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Carbon footprint and mitigation strategies of three chemistry laboratories†

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As the global imperative for decarbonization gains momentum, the need for action in chemistry laboratories becomes increasingly apparent. This study examines the 2019 carbon footprint of three French chemistry laboratories encompassing energy, purchases, travels, and commutes. The average per capita carbon footprint stands at 5.6 teqCO_2 per year, positioning chemistry laboratories slightly above the median calculated across all disciplines. Key contributors are purchases (31–42%) and heating (23–33%), driven by heavy equipment, consumables and fume hoods. Attainable mitigation strategies suggest a 40–50% reduction by 2030. Pivotal efforts involve transitioning heating sources to renewables, extending the equipment lifespan, collaborative resource management, as well as a limitation in the use of planes and combustion engine vehicles. Such changes imply actions at the level of the government, the university, the laboratory and the individual. We suggest fostering a sustainable research environment in chemistry laboratories by rationalizing experimental practices and dedicating time to consider the socio-environmental implications of research.

Introduction

Measurable proof of the accumulation of carbon dioxide in the atmosphere and its relationship with the combustion of fossil fuels for human activities was established by the chemist Charles Keeling, shortly before 1960. In the same period, the physicist Edwards Teller warned the leaders of the American Petroleum Industry against global warming and sea level rise. In addition, a report addressed in 1965 to the President Johnson by his Scientific Advisory Committee predicted marked changes in the climate by 2000.[1]

Since then, scientists have achieved numerous measurements and models that leave no doubt about the urgency and seriousness of the situation that humanity faces. These works are used and made available to the public and policy-makers through the reports of the Intergovernmental Panel on Climate Change.[2] Reducing greenhouse gas (GHG) emissions (and more broadly the environmental footprint) due to research activity has gradually become a moral imperative and a credibility issue for the scientific community. Indeed, the academic world plays a major role in the production and dissemination of knowledge on the subject, in particular through the training of students. Scientists are also prompted to contribute to the public debate on climate change and mitigation issues, and their behavior in their professional, as well as personal life, is expected to be congruent with their message.[3] Many scientists have joined calls for urgent climate action, sometimes even through civil disobedience acts.[4] Since many countries have committed to reach carbon neutrality by 2050 through the Paris Climate Change Agreement, the transition to a less GHG-emitting way of doing research is also a strategic imperative; the sooner, the better.

However, there are few publications quantifying the GHG emissions due to academic research activities.[5,6] Those that do exist often focus on the carbon footprint of large conferences or large facilities such as telescopes.[7–13] A few studies on the perimeter of a laboratory or a university were also reported.[14–20] Even fewer publications proposed reduction strategies. The most discussed aspect concerns air travel and international conferences, with the possibility of turning towards virtual events.[21–23] A number of studies focused on the consumption of single-use plastics,[24,25] which is a visible part of the goods purchased and thrown away in experimental

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† Electronic supplementary information (ESI) available: Details on the context of the study (Table S1 and Fig. S1), details on purchase/equipment, including the LCA case study on acetone distillation (Tables S1–S3), and additional figures for purchases (Fig. S2 and S3), energy (Fig. S4 and Tables S4–S6), travels/business trips (Table S7, S8 and Fig. S5), and commutes (Table S9 and Fig. S6–S8). See DOI: **https://doi.org/10.1039/d3gc03668e**

laboratories, or on the carbon footprint of analytical methods.[26,27] Few debates actively engage the scientific communities on other purchases, although they can represent a major part of the indirect emissions of an experimental lab.[28]

In this article, we focus on the case of chemical academic research. We quantify the 2019 emissions from three French chemistry laboratories that are different in size, location (Fig. S1†) and fields of expertise. The calculation protocol is based on the open-source web-application "GES 1point5" following the GHG protocol.[17] This tool was developed by academic staff within the research project Labos 1point5 to meet the specific needs of research laboratories.

Research in chemistry has several specificities that can affect emissions: (i) the consumption of various chemicals, in particular organic solvents used for synthesis, purification and cleaning; (ii) the intensive use of fume hoods that induces important demands for both electricity and heating; (iii) several devices using extreme conditions in terms of temperature (ovens, freezers and cryogenic systems), high vacuum (electron microscopes, X-ray scattering instruments), and/or high electrical power (lasers, electromagnets). They add to other activities related to office work, lab life, commutes and travels.

Here, we estimate the direct and upstream GHG emissions from energy, purchases, travel, and commutes. For each emission category, we further evaluate the objective of a 50% decrease of GHG emissions by 2030. To do so, we gather and evaluate a pool of reduction measures for chemistry laboratories which are keen to transition to low-carbon research. Such a task is the first step in the construction of a rational strategy to tackle, at the laboratory scale, the human-induced impacts of research activities on the habitability of Earth's surface.

Methods

We investigate three laboratories located in three French cities: Lille, Bordeaux and Rennes (Table 1 and Fig. S1†). The laboratories cover a wide range of chemical disciplines with some differences between laboratories: Lab 1 focuses on physical and analytical chemistry while Labs 2 and 3 also include organic and inorganic synthesis, as well as theoretical chemistry. We quantify the carbon footprint of each laboratory for the year 2019 using GES 1point5,[29] a web application specific to the research sector.[17,28] We used GES 1point5 because (i) it provides a standardized framework to assess GHG emissions from research laboratories and (ii) it is associated with a laboratory emission database gathering data from more than 100 laboratories employing more than 20 000 research staff in France. 2019 was chosen to be the last year for which consolidated data without a direct impact of the COVID pandemic were available. The data are distributed in four categories: (i) buildings (related to electricity and heating consumption of buildings), (ii) purchase of goods and services (including IT), (iii) business travels and (iv) commutes. Electricity and heating emissions are calculated from annual consumption figures from the buildings associated with each laboratory. When a single building is shared with other services, the corresponding part of energy consumption is attributed by the surface share. In 2019, the French electricity mix was composed of 70.6% nuclear, 11.2% hydraulics, 7.9% fossil combustibles (gas, coal, petrol), 6.3% wind, 2.2% solar, and 1.8% bioenergies,[30] corresponding to 60 geqCO_2 per kW h. Professional travel emissions are calculated by compiling, for each voyage, the geodesic distance and the type of vehicle with the corresponding kilometric emission factor (EF). The travel distance is calculated by multiplying geodesic distances with the following factors: 1.3 for car, 1.2 for train and suburban train, 1.7 for metro, and 1.5 for bus and tram (as implemented in GES 1point5). Emissions associated with flying include the effect of contrails. Commute emissions are determined *via* a questionnaire (managed by GES 1point5, see Commutes in the ESI† for details)[17] submitted to the following staff members: PhD students, postdocs, administrative and technical staff, assistant professors, professors and permanent researchers. They can choose up to two types of commuting distances and means of transport representative of a typical working week. The response rate was approximately 50% and the total commute emissions were proportionally extended for each socio-professional class. Purchase emissions are estimated by combining two procedures, following ref. 28. For the fraction of purchases related to office computers, emissions are evaluated per unit using supplier's EFs. For all other purchases, excluding travel tickets, emissions are calculated by multiplying their tax free price by the monetary emission factors of the GES 1point5 EF database[28] (Table S1†). This hybrid EF database combines environmentally extended input–output (EEIO) EFs with corrections that either use a life-cycle assessment (LCA) or supplier prices to estimate monetary EFs for gases, plasticware and gloves or carbon intensities from representative companies that sell certain types of goods to research labs (such as Sigma Aldrich for chemical products). All purchase-associated EFs are cradle-to-gate, *i.e.* including production and

