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► **To cite this version:**

Pierrick Martin, Sylvie Brau-Nogu , Mickael Coriat, Philippe Garnier, Annie Hughes, et al.. The carbon footprint of IRAP. 2022. hal-03714571

**HAL Id: hal-03714571**

**<https://hal.science/hal-03714571>**

Preprint submitted on 17 Oct 2022

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# The carbon footprint of IRAP

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25 April 2022

arXiv:2204.12362v1 [astro-ph.IM] 26 Apr 2022

# 1 Summary

We present an assessment of the greenhouse gases (GHG) emissions of the Institute for Research in Astrophysics and Planetology (IRAP), located in Toulouse (France). It was performed following the established “Bilan Carbone” methodology, over a large scope compared to similar previous studies, including in particular the contribution from the purchase of goods and services as well as IRAP’s use of external research infrastructures, such as ground-based observatories and space-borne facilities. The carbon footprint of the institute for the reference year 2019 is  $7400 \pm 900 \text{ t CO}_2\text{e}$ . If we exclude the contribution from external research infrastructures to focus on a restricted perimeter over which the institute has some operational control, IRAP’s emissions in 2019 amounted to  $3300 \pm 400 \text{ t CO}_2\text{e}$ .

Over the restricted perimeter, the contribution from purchasing goods and services is dominant, about 40% of the total, slightly exceeding the contribution from professional travel including hotel stays, which accounts for 38%. Local infrastructures make a smaller contribution to IRAP’s carbon footprint, about 25% over the restricted perimeter. We note that this repartition may be specific to IRAP, since the energy used to produce the electricity and heating has a relatively low carbon footprint. Over the full perimeter, the large share from the use of ground-based observatories and space-borne facilities and the fact that the majority of IRAP purchases are related to instrument development indicate that research infrastructures represent the most significant challenge for reducing the carbon footprint of research at our institute.

With  $\sim 260$  staff members employed at our institute, our results imply that performing research in astronomy and astrophysics at IRAP according to the standards of 2019 produces average GHG emissions of  $28 \text{ t CO}_2\text{e/yr}$  per person involved in that activity. This figure lies well above the target global average budget of  $2 \text{ t CO}_2\text{e/yr}$  per capita by 2050. However, the footprint is spread across a variety of social and economic sectors, and so are the benefits of the research activity. As a consequence, the emission reduction to be achieved by scientific research should be made on open and democratic grounds, in a debate reaching beyond scientific communities and informed by facts and figures such as those presented here.

Regardless of the exact reduction goals for our community, the magnitude of the challenge and the necessity to quickly engage into an effective transition calls for acting on all aspects of the problem: lowering the carbon intensity of our activities, reducing their pace, and shifting our work practices towards less emission-intensive options. At the level of our own institute, we show that emissions in the restricted perimeter can be reduced by up to 30%, by changing our traveling habits and adopting different practices for commuting. Revising the criteria for the purchase of goods and services could provide an additional significant reduction. At the community level, the most urgent objective should be to lower the carbon footprint of research infrastructures and avoid that it keeps growing with the deployment of new facilities.

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## 2 Introduction

In a 2018 Special Report ‘Global warming of 1.5 °C’ [25], the Intergovernmental Panel on Climate Change (IPCC) presented evidence that anthropogenic emissions, such as greenhouse gases (GHG) and aerosols and their precursors, have increased the global mean surface temperature by approximately +1.0 °C (with a likely range of 0.8-1.2 °C) above 1850-1900 pre-industrial levels. The increase in carbon dioxide content of the atmosphere is unprecedented over geological times. From past and ongoing emissions, the expected increase rate is 0.1-0.3 °C/decade, which would lead to +1.5 °C sometime during 2030-2050 if no mitigation measures are taken. Subsequent releases of IPCC reports have confirmed this conclusion, and strengthened the attribution of climate change to human influence [24]. The phenomenon seems to be accelerating, and each of the last four decades has been successively warmer than any decade that preceded it since 1850.

The IPCC reports that the impacts of anthropogenic climate change are already perceptible in the intensity and frequency of climate and weather extremes, such as floods, heat waves and droughts. These changes affect entire human societies, and concerns are progressively shifting to adaptation to climate change, especially in developing countries [16]. Natural ecosystems are also strongly affected, with an unprecedented collapse in biodiversity. While land use and sea exploitation are the dominant drivers of biodiversity loss, climate change is having a growing impact on biodiversity, exacerbating other drivers. The global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that the rate of species extinction across the globe is tens to hundreds of times higher than the average rate over the past 10 million years, and is accelerating [9].

The main messages from the IPCC report can be summarized as follows: (i) every fraction of a degree counts, and there are significant differences between a +1.5 °C and +2.0 °C global warming scenario in terms of adverse consequences; (ii) our choices over the next two decades are crucial to secure emission pathways remaining below or only slightly overshooting +1.5 °C; (iii) such pathways require far-reaching and systemic transitions and transformation in nearly all sectors of human activity. The latter is emphasized in the IPBES report, which states that sustainability in our use of nature for 2030 and beyond may only be achieved through “fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values”.

The +1.5 °C scenario with no or limited overshoot requires anthropogenic CO<sub>2</sub> emissions to drop by 40-60% by 2030 relative to the 2010 levels [25]. This implies an average reduction rate of 7.6% every year over the next decade [35]. We recently went through an unexpected episode that illustrates the magnitude of the necessary changes. In 2020, as a result of the drastic global response to the COVID-19 pandemic, CO<sub>2</sub> emissions fell by 6.4% [and subsequently bounced back; see 33]. This is

about the level of reduction we need to achieve every year, sustained over more than a decade.

Over the past decade, a growing fraction of the scientific community has recognized the urgency of these results, mirroring the increasing concern within civil society [e.g. 1, 20, 12]. Complementing the legitimate and necessary calls to stand up as scientists to warn citizens and policymakers of the major threat posed by climate change [31], a growing number of individuals and institutions are now willing to assess the environmental impact of scientific research as it is currently practiced.

In the field of astronomy and astrophysics, several quantitative assessments and discussions about our impact on the environment – mostly focussing on GHG emissions – have recently been published. These studies have addressed several different facets of the community and its activities: a single research institute [18], a national community [32, 37], existing or planned research infrastructures [14, 6], high-performance computing [29], large astronomy meetings [10], and possible mitigating solutions [26, 11]. Despite their differences, these studies all find that significant efforts must be made to align our research practices with IPCC-recommended trajectories for the next decades.

In this paper, our goal is to contribute to this collective reflection by presenting a carbon footprint assessment for the Institut de Recherche en Astrophysique et Planétologie (IRAP) located in Toulouse, France. Our reporting uses 2019 as the reference year and includes a large number of emission sources not considered by earlier studies, e.g. the emissions from purchased goods and services, and an estimate for the impact of using large-scale research equipments such as ground-based observatories and space-borne telescopes and probes. The result suggests that previous efforts were most likely underestimating the carbon footprint of research in astronomy by a large factor, which puts us even further away from the assigned goals for sustainability of human activities. Our work strengthens the evidence that massive GHG emissions are at the very heart of our research activities and highlights the urgent need for an ambitious community-wide plan for the future, challenging the deep cultural roots of astrophysics as we exercise it today.

## 3 Methodology and scope

### 3.1 Local and national context

In France, the practice of GHG emission assessment in the public and private sectors was formalized by legislation passed in 2010 [21], extended and complemented by further legislation in 2015 [22]. The objectives and requirements of these GHG emission assessments are summarized in a practical guide by Ref. [27]. Together, these documents identify the private and public actors that are legally bound to conduct an

assessment of their GHG emissions, and define the minimal standards for conducting, publishing, and updating such assessments.

A research laboratory, as it is legally structured in France, is not subject to this legal obligation, which applies to higher-level institutions such as universities and national research organizations like the “Centre National de la Recherche Scientifique (CNRS)”. The latter, however, are often very large entities, gathering up to a few tens of thousands employees involved in very different fields of activity, and spread over a large number of geographical sites. Conversely, laboratories seem the relevant scale for initiating such an assessment: they employ a few tens to a few hundreds of people located at a small number of physical sites, are relatively homogeneous in terms of their activity, and offer a more direct and efficient access to the administration, which is key to collecting the relevant data.

The idea of conducting a carbon footprint assessment at IRAP was promoted by a group of a dozen persons organized in an official commission of the institute since 2018. The commission has representatives on the institute council and its role is to assist the direction of the institute in all efforts related to reducing the environmental impact of institute activities, e.g. raising staff awareness, waste management, promoting environment-friendly options for travel, etc. The formal decision to conduct a carbon footprint assessment was taken jointly with the institute’s direction, and the work started in late 2019. Similar developments occurred in six local institutes that together with IRAP form the “Observatoire Midi-Pyrénées” (OMP) research federation. Although these institutes specialise in different scientific domains (oceanography, geophysics, biosphere, ecology, climatology), it was relevant to join forces because office space, services and facilities are largely shared among OMP institutes.

### 3.2 Methodology and tools

As a first step, 24 OMP staff members, including eight from IRAP, followed a 40 h training course about how to conduct a carbon footprint assessment with the Bilan Carbone (BC) methodology. This training was funded by the participants’ institutes and the CNRS. The training was delivered by the “Institut Formation Carbone”<sup>1</sup>. BC is a carbon accounting methodology and set of tools that have been developed and used in France for more than 20 years. It has been applied to private companies, industries, and structures of all kinds and sizes including universities and research institutes. The method is compatible with other reporting methods such as the GHG Protocol [38] or ISO 14064-1 [17]. The method is based on emission factors taken from the “Base Carbone” database<sup>2</sup> of the French “Agence pour le Développement et la Maîtrise de l’Energie (ADEME)”.

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<sup>1</sup>[https://www.if-carbone.com/IFC\\_WEB](https://www.if-carbone.com/IFC_WEB)

<sup>2</sup><http://www.basecarbone.fr/fr/accueil/>

Our work complements community efforts emerging in France to systematically track the carbon footprint of research institutes [23] by providing an in-depth and more complete assessment of our institute. This is important because, as we show later, our results suggest that the perimeter of the assessment needs to be widened as much as possible in order not to miss potentially dominant emission sources.

As recommended in the BC methodology, intermediate results were reported to the institute in July 2021, after approximately six months of data collection. The purpose of this mid-term restitution is to inform colleagues, validate the data obtained so far, and agree on final steps. The present document constitutes the final report, which will serve as a basis for the definition of a long-term reduction plan.

### 3.3 Cartography of activities and flows

Carbon accounting following the BC method starts with a cartography of the institute that aims to capture all its activities and the input and output flows that they generate. The main guiding principles of this exercise are relevance and completeness. Such a cartography is meant to provide a strategic view of the institute, allowing a census of everything that the institute critically depends upon, as well as a perspective on everything that the institute produces and delivers to external partners<sup>3</sup>.

The overall philosophy of the BC method is to identify the organization’s most powerful lever arms to achieve large GHG emission reductions globally, rather than compiling a list of the emissions that an organization is directly or solely responsible for. An exhaustive approach is key to developing a perennial and effective reduction plan since it takes into consideration the deep changes that may be required to achieve significant permanent reductions. Carbon accounting over a highly restricted scope risks excluding an organization’s dominant sources of emissions and hiding the reasons behind certain sources of carbon emissions. As such, the reduction measures based on a restricted carbon footprint assessment may have limited effectiveness in the long term. As an example, there has been a strong focus within the scientific community on the impact of air travel, and several reports have identified it as the major contributor to their carbon footprint [e.g. 18]. In the case of IRAP – but the result is likely to apply to many other astronomy institutes – we show below that air travel is not the dominant source of emissions. As such, flights should not be the only target of reduction measures if IRAP is to achieve a reduction trajectory compatible with IPCC recommendations.

