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PAPER

An open-source tool to assess the carbon footprint of research

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Abstract

The scrutiny over the carbon footprint of research and higher education has increased rapidly in the last few years. This has resulted in a series of publications providing various estimates of the carbon footprint of one or several research activities, principally at the scale of a university or a research center or, more recently, a field of research. The variety of tools or methodologies on which these estimates rely unfortunately prevents any aggregation or direct comparison. This is because carbon footprint assessments are very sensitive to key parameters (e.g., emission factors) or hypotheses (e.g., scopes). Hence, it is impossible to address fundamental questions such as: is the carbon footprint of research structurally different between disciplines? Are plane trips a major source of carbon emissions in academic research? Massive collection and curation of carbon footprint data, across a large array of research situations and disciplines, is hence an important, timely and necessary challenge to answer these questions. This paper presents a framework to collect and analyse large amounts of homogeneous research carbon emission data in a network of research entities at the national scale. It relies on an open-source web application, *GES 1point5*, designed to estimate the carbon footprint of a department, research lab or team in any country of the world. Importantly, *GES 1point5* is also designed to aggregate all input data and corresponding GHG emissions estimates into a comprehensive database. *GES 1point5* therefore enables (i) the identification of robust local or national determinants of the carbon footprint of research and (ii) the estimation of the carbon footprint of the entire research sector at national scale. A preliminary analysis of the carbon footprint of more than one hundred laboratories in France is presented to illustrate the potential of the framework. It shows that the average emissions are 479 t CO_2e for a research lab and 3.6 t CO_2e for an average lab member (respectively 404 and 3.1 t CO_2e without accounting for the indirect radiative effects of aviation), with the current scope of *GES 1point5*.

Availability and implementation: *GES 1point5* is available online at http://labos1point5.org/ges-1point5 and its source code can be downloaded from the GitLab platform at https://framagit.org/labos1point5/l1p5-vuejs.

1. Introduction

Drastic reductions of GHG emissions are needed to bend current global emission rates. After signing the Paris Agreement, many countries including France have committed to reaching carbon neutrality by 2050. These commitments require the implementation of very ambitious GHG mitigation strategies in all sectors of the economy. Although it may be expected that the direct contribution of research to national GHG emissions is relatively small, especially in comparison to other sectors of activities, academia is bound to contribute to these GHG reduction efforts for several important reasons. First, because of the role that academia plays in producing and imparting knowledge on climate change and its impacts on ecosystems and societies. Second, because scientists contribute more and more actively to the public debate around climate change mitigation and adaptation. As a consequence, their consistency and 'credibility' (Attari *et al* 2016) are more and more often scrutinized. Third and finally, because available assessments suggest that the carbon footprint of academics is above the per-capita median value in their countries of residence, (Nature Astronomy 2020; Spinellis and Louridas 2013; Fox *et al* 2009; Grémillet 2008). The work presented in this paper builds on these imperatives and thrives to contribute to making academia a leading sector in the transition towards a low-carbon society.

At the international level, only a small number of studies assess the carbon footprint of research. These studies tend to focus on one single entity such as a research department or a university (Güereca *et al* 2013; Wynes *et al* 2019), a specific event such as a conference (Spinellis and Louridas 2013; Desiere 2016; Stroud and Feeley 2015; Klöwer *et al* 2020), a single source of GHG emissions such as air-travel (Ciers *et al* 2019), a specific research project (Achten *et al* 2013; Barret 2020; Aujoux *et al* 2021), one single year (Güereca *et al* 2013), or specific instruments in a field of research (Knödlseder *et al* 2022). These estimates most often rely on widely accepted carbon footprint assessment standards. The GHG Protocol[15] offers international standards to account for GHG emissions at corporate, city or country levels. In France, *Bilan Carbone*®[16] offers a costly generic methodology (developed as a set of spreadsheets) which may be used for all sectors of the French economy. However, even when following a standard protocol, the sources accounted for may differ significantly between the reported carbon footprint estimates. This is particularly the case for scope 3 emissions (Robinson *et al* 2015; Valls-Val and Bovea 2021). To the best of our knowledge, only two studies have thrived to build a generic tool at university level, but these do not account for research activities. Finally, other tools, freely available, are designed to estimate individual or households' GHG emissions and are unfit to the research context, e.g., (myclimate) [17,18,19,20,21]

This literature, of rapidly increasing volume (Li *et al* 2021), helps us understand the size and drivers of research carbon footprints for specific fields, situations or locations. But aggregating or comparing the results of individual studies is complicated because of the known sensitivity of the carbon footprint to the methodology used. To the best of our knowledge, no studies have been designed to estimate a comprehensive carbon footprint for a wide variety of research laboratories over multiple years. When contrasted methodologies are used, comparing their carbon footprints is virtually impossible since discrepancies in the results cannot be robustly attributed to differences in GHG emissions. Comparisons are possible only at the price of numerous assumptions and *a posteriori* parameter adjustments (Helmers *et al* 2021). This overview points to two gaps that need to be addressed jointly: (i) a tool specifically designed to estimate the carbon footprint of research with a transparent and accessible methodology and (ii) a database of carbon footprints assessed with the same methodology to enable a robust comparison of research carbon footprints across institutions, contexts or disciplines.

This paper presents an open-source web application, *GES 1point5*, as part of a framework to build a comprehensive, nation-wide database on the carbon footprint of research. *GES 1point5* is freely available, and takes into account the most common and often predominant emission sources in research labs: buildings, digital devices, commuting, and professional travel. It is currently used by almost five hundred research labs in France.

[15] https://ghgprotocol.org/.
[16] https://associationbilancarbone.fr/les-solutions/.
[17] https://co2.myclimate.org/en/.
[18] https://carbonfootprint.com/.
[19] https://offset.climateneutralnow.org/footprintcalc.
[20] https://nosgestesclimat.fr/simulateur/bilan.
[21] https://goodplanet.org/en/carbon-calculator/individual/.

It is built as a web application, which makes it more user-friendly, operating system agnostic and interoperable than spreadsheets. The hypotheses, values and methodology are exhaustively and transparently presented in the tool. *GES 1point5* is developed by an interdisciplinary team of engineers and researchers from various research fields in France who interact in the *Groupement De Recherche (GDR) Labos 1point5*[22]. *Labos 1point5* gathers hundreds of scientists and research staff working together to estimate and mitigate the impacts of research activities on the environment.

More specifically, *GES 1point5* allows research labs to (i) estimate the emissions attributed to the energy consumption and refrigerant gases of their buildings, those attributed to the purchase of their digital devices, commuting, professional travel as well as the associated uncertainties, (ii) easily highlight, via a graphic interface, the drivers of their main GHG emissions, and (iii) design emission reduction actions and evaluate their mitigation effects over time. Because they rely on a standardized protocol, *GES 1point5*-based carbon footprints can be aggregated and compared between research labs, disciplines, or contexts. This will, in turn, widely increase our understanding of prevailing emission sources within research activities as well as their heterogeneity (e.g., disciplinary, sociological, or geographic). At the national scale, the data collected will allow to estimate the carbon footprint of the public research sector and thus support the exploration of evidence-based emission reduction strategies. Notwithstanding the specific institutional context of the public research sector in France, *GES 1point5* is a standardized tool that may be used in any foreign research center with minimal adjustments (see section 3.2). A French and an English version of *GES 1point5* are built-in in the current version to ease the application deployment in any country.