Table 1 Chemistry laboratories investigated. Data correspond to year 2019

Lab #	Name	Staff Number	Surface m^2	Heating System	Hoods Number
Lab 1	LASIRE[31]	76	3570	Urban heating network (natural gas)	59
Lab 2	ISM[32]	222	10 000	Natural gas	217
Lab 3	ISCR[33]	468	16 447	Urban heating network (natural gas 91%, waste 9%)	315

transport to the point-of-sale. The different goods and services are identified through the NACRES accountability identification system used in French academic institutions. Annual emissions per capita are computed by dividing annual emissions by the number of staff, considering all persons working in the laboratory for the full year 2019 (including technicians and lab administrative support staff). Uncertainties are calculated according to the GES 1point5 tool.[17,28] The following emissions are not considered: emissions related to (i) building construction, (ii) the use of large research infrastructures (such as large servers, synchrotrons, *etc.*), (iii) instrumentation owned by the laboratory before 2019, and (iv) staff meals. References to the full results can be found on the GES 1point5 website: Lab 1: LASIRE;[31] Lab 2: ISM;[32] Lab 3: ISCR.[33]

Starting from the carbon footprint of the three laboratories in 2019, we identify GHG mitigation strategies for the most significant items, with the aim of reducing emissions by 50% in 2030, compared to the 2019 levels. This objective is aligned with the "Plan Climat du MESR" published in November 2022 by the French Ministry of Higher Education and Research.[34] Firstly, we review existing sustainability plans or policies at the hosting university or research center. These plans often include specific actions that could be implemented to reduce GHG emissions, such as the use of renewable energy. We prioritized these actions as they are already planned and endorsed by the hosting institution. Secondly, we conducted a review of the existing literature on GHG reduction solutions for research laboratories, including peer-reviewed articles, government reports, and sustainability guides specific to chemistry.[35,36] Finally, we engaged in discussions with colleagues in the laboratories and across the hosting institutions to gather their valuable perspectives and insights into GHG reduction solutions.

Results & discussion

Purchases and heating dominate emissions

Emissions per capita are shown in Fig. 1 for each of the three laboratories considered. The total emissions span from 4 to 6 $teqCO_2$ per pers. with a standard deviation of 1 $teqCO_2$ per pers. The variability among laboratories is significant enough to observe a difference between Lab 1 on one side, and Labs 2 and 3 on the other. Looking at emissions broken down by categories, purchases dominate emissions followed by heating for Labs 1 and 3, while the order is inversed for Lab 2. Purchases account for 32–42% of emissions per capita, while heating represents 23–33%. A 2-fold variation of heating emissions per capita is observed between Lab 1 and Lab 2, as well as a significant difference in purchase-related emissions between Lab 1 and Lab 3. The importance of the three other emission categories (electricity, travels and commutes) depends on the laboratory with the electricity share being the most variable (7–18%), followed by travels (11–16%) and commutes (8–12%). We observe that, for the three laboratories, the total emissions are of the same order of magnitude as the median emissions for the >100 laboratories in all disciplines (noted Lab 1p5) or

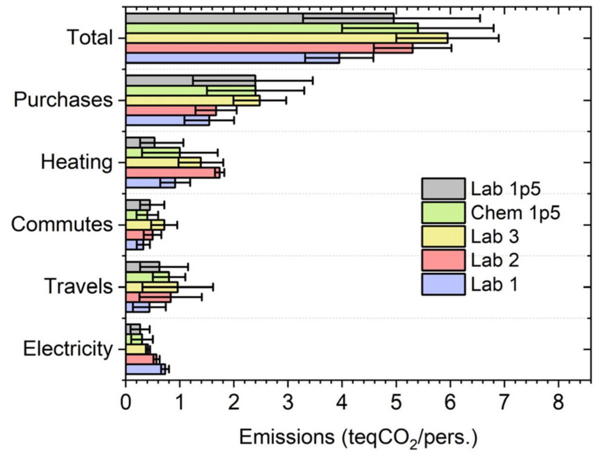

Fig. 1 GHG emissions per capita and per emission category for the three laboratories. "Lab 1p5" and "Chem 1p5" represent the median laboratory emissions from the GES 1point5 database for all disciplines (>100 laboratories) and for chemistry (9 laboratories), respectively.

for the 9 chemistry laboratories in the GES 1point5 lab emission database (noted Chem 1p5).[28] In contrast, heating and electricity emissions are 60 to 190% higher than the GES 1point5 median for the three chemistry laboratories, while heating emissions are twice larger for Chem 1p5 than for Lab 1p5 but no differences in electricity emissions were observed between these two.

