



Carbon footprint and mitigation strategies of three chemistry laboratories

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1 **Carbon footprint and mitigation strategies of three chemistry**
2 **laboratories**

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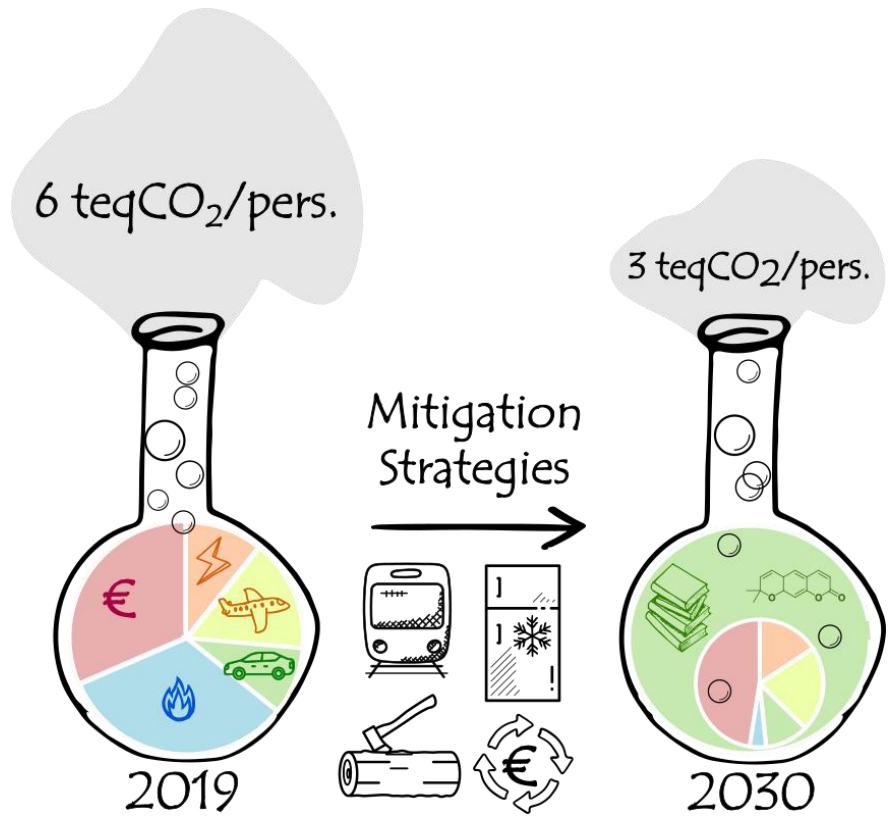
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23 **KEYWORDS** Sustainability, greenhouse gas, decarbonization, life cycle assessment, environment,
24 sustainable research

25 **ABSTRACT:**

26 As the global imperative for decarbonization gains momentum, the need for action in
27 chemistry laboratories becomes increasingly apparent. This study examines the 2019
28 carbon footprint of three French chemistry laboratories encompassing energy,
29 purchases, travels, and commutes. The average per capita carbon footprint stands at
30 5.6 teqCO₂/year, positioning chemistry laboratories slightly above the median
31 calculated across all disciplines. Key contributors are purchases (31–42%) and heating
32 (23–33%), driven by fume hoods, heavy equipment and consumables. Attainable
33 mitigations strategies suggest a 40-50% reduction by 2030. Pivotal efforts involve
34 transitioning heating sources to renewables, extending equipment lifespan,
35 collaborative resource management, as well as a limitation in the use of planes and
36 thermic cars. Such changes imply actions at the level of the government, the university
37 and the individual. We suggest fostering a sustainable research environment in
38 chemistry laboratories by rationalizing experimental practices and dedicating time to
39 consider the socio-environmental implications of research.

40 Graphical abstract

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44

45 **Introduction**

46 Measurable proofs of the accumulation of carbon dioxide in the atmosphere and its
47 relation with the combustion of fossil fuels for human activities were established by the
48 chemist Charles Keeling, shortly before 1960. At the same period, the physicist
49 Edwards Teller warned the leaders of the American Petroleum Industry against global
50 warming and sea level rise. In addition, a report addressed in 1965 to the president
51 Johnson by its Scientific Advisory Committee, predicted marked change in the climate
52 by 2000.¹