In this cartography, the IRAP is described as a structure where the following core activities and duties are performed:

1. Instrument development including hardware and software

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<sup>3</sup>This exercise goes beyond carbon emissions. It provides a critical examination of how an organization’s activities depend on fossil fuels and other primary resources, thereby revealing the vulnerability of an organization to future evolutions in the supply and pricing of commodities.



2. Observations, laboratory experiments, and data analysis
3. Analytical and numerical modelling of natural phenomena
4. Teaching, training, and public outreach
5. Animation and participation in the scientific community

The fifth category includes a broad range of activities, such as participation in national and international conferences, expert panels, selection committees and time allocation committees at the national and international level. The fourth category extends significantly beyond the perimeter of the institute. We decided to mostly exclude it from our reporting since most of the impact of teaching and training, including the commuting of students, is more appropriately assessed at the level of universities and schools. What remains inside our scope from the fourth category are expenses connected to students directly using our resources and facilities (e.g. electricity used during their internships in the institute), the commuting of students affiliated to IRAP for the whole of 2019 (mostly PhDs), and regular transfers of the staff between the institute facilities and teaching sites.

The above activities are associated with flows that can be inputs, outputs, or internal in nature. These can be further organized into the following categories: (i) people, e.g. commuting of the staff, scientific visitors, professional travel, conference attendees, etc ; (ii) material, e.g. electronic components, chemical products, computer equipments, etc ; (iii) services, e.g. subcontracting, numerical resources, observational data, etc ; (iv) internal support, e.g. heating, electricity, administration, canteen, etc.

A major input to our activity is the large amounts of observational data from research infrastructures like ground-based observatories or space-borne telescopes. This is counted as external service, that we generally do not own, control or pay for, but nevertheless has a significantly impact on our activities. Similarly, some crucial numerical resources such as supercomputing, cloud storage, astronomical databases and various internet facilities, are counted as external services because their operations and related impacts are external to the institute (computing and data storage performed on site at IRAP is accounted for in the purchase of computer equipment and consumption of electricity however). We note that emissions in the same flow category are not necessarily treated in the same way. In practice, the accounting is driven by the format and availability of the related information.

### **3.4 Scope and boundaries**

Based on the above cartography of our activities and associated flows, we define the temporal, organizational, and operational scope of our carbon footprint assessment as follows:

**Reference year:** We adopted 2019 as reference year. As this was before the COVID-19 pandemic, it presents a snapshot of our recent activities as they were before lockdowns and travel restrictions. Whether the carbon footprint will be affected in the long term by changes in activity or attitude patterns following COVID-19 remains to be seen. Moreover, the actual distribution of our emissions, as presented below, suggests that that COVID-related restrictions in 2020 and 2021 had only a minor impact on our carbon footprint.

**Organisation:** The assessment concerns IRAP, a research institute spread over three sites (two in Toulouse and one in Tarbes), two of which are shared with other institutes (the Belin site in Toulouse and the Tarbes site). These three buildings and their related support services are areas over which IRAP has significant effective control, and where it can rapidly implement mitigation measures. Our footprint goes beyond these sites, and the numerous facilities that are necessary to our daily work, such as external computing centers and other research infrastructures, are included as external service providers in our assessment. Teaching and training activities, which concerns a non-negligible fraction of IRAP staff, is essentially left out of the scope as explained above.

**People:** We consider all persons that were employed for the whole of 2019, whether their status was permanent or not. This excludes most undergraduate students, short-term interns, and PhDs and postdocs that left the institute during 2019. In total, we identified 116 researchers, 28 postdocs, 78 engineers, technicians and administrative staff, and 41 PhD students that were employed at IRAP over the full year of 2019.

**Operations:** According to the ISO14069 nomenclature, we include emissions for the following categories of activity (usually termed scope): direct emissions from owned or controlled sources (scope 1), indirect emissions from the generation of purchased energy (scope 2), and all other indirect emissions (scope 3). In our case, the latter category is by far the dominant one.

## 4 Data collection and emissions assessment

### 4.1 User survey

Most of the data used in the assessment were obtained from our administration in the form of listings of our consumption, purchases, and travel. For the data that were not available to the administration (commuting practices, meals, and use of computing/data storage resources external to our institute), we conducted an online user survey. The survey form was based on a protocol provided in [23], but was expanded and adapted to suit our needs.

The response rate was 59% among faculty and staff researchers, 51% among engi-

Source	Activity data	Emission data (t CO <sub>2</sub> e)
Electricity	Roche: 1863 MWh	113 ± 11
	Belin: 398 ± 80 MWh	24 ± 5
	Tarbes: 15 ± 3 MWh	1 ± 0.2
	Total: 2276 ± 80 MWh	138 ± 12
Heating	Roche: 857 MWh	59 ± 18
	Belin: 177 ± 35 MWh	40 ± 8
	Tarbes: 38 ± 8 MWh	9 ± 2
	Total: 1072 ± 36 MWh	108 ± 20
Water	Roche: 4271 m <sup>3</sup>	1.7 ± 0.3
	Belin: 428 ± 86 m <sup>3</sup>	0.2 ± 0.04
	Tarbes: 45 ± 9 m <sup>3</sup>	0.01 ± 0.002
	Total: 4744 ± 86 m <sup>3</sup>	2 ± 0.3
Air conditioning	Roche: 11.1 kg of R410A	21 ± 6
	Tarbes: 1.59 kg of R410A	3.1 ± 0.9
	0.92 kg of R22	1.6 ± 0.5
	0.19 kg of R32	0.13 ± 0.04
	Total	26 ± 6
Waste	155 ± 41 tons	55 ± 20
Food	44500 ± 15000 meals	85 ± 50
Commuting	(1.6 ± 0.3) × 10 <sup>6</sup> km	174 ± 67
Internal commuting	(1.0 ± 0.2) × 10 <sup>5</sup> km	10 ± 4
Professional travel	flight : (5.9 ± 0.1) × 10 <sup>6</sup> km	1126 ± 48
	train: (2.5 ± 0.03) × 10 <sup>5</sup> km	1.2 ± 0.1
	car/cab: (1.8 ± 0.06) × 10 <sup>5</sup> km	42 ± 6.0
Hotel	3996 ± 59 nights	75 ± 6
Computer equipment	139 (139-153) units	81 ± 40
Goods and services	3.657 M€	1335 ± 342
External computing	7.0 ± 3.5 MhCPU	33 ± 26
External storage	293 ± 129 TB	26 (4-63)
Data flow	293 ± 129 TB	1.5 (0.3-3.2)
Observational data	space: 46 missions	2800 ± 600
	ground: 39 observatories	1300 ± 500
Total (restricted perimeter)		3258±359
Total (full perimeter)		7418±860

Table 1: Summary of emission sources. Uncertainties are quoted as a range of values when they are strongly asymmetric. The uncertainties for the emission data include relative uncertainties on activity data and emission factors added in quadrature. For some categories (meals, commuting, internal commuting, external storage), activity data are presented in an aggregate form and uncertainties are propagated from individual items quadratically. The total is given over the full perimeter of the assessment, and over a restricted perimeter that excludes the contribution of external research infrastructures including external computing and storage.

Source	Incoming MWh PCI	Delivered MWh	Combustion only		Full LCA	
			$\frac{\text{tCO}_2\text{e}}{\text{MWh PCI}}$	t CO <sub>2</sub> e	$\frac{\text{tCO}_2\text{e}}{\text{MWh PCI}}$	t CO <sub>2</sub> e
Wood	45927		0.0132	606	0.0244	1121
Natural gas	10585		0.187	1979	0.227	2403
Total	56512	51136		2585		3524
EF ( $\frac{\text{kgCO}_2\text{e}}{\text{kWh}}$ )				0.0506		<b>0.0689</b>

Table 2: Calculation of the emission factor (EF) of the university boiler house in 2019, based on the total wood and gas consumption during the year. The final emission factor is obtained by dividing the total CO<sub>2</sub>e emissions obtained from life cycle analysis (LCA) by the total energy delivered by the boiler house in 2019.

neering, technical, and administrative personnel, and 29% among PhD students and postdocs. The lower response rate among PhD students and postdocs is due to the fact that many of those that were at our institute in 2019 had left by the time we conducted the survey. We extrapolated the data collected to the entire population by assuming that the sample available is representative within each of the three personnel subcategories listed above. Following the BC methodological guide we assigned to these data a nominal uncertainty of 50%.

## 4.2 Electricity and heating

As described in Sect. 3.4, IRAP is spread over three different sites: the Roche and Belin buildings in Toulouse, and another building in the city of Tarbes. The Roche building is entirely occupied by IRAP while the Belin and Tarbes premises are shared with other laboratories. The Roche site is connected to the heating network of the university, while the heating on the Belin and Tarbes sites is provided by natural gas boilers. Since the electricity and gas consumption is measured at the building level, we estimated our share at the Belin and Tarbes sites based on the relative surface occupancy of the different laboratories. Emission factors for the electricity and gas were taken from ADEME.

The university heating network is supplied by a boiler house fuelled by both wood and natural gas. The main fuel in 2019 was wood. The preliminary emission factor for the 2019 heat production provided by the boiler house services did not include the upstream and methane emissions for the use of wood as a fuel. We therefore calculated our own emission factor based on a life cycle analysis (LCA) for wood and gas fuels and the heat production data of the boiler house in 2019, and obtained a final emission factor of 0.0689 kg CO<sub>2</sub>e/kWh. Table 2 provides details on the calculation of this emission factor. Note that wood combustion is considered to emit biogenic CO<sub>2</sub> not fossil CO<sub>2</sub>. Whatever its origin, biogenic or fossil, CO<sub>2</sub> gas increases the greenhouse effect in the same way. However, unlike fossil fuels, biomass can be renewed on a human timescale, although the exact length of the cycle varies considerably (e.g.

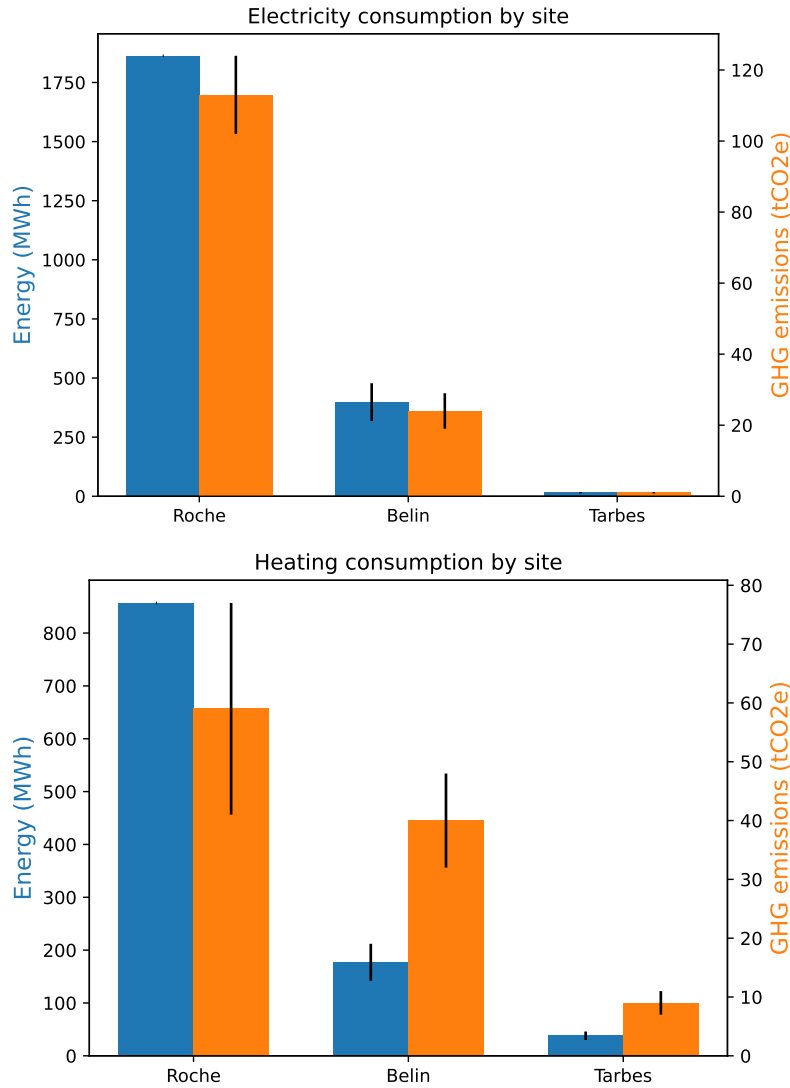


Figure 1: Electricity and heating consumption at IRAP, and the corresponding GHG emissions. Data for the three sites of the institute are shown separately.

annual crops vs. forests). For biomass of forest origin, biogenic carbon emissions are not counted if this biomass comes from a country where harvesting remains below the biological growth of the forest, which is the case in France. Therefore, the emission factor for wood combustion listed in Table 2 only takes into account methane emissions.