Purchases

Fig. 2A displays purchase emissions per capita broken down into sub-categories. Lab equipment and consumables dominate purchase emissions for the three laboratories. Additional information is provided in Table S2† concerning the most expensive equipment acquired in Lab 2. Interestingly, the three laboratories have similar emissions associated with equipment with an average 0.9 $teqCO_2$, while consumables and other purchases (including hosting, services and lab life) are 2 to 4 times higher for Lab 3, compared to Labs 1 and 2. The remaining maintenance and IT sub-categories account for less than 20% of purchase emissions. We further analyze consumable emissions by type (Fig. 2B) and find that chemicals and laboratory supplies dominate emissions, followed by solvents and gases, and again, a significant discrepancy exists between laboratories. In particular, emissions associated with chemicals and lab supplies are 3 to 5 times higher in Lab 3 compared to the other two.

The purchases category accounts for the highest emissions in Labs 1 and 3 (Fig. 1) and, therefore, should be targeted by strong reduction actions. It is also the most challenging category as there are many different contributions to purchases, requiring an array of actions. We consider five mitigation strategies (MS): increase the lifetime of equipment by 25% (MS1) and further reduce by 25% laboratory equipment purchases by pooling (MS2), reduce by 10% the use of chemicals by pooling (MS3), reduce acetone purchases by recycling (MS4) and

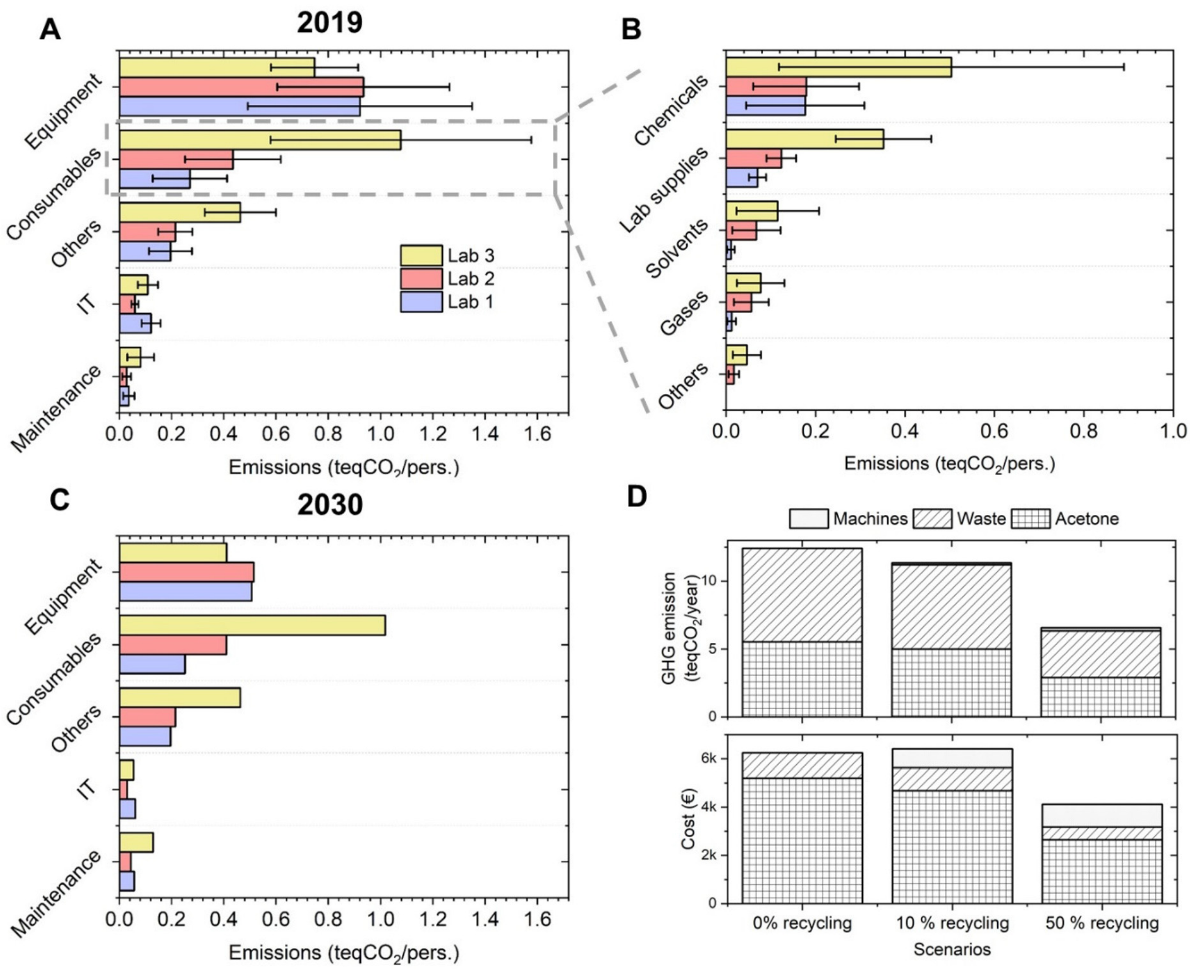

Fig. 2 Purchase emissions and mitigation strategies. A: Purchase emissions from the three laboratories in the year 2019 ("others" comprises hosting, services and lab life). B: Focus on consumables ("others" comprises biochemistry and biology supplies). C: Projected emissions in 2030 by implementation of the mitigation strategies discussed in the text. D: Comparison of yearly GHG emissions and cost associated with different acetone recycling scenarios for Lab 2. "Machines" comprise the cost and GHG emissions associated with the production and electricity consumption of the distillation/chiller system; "waste" comprises the cost of solvent destruction by an external company and GHG associated with their incineration and transport to the incinerator; "acetone" comprises the cost and GHG emissions of purchases and associated production. It also takes into account the losses by evaporation of acetone that is degraded in CO_2.

increase the lifetime of IT equipment (MS5) by 50%. As MS1 and MS2 imply an increase of maintenance, we apply an increase in their emissions by 50%. As part of the evaluation of MS4, a life cycle assessment (LCA) is conducted to estimate the effectiveness of recycling acetone in Lab 2, using a distillation/chiller unit (see Table S3† and associated text for details of the LCA methodology). The results (Fig. 2D) reveal that the emissions resulting from the purchase and use of the distillation/chiller unit are negligible. Consequently, the recycling rate achieved through this unit directly translates into a reduction in emissions associated with the production and disposal of acetone. In addition, a 50% recycling rate yields 35% economic cost savings. These findings highlight the environmental and economic benefits of recycling acetone, especially in laboratories where large quantities are consumed. Implementing a recycling system requires organizational efforts to (i) set a dedicated and safe space for recycling, (ii) adapt the chain of waste disposal and recycled solvent supply, and (iii) use the recycled solvent purposely.

