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comment

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Averting the imminent climate crisis requires large reductions in greenhouse gas emissions within this decade. To provide a benchmark for reduction and to identify the main sources, we estimate the carbon footprint of astronomy research in the Netherlands over 2019.

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Reducing greenhouse gas emissions by >50% before 2030 is widely accepted to be essential to limit the impact of the current climate crisis, as noted in the 2015 Paris Agreement, illustrated by the increased occurrence of natural disasters and highlighted in the 2021 report by the Intergovernmental Panel on Climate Change. Realizing the need to respect our planetary boundaries[1] and the fact that planet Earth is our only feasible habitat for now, astronomers from around the world see it as their responsibility towards society to increase popular awareness of this problem and the need for environmentally sustainable development[2–4]. In 2020, the Dutch Astronomy Council, consisting of the directors of all astronomical institutes in the Netherlands (see below), installed a working group to investigate how the carbon footprint of its member institutes could be reduced.

As a first result from this working group, this article provides an estimate of the CO_2 emission arising from professional astronomy activities in the Netherlands. The year 2019 is chosen as a benchmark since it pre-dates the COVID-19 pandemic, which artificially decreased emissions in 2020, especially those due to air travel. Furthermore, 2019 is suitable because in that year, CO_2 emissions in the Netherlands were similar to 1990 levels, which are often used as comparison levels for emission goals.

Professional astronomy in the Netherlands is carried out at four universities (Amsterdam, Groningen, Leiden, Nijmegen), united in NOVA, and two research institutes (ASTRON, SRON) of the Dutch national science foundation NWO. Astronomers at the European Space Research and Technology Centre (ESTEC) are not part of this study, as they are an international organization with their own sustainability report. Direct emission data for ASTRON and SRON are from a 2020 report by the consultancy Arcadis investigating the CO_2 footprint of all nine NWO institutes. We follow this report in ignoring indirect emission sources such as food consumption, furniture wear and real-estate construction, which presumably lead to little annual CO_2 emission. We also neglect emission due to material consumption, which may be important for institutes developing hardware.

This study provides a lower limit to the CO_2 footprint of astronomy in the Netherlands because three potentially large sources are left out. First, our study focuses on research and does not include emission due to education, such as the heating and lighting of classrooms. Second, emissions due to the use of observatories are not included, even if (partly) funded by Dutch taxpayer money (for example, the European Southern Observatory (ESO), the Isaac Newton Group of Telescopes). Nearly all astronomical facilities are used by astronomers from around the world, and the contribution by astronomers from the Netherlands could be estimated by obtaining usage data from observatory staff[5]. However, because the lead proposer may not be the actual observer and because ever more observations are carried out in 'service mode' (that is, by observatory staff) or by robotic telescopes, this topic deserves a separate study. Regardless of national breakdown, many international observatories such as ESO are already working to reduce their CO_2 footprint. Third, our study does not include space missions, although rocket launches emit up to 300 tonnes of CO_2 if conventional (fossil) fuel is used. Using H_2 as fuel may diminish the CO_2 emission, depending on how the H_2 is produced, but it imposes limits on the size and the mass of the payload. Moreover, the launch is a minor part of the CO_2 emission from a space mission, as it roughly equals that of one to two conventional meetings of an international consortium[6].

Results

Table 1 presents our estimates for the CO_2 emission per institute and per source. Based on data from institute and/or facility management, the six Dutch institutes together emit about 4,900 equivalent tonnes of CO_2 (tCO_2e) annually, which is 4.7 tCO_2e per researcher per year on average, with most institutes being responsible for between 3 and 4 tCO_2e per researcher per year. The method to estimate each source is described in the following sections, and specific details per institute are given in the Supplementary Information. The number of research staff per institute includes MSc students (who work mostly at their institute) but not BSc students (who work mostly in classrooms). The staff count for Groningen includes both the Kapteyn Institute and the local SRON and NOVA laboratories; the number for Leiden includes the Sackler laboratory; the number for ASTRON includes JIVE (Joint Institute for VLBI ERIC) and the NOVA Optical Infrared group.