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

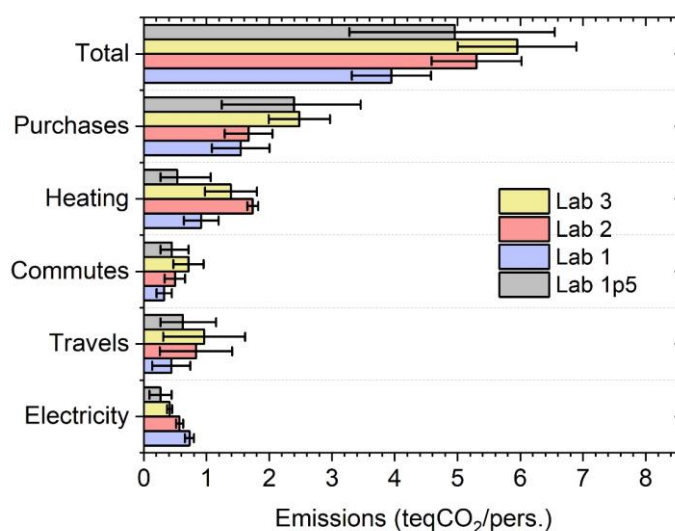
68 However, there are still few publications quantifying the GHG emissions of academic
69 research activities.^{5,6} Those that do exist often focus on the carbon footprint of large
70 conferences or large facilities such as telescopes.⁷⁻¹³ A few studies on the perimeter of
71 a laboratory or a university were also reported.¹⁴⁻²⁰ Even fewer publications propose
72 reduction strategies. The most discussed aspect concerns air travel and international
73 conferences, with the possibility to turn towards virtual events.²¹⁻²³ A number of studies
74 focus on the consumption of single-use plastics,^{24,25} which is a visible part of the goods
75 purchased and thrown away in experimental laboratories. Few debates animate the
76 scientific communities on other purchases, although they can represent a major part of
77 the indirect emissions of an experimental lab.²⁶

78 In this article, we focus on the case of chemical academic research. We quantify the
79 emissions of three French chemistry laboratories that are different in size, location
80 (**Figure S1**) and fields of expertise. The calculation protocol is based on the open-
81 source web-application GES 1point5 following the GHG protocol.¹⁷ This tool was
82 developed by academic staff within the research project Labos 1point5 to meet the
83 specific needs of research laboratories. Research in chemistry has several specificities
84 that could affect its emissions: (i) the consumption of various chemicals, in particular
85 organic solvents used for synthesis, purification and washing; (ii) the intensive use of
86 fume hoods that induces important demands on both electricity and heating; (iii) several
87 devices using extreme conditions by means of temperature (ovens, freezers and
88 cryogenic), high vacuum (electron microscopes, spectrometers), and/or high electrical
89 power (lasers, electromagnets). They add-up to other activities related to the office
90 work, lab life, commutes and travels.

91 In this work, we estimate the direct and upstream GHG emissions from energy,
 92 purchases, travels, and commutes for three laboratories in 2019. For each emission
 93 category we further evaluate the objective of a 50 % decrease of GHG emissions by
 94 2030. To do so, we gather and evaluate a pool of reduction measures for chemistry
 95 laboratories which are keen to transitioning to low-carbon research. Such a work is a
 96 first step in the construction of a rational strategy to tackle, at the lab scale, the human-
 97 induced impacts of research activities on the livability of Earth surface.