In the next sections, we first present the main features of the French research system, and the goals of *GES 1point5*; we then explain the methodology (section 3) and the implementation of *GES 1point5* (section 4) together with an illustration of its outputs, namely the GHG inventory and the carbon footprint of a fictitious research lab (section 5). A preliminary analysis of the typology of GHG inventories across 112 French research laboratories is presented (section 6). Future developments, research perspectives and conclusion are finally addressed.

2. Context and goals

The French research system encompasses several types of institutions[23]: national research institutes (such as CNRS, INRAe, CEA, IRD, INRIA, ...), semi-public research institutions (such as CIRAD, Ifremer, ...) and higher education institutions (such as universities, *grandes écoles*,...). These institutions take part in social structures called *laboratoires* (referred to as research labs in the following sections). Their financial contributions to the operation of research labs may be multiple, e.g. they may pay the salaries or stipends of its members, provide fixed assets such as buildings or infrastructures, and pay for resources such as supplies and electricity. A typical research lab benefits from the involvement of several public institutions. It comprises between ten and at most a few hundred members, and occupies one or several buildings. France counts over 1000 public research labs overall. According to the French legislation, all legal public entities comprising at least 250 staff members are bound to build their GHG inventory and define a mitigation action plan every three years, following a pre-defined methodology (MEEM 2016). Research labs, be they below or above the 250 member-threshold, do not have to comply with this legislation as they are not considered legal entities.

Many decisions are taken at the scale of research labs. For example, experimental designs, scientific goals, as well as access to research facilities are decided and managed at the research lab scale; a fraction of the annual budget is also managed at lab scale. Consequently, the research lab is a relevant scale to tackle the question of the research's carbon footprint. *GES 1point5* is specifically designed to address this question and meet the following goals. At the research lab scale, one should be able to analyse the carbon footprint to understand (i) the main emission sources and their relative contributions, (ii) the relative contributions of its members according to various groupings such as seniority or discipline. One should also be able to make decisions to reduce the carbon footprint of the lab and monitor the actions implemented over time. For example, contrasted mitigation decisions or policies may be experimented at lab scale to reduce emissions from professional travel (e.g., an internal carbon tax or individual emission quotas). On a smaller scale, *GES 1point5* can also be used to estimate the carbon footprint of specific research projects or research teams within the lab. On a larger scale, *GES 1point5* enables extrapolation to assess the overall carbon footprint of the research sector, and to describe the distribution of emission sources across localities or disciplines.

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[22] https://labos1point5.org/.
[23] https://sciencemag.org/careers/2006/04/finding-your-way-around-french-research-system.

3. *GES*1*point*5 methodology

To operate on a common ground, *GES 1point5* is designed to comply with the official GHG inventory methodology. It is all the more relevant as the French legislation abides by the GHG protocol standard (WRI and WBCSD 2004), which is one of the most used standards in the world. *GES 1point5* is specifically adapted to the context of research labs both in its estimation of carbon footprints and methodological choices (for example it tackles the partitioning between teaching and research). Therefore, *GES 1point5* may be virtually used by research centers in any country. In the next two subsections, we present the scope of *GES 1point5* inventory, i.e., the GHG emission sources considered, as well as the key hypotheses relative to emission factor values. Methodological choices are comprehensively presented in the *GES 1point5* online documentation.

3.1. Scope

The GHGs considered in *GES 1point5* are those of the Kyoto protocol. *GES 1point5* takes into account the most common and often predominant emission sources in research labs: buildings (through energy consumption for heating, electricity, and refrigeration processes), purchase of digital devices, commuting, and professional travel (due to the use of cars, trains, ships or planes to attend meetings or for field work).

3.2. Emission factors

Emission factors represent the amount of GHG emissions (expressed in carbon dioxide equivalent, CO_2e) generated by a unit of activity. GHG emissions are estimated as follows: for each source of emission, the amount of activity is collected or estimated, and then multiplied by the corresponding emission factor. For example, the emissions of a gasoline-fueled car over a year are calculated as the product of the kilometers traveled over the year by the emission factor of 1 km traveled.

The emission factors considered in *GES 1point5*, as well as their uncertainties mainly stem from the official ADEME database[24], which is specifically adapted to the French context. The ADEME database generally includes several types of emission factors for one source of emission.

In the case of air travel, ADEME provides four types of emission factors per passenger-kilometer traveled: a factor related to jet fuel combustion, a factor related to upstream emissions from jet fuel production, a factor related to aircraft manufacture, and a factor related to other radiative effects such as contrails (i.e., fugitive emissions). *GES 1point5* presents air-travel emissions both with and without non-CO2 radiative effects. According to (Lee *et al* 2021), 2/3 of the net warming effects of aviation are due to non-CO_2 effects, in which contrails are predominant. ADEME has chosen a radiative forcing index of 2, which leads to a contribution of 45% of non-CO_2 emissions in the global emission factor of air travel. *GES 1point5* follows the regulatory figures published by ADEME. Various actors only account for CO_2 emissions due to jet fuel combustion. This is the case of the International Civil Aviation Organisation[25]. French transportation companies, which are compelled to publish the GHG emissions generated by their services, also generally do not include the contrails of flights (Ministère de la transition écologique et solidaire 2018). By default, *GES 1point5* carbon footprint table posts air travel emissions with contrails as their contribution is more and more documented although not yet fully understood. A button added on top of the table allows the user to switch from calculations with contrails to calculations without contrails.

When emission factors are missing in the ADEME database, *GES 1point5* relies on emission factors provided in the most recent available literature together with conservative estimates for associated uncertainties. Furthermore, the interdisciplinary *GES 1point5* team has created customized emission factors to take into account specific research lab activities. For example, the application includes an emission factor for research campaigns at sea. A detailed explanation of how these emission factors have been estimated is provided in the online documentation of the tool.

Regarding digital devices, our emission factors stem from a tool developed by EcoInfo—a group focused on the footprint of digital technologies[26]. The tool is named Ecodiag[27] and emission factors include emissions from manufacturing (raw material extraction, assembly, packaging) and distribution. They are retrieved from the figures provided by manufacturers, or from default average values when the precise model is not provided or known. Emission factors are estimated for basic configurations, and for lack of a better solution, configuration options such as more powerful CPU/GPU or additional RAM and hard drives are ignored. Emissions from the on-site electricity consumption of devices are already included in the emissions of buildings. Emissions from digital devices outside the laboratory (e.g. cloud servers, calculation platforms) are not considered in this version of *GES 1point5*.

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[24] https://bilans-ges.ademe.fr/en/accueil/.
[25] https://icao.int/environmental-protection/Carbonoffset/Pages/default.aspx.
[26] https://ecoinfo.cnrs.fr/.
[27] https://ecoinfo.cnrs.fr/ecodiag-calcul/.

Figure 1. *GES 1point5* home page offers its user the opportunity to estimate GHG emissions anonymously or using an authenticated account. The application menu, on the left, allows to navigate between documentation pages and the different emission sources forms.

GES 1point5 stores around 1000 emission factors including those of more than 600 district heating systems installed in France. They are updated once a year. For example, those listed as 2020 were obtained from ADEME's carbon database at the beginning of 2021. The estimation of GHG emissions in *GES 1point5* is based on emission factor values that are the closest in time to the year of the inventory. For emission factors that are bound to change on a yearly basis, typically because the energy mix changes each year (e.g. electricity, district heating), we use the emission factor that relates to the year considered in the inventory (or the closest year if the year's emission factor is not yet available in the ADEME carbon database). For example, the emission factors for district heating available in the ADEME carbon database in December 2021 are those for 2018. Therefore, for the 2018, 2019 and 2020 GHG inventories, the calculations currently rely on 2018 emission factors.