The effectiveness of the mitigation strategies (Fig. 2C and S3†) is ranked similarly across all laboratories: MS2 ≥ MS1 ≫ MS5 ~ MS3 ≫ MS4. Labs 1 and 2 reduce their purchases emissions by approximately 30%, with the reduction in Lab 3 being 15%. This disparity is primarily due to the differing distribution of purchase emissions, with Lab 3 having a higher proportion of emissions due to consumables. It is worth noting that the increase of maintenance emissions is outweighed by the overall gains achieved through MS1 and MS2. Overall, the five mitigation strategies reduce total GHG emissions by 12%, 8% and 6% in Labs 1, 2 and 3, respectively.

Note that the mitigation strategies do not take consumable reduction into account, although they could be replaced by reusable glassware. Readers interested in this aspect can refer to ref. 25 which discusses single-use plastics in biological laboratories. It is crucial to assess and compare the impacts of potential solutions to ensure that they do not cause burden-shifting between life cycle stages. For instance, switching from disposable to reusable lab supplies may reduce the production of raw material and waste generated by the lab, but it may increase the environmental impact associated with cleaning and sterilization of reusable supplies.

Also, the mitigation strategies considered here are only demand-driven, meaning they are based on changes from the users at the lab. The method used to estimate purchase emissions is based on average monetary emission factors, which do not allow us to differentiate suppliers, and therefore do not consider supply-driven strategies such as purchasing more sustainable lab equipment, lab supplies, and chemicals.

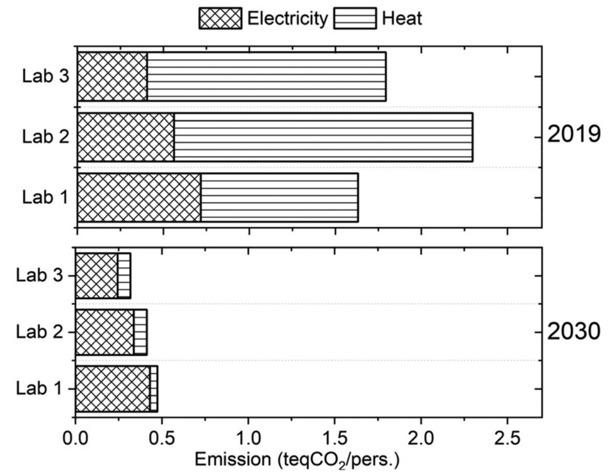

Fig. 3 GHG emissions associated with energy use per lab in 2019 (top panel) and mitigation strategies for 2030 (bottom panel) with: 40% reduction for electricity and heat; switch to 50% wood and 50% geothermal for heating systems (see Table S1† for heating systems in 2019).

Energy

Energy consumptions related to electricity and heating categories are comparable in all three labs (details in Fig. S4†) and range from 14 300 kW h per pers. (Lab 3) to 17 000 kW h per pers. (Lab 2). Such amounts are 2 to 3 times higher than the average individual French household consumption, which is approximately 6850 kW h per pers. per year.[37] The main building of Lab 2 consumes around 10 times more electricity than a similarly sized education building within the hosting university, indicating that electricity consumption is directly connected to research activities. Using fume hoods can also lead to significant heat loss as the air being exhausted is warmer (or cooler) than that being drawn from outside to compensate. Lab 1 consumes more electricity than Labs 2 and 3 by 30 and 80%, respectively, but it has 40% lower heating requirements. The discrepancies observed could be explained by (i) Lab 1 involving more physics-related activities that require electrically powered equipment, whereas (ii) Labs 2 and 3 involve more chemistry-related activities that require the use of fume hoods and subsequent heating compensation.

Energy-associated emissions (Fig. 3) range from 1.6 teqCO_2 per pers. (Lab 1) to 2.3 teqCO_2eq per pers. (Lab 2). Electricity generates less emission than heating because France has a low-carbon electricity mix (60 geqCO_2 per kW h in 2019). In comparison, the world electricity mix generated 475 geqCO_2 per kW h in 2019 with the most carbon-intensive mix reaching up to 875 geqCO_2 per kW h.[38] If the laboratories considered were to use the world electricity mix, the carbon footprint of electricity would be multiplied by 8 and the share of electricity in the total laboratory footprint would go up dramatically, to 65% for Lab 1 and 33% for Lab 3 (see Fig. 6B below). Electricity-related emissions would then dominate all other emission categories for Labs 1 and 2. Concerning heating, fuel sources vary slighlty in the three labs: Lab 2 relies on a dedicated heating network based on natural gas (227 geqCO_2 per kW h), whereas Labs 1 and 3 are furnished through a district heating network based on natural gas and waste (206 and 184 geqCO_2 per kW h resp.).

Energy management is a crucial factor in decreasing the carbon footprint of chemistry laboratories. French universities are being targeted by the government's plan for energy sufficiency launched in 2022, which aims at achieving a 40% reduction in energy consumption by 2030.[34] Examples of generic solutions taken at the scale of the University of Bordeaux[39] (host of Lab 2) include daily-life operations and infrastructures, as detailed in Table S4.† Alongside general measures, chemistry labs have several levers that are specific to their activity, such as management of fume hoods,[40–43] cooling systems (*e.g.* ultra-low temperature freezers),[41,44–46] and equipment (*e.g.* lasers). These examples are further discussed and tabulated in Table S5.† To prioritize efforts and improve mitigation strategies, a precise electricity monitoring system is essential, with submetering campaigns identifying unnecessary load/demand and ensuring equipment is not left on and forgotten. Although such a monitoring system is still absent in the studied labs, data from the Laboratory Benchmarking Tool[42] indicate that ventilation uses 35%, equipment 30%, cooling 23%, and lighting 12% electricity (from 15 US chemistry and biology labs).