98 Results & Discussion

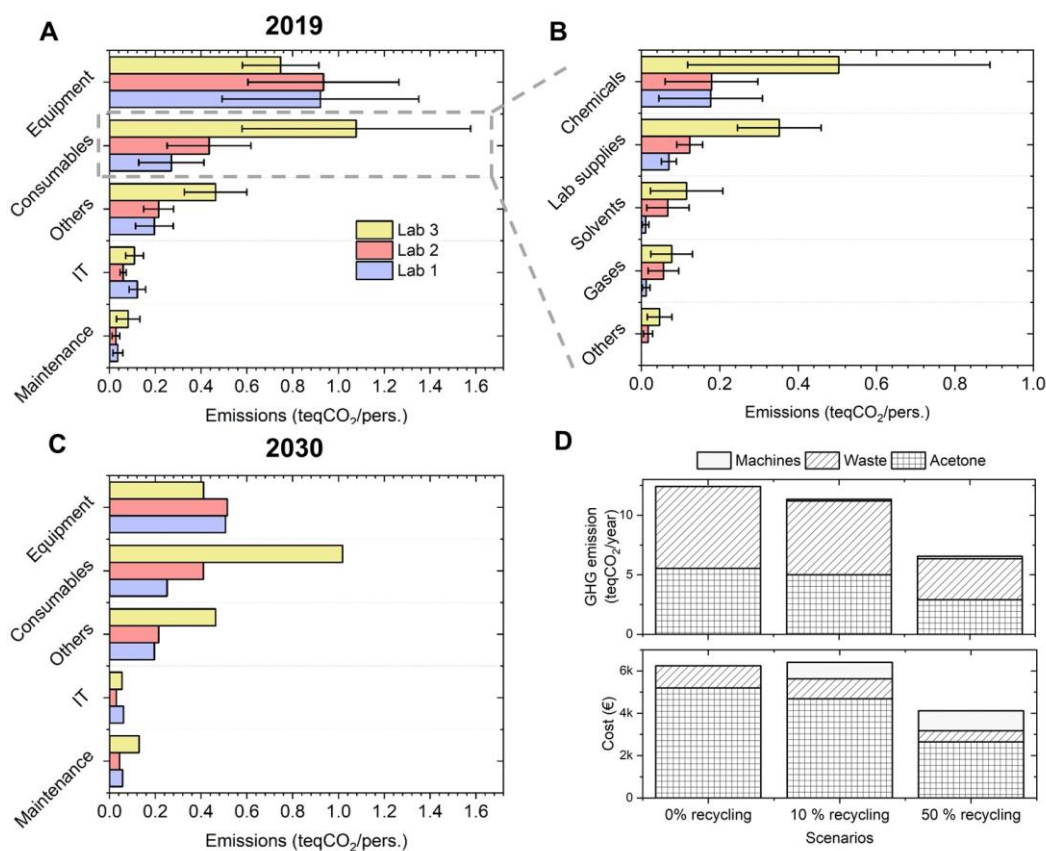
99 **Purchases and heating dominate emissions.** Emissions per capita are displayed on
 100 **Figure 1** for each of the three laboratories considered. The total emissions span from 4
 101 to 6 teqCO₂/pers. with a standard deviation of 1 teqCO₂/pers. The variability among
 102 laboratories is significant enough to observe a difference between Lab 1 on one side,
 103 and Labs 2 and 3 on the other. Looking at emissions broken down by categories,
 104 purchases dominate emissions followed by heating for Labs 1 and 3, while the order is
 105 inverted for Lab 2. Purchases account for 31-42 % of emissions per capita, while
 106 heating represents 23-33 %. A 2-fold variation of heating emissions per capita is
 107 observed between Lab 1 and Lab 2, as well as a significant discrepancy in purchase-
 108 related emissions between Lab 1 and Lab 3. The importance of the three other emission
 109 categories (electricity, travels and commutes) depends on the laboratory with the
 110 electricity share being the most variable (7-18 %), followed by travels (11-16 %) and
 111 commutes (8-12 %). We observe that, whatever the chemistry laboratory studied here,
 112 the total emissions are equal or higher to the median emissions calculated from the
 113 laboratory database of the GES 1point5.²⁶ In particular, heating and electricity
 114 emissions are 60 to 190 % higher than the GES 1point5 median for the three chemistry
 115 laboratories. In the following sections, we detail the analyses of emissions per category,
 116 and the associated mitigation strategies.



117 **Figure 1.** GHG emissions per capita for the three laboratories per emission category. Gray: “Lab 1p5”
 118 represents the median laboratory emissions from the GES 1point5 database (>100 laboratories from all
 119 disciplines).
 120

121 **Purchases**

122 **Figure 2A** display purchases emissions per capita broken down by sub-category. Lab
 123 equipment and consumables dominate purchases emissions for the three laboratories.
 124 Additional information is provided in **Table S3** concerning the most expensive
 125 equipment acquired in Lab 2. Interestingly, the three laboratories have equivalent
 126 emissions associated to equipment with an average 0.9 teqCO₂, while consumables and
 127 other purchases (including hosting, services and lab life) are 2 to 4 times higher for
 128 Lab 3, compared to Lab 1 and 2. The remaining maintenance and IT sub-categories
 129 account for less than 20 % of purchases emissions. We further analyze consumables
 130 emissions by type (**Figure 2B**) and find that chemicals and lab supplies dominate
 131 emissions, followed by solvents and gases, and again, a significant discrepancy exists
 132 between laboratories. Especially, emissions associated to chemicals and lab supplies
 133 are 3 to 5 times higher in Lab 3 compared to the two others.



134

135 **Figure 2.** Purchases emissions and mitigation strategies. A: Purchases emission from the three
 136 laboratories for year 2019 (“others” comprises hosting, services and lab life). B: Focus on consumables
 137 (“others” comprises biochemistry and biology supplies). C: Projected emissions in 2030 by
 138 implementation of the mitigation strategies discussed in the text. D: Comparison of yearly GHG
 139 emissions and cost associated with different acetone recycling scenarios for Lab 2. “Machines”
 140 comprise the cost and GHG emissions associated to the production and electricity consumption of the
 141 distillation/chiller system; “Waste” comprises the cost of solvents destruction by an external company
 142 and GHG associated to their incineration and transport to the incinerator; “Acetone” comprises the
 143 cost and GHG emissions of purchases and associated production. It also takes into account the losses
 144 by evaporation of acetone that is degraded in CO₂.