To adapt *GES 1point5* in a country other than France, a few emission factors need to be adjusted. In particular, emission factors relating to electricity consumption (i.e., the carbon intensity of the national electric grid) and its derivatives like electric vehicles (trains, cars, bicycles) depend on the electricity generation mix of the country. The range of carbon intensities can vary by a factor of 10 or more between countries. The carbon-intensity was 79 gCO_2/kWh in France in 2013, whereas the United States, China and India reached 522, 766, and 912 gCO_2/kWh respectively the same year. (Source IEA 2013. CO_2 emissions from fuel combustion—highlights, retrieved from ADEME carbon database in January 2022). To ease the adjustment of the emission factors, they are stored within the same directory in an editable file format.
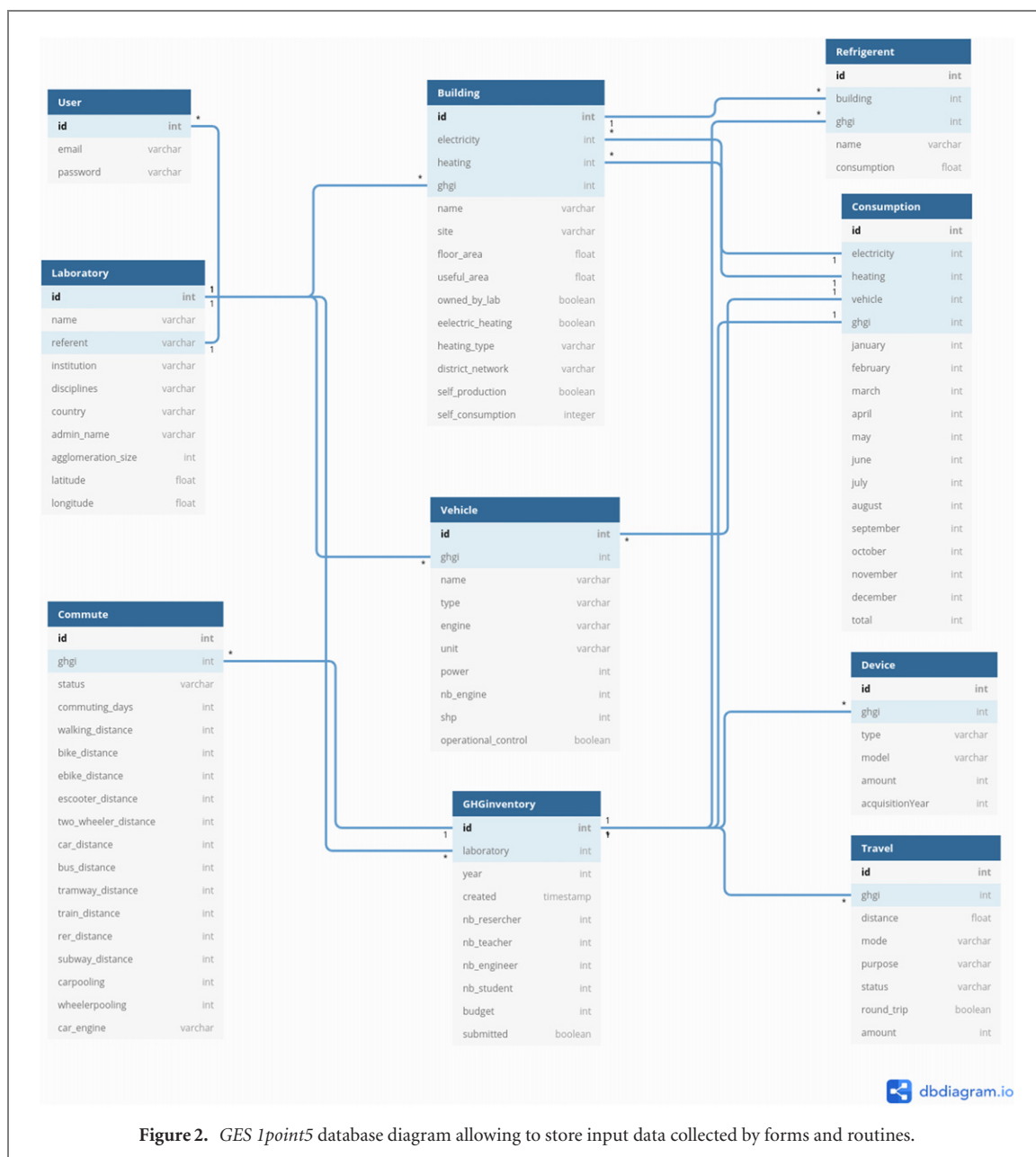
Figure 2. *GES 1point5* database diagram allowing to store input data collected by forms and routines.

4. Implementation

GES 1point5 has been implemented as a single-page web application. On the frontend side, the VueJS framework[28] and the Buefy library[29] have been chosen to build and design the user interface. On the backend side, the python-based django framework[30] coupled with the django REST library have been used to create the application programming interface (API) that interacts with the database. The application uses input information that can be gathered reasonably easily (provided support is granted by the administrative services) and converts it into a GHG footprint. For each emission source considered in *GES 1point5*, the tool converts GHG-emitting activity levels into CO_2e, using emission factors as described in section 3.2.

From its home page (figure 1), the application offers its users the opportunity to estimate GHG emissions anonymously or using an authenticated account. In the latter case, *GES 1point5* stores the entries in a database, described in figure 2, and provides output figures and tables as described in the following sections.

28 https://vuejs.org/.

29 https://buefy.org/.

30 https://djangoproject.com/.

Figure 3. Form to add a new vehicle to the inventory of the research lab. The vehicle can be either a car, a motorcycle, a bike, a scooter, an aircraft or a ship. The form requires to define the vehicle motorisation, its annual energy consumption or the number of hours/days of operation.

4.1. Inputs

To gather the required data, *GES 1point5* provides a set of forms and routines that are briefly explained below:

- General information: year of the GHG inventory; number of lab members by position (i.e., researchers, faculty, engineers, PhD students and post-doctoral fellows). These data are useful to perform statistical analyses of the emissions across the various positions, e.g. emissions from commuting, or from traveling.

- Buildings: floor area; consumption of electricity, heat, and refrigerant gases; particularities related to the generation of electricity, when applicable (e.g. use of solar panels). The floor area is used to compute emission ratios per square meter. When a laboratory covers part of its electricity consumption through self-generation, emissions relate to net consumption, i.e. the consumption metered through the power company minus self-consumption.

- Vehicles operated by the laboratory: type (e.g. car, motorcycle, aircraft); type of fuel; power, distances traveled, number of hours of operation when applicable. These data serve to compute the energy consumed by the various vehicles. Figure 3 presents the form dedicated to adding a new vehicle and entering the features needed to calculate its energy consumption.

- Digital devices purchased by the laboratory: type (e.g. desktop, server, monitor, video projector, smartphone, printer, wifi hub); brand name; model.