For the natural gas used in the heating of the Belin and Tarbes sites, we use an emission factor of 0.227 kg CO<sub>2</sub>e/kWh corresponding to the French gas mix in 2015 (more recent estimates were not available). For the electricity, we use an emission factor of 0.0607 kg CO<sub>2</sub>e/kWh corresponding to the French electricity mix in 2019.

Electricity and heating consumption, together with their corresponding GHG emissions, are listed in Table 3 and presented in Fig. 1. We note that there are no uncertainties associated with the electricity and heat consumption data for the Roche site as it is accurately metered. For the Belin and Tarbes sites, we added a conservative 20% uncertainty related to the calculation of IRAP's share based on surface occupancy. In addition, we used uncertainties of 5% and 10% for the natural gas and electricity emission factors, respectively, as provided in the ADEME database. For the university heating network, we used the generic 30% applied to heating networks in the ADEME database. In total, electricity and heating consumptions emit  $246 \pm 23$  t CO<sub>2</sub>e.

### 4.3 Waste production

Waste production is associated with a carbon footprint that was estimated from the information provided by the logistical services of the institute. The weight of IRAP's waste is not systematically calculated, so our estimates are based on the number of containers for each type of waste, the frequency of collection, and the volume of containers. Assuming 41 weeks with full containers (a time period corresponding to the university's operations excluding vacations), we estimated a total volume of waste of 508 m<sup>3</sup> per year, separated into several types: paper (9% of total volume), cardboard (17%), dry recyclable waste (16%), household waste (58%). Assuming a density of 0.3 kg/l for dry waste, we deduce a yearly collected weight of 155 tons. In the absence of a better estimate, we assumed an uncertainty of 50% on the collected mass of each type of waste for each of the three sites of the institute.

Appropriate emission factors for each type of waste, which depends on their end of life, i.e. burning or recycling, were taken from the ADEME database with a recommended uncertainty of 30%. This leads to a total emission from waste production of 55 t CO<sub>2</sub>e, with a final uncertainty of 20 t CO<sub>2</sub>e resulting from quadratic combination of relative uncertainties for each type of waste and quadratic sum over all types of waste.

IRAP's waste-related carbon footprint is essentially due to household waste, 58% of total emissions, that is burnt, and to the recyclable waste, 39% of emissions, that is only partially recycled. Increasing the share of waste that is recycled, and most importantly limiting the amount of waste produced, are necessary to reduce the carbon footprint of IRAP's waste production.

### 4.4 Water consumption

Water consumption is measured at the building level. As for electricity and heating, we estimated our share of the water consumption at the Belin and Tarbes sites based on the relative surface occupancy of the laboratories. We associated a conservative

Site	Electricity		Heating		Water	
	MWh	t CO <sub>2</sub> e	MWh	t CO <sub>2</sub> e	m <sup>3</sup>	t CO <sub>2</sub> e
Roche	1863	113 ± 11	857	59 ± 18	4271	1.7 ± 0.3
Belin	398 ± 80	24 ± 5	177 ± 35	40 ± 8	428 ± 86	0.2 ± 0.04
Tarbes	15 ± 3	1 ± 0.2	38 ± 8	9 ± 2	45 ± 9	0.01 ± 0.002
Total	2276 ± 80	138 ± 12	1072 ± 36	108 ± 20	4744 ± 86	2 ± 0.3

Table 3: Electricity, heating and water consumption per site and their corresponding GHG emissions.

20% uncertainty on these estimates, except for the Roche site where water consumption is metered and should have a negligible uncertainty.

The related GHG emissions were estimated from the ADEME emission factors for water distribution  $0.262 \pm 0.052$  kg CO<sub>2</sub>e/m<sup>3</sup> and wastewater treatment  $0.132 \pm 0.015$  kg CO<sub>2</sub>e/m<sup>3</sup>. Water consumption is detailed in Table 3 and contributes to a total of  $2 \pm 0.3$  t CO<sub>2</sub>e.

## 4.5 Air conditioning

In addition to the electricity consumption already taken into account in Sect. 4.2, air conditioning also contributes to GHG emissions due to refrigerant gas leakage.

For the Roche site, the leakage was estimated based on the amount of gas refilled during the year, totalling 11.1 kg of R410A gas. Using a global warming potential (GWP) of 1928 over 100 yr, with a 30% uncertainty as recommended by ADEME, this corresponds to  $21 \pm 6$  t CO<sub>2</sub>e. The uncertainty is here related to the GWP only since the amount of gas refilled is precisely monitored and billed by the maintenance company.

For the Tarbes site, the IRAP share of refrigerant gas leakages are 0.92 kg of R22, 0.19 kg of R32, and 1.59 kg of R410A. Using global warming potentials of 1760 and 677 for R22 and R32 respectively, we obtain equivalent emissions of  $4.8 \pm 1.0$  t CO<sub>2</sub>e assuming 30% uncertainty on the GWP.

Unfortunately, we could not obtain the refrigerant gas consumptions for the air conditioning system on the Belin site. However, air conditioning is mainly used in technical and common rooms in this building, unlike the Roche site where air conditioning is provided in each office, suggesting that GHG emissions due to refrigerant gas leakage on the Belin is significantly below the result for the Roche site. The final IRAP carbon footprint should not be significantly impacted by this omission. Overall, refrigerant gas leakage contributes a total of  $26 \pm 6$  t CO<sub>2</sub>e.

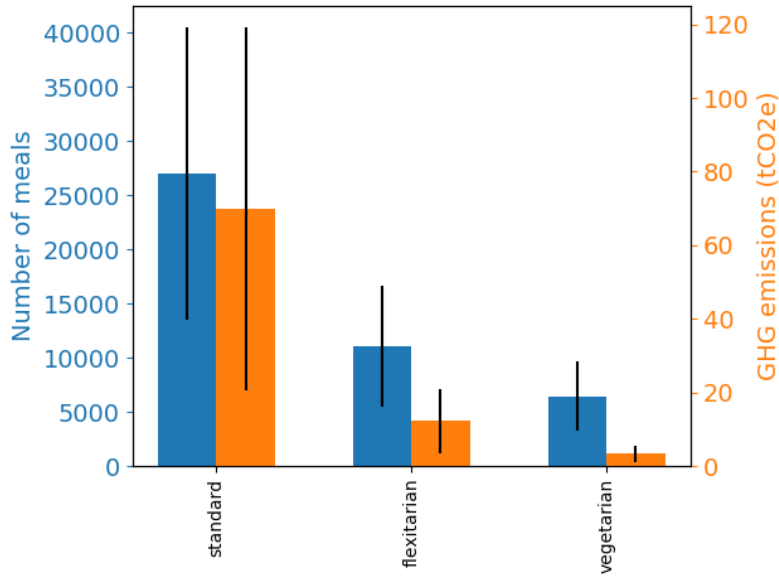


Figure 2: Number of meals and their corresponding GHG emissions.

## 4.6 Meals

Meals taken at the workplace are necessary to the personnel to carry out their work, and therefore must be included in a GHG assessment. Following the ADEME recommendations for entities that are not part of the food and agriculture business, we take a simplified approach based on the number of meals [4]. The main factor that determines GHG emissions from a meal is its content in animal products<sup>4</sup>.

From our user survey, we estimated the number of meals in three categories: standard, flexitarian (reduced amount of animal products), and vegetarian. As for all activity data extracted from the user survey, we assume these numbers have an uncertainty of 50%. We apply the emission factors proposed by ADEME to these three meal categories under the hypothesis that the meat content in non-vegetarian meals is composed of 25% of high-carbon meats (namely beef) and for 75% of lower-carbon meats (namely chicken) or fish. This yields 2.585 kg CO<sub>2</sub>e/meal for standard meals, 1.103 kg CO<sub>2</sub>e/meal for flexitarian meals, and 0.510 kg CO<sub>2</sub>e/meal for vegetarian meals, with uncertainties of 50%.

The results for the number of meals and GHG emissions are shown in Fig. 2. Meals contribute a total of  $85 \pm 50$  t CO<sub>2</sub>e to IRAP’s carbon footprint. We note that 75% of these meals are provided by a canteen, and, specifically, 73% by the CNRS canteen.

<sup>4</sup>See, e.g., <https://ourworldindata.org/environmental-impacts-of-food>.



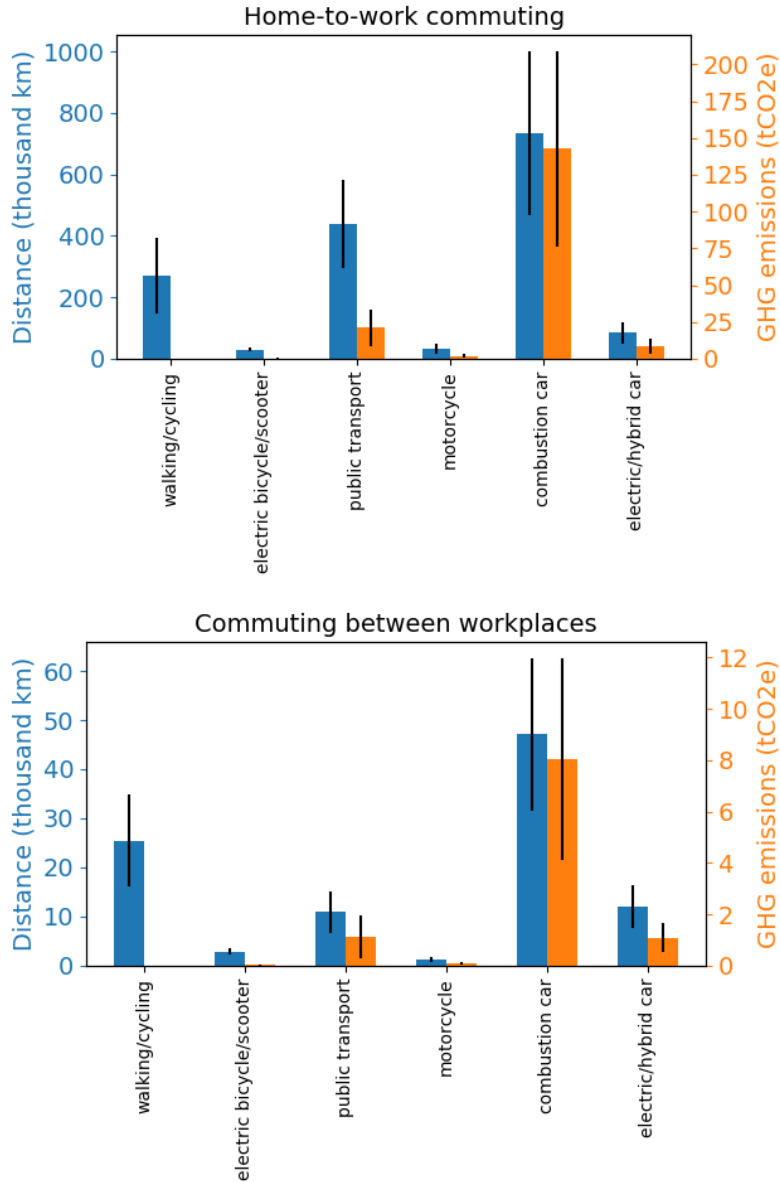


Figure 3: Distances and corresponding GHG emissions from home-to-work commuting and commuting between workplaces. Distances and GHG emissions are shown according to the mode of transportation. We used several subcategories and accounted for ride-sharing to estimate the GHG emissions, see text for details. When aggregating distances for several subcategories, uncertainties are propagated quadratically.