The data for power and heating should be complete as they are based on bills that were paid; the main uncertainty in these estimates is the conversion to CO_2, which is often through certificates. Following the Arcadis report, we only accept certificates as green if they are from renewable sources (solar and wind) in the Netherlands. Buying certificates abroad (for example, from Scandinavian waterfalls) sounds greener than it is, because the actual power being used is still based on fossil energy. The estimates for indirect emission sources (air travel, commuting and supercomputing) are more uncertain since the underlying data may be incomplete, especially for supercomputing.

Business travel. Anonymous flight data were provided by the institute secretaries and fed into the emission model created by Didier Barret[6]. This model includes a statistical correction for stopovers, as well

Table 1 | Equivalent CO_2 emission per source per institute

	Leiden	Amsterdam	Nijmegen	Groningen	ASTRON	SRON	Total
Number of research staff	320	100	70	190	210	150	1,040
Emission sources (tonnes per year)							
Air travel	792	275	228	222	425	113	2,055
Electricity[a]	0	0	127	254	0	1,027	1,408
Heating/cooling	248	23	0	71	85	316	743
Commuting	72	10	9	132	168	85	476
Supercomputing	53	17	12	31	35	25	172
Total	1,165	325	376	710	713	1,566	4,854
Total per staff member	3.6	3.2	5.4	3.7	3.4	10.4	4.7

[a]Includes local computing. Zero means 100% green power.

as a multiplier to account for radiative forcing: that is, the stronger greenhouse effect produced by CO_2 emitted at high altitude. We adopt the commonly used value of 2 for this multiplier[6], although the actual value may be closer to 3 to include non-CO_2 effects such as NO_x emission and reflection by contrail cirrus. We neglect CO_2 emissions from business travel other than by air. Most other business travel is by train, which in the Netherlands uses 100% green power. Business travel by car is mostly used for short distances, and counted under 'Commuting' below.

Office heating and power. Data on heating and electricity use were provided by the housing and facility managers. Most buildings are heated with natural (that is, fossil) gas, in some cases complemented by aquifer thermal energy storage (ATES). When buildings are shared with other users (for example, the Physics department), we have scaled the heating bill to the relative floor area used by astronomers.

Electrical power for lights, computers and laboratory equipment has been converted from kWh to tCO_2e using a factor of 0.34 kg CO_2 kWh^{-1} recommended for 'grey' (fossil-based) power by the Netherlands Bureau of Statistics (CBS) for 2019. The contributions by solar panels on various institutes' roofs have been included. Several institutes use partly or entirely 'green' (that is, certified to be Dutch windmill-based) power, which is why some entries in Table 1 equal zero. This neglects the CO_2 emission from the production, placement and eventual recycling of windmills, for which the current European average emission is 7.4 g kWh^{-1}, that is, 2% of that of fossil power.

Commuting. The CO_2 emission due to commuting is based on (anonymized) data on cost reimbursement provided by Human Resources staff where possible, and otherwise estimated (see Supplementary Information). Only commuting by car and motorcycle is taken into account, assuming 100% fossil fuel, that is, ignoring hybrid and fully electric vehicles, which as of January 2020 accounted for 4.6% of cars in the Netherlands. The conversion from km to tCO_2e assumes an emission of 120 g CO_2 km^{-1}, which is the 2012 average for new cars in the Netherlands, that is, assuming an average fleet age of 7 years. This emission estimate may be optimistic, as it was measured (by the carmakers) under idealized test conditions.

Computing. The carbon footprint due to (super)computing only takes international ('Tier-0') facilities into account, such as PRACE. Institute computers are included in the electricity budget above, and the national ('Tier-1') supercomputing facility SURF does not contribute any CO_2 emission as it uses 100% green power (through certificates). However, local ('Tier-2') facilities outside the institutes, such as the Peregrine cluster in Groningen and the Little Green Machine in Leiden, are accounted for.

Usage data for the various facilities were provided by the computer support staff of the institutes. The total of 620 MWh corresponds to 172 tCO_2e, assuming 18% green power, the grid average for 2019. We have divided this emission over the institutes in proportion to their size.