- Commuting: a standardized online survey dedicated to collecting the commutes of the lab members is embedded in *GES 1point5*. The survey is sent to all lab members and collects the number of commuting days per week, the modes of transportation used and the distances traveled for one or two frequent standard commutes. The data are automatically imported in *GES 1point5* and corrected for non-response by the number of lab members according to their academic position. To raise the respondent's awareness, *GES 1point5* displays an estimate of the respondent's annual commuting emissions at the end of the survey, as presented in figure 4. From this display, the respondent can simulate different commuting scenarios and thus estimate emission reduction options. Once the survey period is over, *GES 1point5* provides a curation tool to analyze the survey results and remove potential extreme answers as shown in figure 5.

- Professional travel: raw data are extracted from the information systems of the various research institutions that pay for the trips of lab members. For each trip, these data include information on date, departure and destination places (cities, countries), travel modes, travel purpose and lab member position. These data are imported as a tab-separated values (.tsv) file into *GES 1point5*. Table 1 defines the
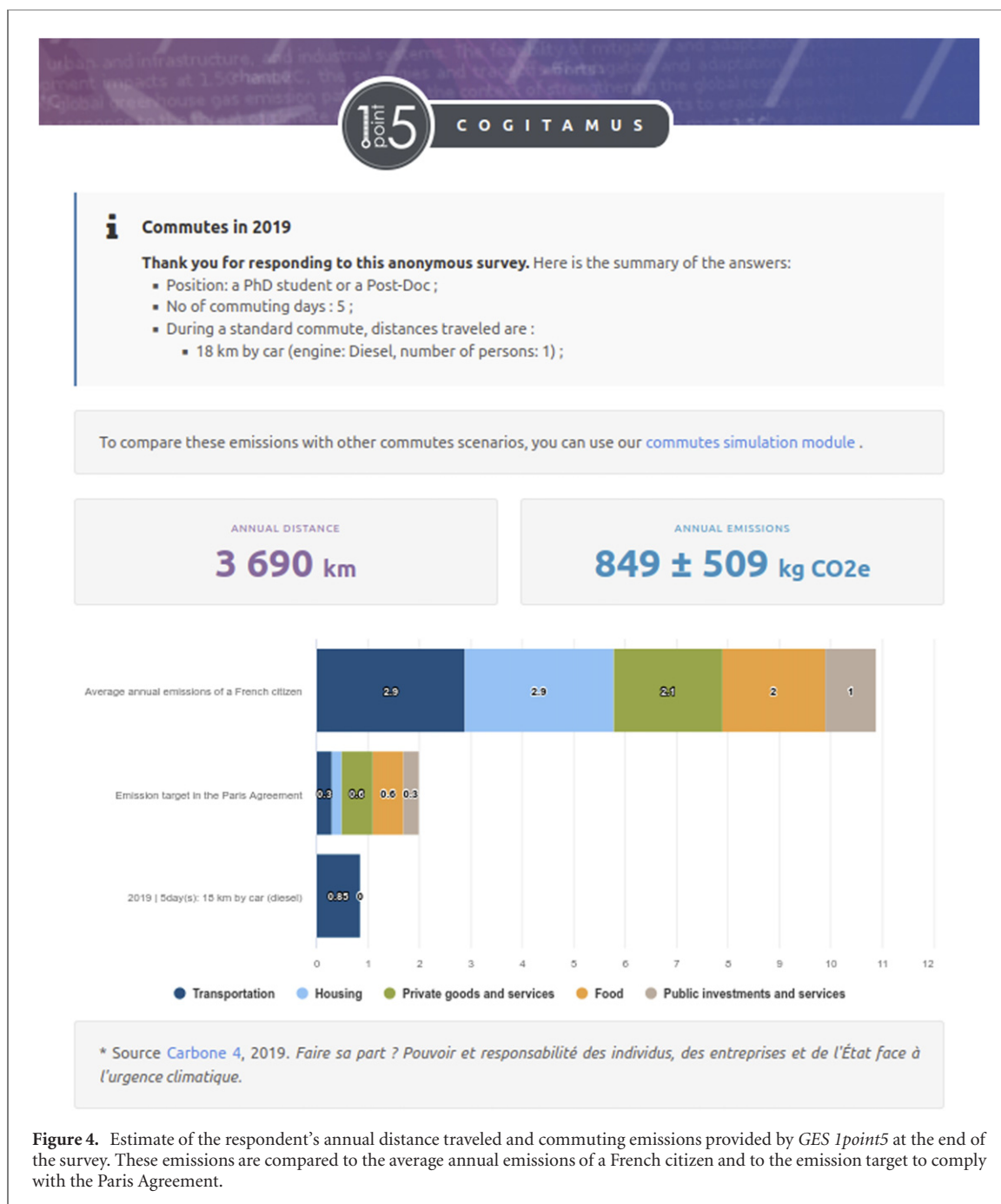
Figure 4. Estimate of the respondent's annual distance traveled and commuting emissions provided by *GES 1point5* at the end of the survey. These emissions are compared to the average annual emissions of a French citizen and to the emission target to comply with the Paris Agreement.

required format. For each leg of a trip, collected data allow to calculate the distance traveled and multiply it by the emission factor of the transportation mode used.

No personal data as defined by the European General Data Protection Regulation[31] (GDPR) is stored by GES 1point5. The commuting survey complies with the GDPR. Professional travel data are collected anonymously. Furthermore *GES 1point5* abides by strict data minimisation rules: it does not store the origin and destination locations of the professional trips; it only stores travel distances.

4.2. Outputs

As mentioned above, *GES 1point5* complies with the French legislation, which itself abides by the GHG protocol standard (WRI and WBCSD 2004). *GES 1point5* thus provides results for scope 1 (direct emissions from owned or controlled sources) and scope 2 (indirect emissions from the generation of purchased electricity, heating and cooling), as well as the following scope 3 emission categories: energy-related emissions not included in

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[31] https://eur-lex.europa.eu/eli/reg/2016/679/oj.

Table 1. Column description of the .tsv file accepted by *GES 1point5* to import professional trips relating to business travel.

Column ID	Description
Trip number	A trip is a set of legs. The trip number is a simple sequence number (from 1 to n) which allows to gather all the legs of the same trip. One line per leg of the same trip. If the return trip is different from the outward trip, extra lines must be created
Departure date	A date in dd/mm/yyyy format
Departure city	The departure city name. This field is used to obtain the departure city geographic coordinates using the *geonames* database[32]
Departure country	The departure country or its ISO3166 code
Destination city	The destination city name. This field is used to obtain destination city geographic coordinates using the *geonames* database
Destination country	The destination country or its ISO3166 code
Travel mode	This field can take a value among ['plane', 'train', 'car', 'taxi', 'bus', 'tramway', 'Paris suburban express railway including RER', 'subway', 'ferry']
Number of people in the car	In case of a trip in a car or a taxi, number of people in the vehicle
Roundtrip	If the outward and return trips are identical, enter 'YES', otherwise 'NO'
Travel purpose (optional)	This optional field allows the application to perform emission statistics based on the travel purpose. This field can take a value among ['field study', 'conference', 'seminar', 'teaching', 'collaboration', 'visit', 'research management', 'other']
Agent position (optional)	This optional field allows the application to perform emission statistics based on the agents' position. This field can take a value among ['Researcher or professor', 'Engineer, technician or assistant', 'PhD student or Post-Doc', 'Guest']