145 Purchases category is the most emitting in Labs 1 and 3 (**Figure 1**) and, therefore,
 146 should be targeted by strong reduction actions. It is also the most challenging category

147 as there are many different contributions to purchases, requiring an array of actions.
148 We consider five mitigation strategies (MSs): increase the lifetime of equipment by
149 25 % (MS1) and further reduce by 25 % lab equipment by pooling (MS2), reduce by
150 10 % the use of chemicals by pooling (MS3), reduce acetone purchases by recycling
151 (MS4) and increase by 50 % the lifetime of IT equipment (MS5). As MS1 and MS2
152 imply an increase of maintenance, we apply an increase of their emissions by 50 %. As
153 part of the evaluation of MS4, a life cycle assessment (LCA) is conducted to estimate
154 the effectiveness of recycling acetone in Lab 2, using a distillation/chiller unit
155 (**Table S4**). The results (**Figure 2D**) reveal that the emissions resulting from the
156 purchase and use of the distillation/chiller unit are negligible. Consequently, the
157 recycling rate achieved through this unit directly translates into a reduction in emissions
158 associated with the production and disposal of acetone. In addition, a 50% recycling
159 rate yields 35% economic cost savings. These findings highlight the environmental and
160 economic benefits of recycling acetone, especially in laboratories where large
161 quantities are consumed. Implementing a recycling system requires organizational
162 efforts to (i) set a dedicated and safe space for recycling, (ii) adapt the chain of waste
163 disposal and recycled solvent supply, and (iii) use the solvent purposely.

164 The effectiveness of the mitigation strategies (**Figure 2C and S2**) is ranked similarly
165 across all laboratories: $MS2 \geq MS1 \gg MS5 \sim MS3 \gg MS4$. Labs 1 and 2 reduce their
166 emissions by approximately 25 %, Lab 3 reduction being 15 %. This disparity is
167 primarily due to the differing distribution of purchases emissions, Lab 3 having a higher
168 proportion of emissions due to consumables. It is worth noting that the increase of
169 maintenance emissions is outweighed by the overall gains achieved through MS1 and
170 MS2. Overall, the five mitigation strategies reduce total GHG emissions by 12 %, 8 %
171 and 6 % in Labs 1, 2 and 3, respectively.

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

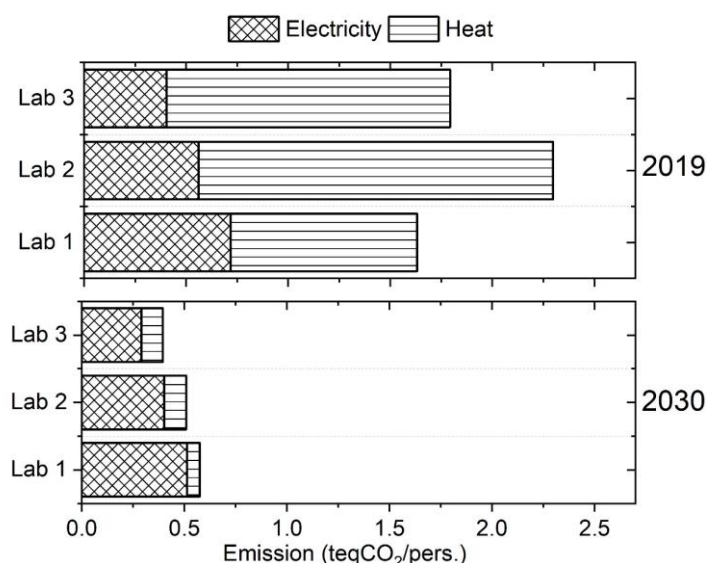
180 Also, the mitigation strategies considered here are demand-driven only, meaning they
181 are based on changes from the users at the lab. The method used to estimate purchase
182 emissions is based on average monetary emission factors, which does not enable to
183 differentiate suppliers. and therefore considering supply-driven strategies. As a result,
184 it is not possible to take into account supply-driven strategies include purchasing more
185 sustainable lab equipment, lab supplies, and chemicals.

186 **Energy**

187 The energy consumption related to electricity and heating categories are comparable in
188 all three labs (details in **Figure S3**) and ranges from 14 300 kWh/pers. (Lab 3) to
189 17 000 kWh/pers. (Lab 2). Such amounts are 2 to 3 times higher than the average
190 individual French houses consumption, which is approximately 6 850 kWh/pers/year.²⁷
191 The main building of Lab 2 consumes around 10 times more electricity than a similarly-
192 sized education building within the hosting university, indicating that electricity
193 consumption is directly connected to research activities. Using fume hoods can also

194 lead to significant heat loss as the air being exhausted is warmer (or cooler) than that
 195 being drawn from outside to compensate. Lab 1 consumes more electricity than Labs 2
 196 and 3 by 30 and 80 %, respectively, but it has less heating requirements by 40 %. The
 197 discrepancies observed are explained by (i) Lab 1 involves more physics-related
 198 activities that require electrically powered equipment, whereas (ii) Labs 2 and 3 have
 199 more chemistry-related activities that require the use of fume hoods and subsequent
 200 heating compensation.