Fig. 3 illustrates the potential reduction by implementing energy savings of 40% for both electricity and heat and transitioning to renewable energy sources for heating systems. These ambitious measures are in agreement with investments or regulations that are already active in the host universities/countries. Another way to reduce electricity-related emissions is to install photovoltaic panels on the laboratories' roofs and parking lots. We estimate that 30 to 50% of the electricity consumed by the laboratories in 2019 could be generated this way, which amounts to 12–30% reduction of electricity-related emissions (see ESI, Table S6†). Considering the difficulty of achieving a 40% reduction in electricity consumption, we maintain this figure in our scenario, anticipating that it will be achieved through a combination of energy savings and the in-place installation of solar panels.

Adding up all these mitigation strategies for heat and electricity, the results indicate a significant decrease in energy-related emissions, ranging from 71% in Lab 1 to 82% in Lab 2. Transitioning from gas heating to a less emissive system (such as wood or geothermal) can independently reduce the impact of heating by 90%. Notably, the decarbonization of heating systems emerges as the primary lever.

Travel/business trips

The emissions of professional travel are depicted Fig. 4 (top graph). They are dominated by long-distance (>600 km) travel by planes, which represent, in the three labs, 87 to 92% of the emissions. The prevalence is related to cumulated distances of travel by plane being 78 to 85%, as detailed in Tables S7 and Fig. S5.† Besides, trains in France are largely electric with an energy mix mostly nuclear, *i.e.* poorly carbon emissive (2 to 30 $geqCO_2$ per pers. per km depending on the type of train).[47] Interestingly, in one of the laboratories (Lab 1) the number of trips per person is half as high compared to Labs 2 and 3. In addition, trains are favored in Lab 1 with 21% of the total distance, compared to Labs 2 (17%) and 3 (13%). The smaller travel footprint of Lab 1 could be attributed to its geographic location within the Lille metropolis, a densely populated region that offers convenient train connections to Paris, Belgium, the Netherlands, and the UK.

As the predominant impact of professional trips relates to plane travels, it could be reduced either by using less impacting travel means, or by reducing the flight frequency. We assessed the following mitigation strategies on plane travels (Fig. 4) which, we believe, combine the quality of international exchange and research dissemination with the follow-up of the Cop21 agreements:

- Travels >600 km: replace 30% of long-distance journeys by online meetings,

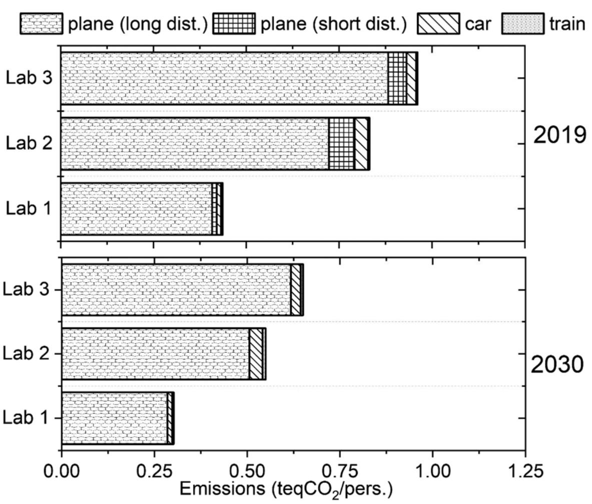

Fig. 4 GHG emissions associated with professional travels per lab in 2019 (top panel) and mitigation strategies for 2030 (bottom panel) with: short distance plane trips (<600 km) replaced by train trips and 30% long distance trips replaced by remote attendance.

- Travels <600 km: switch from plane to train. The duration of several trips below 600 km are detailed in Table S8.†

Combining both measures leads to about 30% reduction in travel emissions. To promote train *versus* plane journeys, French institutions ruled that trains should be imposed for trips less than 3 to 4 h long. To improve the acceptability of longer train journeys, the use of first class would enable staff to work remotely in a comfortable space not afforded in planes. Other incentives may be implemented, such as an extra hotel night to adapt to train schedules, and specific support such as child care for single parents. The train attractiveness (cost, duration, frequency) is also dependent on (i) investing in the train network and (ii) tax strategies for planes and trains. For reasons of both social equality and care for the environment, evaluating researchers on the basis of the number of conferences they attend per year (*e.g.*, ERC applications) has become inappropriate.

Commutes

The emissions related to commutes are evaluated *via* a survey which is detailed in the ESI (Fig. S6–8 and Table S9†). The results show that in Labs 2 and 3, the main means of transportation is the car (mostly combustion engine), while in Lab 1, it is the subway. The three labs are directly connected to bus, tramways, metro and or train networks, so the disparities are not *a priori* due to infrastructures. The second finding is that young researchers (PhD, post doc) demonstrate a higher inclination towards using the least emissive transportation (public transport, walking, and cycling) than permanent staff. This is possibly due to a shorter commuting distance, lower costs, and perhaps a greater environmental sensitivity.

Cars are responsible for 91, 82 and 86% of the emissions due to commutes, and they emit 0.3, 0.4 and 0.6 $teqCO_2$ per pers. for Labs 1, 2 and 3, respectively (Fig. 5). This is because cars are the primary mode of commuting, while France's decarbonized electricity leads to low-GHG public transportation.

In 2019, prior to the COVID-19 pandemic, homeworking was limited in the three laboratories: according to our data, 75% of Lab 1 employees commuted to work five days a week, while this percentage was 85% for Labs 2 and 3. Remote research is limited to non-experimental tasks. Yet, remote work allows for literature research, writing articles/grants, data analysis, placing orders, and creating equipment usage protocols. However, telecommuting might lead to rebound effects like longer commutes for those relocating or increased heating expenses for home-based work.[48,49] These effects have not been taken into account because we considered the emissions of staff at home to be outside the scope of the study.