[32] https://www.geonames.org/

Figure 5. *GES 1point5* data curation tool to analyze the survey results and remove potential extreme answers.
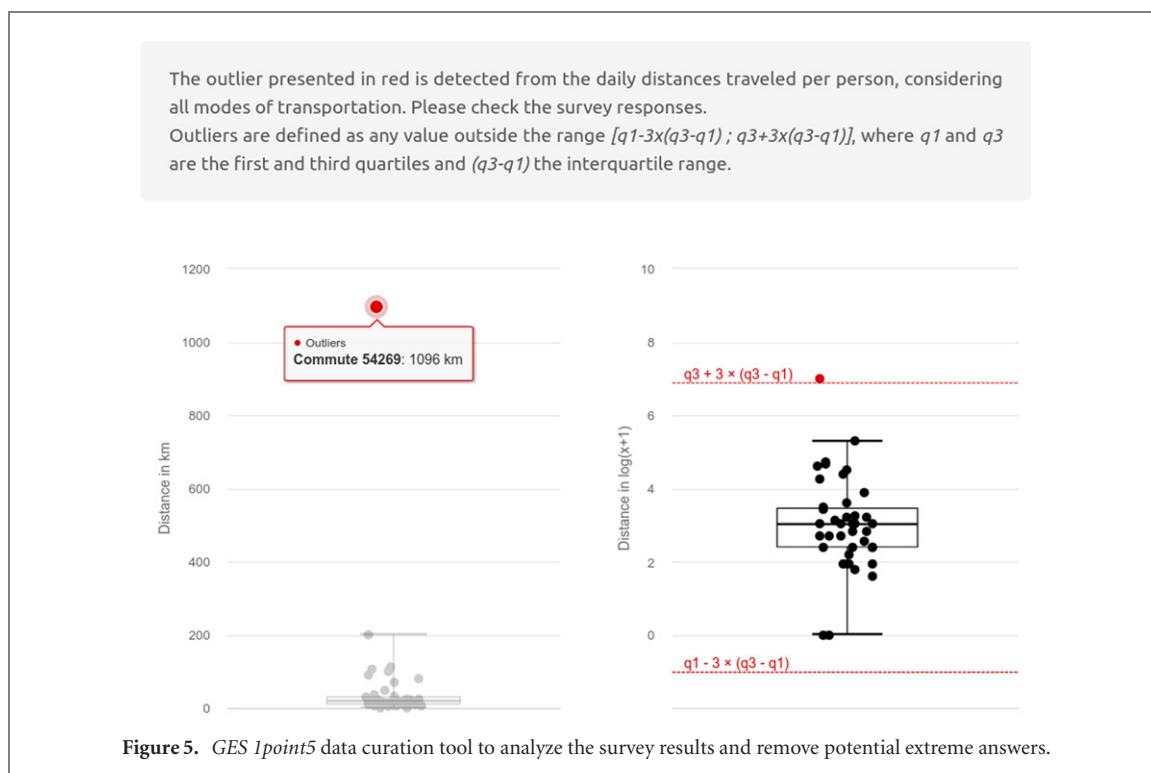
scope 1 or 2, fixed assets, business travel, employee commuting. The resulting table, presented in figure 6, can be downloaded by the user.
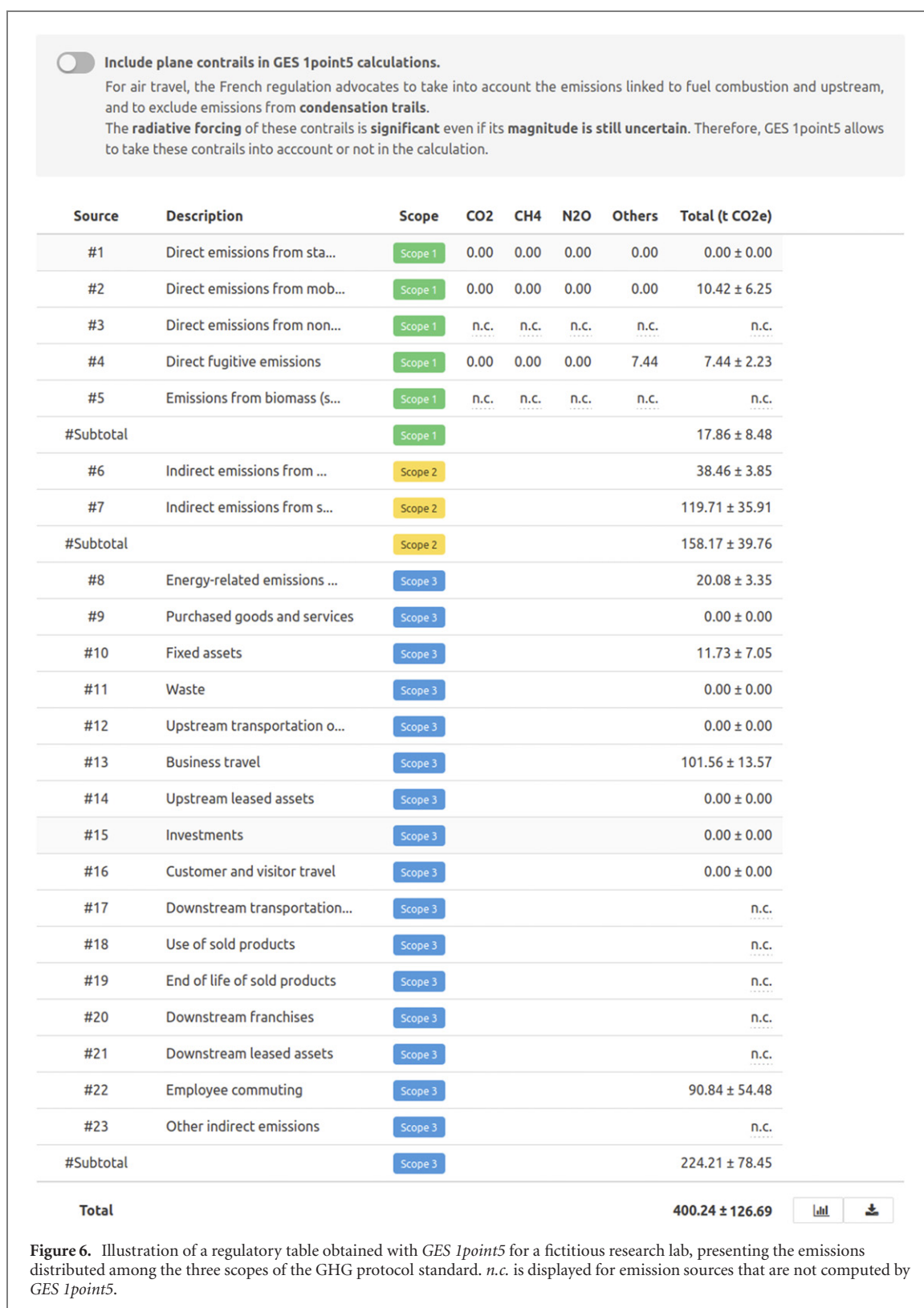
In addition to displaying GHG emissions distribution within the three regulatory and GHG protocol scopes, *GES 1point5* provides a user-friendly synthetic table and a graphical representation of carbon footprints (i.e., GHG emissions are aggregated per activity). This additional representation is designed to help users to identify predominant emission sources and decide which actions to implement in order to efficiently mitigate emissions. For example, while direct and indirect emissions generated from buildings heating and cooling systems are split among the three scopes in the regulatory display, they are aggregated in the carbon footprint representation. Similarly, the travel carbon footprint aggregates GHG emissions of vehicles, commutes and professional travels. A few additional examples are provided in figures 9 and 10. Finally, when users have entered all input data and therefore obtained regulatory and carbon footprint estimates and corresponding results in a downloadable format, they are invited to submit their data. Data are then stored in *GES 1point5* database, as described in figure 2. The submitted data contribute to the construction of a national database aggregating hundreds (as of 2022) of carbon footprints from a large variety of research labs in France. This database can be used to perform in depth research on the carbon footprint of the French public research sector as explained in section 2.

