKI would need to either reduce

[3] https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

[4] https://sustainability.mit.edu/resource/mit-campus-greenhouse-gas-emissions-reduction-strategy

its present energy consumption by an additional 15% (220 MTCO2e per year), or purchase more offsets, or a combination of these two approaches. The equivalent in metered electricity would be 155 MWh per year.

For reference, MKI approximately achieved a 15% overall reduction during the COVID shutdown by completely curtailing travel for a full calendar year—this is the approximate scope of the reduction needed to meet MIT's energy goals for the next decade, even if continued travel reductions of this scope are not realistic.

A more balanced approach would begin with strategies to reduce the heat load on the McNair building, and couple these with efforts to reduce electricity demand, travel and commuting in proportion.

Section 4.2 suggests a potential path to address our HVAC load, by replacing the single pane windows in McNair with double pane glass. McNair's call for steam in winter months is of similar magnitude to the estimated heat loss through North Facade windows. If the amplitude of seasonal variation in HVAC load can be reduced by a factor of 2, it would decrease MKI's carbon footprint by 100 MTCO2e for heating, and 50 MTCO2e for cooling, together accounting for 68% of the total target reduction of 220 MTCO2e.

Reductions in commuting are widely anticipated in the post-pandemic world thanks to hybrid work arrangements, although the size of this change is yet to be determined. If one assumes a typical employee who commuted five days per week pre-pandemic now commutes four days per week, this 20% reduction lowers MKI's footprint by 20 MTCO2e per year. However as more working hours are spent off site, employers may need to engage with and educate their workforce on strategies to reduce home emissions (e.g. from home heating) and quantify how many fewer miles are actually driven.

Likewise air travel is still far below pre-pandemic levels, with MKI travel in early 2022 still a factor of five lower than in 2019. If we can manage a transition back to 75% of pre-pandemic travel rather than 100%, it would reduce GHG emissions by 63 MTCO2e per year.

Taken together, a coordinated program of window replacement in McNair, 20% reduction in commuting and corresponding reduction in air travel would reduce overall GHG emissions by 233 MTCO2e per year, which would immediately bring MKI into alignment with MIT's stated goals for carbon reduction with 5% margin, *and demonstrating reduction of both net and gross emissions.* Additional strategies to expand this margin are already being employed, for example by relocating an increased fraction of MKI's high-performance computing cluster to the energy-efficient MGHPCC facility in Holyoke.

MKI can also explore offsets similar to those purchased by MIT as another element of any comprehensive strategy to address greenhouse gas emissions. However it would make a strong statement if we can achieve MIT and international targets using a balanced approach of offsets and direct reduction in gross energy consumption.

8. CONCLUSIONS

We performed an audit of MKI's carbon footprint, taking into account the contributions from air travel, commuting, and utility consumption from steam, electricity, gas and chilled water. Travel patterns were examined for different constitutencies of our community, and utility usage was examined by building. The results may be summarized as follows:

1. Our best estimate of MKI's total carbon footprint is 1826 metric tons of CO2 (equivalent) per year. This is equivalent to 12 MTCO2e per capita.

2. The largest contributor to the overall budget is from heating our physical plant. In particular heating for the McNair Building is the worst offender of all sources considered. McNair sees high thermal load from antiquated windows, and uses steam and cold water without modern thermostatic control in an inefficient climate control system.

3. Air travel comprises about 15% of the carbon footprint. As a subdominant contributor to the overall footprint, reduction in air travel alone cannot achieve sufficient savings to meet MIT's long-term goals for emissions mitigation (unless air travel is curtailed entirely and permanently).

4. Travel for the Astrophysics Colloquium is a negligible portion of our total carbon budget. The largest contributions to air travel are from postdocs, for whom travel is a critical part of professional development, and from Research Scientists, who travel in part for professional development and in part to advocate for and operate our ongoing experiments and spaceflight missions. Faculty contribute largest per capita air travel emissions.

5. MKI has benefited directly from MIT's decision to purchase carbon offsets in a solar farm in North Carolina; this action has already reduced our net greenhouse gas emissions (from the physical plant) by 20% relative to 2014 levels, without any action by MKI. An additional 15% savings from our present emissions level is needed to meet MIT's goal of an overall 32% reduction between 2014 and 2030.

6. There was a unique opportunity during the COVID shutdown to examine patterns of air travel and commuting, but to meet long-term MIT goals MKI must reduce its net emissions by 220 MTCO2e per year below present levels. This would most likely require a concerted effort to mitigate gross emissions associated with heating the McNair building, or to reduce electricity consumption (including electricity for high performance computing clusters), or to increase our investment in clean energy production sites off-campus, thereby reducing net emissions through carbon offsets.

A comprehensive strategy for reducing MKI's net carbon footprint to targeted levels will likely combine elements of these three strategies: reducing transportation-related emissions, economizing utility consumption for the physical plant, and purchase of offsets. A determination of how to apportion effort between these three strategies, and the incentive structures to achieve the remaining 15% target (i.e. 220 MTCO2e/year), is beyond the scope of this report. However a new MKI Sustainability Team has been formed to recommend actions at the level of individuals, the MKI department, and for advocacy to MIT at the University level. It does appear possible that with deliberate action MKI could meet the ambitious goals laid out by the Paris Accord and by MIT for emission reductions over the 2020-2030 decade.

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