We focus commute mitigation measures on replacing cars with strategies that depend on the home-to-work one-way distance (Fig. 5):

- $0 \leq 5$ km: trips made by combustion engine cars are substituted by bicycle or walk

- $5 \leq 10$ km: trips made by combustion engine cars are substituted by electric bicycles (50%) or by subway/train (50%)

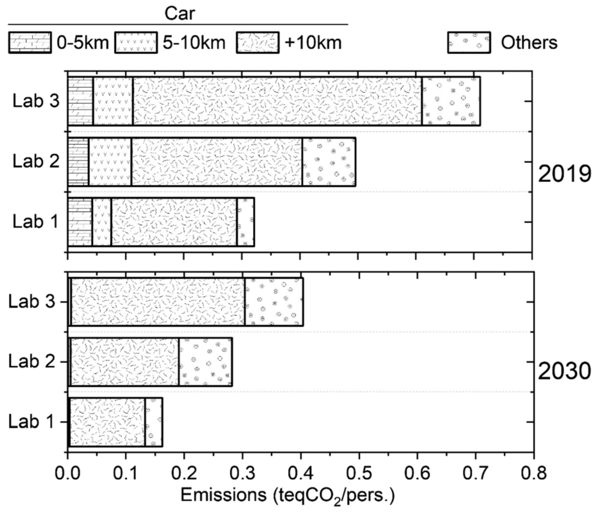

Fig. 5 GHG emissions associated with commutes per lab in 2019 (top panel) and mitigation strategies for 2030 (bottom panel) with 0–5 km: trips made by combustion engine cars are made by bicycle or walking; 5–10 km: trips made by combustion engine cars are made by electric bike or subway/train; +10 km: trips made by combustion engine cars are made either by electric car or by carpooling (2 person per car) + people work from home 1 day per week on average. Distances are one-way home-to-work.

- +10 km: trips made by combustion engine cars are substituted by electric cars (33%) or by carpooling with 2 persons per car (33%). In addition to this, 33% of people work from home 1 day per week.

- Travels made by any means of transportation except combustion engine cars are kept unchanged.

Once again, we have selected these measures for their ease of implementation and their low associated cost (bicycle, public transportation, carpooling). Since 2020, in order to encourage employees to go to work by bicycle or by carpooling, the French government provides financial support (200€–300€ per year per employee).

Summary of the actions

Fig. 6 summarizes emissions in 2019 and projected for 2030 if all the mitigation strategies discussed above were to be implemented. The result is encouraging, with a total reduction in emissions in the range of 40–55% for the three laboratories. If we consider absolute reductions by category, heating represents 40–50% of the reduction effort, followed by purchases (15–25%) and electricity (5–15%), and then travel and commutes (5–10% each). In this scenario, half of the reduction effort depends on the institution (heating) while the other half is directly controlled by the laboratory personnel. When we look at the relative reduction by category, heating emissions are divided by 20, while the other four categories, on average, go down by 20–45% of their initial value.

If the laboratories were located in regions where the electricity mix was highly carbon emissive, decarbonizing the mix would be the most efficient strategy, primarily impacting the electricity and train travel categories. For example, if a virtual lab (calculated as a weighted average of our 3 labs) using the world electricity mix in 2019 switched to a decarbonized mix, such as the French one, it would reduce its carbon footprint by

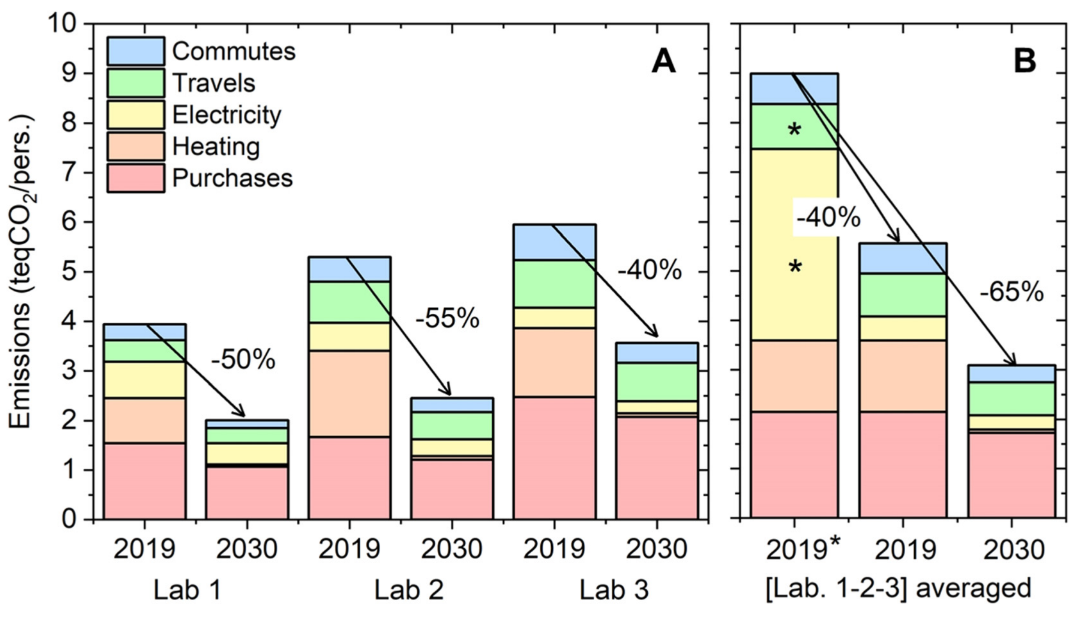

Fig. 6 Analysis of the mitigation scenario for the three laboratories. GHG emissions by category in 2019, and projected in 2030, if the mitigation strategies discussed in this work were implemented A: Data for laboratories 1, 2 and 3. B: Data for a virtual laboratory whose emissions are the weighted average of the emissions of the three laboratories [Lab. 1–2–3]. 2019 emissions are given considering the electricity world mix (affecting travels and electricity, marked with *, left bar) or the French electricity mix (center bar). 2030 projections are given using the French electricity mix (right bar).

40%, with the potential for a total reduction of 65% by 2030 considering the sum of all the suggested actions (Fig. 6B).