5. Results

5.1. A database of carbon footprints

Since the public release of *GES 1point5* in October 2020, more than 800 GHG inventories have been initiated by more than 470 different research labs. This evolution, presented in figure 7, shows the growing interest of French research labs in monitoring their carbon footprint as well as the software learnability and operability by non-specialists. The data thus collected contribute to the creation of a unique database to identify robust determinants of the carbon footprint of research.

Thus far, 112 GHG inventories have been submitted for the year 2019 into *GES 1point5* database, which means that they are complete and verified. Considering the current scope of *GES 1point5*, the average emissions are 479 t CO_2e for a research lab (404 t CO_2e without contrails of aviation emissions) and 3.6 t CO_2e for a lab member (3.1 t CO_2e without contrails). Note that purchased goods are not yet included in these estimates. Figure 8 shows the emissions of every source normalized by the size (headcount) of the laboratory. Figure 8 is the first ever that presents the distribution of carbon footprints between research labs at the scale of a country. Although these figures will be updated as the database grows and with the inclusion of purchased goods and services, it conveys at least two important messages. First, there are three sources of comparable emission levels, namely travel, commutes and heating while electricity, digital devices and cooling are less predominant.

⬤ **Include plane contrails in GES 1point5 calculations.**

For air travel, the French regulation advocates to take into account the emissions linked to fuel combustion and upstream, and to exclude emissions from **condensation trails**.

The **radiative forcing** of these contrails is **significant** even if its **magnitude is still uncertain**. Therefore, GES 1point5 allows to take these contrails into acccount or not in the calculation.

Source	Description	Scope	CO2	CH4	N2O	Others	Total (t CO2e)
#1	Direct emissions from sta...	Scope 1	0.00	0.00	0.00	0.00	0.00 ± 0.00
#2	Direct emissions from mob...	Scope 1	0.00	0.00	0.00	0.00	10.42 ± 6.25
#3	Direct emissions from non...	Scope 1	n.c.	n.c.	n.c.	n.c.	n.c.
#4	Direct fugitive emissions	Scope 1	0.00	0.00	0.00	7.44	7.44 ± 2.23
#5	Emissions from biomass (s...	Scope 1	n.c.	n.c.	n.c.	n.c.	n.c.
#Subtotal		Scope 1					17.86 ± 8.48
#6	Indirect emissions from ...	Scope 2					38.46 ± 3.85
#7	Indirect emissions from s...	Scope 2					119.71 ± 35.91
#Subtotal		Scope 2					158.17 ± 39.76
#8	Energy-related emissions ...	Scope 3					20.08 ± 3.35
#9	Purchased goods and services	Scope 3					0.00 ± 0.00
#10	Fixed assets	Scope 3					11.73 ± 7.05
#11	Waste	Scope 3					0.00 ± 0.00
#12	Upstream transportation o...	Scope 3					0.00 ± 0.00
#13	Business travel	Scope 3					101.56 ± 13.57
#14	Upstream leased assets	Scope 3					0.00 ± 0.00
#15	Investments	Scope 3					0.00 ± 0.00
#16	Customer and visitor travel	Scope 3					0.00 ± 0.00
#17	Downstream transportation...	Scope 3					n.c.
#18	Use of sold products	Scope 3					n.c.
#19	End of life of sold products	Scope 3					n.c.
#20	Downstream franchises	Scope 3					n.c.
#21	Downstream leased assets	Scope 3					n.c.
#22	Employee commuting	Scope 3					90.84 ± 54.48
#23	Other indirect emissions	Scope 3					n.c.
#Subtotal		Scope 3					224.21 ± 78.45
Total							400.24 ± 126.69

Figure 6. Illustration of a regulatory table obtained with *GES 1point5* for a fictitious research lab, presenting the emissions distributed among the three scopes of the GHG protocol standard. *n.c.* is displayed for emission sources that are not computed by *GES 1point5*.