## 4.7 Commuting

Emissions from home-to-work commuting are included in IRAP’s GHG assessment according to French legislation and the BC method. We also consider here commut-

ing between workplaces (e.g., between the institute and a teaching site). These trips are not covered in our assessment of professional travel since they are undertaken by IRAP personnel via private means. We estimated commuting distances using the survey (uncertainties are assumed to be 50%) and converted them to GHG emissions using BC tools. The modes of transportation that we consider, along with their emission factors, are listed in Table 4. Walking and cycling are assumed to generate zero emissions. We also took into account ride-sharing for cars and motorcycles. The results are summarized in Fig. 3.

The total estimated GHG emissions are  $174 \pm 67$  t CO<sub>2</sub>e from home-to-work commuting and  $10 \pm 4$  t CO<sub>2</sub>e from commuting between workplaces. In both cases, conventional cars represent the principal source of emissions. We note that for commuting between workplaces the median distance travelled by car is 2.5 km.

We also evaluated the impact of working remotely on GHG emissions. In 2019 (i.e. before the COVID-19 pandemic), working remotely was a relatively rare practice at our institute. Through the survey we estimated that remote working was practised by staff members for a grand total of about 100 days per week, i.e., less than 10% of the total working time. This permitted to avoid 31 t CO<sub>2</sub>e from commuting. However, working remotely is also associated with rebound emissions that we estimated based on Ref. [2]. The rebound effects taken into account are those due to new transport usage, the usage of the private residence as workplace (increased heating and energy consumption etc.), and increased use of video communications. This yields  $\sim 9$  t CO<sub>2</sub>e of rebound emissions, and therefore a net balance of 22 t CO<sub>2</sub>e that were avoided in 2019 thanks to remote working. We emphasise that this figure should not be subtracted from our final total. We evaluate them here simply to provide an order of magnitude estimate for the reductions that would be made possible by remote working.

## 4.8 Professional travel and hotel stays

The emissions related to professional travel, transport and hotel nights, were estimated based on travel listings containing the following information: transport mode (flight, train, car...), departure and destination locations, and dates. For each trip, online tools were used to estimate the distance from departure to destination<sup>5</sup>. We assumed an uncertainty of 20% on travelled distances, except for flights outside France with an increased uncertainty of 50% to include the non-geodesic distances induced by possible flight connections.

GHG emissions were computed for each trip based on transport mode and distance, and the appropriate emission factor retrieved from the ADEME database. Regarding air travel emission factors, three different emission factors are provided depending on travelled distance, and the effect of contrails is taken into account by multiplying the

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<sup>5</sup><https://labos1point5.org/ges-1point5>

Transportation mean	Fabrication	Upstream	Combustion
Petrol car	0	37 g CO <sub>2</sub> e/km ±60%	164 g CO <sub>2</sub> e/km ±60%
Diesel car	0	39 g CO <sub>2</sub> e/km ±60%	151 g CO <sub>2</sub> e/km ±60%
Electric car	84 g CO <sub>2</sub> e/km ±70%	20 g CO <sub>2</sub> e/km ±70%	0
Hybrid car	48 g CO <sub>2</sub> e/km ±70%	29 g CO <sub>2</sub> e/km ±70%	106 g CO <sub>2</sub> e/km ±70%
Motorcycle	0	12 g CO <sub>2</sub> e/km ±60%	52 g CO <sub>2</sub> e/km ±60%
Bus	0	0	137 g CO <sub>2</sub> e/km/pass. ±60%
Subway/Tram	0	3.0 g CO <sub>2</sub> e/km/pass. ±60%	0
Train	0	2.5 g CO <sub>2</sub> e/km/pass. ±60%	0
Electric bike/scooter	0	11 g CO <sub>2</sub> e/km ±50%	0

Table 4: Individual modes of transportation considered in our estimate of GHG emissions from commuting with their emission factors and uncertainties. Emission factors are decomposed into fabrication of batteries (electric and hybrid cars only), upstream emissions related to the production of fuel/energy, and combustion. For public transportation, emission factors are given per passenger.

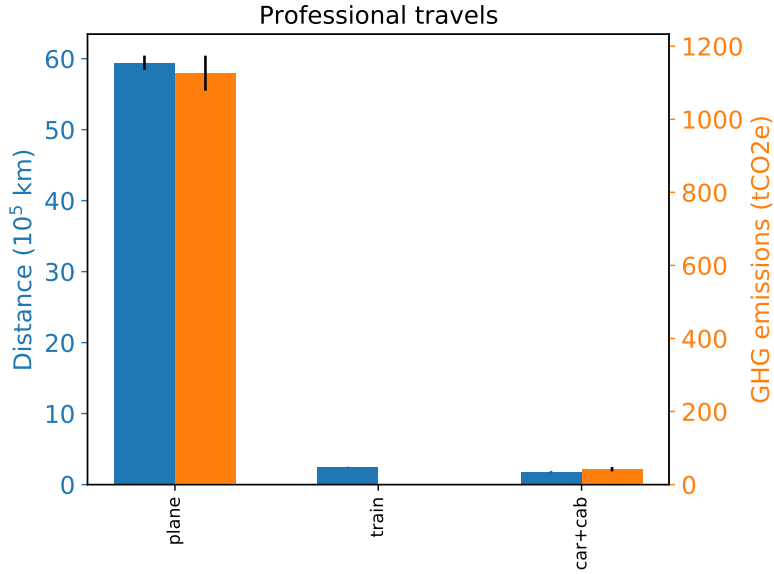


Figure 4: Distances and GHG emissions from professional travel, shown according to the mode of transportation, with car and taxi grouped into a single category.

Transport mode	Distance (km)	Emissions (t CO <sub>2</sub> e)
Flight	5942809 (93.3%)	1126.2 (96.3%)
Train	247203 (3.9%)	1.2 (0.1%)
Car	179794 (2.8%)	41.9 (3.6%)
Cab	728 (0.01%)	0.2 (0.01%)

Table 5: Total distances and associated emissions from professional trips by IRAP staff members for the different modes of transportation. Their relative contribution is shown in parentheses. Uncertainties on the figures can be found in Table 1.

final CO<sub>2</sub> equivalent emissions by a factor two, as recommended by ADEME. Uncertainties on emission factors were taken from the ADEME database, with in particular a 45% uncertainty for flights, and we combined them quadratically with the relative uncertainty on travelled distances. The total distances travelled by IRAP personnel per transport mode in 2019 (see also Fig. 4), and the resulting CO<sub>2</sub>e emissions are presented in Table 5.

The professional travel considered here includes trips by people who are not employed at IRAP (e.g. visitors for short-term collaboration, seminar speakers,...). These are included because they are part of the normal working of the institute, and a necessary contribution to our research activities. They typically consist in one return trip per person, and represent about 15% of the carbon emissions due to professional travel at IRAP.

The total distance travelled in France is  $1.05 \times 10^6$  km, about the same distance in Europe, and  $4.27 \times 10^6$  km outside of Europe. The average distance travelled per return trips are 1000, 2100, and 15000 km, respectively. The average distance travelled per person per year is about 25000 km, or 34000 km if administrative and technical staff are excluded from the calculation (i.e. assuming that trips are only undertaken by research staff). This corresponds to  $\sim 4.6$  t CO<sub>2</sub>e and  $\sim 6.3$  t CO<sub>2</sub>e per person per year, respectively. Train represents 3.8% of the travelled distance, and 58% of ground transport, but only 0.1% of emissions due to its very low emission factor compared to aircrafts and cars.

The professional travel practices and the associated emissions are very unevenly distributed within the institute, as illustrated in Fig. 5. About 20% of IRAP’s professional travel emissions are due to only a dozen staff members, and 50% of the emissions originates from fewer than 20% of the travellers. Roughly 10% of IRAP staff members did not travel at all in 2019. In principle, this concentrated emission profile should make it easier to engage efficient reduction measures, and reasonable limits on the number of allowed trips per year would translate into significant emission reductions. This is addressed more quantitatively in Sect. 6.2.

The duration and destination of each trip yields the number of nights away from home, assumed to be spent in hotels, with a 20% uncertainty on that number to cover possible inaccuracies in the listings or alternative accommodation (e.g. with friends or family). Emission factors for hotel nights in each country were taken from the full set of conversion factors proposed by the United Kingdom Department for Business, Energy and Industrial Strategy<sup>6</sup>, with associated uncertainties of 80%. The total number of hotel nights was 3996 in 2019, leading to 75.2 t CO<sub>2</sub>e emissions with an uncertainty of 6.4 t CO<sub>2</sub>e resulting from quadratic combination of relative uncertainties for each travel and quadratic sum over all missions.

In summary, professional travel emissions contributed 1245 t CO<sub>2</sub>e of IRAP’s GHG emissions in 2019, with 94% of that amount arising from transport, mostly air travel, and a non-negligible 6% arising from hotel accommodation.

## 4.9 Purchase of good and services

As mentioned in Sect. 3.3, our activities rely on important input flows of material and services, e.g. the purchase of electronic equipment, and subcontracting the design of certain instrument components. Not included in this category are the acquisition of computers, use of external numerical resources, personal travel services, and use of observational data since we deal with these sources using specific approaches in other sections below.