201 Energy-associated emissions (**Figure 3**) range from 1.6 teqCO₂/pers (Lab 1) to
 202 2.3 teqCO₂/pers. (Lab 2). Electricity generates less emissions than heating because
 203 France has a low-carbon electricity mix (60 geqCO₂/kWh in 2019). In comparison, the
 204 world electricity mix generated 475 geqCO₂/kWh in 2019.²⁸ If the laboratories
 205 considered were to use the world electricity mix, the carbon footprint of electricity
 206 would be multiplied by 8 and the share of electricity in the total laboratory footprint
 207 would go up dramatically, to 65 % for Lab 1 and 33 % for Lab 3. Electricity-related
 208 emissions would then dominate all other emission categories for Lab 1 and 2.
 209 Concerning heating, fuel sources vary in the three labs: Lab 2 only relies on natural gas
 210 (227 geqCO₂/kWh), whereas Lab 1 and 3 are furnished through a district heating
 211 network based on natural gas and cogeneration (206 and 184 geqCO₂/kWh resp.).



212
 213 **Figure 3.** GHG emissions associated with energy use per lab in 2019 (top) and mitigation strategies for
 214 2030 (bottom) with: 40 % reduction for electricity and heat; switch to 50 % wood and 50 % geothermal
 215 for heating systems (see Table S1 for heating systems in 2019).

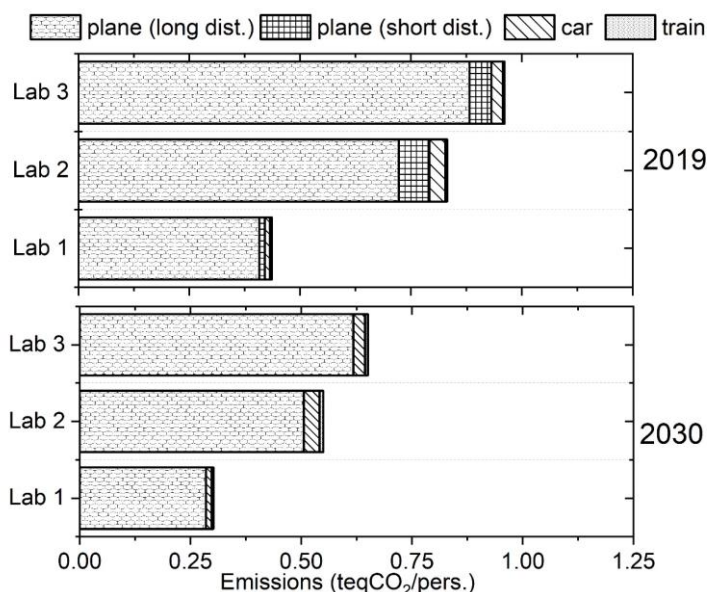
216 Energy management is a crucial factor in decreasing the carbon footprint of chemistry
 217 laboratories. French universities are being targeted by the government's plan for energy
 218 sufficiency launched in 2022, which aims to achieve a 40 % reduction in energy
 219 consumption by 2030.²⁹ Examples of generic solutions taken at the scale of the
 220 University of Bordeaux³⁰ (host of Lab 2) include daily-life operations and
 221 infrastructures, as detailed in **Table S5**. Alongside general measures, chemistry labs
 222 have several levers that are specific to their activity, such as management of fume
 223 hoods^{31–34}, cooling systems (e.g. ultra-low temperature freezers),^{32,35–37} and equipment
 224 (e.g. lasers). These examples are further discussed in **Table S6**. To prioritize efforts, a
 225 precise electricity monitoring system is needed. Although it is absent in the studied
 226 Labs, data from the Laboratory Benchmarking Tool³³ indicates ventilation uses 35 %,

227 equipment 30 %, cooling 23 %, and lighting 12 % of electricity (from 15 US chemistry
 228 and biology labs).

229 **Figure 3** illustrates the potential reduction by implementing energy savings of 40 %
 230 and transitioning to renewable energy sources for heating systems. The results indicate
 231 a significant decrease in emissions, ranging from 65 % in Lab 3 to 78 % in Lab 2.
 232 Notably, the decarbonization of heating systems emerges as the primary lever.

233 **Travels/business trips**

234 The emissions of professional travels are depicted **Figure 4** (top graph). They are
 235 dominated by long-distance (> 600km) travels by planes, which represent, in the three
 236 labs, 87 to 92 % of the emissions. The prevalence is related to cumulated distances of
 237 travels by plane being 76 to 82 %, as detailed in **Table S7**. Besides, trains in France are
 238 largely electric with an energy mix mostly nuclear, i.e. poorly carbon emissive (2 to 30
 239 $\text{geqCO}_2/\text{pers.}/\text{km}$ depending on the type of train)³⁸. Interestingly, in one of the
 240 laboratories (Lab 1) the number of trips per person is half as high compared to Lab 2
 241 and 3. In addition, trains are favored in Lab 1 with 21 % of the total distance, compared
 242 to Labs 2 (17 %) and 3 (13 %). The smaller travel footprint of Lab 1 could be attributed
 243 to its geographic location within the Lille metropolis, a densely populated region that
 244 offers convenient train connections to Paris, Belgium, the Netherlands, and the UK.