Second, there is an important heterogeneity between labs (i.e., marked dispersion in the carbon footprint per source). While the first point strongly depends on the emissions sources taken into account (in particular the temporary exclusion of purchased goods), the second is a robust observation which suggests that there cannot be a *one-size-fits-all* emission mitigation solution for all the laboratories, but locally customized solutions.
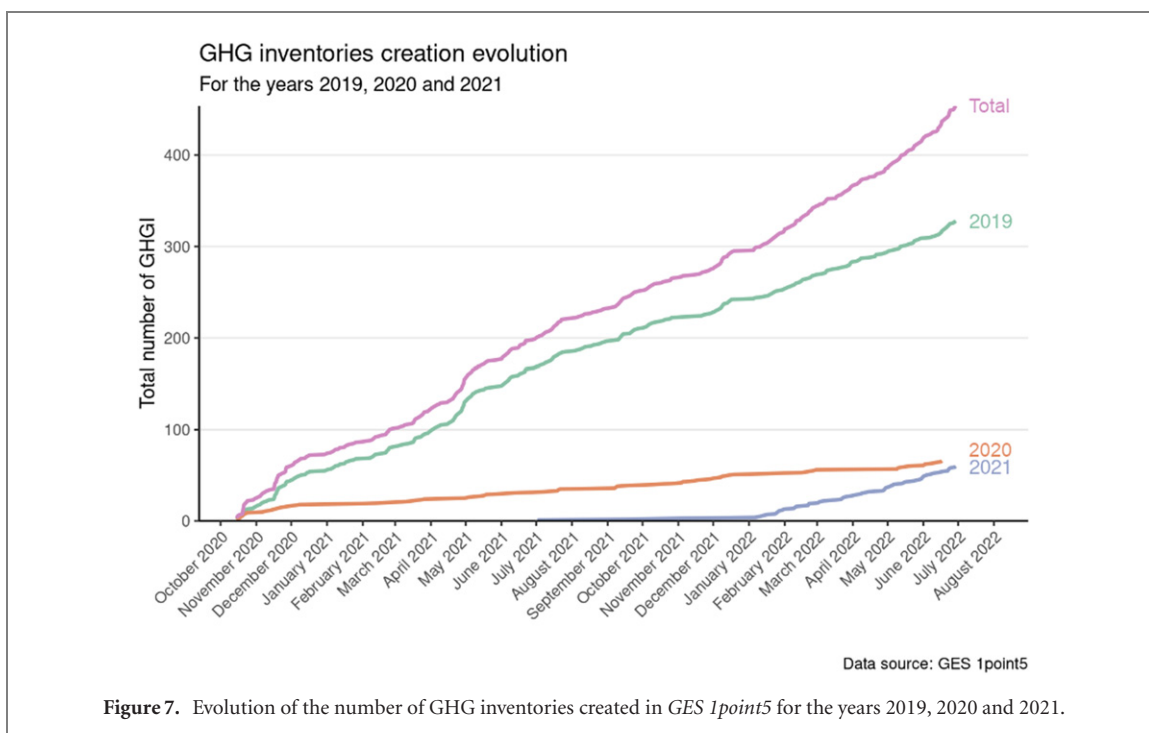
Figure 7. Evolution of the number of GHG inventories created in *GES 1point5* for the years 2019, 2020 and 2021.
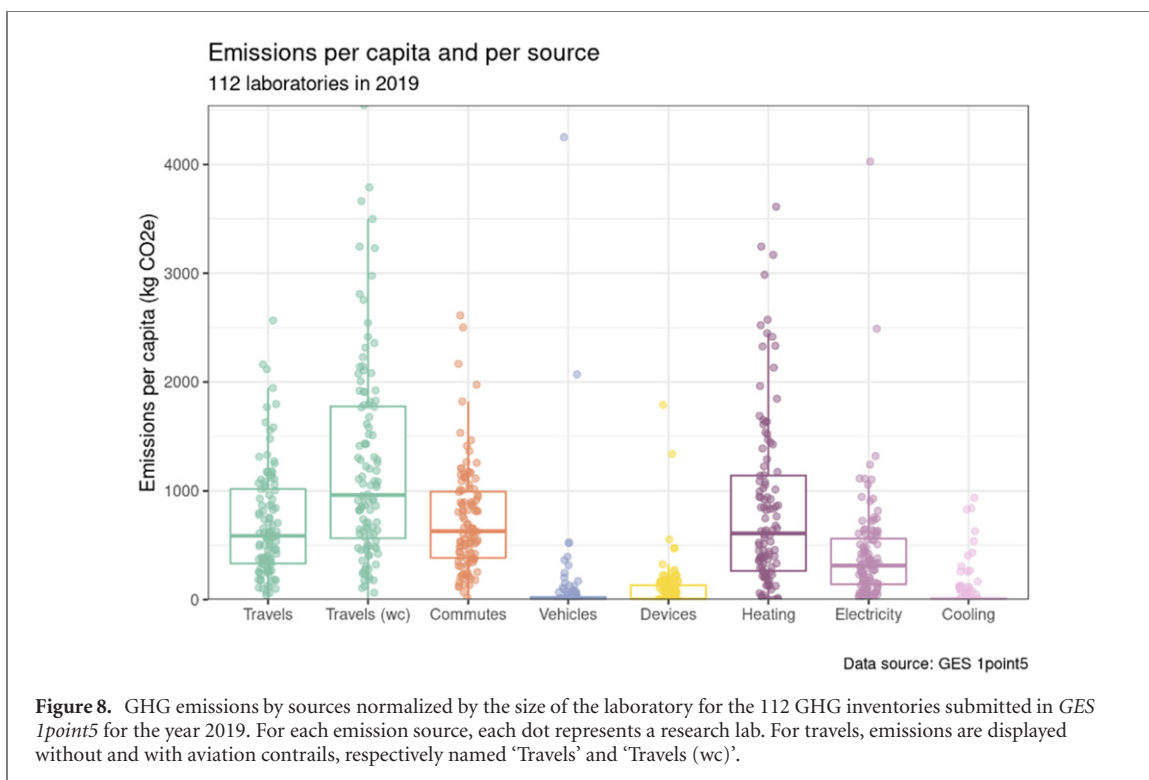
Figure 8. GHG emissions by sources normalized by the size of the laboratory for the 112 GHG inventories submitted in *GES 1point5* for the year 2019. For each emission source, each dot represents a research lab. For travels, emissions are displayed without and with aviation contrails, respectively named 'Travels' and 'Travels (wc)'.

5.2. Case study of an average laboratory in 2019

This section provides and discusses results of the 2019 carbon footprint of an average but fictitious research lab named Cogitamus. The input data are fictitious. They were built so as to reach the average and the distribution of the emissions of the 112 laboratories presented in section 5.1. This example does not provide a representative case of the French research labs since the original sample is not representative of the population of French research labs and there is a large heterogeneity between research labs. It only aims at illustrating *GES 1point5*, including its visual outputs. Cogitamus fictitious lab comprises 139 members distributed as follows: 25 researchers, 30 associate professors, 38 engineers or administrative staff and 46 PhD students or postdoctoral fellows. It is located in a city of more than 250 000 people. Its 2019 budget amounts to 2 800 000 Euros. Cogitamus occupies one building shared with another lab and 80% of the total floor space, 6400 m^2. In 2019, the fictitious building consumed 870 000 kWh LHV (lower heating value) from the Paris and neighbouring

|	CARBON FOOTPRINT OF THE LABORATORY	CARBON FOOTPRINT *PER CAPITA*	CARBON INTENSITY
	479.04 ± 238.61 t CO2e	3 606 ± 1 755 kg CO2e	171 ± 85 g CO2e / €

⬤ Include plane contrails in GES 1point5 calculations.

For air travel, the French regulation advocates to take into account the emissions linked to fuel combustion and upstream, and to exclude emissions from **condensation trails**.

The **radiative forcing** of these contrails is **significant** even if its **magnitude is still uncertain**. Therefore, GES 1point5 allows to take these contrails into acccount or not in the calculation.