Conclusion & outlook

Our calculations of the 2019 carbon footprint for the three laboratories yield an average carbon footprint per researcher of *ca.* 5.6 $teqCO_2$. This ranks chemistry laboratories slightly higher than the median of 5.0 $teqCO_2$, calculated on the basis of 100 laboratories from all disciplines using the same methodology.[28] It is important, for such comparisons, to pay attention to any possible variation in scope. A recent study from Martin *et al.* showed a yearly 28 $teqCO_2$ per pers. emission for an astronomical institute.[19] However, Martin *et al.*'s work includes specific large research infrastructures. Specific large facilities such as characterization platforms and synchrotrons are also used in chemistry, but were not considered in this study. Larsen *et al.* obtained 14 $teqCO_2$ per pers. for the Department of Natural Sciences of a Norwegian Technical University, including building construction and central administration. If these two categories were not considered, the GHG emission would be 7 $teqCO_2$ per pers., which is close to our results.[20]

One limitation of our study is the use of monetary emission factors for assessing the GHG emissions of purchases. LCA based on physical flows is in principle more precise if the inventory of materials can be made and if the full production cycle is well-known. However, this is rarely the case for scientific purchases. Firstly, laboratory accountability is monetary, not by mass, and thus mass inventories of purchases are difficult to make. Secondly, LCA does not give accurate results for niche products where the share of production costs is small relative to the share of research and development.[28,50] This is related to the well-known truncation problem in LCA: emissions associated with R&D activities such as heating, commuting, travel and investments are rarely taken into account because they are unknown, resulting in underestimated EFs. As a result, a cooperative effort between researchers and suppliers is needed to refine emission factors of laboratory supplies and equipment. Other categories have their own bias. For instance, one could argue that staff responding to the commuting questionnaire are the ones most concerned about environmental issues. It is also important to recognize that assessing the carbon footprint alone provides an incomplete understanding of the overall environmental impact of the laboratories. Other environmental factors, such as the emission of toxic, acidifying and eutrophying substances, water use and resource depletion, have to be considered. For example, the adoption of electric cars is associated with higher mineral resource usage compared to combustion engine cars, and the utilization of wood for heating can generate fine particles. Thus, it is recommended to conduct LCAs to assess specific mitigation strategies and avoid burden shifting. From a broader perspective, the use of LCA can help chemists to identify the most impactful stages and materials in their research and product development.[27,51]

Altogether, our mitigation strategies show a possible reduction of 40 to 55% for the three laboratories, which is very encouraging. However, this implies a combination of actions at the level of the government (*e.g.* public transportation), the university (*e.g.* thermal isolation of buildings) and the individual (*e.g.* appropriate use of the fume hood sashes). Collective actions are generally difficult to implement, unless strong incentives are given by the administration. Similarly, individual actions (such as reducing flying for professional purposes) are easier to accept when one feels that others share the burden. In addition, the organization of the academic system itself has a strong impact on the environmental burden of research. Indeed, a number of works identified how professional success is associated with international travel.[13,52] International collaborations and invitations to international conferences as invited scientists are considered as markers of scientific excellence. Moreover, the current funding model, which prioritizes project-based investments, tends to favor purchasing new equipment, whereas a more sustainable approach could be achieved by allocating resources to hiring additional staff for equipment maintenance and the design of customized solutions. Beyond research policy, the whole society has evolved towards an intensive use of technology. As in other sectors, the access to innovative technologies has pushed academics to carry out numerous and more sophisticated experiments, potentially compromising the depth of academic contributions. Rationalizing the experimental part of research[53] (by identifying useless experiments and oversized analysis) should lead to a significant decrease of the environmental impact of research. Additionally, substantial financial savings could be redirected to recruit people to achieve administrative tasks or take environmental actions. Some researchers may also decide to spend more time teaching, rethink the purpose of their research, or organize transitions. In particular, more efforts could be devoted to green chemistry and energy savings.

Overall, conducting research from a sustainable development perspective requires a multidisciplinary approach. Social sciences are particularly important, since they can help in anticipating the behavior of collectives with respect to current environmental challenges and in accompanying the change toward more sustainable research.

Abbreviations

CF	Carbon footprint
EF	Emission factor
GHG	Greenhouse gases
MS	Mitigation strategy
LCA	Life cycle assessment
$teqCO_2$	Ton of equivalent CO_2

Author contributions

All the authors contributed equally to the preparation of the manuscript and gave approval to the final version.

Conflicts of interest

There are no conflicts to declare.