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<sup>6</sup><https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019>

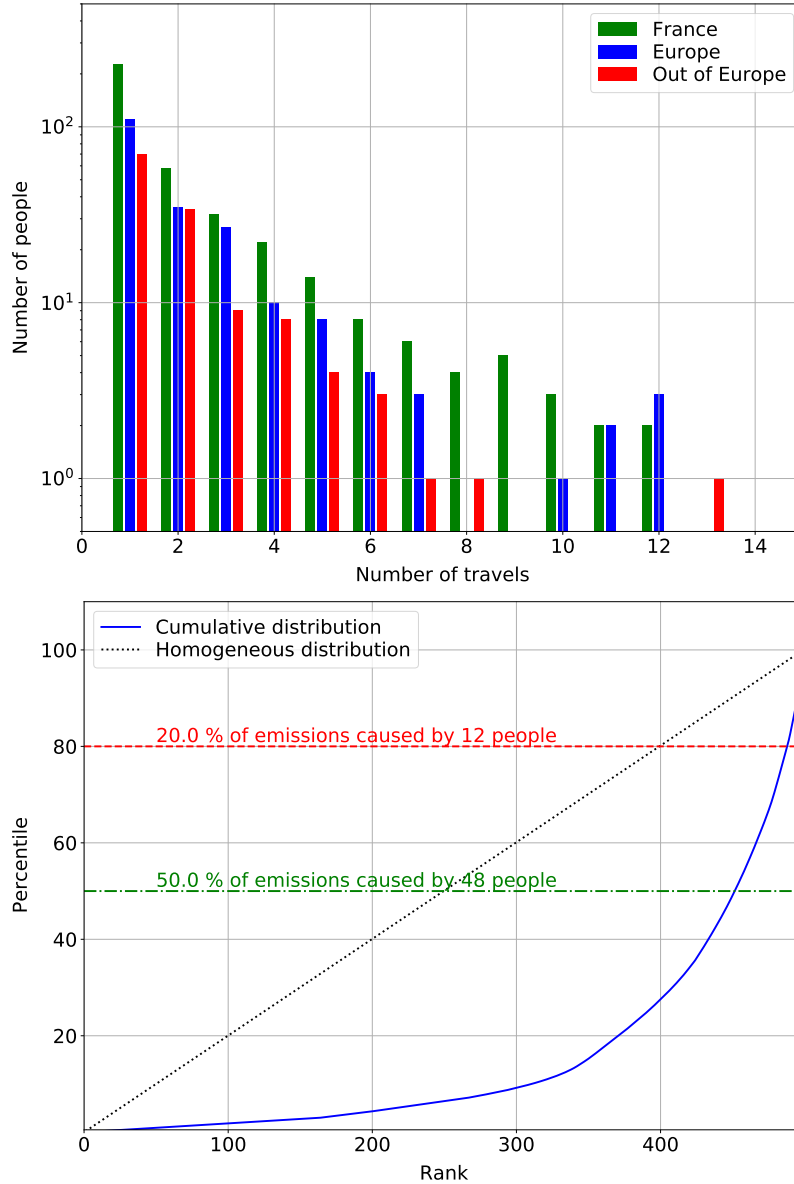


Figure 5: Top panel: Distribution of the number of trips per person per year as a function of destination (France, Europe, out of Europe). Bottom panel: Cumulative distribution of GHG emissions over travellers (including IRAP staff and visitors).

Ideally, the environmental impact of goods and services purchased in the context of our activities would be assessed and communicated by the suppliers. This so-called supplier-specific information, however, rarely exists and it is beyond the scope of our work to calculate it *ab initio* since it would require conducting complete GHG accounting for a wide diversity of products, based on the physical flows needed to produce them. Instead, we used a cost-based approach that converts the economic value of the purchased goods and services into an estimate for the associated GHG

ID	Category	Expense (k€)	Emission (t CO <sub>2</sub> e)	Share (%)
E	Consulting/Insurance/Human Resources	493	122	9.17
I	Computing/Telecommunications	668	117	8.77
O	Optical	518	174	13.01
T	Electronics	673	262	19.64
R	Mechanics/Automation	354	144	10.78
C	Communication/Documentation	159	44	3.30
P	Nuclear/Particle Physics	144	134	10.02
A	General supplies	139	59	4.43
F	Freight/Transport	43	28	2.16
V	Vacuum	82	55	4.10
B	Buildings/Infrastructure	128	53	3.96
G	Cryogenics/Laboratory gases	28	28	2.10
N	Chemistry/Biology	47	54	4.05

Table 6: Distribution of the main sources of GHG emissions in the purchase of goods and services, listing only those with an individual share  $> 2\%$  (which together account for more than 95% of the total). The first column lists the identifier in the French NACRES nomenclature.

emissions using economic sector-average emission factors (typically equating a k€ or M€ of expenditure on a given family of products, e.g. electronic equipment or software development, to kg CO<sub>2</sub>e or t CO<sub>2</sub>e).

In practice, our activity data for this category are IRAP’s annual expenditure through the Paul Sabatier University or CNRS, sorted into about 2000 categories that are labelled according to a specific code (NACRES, standing for Nomenclature Achats Recherche Enseignement Supérieur). We associated these expenditure categories with emission factors obtained from ADEME for about 35 broad activity classes [3]. We tested an alternative set of  $\sim 400$  factors from the United States Environmental Protection Agency (EPA) [36], with a much finer description of industrial and economic activities. The difference between the final results calculated using the ADEME and EPA factors was at the 25% level, and there was overall good agreement in the distribution of emissions over the different expenses<sup>7</sup>. We therefore kept the ADEME set of emission factors since it is more relevant to France than the EPA set. The expenditure-based approach is admittedly the least precise approach in GHG accounting, but it offers a way forward when other GHG accounting techniques cannot be achieved within a reasonable amount of time.

The expenditure on goods and services at IRAP for 2019 amounts to 3657 k€, ex-

<sup>7</sup>The EPA set of emission factors for the different GHG gases was converted into CO<sub>2</sub>e using global warming potential values for a 100-year time horizon from the GHG Protocol [30] and the spendings in 2018 US dollars were translated into 2019 euros using a currency exchange rate of 0.911.

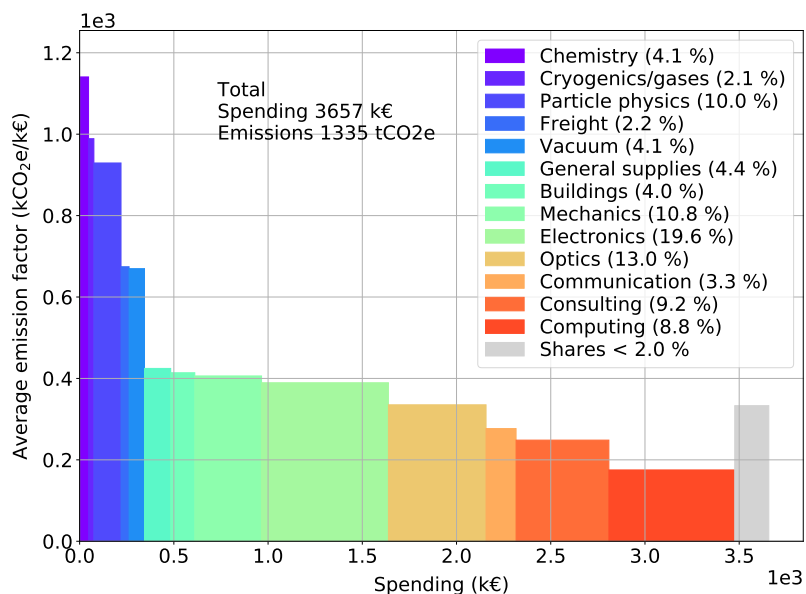


Figure 6: Average emission factors for the purchase of goods and services, organized by the main categories of expenditure, as a function of the cumulative expenditure. The size of the rectangles is proportional to the GHG emissions. The last gray block aggregates all shares that individually contribute less than 2% of the total GHG emissions. The fractional contribution to the GHG emissions for each category is shown in parentheses.

cluding all expenses that are dealt with in a more specific way in other sections of this paper (e.g. energy, computers, travel etc). The uncertainty on total expenses is assumed to be zero, and the final uncertainty on GHG emissions is computed as the quadratic sum of uncertainties over all broad purchase categories, assuming for the latter a relative uncertainty of 80% as recommended by ADEME and the BC method. Such an approach in computing the uncertainty is justified by the large number of different purchases, with a mix of tailor-made products and mass-consumption items.

The emissions from the purchase of goods and services amount to  $1335 \pm 342$  t CO<sub>2</sub>e. These GHG emissions divided by the expenditure correspond to an average emission factor of 365 kg CO<sub>2</sub>e/k€, which is of the same order as the emission factor for electronic, optical, and computer equipment in the ADEME database ( $\sim 400$  kg CO<sub>2</sub>e/k€). The distribution of the emissions into broad purchase categories is presented in Table 6, and the corresponding average emission factors are illustrated in Fig. 6. The bulk of the emissions is due to the purchase of technical equipment, most likely in connection to the numerous instrument development projects based at IRAP. The share related to the local infrastructure amounts to  $\lesssim 10 - 15\%$  (obtained by summing categories A, B, and a fraction of E).



## 4.10 Computer equipment

We treat the purchase of computer equipment separately from the purchase of goods because it allows a finer and more reliable assessment of the associated GHG emissions. The formal approach to this contribution is to estimate the total equipment in use at the institute during our reference year 2019, and to add up the GHG emissions associated with each machine for an amortization period of typically 4-5 years (which means that machines older than that are not counted, while others have a yearly contribution corresponding to the total GHG emissions due to their production divided by the amortization period). In practice, it was impossible to implement such a calculation owing to the difficulty that we encountered to obtain a robust census of all our computer equipment. Instead, we summed the number of computers and other main peripherals purchased over the period 2018-2020, and computed yearly GHG emissions per type of equipment assuming an amortization period of three years. Such an extraction was made by an automated scanning of purchase listings, but may not be highly accurate because of the lack of uniform, clear labels in the purchase orders. From a visual inspection of the labels and expenses of the different purchases, we consider that the volume of equipment eventually counted in our report is a lower limit, which probably underestimates the true value by at most 10%.

The emission factors for different computer equipment and peripherals were taken from the ECODIAG tool provided by the ECOINFO dedicated working group of the CNRS [15]. They correspond to cradle-to-gate emissions, and do not include end-of-life impacts, while power usage during the equipment lifetime is counted in our electricity consumption (except for the small part used when the equipment is taken out of the institute). ECODIAG offers emission factors for a variety of models for each type of equipment and we selected those labeled as default, which seem to correspond to the typical equipments mainly in use in the French astrophysics research community. Nevertheless, we also extracted a range of emission factors that characterise the diversity of equipment in use at the institute, to illustrate the possible uncertainty range due to the imprecise identification of each item. Emission factor variations depending of the equipment model are typically of the order of 20-40%, or higher in the case of PC/workstations. In addition, ECOINFO warns that they can increase up to threefold depending on the set of options chosen for the equipment. We eventually retain a typical uncertainty on emission factors of 50%, following the recommendation by ADEME.

The results are presented in Table 7. We purchase every year about 120 computers (at least over 2018-2020), for a staff of about 260 people, which suggests a typical lifetime of about 2-3 years per computer and/or a progressive inflation of the average number of computer equipment per person if the actual lifetime is longer. This leads to GHG emissions of  $81 \pm 40$  t CO<sub>2</sub>e.

Equipment	Number	Factor (kg CO <sub>2</sub> e/unit)	Range (kg CO <sub>2</sub> e/unit)	Emission (t CO <sub>2</sub> e)
Laptop	71	300	250-370	21.3
PC/Workstation	45	600	170-650	27.0
Server	6	1300	-	7.8
Standalone screen	10	430	350-590	4.3
Tablet	7	150	-	1.0
Total				80.8

Table 7: Distribution of GHG emissions associated with different types of computer equipment and peripherals. The numbers of items correspond to the average over the period 2018-2020. Total emissions include one screen per workstation, on top of the standalone ones. No emission factor range is given for servers and tablets on the ECODIAG tool.

#### 4.11 External computing, storage, and data flow

We estimated the usage of external resources for computing and data storage via our online survey (Sect. 4.1). For computing, we estimate a total usage of 7 MhCPU. We convert this into GHG emissions using the emission factor of 4.68 g CO<sub>2</sub>e/hCPU estimated by [8] for a computing center in Grenoble with an uncertainty of 80%. It is appropriate to use an emission factor based on a French computing center (low carbon impact of electricity) because > 99% of the computing occurs in centers located in France. This yields  $\sim 33$  t CO<sub>2</sub>e of GHG emissions.

We took a similar approach for external data storage. In this case, we estimate a total of  $\sim 39$  TB of data stored in France and  $\sim 254$  TB of data stored in other countries. The carbon footprint of data storage is highly uncertain and depends on the type of storage (short-term or long-term), the occupancy rate of the storage centers, and the carbon intensity of the electricity. We adopt the overall emission factors estimated in Ref. [7]. For France we have an interval of 7 to 40 g CO<sub>2</sub>e/GB/yr and we adopt a representative value of 25 g CO<sub>2</sub>e/GB/yr. Based on their study of the impact of the electricity carbon intensity, we assign to data storage in countries other than France (mostly U.S.A.) a carbon footprint which is four times larger, namely an interval of 28 to 160 g CO<sub>2</sub>e/GB/yr with a representative value of 100 g CO<sub>2</sub>e/GB/yr. This yields a representative value of 26 t CO<sub>2</sub>e for the associated GHG emissions, within an interval of 4 to 63 t CO<sub>2</sub>e.