245 **Figure 4.** GHG Emissions associated with professional travels per lab in 2019 (top) and mitigation
 246 strategies for 2030 (bottom) with: short distance plane trips (< 600 km) replaced by train trips and 30 %
 247 long distance trips replaced by remote attendance.
 248

249

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

255 - *Travels > 600km*: replace 30 % long distance journeys by online conferences,

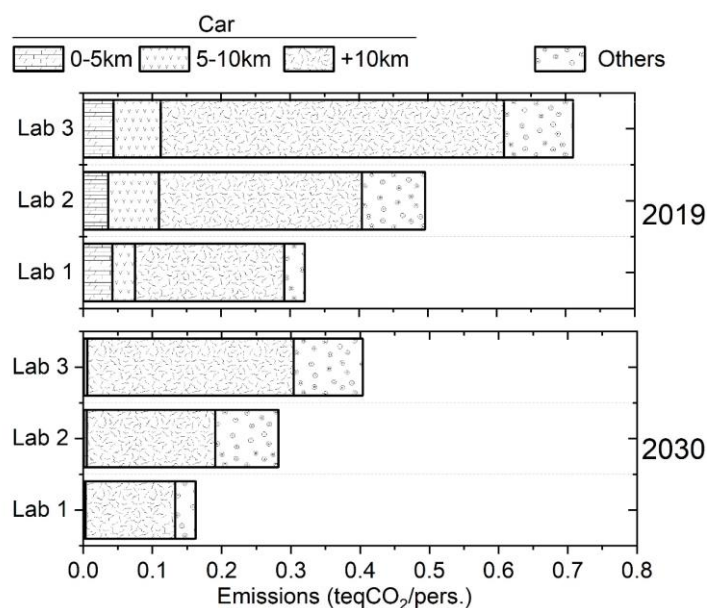
256 - *Travels < 600km*: switch from plane to train. The duration of several trips below
257 600 km are detailed in **Table S8**.

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

268 **Commutes**

269 The emissions related to commutes are evaluated via a survey which is detailed in the
270 supplementary information (**Figures S5-7 and Table S9**). The results show that in Lab
271 2 and 3, the main means of transportation is the car (mostly thermic), while in Lab 1 it
272 is the subway. The three labs are directly connected to bus, tramways, metro and or
273 trains, so the disparities are not *a priori* due to infrastructures. The second finding is
274 that young researchers (PhD, post doc) demonstrate a higher inclination towards using
275 the least emissive transportations (public transport, walking, and cycling) than
276 permanent staff. This is possibly due to a shorter commuting distance, lower costs, and
277 perhaps a greater environmental sensitivity.

278 Cars are responsible for 91, 82 and 86 % of the emissions due to commutes, and they
279 emit 0.3, 0.4 and 0.6 teqCO₂pers. for Labs 1, 2 and 3, respectively (**Figure 5**). This is
280 because cars are the primary mode of commuting, while France's decarbonized
281 electricity leads to low-GHG public transport.



282

283 **Figure 5.** GHG Emissions associated with commutes per lab in 2019 (top) and mitigation strategies for
 284 2030 (bottom) with 0-5 km: trips made by thermic car are made by bicycle or walking; 5-10 km: trips
 285 made by thermic car are made by electric bike or subway/train; +10km: trips made by thermic car are
 286 made either by electric car or by carpooling (2 person/car) + people work from home 1 day per week on
 287 average. Distances are one-way home-to-work.

288 In 2019, prior to the COVID-19 pandemic, homeworking was hardly spread in the three
 289 laboratories: according to our data, 75 % of Lab 1 employees commuted to work five
 290 days a week, while this percentage was 85 % for Labs 2 and 3. Home chemistry is
 291 limited to non-experimental tasks. Yet, remote work allows for literature research,
 292 writing articles/grants, placing orders, and creating equipment usage protocols.
 293 However, telecommuting might lead to rebound effects like longer commutes for those
 294 relocating or increased heating expenses for home-based work.^{39,40} These effects have
 295 not been taken into account because we considered the emissions of staff at home to be
 296 outside the scope of the study.