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References

1 B. Franta, *Nat. Clim. Change*, 2018, **8**, 1024–1025.
2 V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, Y. Chen, L. Goldfarb, M. I. Gomis, J. B. R. Matthews, S. Berger, M. Huang, O. Yelekci, R. Yu, B. Zhou, E. Lonnoy, T. K. Maycock, T. Waterfield, K. Leitzell and N. Caud, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate ChangeClimate Change 2021: The Physical Science Basis*, IPCC, Cambridge University Press, Cambridg, 2021.
3 S. Z. Attari, D. H. Krantz and E. U. Weber, *Clim. Change*, 2016, **138**, 325–338.
4 S. Capstick, A. Thierry, E. Cox, O. Berglund, S. Westlake and J. K. Steinberger, *Nat. Clim. Change*, 2022, **12**, 773–774.
5 L. A. da Silva, A. R. de A. Dutra, T. C. Soares, R. S. Birch and J. B. S. O. de A. Guerra, *IJSHE*, 2023, **24**, 584–601.
6 K. Valls-Val and M. D. Bovea, *Clean Technol. Environ. Policy*, 2021, **23**, 2523–2542.
7 S. Portegies Zwart, *Nat. Astron.*, 2020, **4**, 819–822.
8 M. Klöwer, D. Hopkins, M. Allen and J. Higham, *Nature*, 2020, **583**, 356–359.
9 S. Jäckle, in *Academic Flying and the Means of Communication*, ed. K. Bjørkdahl and A. S. Franco Duharte, Springer Nature Singapore, Singapore, 2022, pp. 19–52.
10 A. R. H. Stevens, S. Bellstedt, P. J. Elahi and M. T. Murphy, *Nat. Astron.*, 2020, **4**, 843–851.
11 C. Aujoux, K. Kotera and O. Blanchard, *Astropart. Phys.*, 2021, **131**, 102587.
12 L. Burtscher, H. Dalgleish, D. Barret, T. Beuchert, A. Borkar, F. Cantalloube, A. Frost, V. Grinberg, N. Hurley-Walker, V. Impellizzeri, M. Isidro, K. Jahnke and M. Willebrands, *Nat. Astron.*, 2021, **5**, 857–860.
13 O. Berné, L. Agier, A. Hardy, E. Lellouch, O. Aumont, J. Mariette and T. Ben-Ari, *Environ. Res. Lett.*, 2022, **17**, 124008.
14 I. Leon, X. Oregi and C. Marieta, *Sustainable Cities Soc.*, 2018, **42**, 396–406.
15 J. Fry, M. Lenzen, Y. Jin, T. Wakiyama, T. Baynes, T. Wiedmann, A. Malik, G. Chen, Y. Wang, A. Geschke and H. Schandl, *J. Cleaner Prod.*, 2018, **176**, 1254–1270.
16 L. P. Güereca, N. Torres and A. Noyola, *J. Cleaner Prod.*, 2013, **47**, 396–403.
17 J. Mariette, O. Blanchard, O. Berné, O. Aumont, J. Carrey, A. Ligozat, E. Lellouch, P.-E. Roche, G. Guennebaud, J. Thanwerdas, P. Bardou, G. Salin, E. Maigne, S. Servan and T. Ben-Ari, *Environ. Res.: Infrastruct. Sustain.*, 2022, **2**, 035008.
18 J. Cooper, M. Bird, S. Acha, P. Amrit, B. Chachuat, N. Shah and O. Matar, *Procedia CIRP*, 2023, **116**, 444–449.
19 P. Martin, S. Brau-Nogué, M. Coriat, P. Garnier, A. Hughes, J. Knödlseder and L. Tibaldo, *Nat. Astron.*, 2022, **6**, 1219–1222.
20 H. N. Larsen, J. Pettersen, C. Solli and E. G. Hertwich, *J. Cleaner Prod.*, 2013, **48**, 39–47.
21 J. Yates, S. Kadiyala, Y. Li, S. Levy, A. Endashaw, H. Perlick and P. Wilde, *Lancet Planet. Health*, 2022, **6**, e164–e170.
22 S. H. Y. Tseng, C. Lee and J. Higham, *Transp. Res. Part D: Transp. Environ.*, 2022, **113**, 103504.
23 V. Reyes-García, L. Graf, A. B. Junqueira and C. Madrid, *J. Cleaner Prod.*, 2022, **368**, 133174.
24 J. Kilcoyne, Y. Bogan, C. Duffy and T. Hollowell, *PLOS Sustain. Transform.*, 2022, **1**, e0000001.
25 L. Howes, *ACS Cent. Sci.*, 2019, **5**, 1904–1906.
26 P. M. Nowak, A. Bis, M. Rusin and M. Woźniakiewicz, *Green Anal. Chem.*, 2023, **4**, 100051.
27 B. Raccary, P. Loubet, C. Peres and G. Sonnemann, *Adv. Sample Prep.*, 2022, **1**, 100009.
28 M. De Paepe, L. Jeanneau, J. Mariette, O. Aumont and A. Estevez-Torres, Purchases Dominate the Carbon Footprint of Research Laboratories, bioRxiv April 14, 2023, p 2023.04.04.535626. DOI: 10.1101/2023.04.04.535626.
29 Labos 1point5, GES 1point5, https://apps.labos1point5.org/ges-1point5, (accessed July 25, 2023).
30 RTE, *Bilan électrique 2019*, 2019.
31 GES 1point5 and Lasire, BGES 2019 du Lasire, https://apps.labos1point5.org/ges-1point5-results/505787c5-3a5a-4b36-bf72-244289b47b9e, (accessed July 25, 2023).
32 GES 1point5 and ISM, BGES 2019 de l'ISM, https://apps.labos1point5.org/ges-1point5-results/ddbcca6e-8a6e-4e9e-93af-c746dbc4358b.
33 GES 1point5 and ISCR, BGES 2019 de l'ISCR, https://apps.labos1point5.org/ges-1point5-results/9f8aa53f-ee22-424c-a136-445de4697062, (accessed July 25, 2023).
34 Ministère de l'enseignement supérieur et de la recherche, *Plan de sobriété énergétique*, 2023.
35 J. Durgan, M. Rodríguez-Martínez and B. Rouse, *Immunol. Cell Biol.*, 2023, **101**(4), 289–301.

36 Sustainable laboratories - practices to reduce the environmental effects of research, https://www.rsc.org/new-perspectives/sustainability/sustainable-laboratories/, (accessed March 8, 2023).
37 Eurostat, Final energy consumption in households per capita, https://ec.europa.eu/eurostat/databrowser/view/sdg_07_20/default/table?lang=en, (accessed July 25, 2023).
38 Emissions – Global Energy & CO_2 Status Report 2019 – Analysis, https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions, (accessed June 20, 2023).
39 Univ Bordeaux, Le plan de sobriété énergétique de l'université de Bordeaux, https://www.u-bordeaux.fr/actualites/plan-sobriete-energetique, (accessed July 25, 2023).
40 E. Mills and D. Sartor, *Energy*, 2005, **30**, 1859–1864.
41 My green lab, https://www.mygreenlab.org/, (accessed July 25, 2023).
42 International Institute for Sustainable Laboratories, The Laboratory Benchmarking Tool, https://lbt.i2sl.org/, (accessed July 25, 2023).
43 S. Posner, R. Stuart and G. Thompson, *J. Chem. Health Saf.*, 2011, **18**, 34–42.
44 L. A. M. Gumapas and G. Simons, *World Rev. Sci., Technol. Sustain. Dev.*, 2013, **10**, 129–141.
45 C. Drahl, *ACS Cent. Sci.*, 2018, **4**, 1294–1297.
46 A. Espinel-Ingroff, D. Montero and E. Martin-Mazuelos, *J. Clin. Microbiol.*, 2004, **42**, 1257–1259.
47 SNCF, Information sur la quantité de gaz à effet de serre émise à l'occasion d'une prestation de transport. Méthodologie générale., https://medias.sncf.com/sncfcom/pdf/co2/Information_CO2_des_prestations_de_transport_Methodologie_generale.pdf.
48 Y. Shi, S. Sorrell and T. Foxon, *Energy Build.*, 2023, **287**, 112996.
49 S. Simon and W. O'Brien, *Building Cities*, 2023, **4**, 174–192.
50 D. Font Vivanco, *Int. J. Life Cycle Assess.*, 2020, **25**, 280–293.
51 D. Kralisch, D. Ott and D. Gericke, *Green Chem.*, 2015, **17**, 123–145.
52 S. Wynes, S. D. Donner, S. Tannason and N. Nabors, *J. Cleaner Prod.*, 2019, **226**, 959–967.
53 R. Mincigrucci, *Nat. Photonics*, 2023, **17**, 375–375.