Last, we estimated the impact of data transfer over the global network, generated by a variety of day-to-day use of numerical services such as exchanging emails, video-conferencing, or downloading large astronomical data sets. Monitoring of the ingoing and outgoing data flows at IRAP is not performed with a sufficient accuracy, so we had to assume a typical amount of data transferred over the network over a year. As a representative number, we used the total amount of data stored externally, 293 TB ( $\pm 50\%$ ), because these data had to be transferred at least once and such a typical

volume of about 1TB/capita/year encompasses the data flows generated by the regular use of the network by one individual over a year: thousands of emails (hundreds of which with MB-sized attachments), hundreds of hours of audioconferencing or videoconferencing (with data transfer rate of 30-100 MB/h and 500-2400 MB/h, respectively), dozens of hours of web browsing (with data transfer rate of 50-300 MB/h), and downloads of all kinds (papers, software installations or updates, astronomical datasets). There is most likely a large, order-of-magnitude, scatter in data transfer from one individual to another depending on staff category (e.g. in time spent in videoconferencing or amount of data downloaded) and usage profile (e.g. audioconferencing versus high-definition videoconferencing). Nevertheless, our purpose here is to estimate the typical weight that data transfer represents in our final footprint, and the results can easily be rescaled to an actual use case. Ultimately we find that data transfer represents only a very small contribution to our carbon footprint.

The amount of GHG emissions is obtained by associating the volume of data transferred to an electricity consumption, and then with an average carbon intensity for electricity. We considered an emission factor combining both and obtained in Ref. [13], about 1-2 g CO<sub>2</sub>e/GB, for the transfer of data between Orsay and Montpellier in France via the RENATER network. The estimate includes the impact of power consumption, manufacturing and installation of the equipments, and network supervision activities. The cost of data transfer increases strongly with distance/number of nodes between emitter and receiver, and carbon intensity of electricity. Conversely, it decreases with increasing load of the network and increasing lifetime of the equipments. To be more representative of international data transfer, over long distances and consuming electricity that has on average a much higher carbon intensity than in France, we considered a typical range of 2-10 g CO<sub>2</sub>e/GB as emission factor, with a baseline value of 5 g CO<sub>2</sub>e/GB. The latter value is consistent with that extrapolated for 2019 in Ref. [5]. Eventually, this yields yearly GHG emissions of about 1.5 t CO<sub>2</sub>e for all IRAP staff, with a likely range 0.3-3.2 t CO<sub>2</sub>e.

## 4.12 Research infrastructures

Scientists from our institute use a long list of research infrastructures, such as space telescopes, space probes and ground-based observatories. According to the BC method, the carbon footprint associated with the use of these facilities needs to be included in the institute's carbon footprint estimate. Details of the carbon footprint estimation method for research infrastructures are presented separately in Ref. [19]. In short, we identified the facilities that were used from all refereed publications co-authored by IRAP scientists that were published in 2019, resulting in a list of 46 space missions and 39 ground-based observatories. We estimated the carbon footprint of each facility using monetary ratios, and consolidated the results for space missions with an alternative estimate based on the payload wet mass. Dedicated emission factors for this analysis were derived from published carbon footprint assessment reports. For space missions, we derived an emission factor of 140 t CO<sub>2</sub>e/M€ mission cost and 50 t CO<sub>2</sub>eq/kg payload wet mass, for ground-based observatories we derived

240 t CO<sub>2</sub>e/M€ construction cost and 250 t CO<sub>2</sub>e/M€ operating costs. We note that these emission factors are on the low side of the sector-based estimates provided by ADEME, hence it seems unlikely that our adopted values are significantly overestimated.

As activity data, we gathered full mission cost and payload launch mass estimates for space missions and construction, and yearly operating costs for ground-based observatories from publicly available documents. These data were complemented by information provided directly by some of the facilities, and a parametric cost model for some of the 1–2 metre class telescopes in our list. All activity data collected are provided in the supplementary information of Ref. [19]. Based on these activity data and the aforementioned emission factors, we computed lifecycle and annual carbon footprint estimates.

To determine which fraction of the research infrastructure carbon footprint should be attributed to our laboratory, we use two methods. In the first method, we multiply the annual carbon footprint of an infrastructure with the fraction of peer-reviewed papers in 2019 that have authors affiliated to IRAP. We determined this fraction from the Astrophysics Data System (ADS) using a full text search for the year 2019. For this purpose, we constructed a dedicated query string for each infrastructure with the aim to cover as many infrastructure-related publications as possible while keeping the false positives at a minimum. This results in a footprint of  $20 \pm 3$  kt CO<sub>2</sub>e for IRAP in 2019. Attributing this footprint equally to the 144 astronomers with PhD degree that worked at IRAP in 2019 results in  $139 \pm 23$  t CO<sub>2</sub>e per astronomer. If we instead divide the annual research infrastructure carbon footprint equally by the total number of staff that worked at IRAP in 2019 (263 people), we obtain  $76 \pm 12$  t CO<sub>2</sub>e per IRAP staff member.

We note that this attribution method does not provide IRAP’s share of the total carbon footprint of research infrastructures among all existing astronomical institutes in the world. Since scientific articles are often signed by authors from multiple institutes, each of these institutes will get the same attribution, implying that the sum of all attributions will exceed the total carbon footprint of all research infrastructures. The share can however be estimated by replacing the number of peer-reviewed papers by the number of unique authors, i.e. multiply the annual carbon footprint of an infrastructure with the fraction of unique authors of peer-reviewed papers in 2019 that are affiliated to IRAP. This results in a carbon footprint of  $4.0 \pm 0.7$  kt CO<sub>2</sub>e for IRAP in 2019. For each of the IRAP astronomers with PhD degree this corresponds to a footprint of  $27.4 \pm 4.8$  t CO<sub>2</sub>e, for each person working at IRAP in 2019, the footprint is  $15.0 \pm 2.6$  t CO<sub>2</sub>e. We note that some double-counting may still occur using this approach since an individual may be affiliated to multiple institutes. But for a given individual, the computation of the share should be accurate.

### 4.13 Emission sources excluded from our scope

Some sources of GHG emissions were not included in our assessment, or only partially, or not in the way they should have been according to the principles of the BC method. The main reason in most cases was the unavailability of, or difficulty in obtaining access to, the relevant data. We list these sources here to provide a complete picture of what should be the full scope of the assessment, and remind that the final carbon footprint we report here is formally a lower limit. All the items listed below constitute possible avenues for improvement of future assessments.

**People:** This should include people attending events organized by the institute, such as workshops or conferences. Doing so would likely increase the institute’s GHG emission, but it would allow the institute to identify a potentially powerful lever arm. IRAP, as the sole or primary organizer of an event, could opt for relocating it to a location that minimizes the total travelled distance, replacing it by a virtual gathering, or, for a recurrent event, reducing its frequency. All such measures would have a very efficient overall return. In practice, however, no major conference or workshop was included in the present assessment because: (i) IRAP was, to our knowledge, rarely the sole or primary organizer of such an event in 2019; (ii) collecting the corresponding travel data for all participants was unfeasible. Ultimately, the only cases we took into account were trips by invited researchers (e.g. seminar speakers) because their travel and accommodation was paid for by the institute.

**Material:** According to the BC methodology, delivery and freight are supposed to be handled as a distinct category, to separate the impact of producing goods from that of transporting them. The expected quantity here is typically the amount of mass transported over a total distance, split into transportation means (rail, road, air, sea). In practice, it was impossible to get such detailed information for all incoming material (e.g. electronic or optical components) and outgoing equipment (e.g. delivery of instruments or parts of instruments). A part of the freight is indirectly included via the purchase of transportation services, but with a monetary approach, rather than a physical one.

**Services:** It is recommended to include the GHG emissions associated with the use of services provided by IRAP to the outside world, e.g. open databases and public software developed and/or maintained at IRAP. The rationale for including this contribution is the same as for conference organization : reducing the subsequent emissions by optimization at the source as much as possible. For numerical services, we do not keep an exhaustive census of the software and databases provided by IRAP, with homogenous statistics about their use. Partial information exists in the case of some community services supported by the institution (the Services Nationaux d’Observations). Assessing the impact of the data storage and transfer generated by IRAP’s SNO would be an interesting avenue to explore in future assessments.

**Internal support:** IRAP relies on support activities, such as administration, maintenance, and financial and insurance services provided by higher-level institutions (mainly the Paul Sabatier University and the CNRS). Not all of these activities are local and easily integrated into our assessment. The BC methodology also re-

quires to include the carbon impact of the construction of buildings, with a specific treatment for amortization over typically 10-20 years. According to this rule, most of our buildings would already be amortized, but some recent installations should have been taken into account but were not. We can however provide an order of magnitude for the most recent building construction in our institute, the “Plateforme d’Ingénierie et d’Instrumentation Spatiale (P2IS)”, inaugurated in 2015. It has a floor surface of 368 m<sup>2</sup> and consists of a mix of offices and technical rooms. According to the ADEME database, emissions from construction range from 650 kg CO<sub>2</sub>e/m<sup>2</sup> for office buildings to 825 kg CO<sub>2</sub>e/m<sup>2</sup> for industrial buildings. This implies total GHG emissions in the range 239 – 304 t CO<sub>2</sub>e for the construction of P2IS, or about 12 – 15 t CO<sub>2</sub>e/yr assuming an amortization period of 20 years, which is a relatively minor contribution in our total footprint. This assessment should however be performed for all extraordinary operation or acquisition, e.g. the purchase of a large equipment for instrumental development. In the absence of a well-established inventory and an easy way to associate these to GHG emissions, we excluded them from the scope of this assessment.

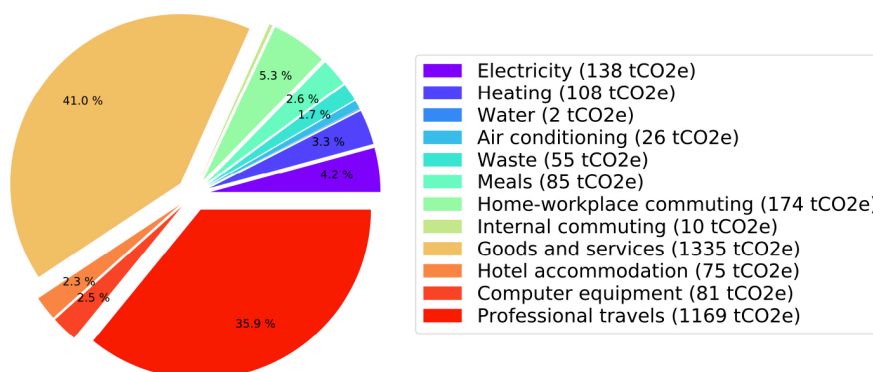
## 5 Synthesis

### 5.1 The carbon footprint of IRAP

The breakdown of all IRAP’s GHG emissions per source is summarized in Table 1 and presented in Fig. 7. The final estimated quantity for 2019 over the full perimeter of the assessment is about 7400 t CO<sub>2</sub>e, or an average of 28 t CO<sub>2</sub>e/yr per staff member. We also defined a restricted perimeter, by leaving out the contribution of external research infrastructures including external computing and storage. Over this restricted perimeter, our emissions amount to 3300 t CO<sub>2</sub>e or an average of 13 t CO<sub>2</sub>e/yr per staff member. The rationale for this distinction is that IRAP has significant operational control over the restricted perimeter, but a more limited one over external research infrastructures, so such a separation is relevant in view of a local reduction plan. This practical distinction is however relevant only to the means and strategies for implementing reduction measures, and should not elide that IRAP’s total 2019 footprint is 7400 t CO<sub>2</sub>e.