Submitted	Carbon footprint	Emissions in t CO2e	Share of the total footprint			
✖	**Carbon footprint of buildings**	183.00 ± 43.73	38 %		±	◀
✖	|-- Heating	119.71 ± 35.91	25 %			
✖	|-- Electricity	55.84 ± 5.58	12 %			
✖	|-- Refrigerants	7.44 ± 2.23	2 %			
✖	**Carbon footprint of digital devices**	11.73 ± 7.05	2 %	📊	±	◀
✖	**Carbon footprint of purchases**	0.00 ± 0.00	0 %	📊	±	◀
✖	**Carbon footprint of travels**	284.32 ± 187.83	59 %			
✖	|-- Commuting	90.84 ± 54.48	19 %	📊	±	◀
✖	|-- Professional travel	193.48 ± 133.35	40 %	📊		
✖	|-- Vehicles	15.87 ± 9.52	3 %	📊	±	◀
✖	|-- Business travel	177.61 ± 123.83	37 %	📊	±	◀
✖	**Total carbon footprint**	479.04 ± 238.61	100 %	📊	±	◀
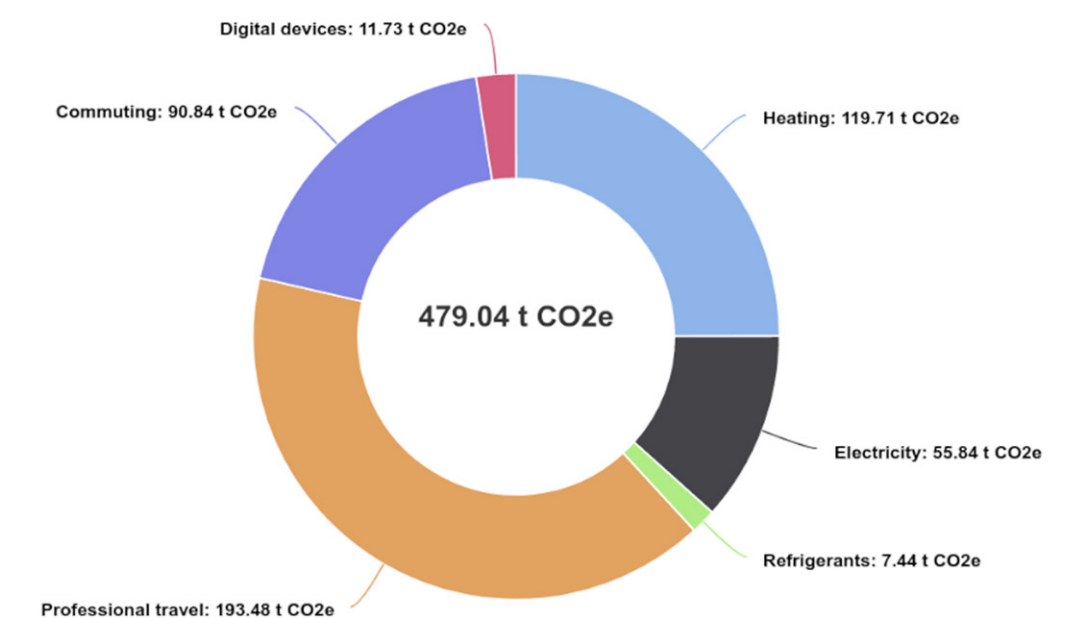
Figure 9. Illustration of the carbon footprint information provided as an output of *GES 1point5* for a fictitious lab (see text for details): table (upper panel) and pie chart (lower panel), showing the distribution of emissions in tons of CO_2e.
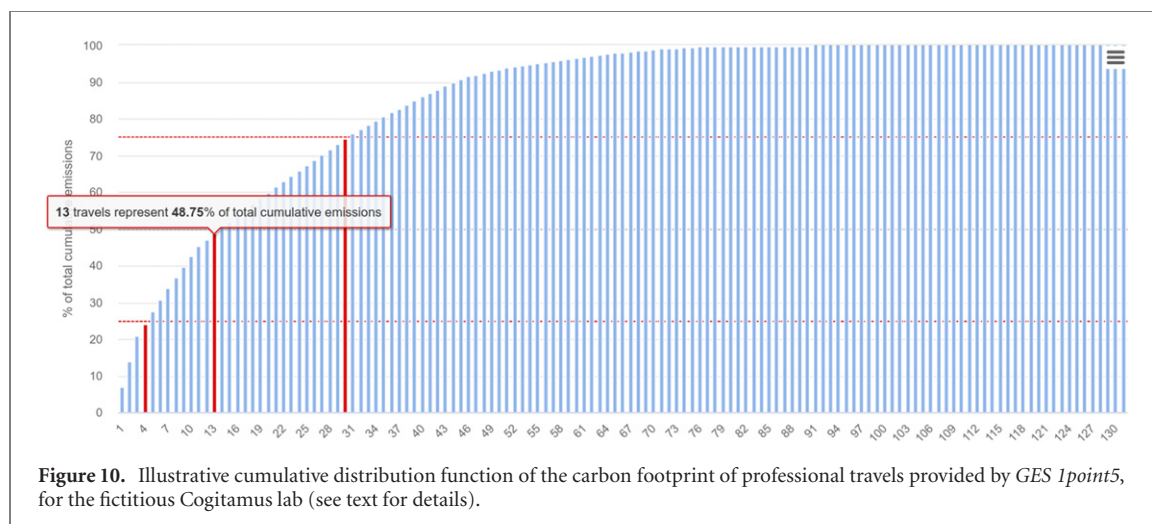
Figure 10. Illustrative cumulative distribution function of the carbon footprint of professional travels provided by *GES 1point5*, for the fictitious Cogitamus lab (see text for details).

municipalities urban heating network, 1 150 000 kWh of electricity and 0.6 kg of the R23 refrigerant gas. Cogitamus also owns three diesel cars, which traveled 69 000 km overall in 2019. For a full reproducibility of the results presented in this section, the fictitious commuting survey results[33], professional travel file[34] and digital devices inventory[35] are freely available.

Figures 6, 9 and 10 illustrate the GHG emissions inventory for Cogitamus that complies with the French regulation and the GHG protocol standard, the user-friendly carbon footprint representation, graphs excerpted from *GES 1point5*, respectively. More specifically, figures 6 and 9 display Cogitamus GHG emissions (400.24 $\pm$ 126.69 t CO_2e without aviation contrails) from two different perspectives, i.e., the regulatory GHG inventory table and the detailed carbon footprint. The latter representation also provides the lab total carbon footprint including the effects of contrails of air travel (479.04 $\pm$ 238.61 t CO_2e), the *per capita* carbon footprint (3 606 $\pm$ 1 755 kg CO_2e) and the carbon intensity of Cogitamus (171 $\pm$ 85 g CO_2e/€). Figure 9 shows that Cogitamus GHG emissions are mainly driven by professional travel (40%), followed by heating (25%) and commutes (19%).

6. Discussion and conclusion

GES 1point5 is a first step in a larger endeavour to inform on, facilitate, and enable emission reductions from research activities in France and at the international level. While an alternative lies in outsourcing both the estimation of GHG emissions and the design of reduction options, *GES 1point5* is developed to help the research community to analyse and decrease its own carbon footprint. It provides the community with a free and transparent tool designed to increase expertise and facilitate broad adoption and mitigation actions. *GES 1point5* is one of the building blocks of the *Labos 1point5* network of research labs which have committed to decreasing their carbon footprint. *GES 1point5* will have a pivotal role in the design and monitoring of mitigation trajectories and a future version will include a scenario-building tool.

The current version of *GES 1point5* focuses on a first set of common emission sources. The next version of *GES 1point5* will address emissions linked to purchased goods and services other than those already taken into account in the tool (e.g., energy consumption, numerical devices). Note that the estimation of the carbon footprint of purchased goods and services is more complex because most emission factors do not exist. For example, it is frequent to use specific chemical solvents in biology labs, with only very little information on their manufacturing and supply chains. The methodology retained by *Labos 1point5* is based on the use of monetary emission factors derived from environmentally-extended input–output analysis (Kitzes 2013; Larsen *et al* 2013). The module is currently tested and improved, in particular to adapt certain monetary emission factors to the specificities of academic research. Finally, *GES 1point5* will also aim at estimating the GHG footprint of large scale scientific infrastructures (e.g. clusters and big supercomputers, particle accelerators, telescopes, etc) that provide research services to multiple research labs. The goal is to estimate emission factors per unit of service provided so that the emissions generated by these large infrastructures may be distributed to the labs using the services.

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[33] https://cloud.le-pic.org/s/FRT9qFW72fCWSnj.
[34] https://cloud.le-pic.org/s/BCmoT7parNCCAak.
[35] https://cloud.le-pic.org/s/oQyj7cY9GHXWBcm.

With carbon footprints transparently estimated, research labs are able to design mitigation strategies based on the trade-off between emission sources. But a large fraction of the carbon footprint is related to other decision making scales such as universities, research institutes, infrastructure operators, etc. It is therefore of utmost importance to provide the means to evaluate decision options at larger scales. *GES 1point5* enables such an endeavour by aggregating a large number of local footprints.

As open source software, *GES 1point5* is freely available and can be reproduced worldwide, provided that the emission factors are country-specific. Users from research institutions around the world may find a real value added in *GES 1point5*, as it is an online tool that presents outputs not only in the GHG Protocol inventory format, but also under the more operational format of carbon footprints. This will enable a fruitful comparison between research centers worldwide to get a deeper understanding on the barriers and levers to change.

Acknowledgments

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://framagit.org/labos1point5/l1p5-vuejs.

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