297 We center commutes mitigation measures on replacing cars with strategies that depend
 298 on the home-to-work one-way distance (**Figure 5**):

299 - $0 \leq 5$ km: trips made by thermic car are substituted by bicycle or walk

300 - $5 \leq 10$ km: trips made by thermic car are substituted by electric bike (50 %) or
 301 subway/train (50 %)

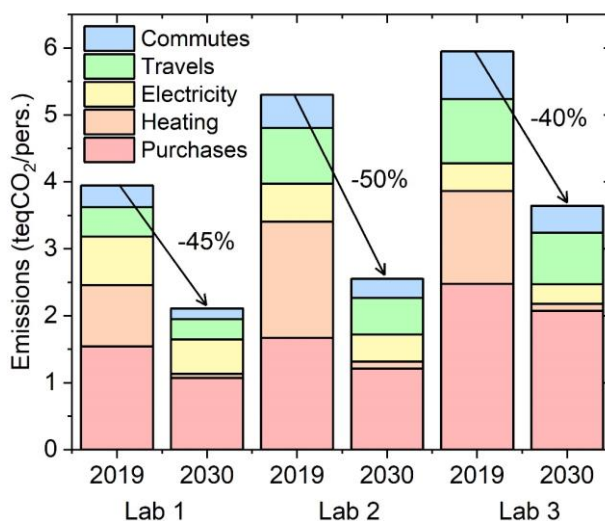
302 - + 10km: trips made by thermic car are substituted by electric car (33 %) or by
 303 carpooling with 2 persons/car (33 %). In addition to this, 33 % of people work from
 304 home 1 day per week.

305 Travels made by any means of transportation except thermic cars are kept unchanged.

306

307 **Summary of the actions**

308 **Figure 6** summarizes emissions in 2019 and projected for 2030 if all the mitigation
309 strategies discussed above were to be implemented. The result is encouraging, with a
310 total reduction in emissions in the range 40-50% for the three laboratories. If we
311 consider absolute reductions by source, heating represents 40-50% of the reduction
312 effort, followed by purchases (15-25%) and electricity, then travels and commutes (5-
313 10% each). In this scenario, half of the reduction efforts depend on the institution
314 (heating) while the other half is directly controlled by the laboratory. When we look at
315 the relative reduction by category, heating emissions are divided by 15, commutes by
316 2, and the other three categories go down by 15-30 % of the initial value.



317 **Figure 6.** Scenarios of emissions for the three labs. GHG emissions by category in 2019, and projected
318 in 2030 if the mitigation strategies discussed in this work are implemented.
319

320 **Conclusion & outlook**

321 Our calculations of the 2019 carbon footprint for the three laboratories yield an average
322 carbon footprint per researcher of ca 5.6 teqCO₂. This ranks chemistry laboratories
323 slightly higher than the median of 5.0 teqCO₂, calculated on the basis of 100
324 laboratories from all disciplines using the same methodology.²⁶ It is important, for such
325 comparisons, to pay attention to any possible variation in scope. A recent study from
326 Martin *et al.* showed a yearly 28 teqCO₂/pers. emission for an astronomical institute.¹⁹
327 However, Martin *et al.*'s work includes specific large research infrastructures. Specific
328 large facilities such as characterization platforms and synchrotron are also used in
329 chemistry, but were not taken into account in this study. Larsen *et al.* obtained 14
330 teqCO₂/pers. for the Natural Sciences department of a Norwegian technical university,
331 including building construction and central administration. If these two categories were
332 not considered, the GHG emission would be 7 teqCO₂/pers. which is close to our
333 results.²⁰

334 One limitation of our study is the use of monetary emission factors for assessing the
335 GHG emissions of purchases. LCA based on physical flows are in principle more
336 precise, but on the one hand laboratory accountability is monetary, not mass
337 accounting, and LCA does not give accurate results for niche products where

338 production costs are small relative to research & development ones.^{26,41} As a result, a
339 cooperative effort between researchers and suppliers is needed to refine emission
340 factors of laboratory supplies and equipment. Other categories have their own bias. For
341 instance, one could argue that staff responding to the commuting questionnaire is the
342 most concerned one. It is also important to recognize that assessing the carbon footprint
343 alone provides an incomplete understanding of the overall environmental impact of the
344 laboratories. Other environmental factors, such as the emission of toxic, acidifying and
345 eutrophying substances, water use and resource depletion, have to be considered. For
346 example, the adoption of electric cars is associated with higher mineral resource usage
347 compared to thermic cars, and the utilization of wood for heating can generate fine
348 particulate matter. Thus, it is recommended to conduct LCAs to assess specific
349 mitigation strategies and avoid burden shifting. On a broader perspective, the use of
350 LCA can help chemists to identify the most impactful stages and materials in their
351 research and product development.^{42,43}