The operation of the local infrastructure – heating, electricity, commuting, food, waste, and ~ 10 – 15% of the purchase of goods and services – makes a relatively small contribution to IRAP’s carbon footprint, about 800 t CO<sub>2</sub>e/yr. Thus, while it remains relevant to reduce IRAP’s consumption of electricity and gas consumption and to switch away from conventional cars for local transport, initiatives focussed on the institute’s local infrastructure will not be sufficient to achieve emission reductions that are compatible with France’s 2050 targets (i.e. reducing emissions by a factor of 5). We note that the relatively small contribution of local infrastructure may be specific to IRAP, and that other astronomy institutes may have quite different emission profiles. The energy used to produce the institute’s electricity and heating

Greenhouse gases emissions for IRAP - Restricted perimeter (2019) - 3258 tCO<sub>2</sub>e



Greenhouse gases emissions for IRAP - Full perimeter (2019) - 7418 tCO<sub>2</sub>e

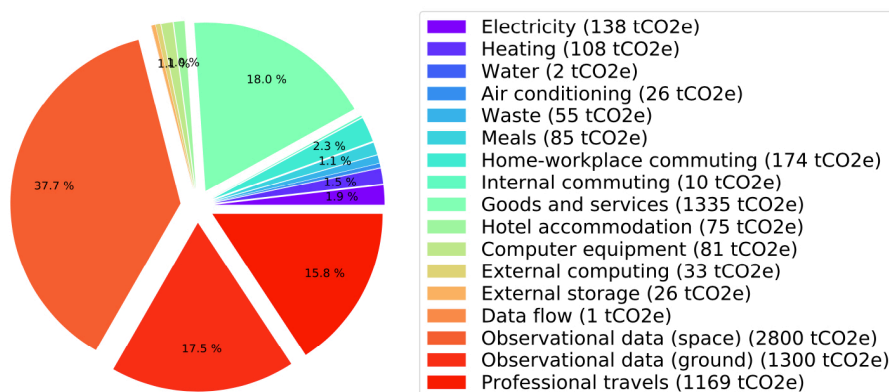


Figure 7: Distribution of IRAP’s GHG emissions in 2019, for the restricted and full perimeter, without and with the use of external research infrastructures, respectively (top and bottom). Only wedges with a relative contribution above 1% are labelled.

has a relatively low carbon footprint, with electricity being predominantly of nuclear origin in France and heating of our largest building arising from biomass burning<sup>8</sup>, corresponding to emission factors of 0.06-0.07 kg CO<sub>2</sub>e/kWh. Assuming a worst-case carbon intensity of ~ 0.8 kg CO<sub>2</sub>e/kWh instead, typical of Australia, the related sources would amount to about 2700 t CO<sub>2</sub>e/yr, comparable to the sum of professional travels and purchase of goods and services at IRAP. A higher carbon intensity of electricity would also affect other sources such as external computing, and to some

<sup>8</sup>For more information about the use of biomass as an energy source, and its actual carbon footprint and possible role in reduction strategies, see <https://easac.eu/publications/details/key-messages-from-european-science-academies-for-unfccc-cop26-and-cbd-cop15/>

extent the purchase of goods and services. If IRAP were situated in a country that relies significantly on fossil fuels for electricity production and heating, we estimate that our total 2019 footprint would be at least 10000 t CO<sub>2</sub>e, or 38 t CO<sub>2</sub>e/yr per staff member.

The most significant sources of GHG emissions at IRAP, ordered by decreasing contribution, are: the use of astronomical research infrastructures, the purchase of goods and services, and professional trips, with a predominant share of air travel in the latter. As mentioned above, the bulk of the emissions from the purchase of goods and services is attributable to the numerous instrument development projects performed at IRAP. Together with the preponderant share from the use of observational data, this clearly points to the main driver of our large carbon footprint: astronomical research infrastructures. More precisely, it is the current practices related to conceiving, designing and developing astronomical research infrastructures, and the scale and cadence at which we deploy them. Moreover, it is likely that a significant fraction of professional trips at IRAP are also connected to instrument development projects, which makes the conclusion even stronger (although we could not check this point owing to the lack of the relevant information).

Whether such a trend can be considered as generic in the community remains to be confirmed by performing exhaustive carbon footprint assessments at other institutes. IRAP has a long history in instrument development and observational data analysis, which certainly weighs in the present result. Institutes that specialise in theory and numerical simulations may have a smaller footprints, although this will depend on the amount of supercomputing performed and the carbon intensity of the electricity powering the computing clusters. Ultimately, however, such a distinction may be irrelevant since research in astronomy and astrophysics requires all of these activities (theory, simulations, observations). What is needed is a community-scale strategy for our use of all resources and facilities.

## 5.2 Comparison and discussion

IRAP's total emissions in 2019 ( $\sim 7400$  t CO<sub>2</sub>e) correspond to 28 t CO<sub>2</sub>e/yr per staff member, on average, from professional activities only. This can be compared to the average footprint of a French resident (combining private and professional emission sources) of 11 t CO<sub>2</sub>e/yr, although that comparison is not directly meaningful as we will discuss below.

More relevant is a comparison with other institutes. Ref. [18] estimated that the annual emissions of the Max Planck Institute for Astrophysics (MPIA) located in Heidelberg, Germany, amounts to 18 t CO<sub>2</sub>e/yr/researcher, and  $\sim 9$  t CO<sub>2</sub>e/yr/staff member if the load is shared over all employees, including all support staff. Therefore, work-related emissions only are 60% higher than the average for German residents, 12 t CO<sub>2</sub>e/yr, which includes the impact of both professional and private activities. Nearly half of the MPIA emissions arise from air travel, and a quarter from the



local electricity consumption of supercomputing [18]. The latter point is an interesting difference between MPIA and IRAP: the emissions from supercomputing at IRAP amount to 0.2 t CO<sub>2</sub>e/yr per researcher, on average, and this covers the impact from electricity consumption, equipment, and operations of the computing centers; at MPIA, supercomputing generates an average 4.6 t CO<sub>2</sub>e/yr per researcher, from electricity consumption only. Only a small part of the difference can be explained by the carbon intensity of electricity, which is a factor  $\sim 4$  higher at MPIA with respect to IRAP.

The situation of Australian astronomers is more alarming, with emissions amounting to 42 t CO<sub>2</sub>e/yr/researcher, or twice the average impact of an Australian resident, 21 t CO<sub>2</sub>e/yr [32], which already ranks among the highest on the planet. We emphasise, however, that the perimeter adopted in the assessments by [32] and [18] is much more restricted than the one used here.

To put these numbers in a global perspective, the world average rate of GHG emissions today is  $\sim 5 - 6$  t CO<sub>2</sub>e/yr per capita. To achieve carbon neutrality, i.e. for anthropogenic emissions to be absorbed by natural carbon sinks from land and oceans, the global average must be reduced to 2 t CO<sub>2</sub>e/yr per capita by 2050. The average emission rates compatible with carbon neutrality will be even lower if the planet's capacity to capture carbon dioxide has been strongly degraded by 2050 and/or if the world population has inflated strongly beyond 10 billion inhabitants [34].

There is ongoing debate in the community about the exact meaning of these emission rates per capita, and the way that the burden of GHG emission reductions should be shared. A common response from those interested in maintaining the *status quo* is to argue that the GHG emissions from astronomy research should be attributed across a much larger population base than researchers and the staff of astronomical research institutes, i.e. over the full production chain including the suppliers of goods and services, or over the general population since the benefits of astronomy research are enjoyed by society at large. However, we stress that in carbon accounting, the objective is not to uniquely identify emissions with a given group of individuals, but rather to quantify all emissions that an activity depends upon to exist and generates while it is in operation. The ultimate goal is to identify all possible avenues for GHG emission reduction.

Our assessment shows that performing research in astronomy and astrophysics at IRAP in 2019 stimulated GHG emissions equivalent to 28 t CO<sub>2</sub>e/yr per person involved in that activity, on average. That these emissions are spread across a variety of social and economic sectors is obvious, and should not be used as an argument to lower our impact by distributing it over a larger population base. One way of viewing the global average target of 2 t CO<sub>2</sub>e/yr per capita by 2050 is as an average budget that should not be exceeded, and within which societies should fit what they deem necessary to human life. In a democratic debate about how this target should be

achieved and which activity sectors should be afforded permission to exceed the average value, the place of research should be discussed (alongside all other sectors) with a quantitative estimate of their costs and benefits. Here we estimate that the carbon cost of astronomy research is 28 t CO<sub>2</sub>e/yr per person employed in that activity when it is performed according to IRAP’s 2019 standards. Obviously, not all activity sectors in society (including research) can be accorded a footprint that exceeds the average allocated budget, otherwise the latter will rapidly be exceeded. Shifting our professional practices to bring the average carbon footprint of astronomy research closer to the target would thus seem an important step to guarantee the future of our field.

## 6 The way forward

### 6.1 Facilitating carbon accounting

Regardless of the strategies that are adopted to reduce our emissions, regular assessments of the institute’s carbon footprint to take stock of the situation, monitor progress, and adjust the emissions reduction plan will be required. During our work to estimate the carbon footprint of IRAP, it became clear that a key challenge lies in the availability of activity data. The problems we faced ranged from information being totally absent (e.g. fine-grained measurements of the numerical data flows generated by our activity), to data being incomplete (e.g. professional travel data missing the departure/arrival locations or the reasons for travelling), or tedious to collect (e.g. constructing a list of computer equipment purchases by hand). In this section, we present some recommendations for how to improve this situation and move towards seamless – or at least less painful – carbon accounting. These recommendations may not be directly relevant for astronomy institutes based outside of France.

Preparing the information in a complete and relevant format at the source is an urgent short term goal. National suppliers responsible for providing services for travel and hotel reservations, computer equipment and catering are ideally positioned to amalgamate global information that can be extracted for later use at different levels, from small entities such as institutes, to research federations such as the “observatoires des sciences de l’univers”, and umbrella institutions like the CNRS. Such a requirement should be rapidly negotiated at the national level.

At the level of campuses, information pertaining to infrastructure such as electricity, heating, water and waste should also be collected centrally and shared among all users of the same site. When a specific mode is used to supply heating, the relevant emission factor should be updated according to the actual operation of the facility (e.g. actual mix of gas and wood in the case of our university).

At the institute level, it is desirable to have activity data organized in the most appropriate way to raise awareness and trigger action. In a laboratory like IRAP, knowing

the carbon footprint of different IRAP-based projects would help staff members appreciate their actual contribution to the institute’s emissions, as well as the required effort to be made. Some development of the software used by our administration is needed to easily associate activity data such as travels and purchases to the relevant department or project within the institute, all this while preserving anonymity of the individuals.

Facilitating carbon accounting requires information that has not previously been collected, or revising the format of the collected information. At least initially, this will imply an increased administrative burden. Care should be taken to not overload our colleagues and ensure that enough time is allocated for them to contribute to this high-priority duty.