Discussion

The numbers in Table 1 add up to approximately 4,900 tCO_2e, corresponding to an average of 4.7 tonnes per researcher (as defined under Results). This number is about 50% of the average CO_2 emission per capita of 9.1 tonnes for the Netherlands, which includes both work and private consumption. Most institutes emit 3–4 tCO_2e per person, with SRON and Nijmegen as outliers. The electricity consumption of SRON is particularly high because of the heat pumps and air treatment systems of its cleanroom facilities, which are power-intensive. The new SRON building is using green power, and Nijmegen will complete its transition to green power by 2024, bringing the CO_2 emission of these institutes in line with the others. The amount of air travel per person is highest for Nijmegen because of several instrumentation projects in development, some of which, like the BlackGEM telescopes in Chile, will in the end be operated robotically. As of 2021, Groningen is using 100% green power, so that its emission should be below 3 tCO_2e per person.

Overall, the main sources of CO_2 emission are seen to be air travel (42%), electricity (29%), and office heating and cooling (15%). Commuting and (super) computing are found to be smaller sources, contributing 10% and 4% respectively. This ranking is the same as in the Arcadis survey of NWO institutes, and also as in the study of greenhouse gas emissions from the Max Planck Institute for Astronomy in Heidelberg in 2018[3]. The situation is somewhat different in countries such as the United States and France, where commuting is a larger contribution to the emission[7]. Commuting is seen to contribute less emission for institutes in the west of the Netherlands, where the population density is higher, commuting distances are smaller, and public transport networks contain more routes. Having decent public transport connectivity would greatly cut down ASTRON's commuting contribution, as surveys among institute personnel have shown.

The overall emission, as well as that by most institutes, is dominated by air travel, presumably to conferences and for instrumentation projects. By number, most of these flights are within Europe, with a notable peak at Garching where ESO,

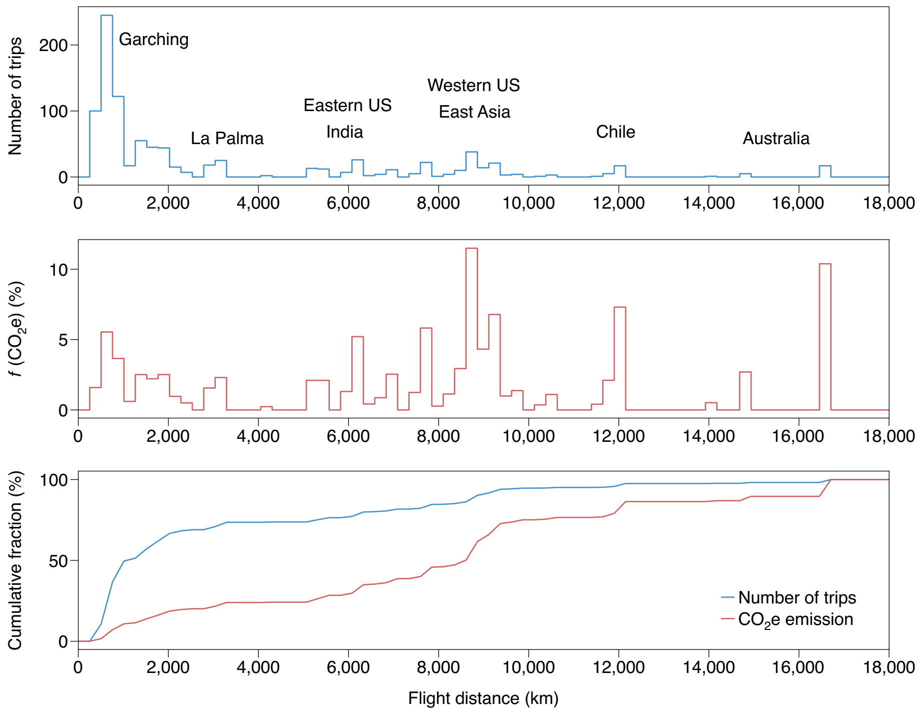

Fig. 1 | The carbon footprint of flights. Number of flight trips by Leiden Observatory staff in 2019 (top) and relative contribution to CO_2 footprint (middle) versus distance. Bottom panel, cumulative distribution of flight number (blue) and effective CO_2 emission (red) over distance.

the Max Planck Institute for Extraterrestrial Physics and the Max Planck Institute for Astrophysics are located (Fig. 1). For such destinations, train travel should be encouraged as much as possible to reduce CO_2 emission, for example by reimbursing train tickets even if they are more expensive than flights (as some institutes are already doing). The recent revival of European night trains may help in this respect as well.