The source of GHG emissions at IRAP with the largest uncertainties, both in terms of activity data and emission factors, was activity related to digital technologies. Our estimates of the use of external storage and data transfer are highly uncertain, as are the estimates for their emission factors, with order-of-magnitude scatter frequently encountered in the literature. Although these activities made a relatively small contribution to our footprint (in part because of the low carbon intensity of electricity in France), the rapidly evolving nature of this field, and in particular the strong and continuous increase in many practices, e.g. the volume of data stored in clouds, massive computing, data flows, requires a careful assessment of its impact, to make sure that it remains under control in terms of environmental sustainability. On the side of activity data, more measurements by the Information & Technology services are clearly needed for us to have a better understanding of the actual situation. An assessment of the ingoing and outgoing flows of data, split into usage, is clearly missing today to guide us towards a better practice. On the side of emission factors, expert work is required to fully appraise the relevant emission factors appropriate at a given time, location, and for a given usage. In France, such an effort is conducted by the ECOINFO research group, and some of their pioneering studies were critical to our estimate. We recommend strong and lasting support from our institutions to this group and, going beyond carbon accounting, regular staff training about the environmental impact of digital technologies.

Finally, as already emphasised and recommended in Ref. [19], there is a crucial lack of reliable information about the carbon footprint of ground-based observatories and space-borne instruments. The first estimates provided in that paper and performed in the context of the present assessment for IRAP suggest that it is a large, if not dominant, share for most institutes. We therefore encourage the entities running these research infrastructures to rapidly assess their total footprint, including construction and operation, and to publicly share them so that all institutes can include the information in a uniform way in their carbon footprint assessments.

We emphasise that widespread carbon accounting by all actors involved in astron-

omy research is just a step towards solutions, and not the solution itself. There is a growing risk that carbon footprint assessment becomes essentially a communication measure, while the hard decisions that must be made to reduce emissions are left aside. Transitioning from fair and relevant carbon accounting to far-reaching reduction strategies requires institutional mechanisms that are yet to be envisaged or implemented. In that respect, the situation in France is enlightening: carbon accounting has been mandatory for more than a decade and companies and institutions of all kinds have published their carbon footprint, but this requirement appears to have had zero impact on France’s GHG emission curves. The reasons are manifold, but the conclusion is inevitable : carbon assessments without emission reduction strategies are ineffective.

## 6.2 Possible avenues for reduction

At the moment of writing, there is no clear target that has been defined for the reduction of emissions from scientific research, or by astronomy in particular. To gauge the magnitude of the necessary reductions, we can consider France’s national reduction targets of 50% by 2030 and 80% by 2050. However, these figures do not account for the fact that some activity sectors of our society will likely be allowed to continue producing a higher level of GHG emissions, and that other activity sectors will be required to achieve even larger reductions in order to compensate those sectors. The appropriate reduction goal for research is a political question that needs to be addressed by a wide-ranging democratic decision process that weighs the GHG emissions from research activities against its societal benefits. Evidently, this discussion should not be restricted to the research community alone.

The distribution of our GHG emissions suggests the contours of a reduction plan. The dominant contribution of astronomical research infrastructures clearly sets the long-term goal of a decarbonization strategy, in an effort going well beyond IRAP and challenging our culture of research. Locally, the quantitative carbon accounting presented above suggests some non-negligible emission reductions that could be achieved in the short term via measures that would not be technically difficult to implement. As outlined in Ref. [28], a successful emissions reduction plan should combine both aspects: initial steps that quickly achieve visible emission reductions to set the organization in motion, and a longer term strategy that attacks the bulk of the emissions footprint.

A local reduction plan should be carefully co-constructed by the institute’s direction and staff. We thus refrain from making strong recommendations or listing priorities here. Instead, we illustrate the magnitude of the emissions reduction that could be expected from some actions that could be implemented immediately with limited impact on our daily research activities. Table 8 summarizes these for a series of possible reduction scenarios:

1. Professional travel: limiting the number of trips per year and per individual

Scenario	Emissions (t CO <sub>2</sub> e)	Gain Rel. Restr. Full
Professional travels (1169 t CO <sub>2</sub> e, 35% restricted total, 16% full total)		
1 - Train in FR	952	-19% / -6.7% / -2.9%
2 - Plane 2 non-EU	977	-16% / -5.9% / -2.6%
3 - Train in FR, Plane 4 EU+2 non-EU	719	-38% / -14% / -6.1%
4 - Train in FR, Plane 2 EU+1 non-EU	508	-57% / -20% / -8.9%
Commuting (184 t CO <sub>2</sub> e, 5.7% restricted total, 2.5% full total)		
1 - <2.5km bike/foot, for the rest -20% car	155	-16% / -0.9% / -0.4%
2 - <5km bike/foot, for the rest -40% car	125	-32% / -1.8% / -0.8%
3 - same as 2 with 50% electric/hybrid cars	103	-44% / -2.5% / -1.1%
4 - 3 days remote working	152	-17% / -1.0% / -0.4%
Meals (85 t CO <sub>2</sub> e, 2.6% restricted total, 1.2% full total)		
1 - 50% standard meals $\mapsto$ flexitarian	65	-24% / -0.6% / -0.3%
2 - standard meals $\mapsto$ flexitarian/vegetarian	37	-56% / -1.5% / -0.7%
3 - 100% vegetarian meals	22	-74% / -1.9% / -0.9%
Computer equipment (81 t CO <sub>2</sub> e, 2.5% restricted total, 1.1% full total)		
1 - 4-year lifetime for computers	59	-27% / -0.7% / -0.3%
2 - 6-year lifetime for computers	50	-38% / -1.0% / -0.4%
Heating and electricity (246 t CO <sub>2</sub> e, 7.6% restricted total, 3.3% full total)		
1 - SNBC national strategy	125	-49% / -3.7% / -1.6%

Table 8: Benefits from various reduction scenarios over a selected set of GHG sources. The gain column lists the gain for the source of emission under consideration, then the gain relative to the restricted perimeter, and lastly the gain relative to the full perimeter.

- in and out of Europe and/or imposing train travel for all domestic travel; the estimated reduction does not include the cost of hotel accommodation.
- 2. Commuting: changing our transport habits by shifting to less carbon-intensive means for short distances, like walking or cycling, and reducing the remaining mileage done by car by diverting a fraction of it towards carpooling and public transportation (which could be even more effective if an increased fraction of personal cars become electric or hybrid as anticipated in France in national reduction strategies), or by extending the practice of remote working (accounting for rebound emissions under the hypothesis of no adjustments in the lab space usage).
- 3. Meals: reducing the meat content in our food by progressive shifting to flexi-

tarian, flexitarian and vegetarian, or vegetarian only meals.

4. Computer equipment: using laptops and other personal computers or workstations over longer times, shifting from an average value of about 2 years in 2019 to 4 and 6 years; this does not apply to servers or tablets or standalone screens.
5. Heating and electricity: reducing our consumption following the objectives set for the buildings sector in the “Stratégie Nationale Bas Carbone (SNBC)”<sup>9</sup>; the exact scenario for achieving this is not specified but would certainly include a better thermal insulation and some optimization of the power distribution.

The solutions considered in Table 8 outline a possible path towards a 20-30% reduction of our footprint over the restricted perimeter. Unsurprisingly, the major step would come from the evolution of our traveling habits. Such changes, however, are not so drastic since emissions from professional travel are very unevenly distributed at IRAP, with 20% (50%) of the total amount being due to 12 (45) people only. Such a concentration should in principle make it easier to efficiently tackle the problem. On top of this, an ensemble of smaller measures can provide a total reduction of about 5%, by acting on the lifetime of computer equipment or adopting different practices for commuting and meals, while an ambitious renovation plan for our buildings would lead to a 4% benefit if we achieve the national objectives of the SNBC.

Even when we ignore the contribution of astronomical research infrastructures and focus on the emissions associated with IRAP’s restricted perimeter, these measures would not achieve the target of a 50% reduction in GHG emissions by 2030. This confirms that meeting the ambitious goal recommended by IPCC for the coming decades will necessarily imply deep changes in our research culture. Over the restricted perimeter most closely controlled by IRAP, i.e. the 3258 t CO<sub>2e</sub>, achieving such reduction target will require reducing the emissions associated with the purchase of goods and services that supply IRAP’s instrument development projects. This presents an unavoidable challenge to our current relation to that facet of our activity. We cannot act on the offer of goods and services, but we can modify our demand by: (i) introducing clauses in purchase rules to disfavor/exclude suppliers not meeting certain environmental standards; (ii) restructuring our activities so as to favor less carbon-intensive purchases. These solutions go beyond IRAP and involve a progressive shift of standards that should be promoted and supported at the institutional level.

In France, the SNBC describes strategies to achieve a reduction of GHG emissions from the industrial sector by 35% by 2030, from a reference level in 2015. While this does not meet the 40-60% goal set by IPCC, it would be step in the right direction, and would contribute to reducing the emissions associated with the purchase of goods and services at IRAP. The impact of the SNBC at IRAP, however, depends on the fraction of purchases coming from French suppliers. We note, moreover, that SNBC has failed to meet its objectives over 2015-2018<sup>9</sup>, with an overall decrease of emissions

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<sup>9</sup><https://www.ecologie.gouv.fr/suivi-strategie-nationale-bas-carbone>

by 1% per year whereas more than 2% were predicted, which mechanically raises the effort to be made in subsequent years. It is increasingly clear that we cannot rely on the decarbonization of our suppliers and partners from other economic sectors to achieve a 50% reduction in GHG emissions at IRAP by 2050.

Formally at least, the predicament at IRAP is simple and is in no way specific to scientific research. As illustrated above, our carbon footprint is the product of our activity data and the carbon intensity of those activities. Reducing IRAP's carbon footprint can be achieved in three different ways: lowering the carbon intensiveness of our existing activities, reducing the pace of our activities, and changing our activities towards low-carbon alternatives. We believe we should make use of all possible levers because: (i) the magnitude of the reduction to be achieved by society within a decade requires us to act on all possible aspects of the problem; (ii) reducing and/or shifting the activity is directly under our control; and (iii) modifying our activities can have quick and direct effects, as opposed to the uncertain decarbonization trajectories of suppliers and partner organizations. These alternatives become especially acute when we consider the full scope of IRAP's GHG emissions, rather than the restricted perimeter.

We emphasize that the carbon intensity of the construction and operation of large research infrastructures is already relatively low : 140-250 t CO<sub>2</sub>e/M€ (see Sect. 4.12 and [19] for more detail). This is at the low end of sector-based emission factors published by ADEME for a broad range of activities, from ~100 t CO<sub>2</sub>e/M€ for tertiary activities with little material or technical input, to ~2000 t CO<sub>2</sub>e/M€ for heavy industries [3]. In other words, instrument development and the operation of telescopes already has a relatively low carbon intensity. Our massive footprint instead comes from the large and growing number of facilities we have at our disposal.

Our recommendation for a community-based reduction strategy would therefore be to divert a growing fraction of our budgets to fund the decarbonization of existing operational infrastructures, to pursue research and development of low-carbon technologies on which future projects will be based, and to reduce the cadence and scale of the deployment of new research infrastructures. The latter point cannot be left out of the equation, otherwise any benefit in decarbonizing existing facilities will promptly be annihilated by an increase in the number of facilities. An effective, long-term emissions reduction plan for IRAP (and astronomy research more widely) requires difficult decisions that must be made today, including for projects that are already under study. The timescales involved in the development of astronomical research infrastructures lock in our emissions for the next decades, and the problem will only be exacerbated if we continue to postpone the implementation of a far-reaching emissions reduction strategy.

## 7 Acknowledgements

We acknowledge the many colleagues who participated in this effort. We are grateful to the director of the institute, Philippe Louarn, for supporting this initiative from the very start. We warmly thank our colleagues from the administration for helping us to collect the necessary data (by alphabetical order): Marie-Pierre Arberet, Teddy Baï, Stéphanie Baylac, Pauline Bénard, Sélim Benguesmia, Jean-François Botte, Sylvie Cieutat, Marjorie Cloup, Christelle Feugeade, Josette Garcia, Jean-Louis Lefort, Danièle Millet. We also acknowledge financial support from IRAP and CNRS for the training to the “Bilan Carbone” methodology.

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