Intercontinental flights contribute the majority of CO_2 emission and are not easily replaced by other means of transportation. For example, of the flights by Amsterdam staff, short trips (<700 km) cause <7% of the CO_2 emission, whereas long trips (>2,500 km) cause 73%. The same trend, that short-distance flights dominate by number but contribute little CO_2 emission, also holds for the other institutes, as illustrated in the bottom panel of Fig. 1. Popular destinations besides the coastal US are seen to be India, China, Japan, and the telescopes in La Palma and Chile; flights to Australia are rare but contribute considerably to the CO_2 emissions. To reduce CO_2 emission, such trips should be avoided, for example by organizing online meetings where possible. The annual meeting of the European Astronomical Society is an example, where the 2020 event led to CO_2 emissions around 3,000 times lower than the year before[8]. For meetings that cannot take place online, reliable CO_2 compensation should be sought, even if this may only be a short-term solution. Organizing international meetings in central, well-connected places also helps to reduce emissions. For more discussion on this topic, see ref. [9].

Even though office heating and commuting are smaller sources of CO_2 emission, it is worth reducing these emissions too. For example, SRON has moved to a new building (in Leiden) in 2021, with better isolation and a modern (ATES) heating system. The ecological benefits will take years to materialize, though, as the construction of such buildings leads to large CO_2 emissions.

To encourage 'green' commuting, NWO reimburses travel by public transport but not by car, except for ASTRON, which is located in a rural area. Indeed, using public transport may not always be practical or even possible, especially in sparsely populated areas. In these cases, the use of (electric) bicycles and hybrid and fully electric vehicles should be promoted, as well as car-sharing. The pandemic may help to reduce commuting overall, as more people are working from home than before 2020, at least for part of the week. Finally, to reduce the emission due to (super)computing, it would help to shunt coal-powered Tier-0 facilities, to adopt efficient coding standards[10] and to avoid large e-mail attachments.

Possible ways forward

To bring the CO_2 emission from astronomy research in the Netherlands in line with the EU goal of 55% reduction in 2030 compared with 1990, we consider three scenarios. First is the 'renewable energy' scenario. If the emission due to electricity, heating/cooling of buildings, commuting and (super)computing is reduced to (near) zero, the 2019 emission is cut by 58%. The gain relative to 1990 will be less, because the astronomical community in the Netherlands has grown substantially in the past 30 years, which leads to more emission from all sources. This option is closest to 'business as usual' (in terms of flying) but requires heavy investments in infrastructure from universities and other host institutes, which take time to bear fruit.

Second is the 'minimal investment' scenario. New buildings, new heating systems and electric vehicles require financial efforts, whereas flying less may save money, depending on the cost of alternative transportation. If flight emission is reduced by a factor of 4, for example, overall emission is reduced by about 30% relative to 2019, which is almost halfway towards the EU target. This option may be financially attractive but requires considerable reorganization of the way astronomers work, along the lines of the 2020–21 pandemic. Having fewer face-to-face and more online/hybrid meetings has the added benefit of being more inclusive, for instance, towards researchers with financial, family or teaching constraints.

Third is the 'equal distribution' scenario, where the goal of 55% reduction is applied to all emission sources equally. For air travel, one option is replacing most destinations within about 1,000 km by train, and cutting the number of long-haul flights by 50% or more. Imposing a carbon budget alongside a financial budget on institutes and/or individual researchers may be a practical way to achieve this reduction, but again requires considerable changes in working habits. Analysing 2020–21 flight data will be useful to see how much reduction can be achieved.

Regardless of scenario, we recommend that both starting and continuing instrumentation projects adopt a 'green policy', which makes their activities compatible with the Paris Agreement. Funding agencies could play a role in this transition by making such policies a requirement for their support.

In summary, depending on scenario, air travel by astronomy researchers will need to diminish by factors of 2–4 by 2030, and maybe more beyond that. With the pandemic experience in mind, this seems a feasible goal and will help to make astronomy research an environmentally sustainable endeavour, at least in the Netherlands. For long-term success, this goal needs to be balanced with social and economic sustainability. At present, we still have a choice about which way we will transform our practices, and we should use this opportunity. ❐

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Competing interests

The authors declare no competing interests.

Additional information

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