352 Altogether, our mitigation strategies show a possible reduction of 40 to 50 % for the
353 three laboratories, which is very encouraging. However, this implies a combination of
354 actions at the level of the government (*e.g.* public transportation), the university (*e.g.*
355 thermal isolation of buildings) and the individual (*e.g.* proper use of the sashes).
356 Collective actions are generally difficult to implement, unless strong incentives are
357 given by the administration. Similarly, individual actions (such as reducing flying for
358 professional purpose) are easier to accept when one feels that others share the burden.
359 In addition, the organization of the academic system itself has a strong impact over the
360 environmental burden of research. Indeed, a number of works identified how
361 professional success is associated to international travels.^{13,44} International
362 collaborations, invitations to international conferences or as invited professor are
363 considered as markers of scientific excellence. Moreover, the current funding model,
364 which prioritizes project-based investments, tends to favor purchasing new equipment,
365 whereas a more sustainable approach could be achieved by allocating resources to
366 hiring additional staff for equipment maintenance and the design of customized
367 solutions. Beyond research policy, the whole society has evolved towards an intensive
368 use of technology. As in other sectors, the access to innovative technologies has pushed
369 the academics to carry out more numerous and more sophisticated experiments,
370 possibly to the detriment of the intellectual input. Rationalizing the experimental part
371 of research⁴⁵ (by identifying useless experiments and oversized analysis) should lead
372 to a significant decrease of the environmental impact of research. Additionally,
373 substantial financial savings could be redirected to recruit people to achieve
374 administrative tasks or take environmental actions. Some researchers may also decide
375 to spend more time teaching, rethink the purpose of their research, or organize
376 transitions. In particular, more efforts could be devoted to green chemistry and energy
377 savings.

378 Overall, conducting research from a sustainable development perspective requires a
379 multidisciplinary approach. Social sciences are particularly important, since they can
380 help to anticipate the behavior of societies with respect to current environmental
381 challenges and to accompany the change toward a more sustainable research.

382 **Methods**

383 We investigate three laboratories located in three French metropolises: Lille, Bordeaux
384 and Rennes (**Table S1** and **Figure S1**). The laboratories cover a wide range of
385 chemistry disciplines with some differences between laboratories: Lab 1 focuses on
386 physical and analytical chemistry while Labs 2 and 3 also include organic and inorganic
387 synthesis, as well as theoretical chemistry.

388 We quantify the carbon footprint of each laboratory for the year 2019 using
389 GES 1point5,⁴⁶ a web application specific to the research sector.^{17,26} The data are
390 distributed in four categories: (i) buildings (related to electricity and heating
391 consumption of buildings), (ii) purchase of goods and services (including IT), (iii)
392 business travels and (iv) commutes. Electricity and heating emissions are calculated
393 from annual consumption figures from the buildings associated to each laboratory.
394 When a single building is shared with other services, the corresponding part of energy
395 consumption is attributed by the surface share. In 2019, the French electricity mix was
396 composed of 70.6 % nuclear, 11.2 % hydraulics, 7.9 % fossil combustibles (gas, coal,
397 petrol), 6.3 % wind, 2.2 % solar, 1.8 % bioenergies,⁴⁷ corresponding to 60
398 geqCO₂/kWh. Professional travel emissions are calculated by compiling, for each
399 travel, the geodesic distance and the type of vehicle with the corresponding kilometric
400 emission factor (EF). Emissions associated to flying include the effect of contrails.
401 Commute emissions are determined via a questionnaire (managed by GES 1point5, see
402 §Commutes in SI for details)¹⁷ submitted to the following staff members: PhD students,
403 postdocs, administrative and technical staff, assistant professors, professors and
404 permanent researchers. They can choose up to two types of commuting distances and
405 means of transport representative of a typical working week. The rate of answers was
406 approximately 50 % and the total commute emissions were proportionally extended for
407 each socio-professional class. Purchases emissions are estimated by combining two
408 procedures. For the small fraction of purchases related to office computers, emissions
409 are evaluated per unit using suppliers EFs. For all other purchases, excluding travel
410 tickets, emissions are calculated by multiplying their tax free price by the monetary
411 emission factors of the GES 1point5 EF database²⁶ (**Table S2**). This hybrid EF database
412 combines environmentally extended input-output (EEIO) EFs with corrections that
413 either use LCA or supplier prices to estimate monetary EFs for gases, plastic-ware and
414 gloves or carbon intensities from representative companies that sell certain types of
415 goods to research labs (such as Sigma-Aldrich for chemical products, for instance). All
416 purchase-associated EFs are cradle-to-gate, i.e. from including production and transport
417 to the point-of-sale. The different goods and services are identified through the
418 NACRES accountability identification system used in French academic institutions.
419 Annual emissions per capita are computed by dividing annual emissions by the number
420 of staff, considering all persons working in the laboratory for the full year 2019
421 (including technicians and lab administrative support staff). Uncertainties are
422 calculated according to the GES 1point5 tool.^{17,26} The following emissions are not
423 considered: emissions related to (i) building construction, (ii) the use of large research
424 infrastructures (such as large servers, synchrotron etc.), (iii) instrumentation owned by
425 the laboratory before 2019, (iv) staff meals. References to the full results can be found
426 on the GES 1point5 website: Lab 1: LASIRE;⁴⁸ Lab 2: ISM;⁴⁹ Lab 3: ISCR.⁵⁰

427 Starting from the carbon footprint of the three laboratories in 2019, we identify GHG
428 mitigation strategies, for the most significant items, with the aim of reducing emissions
429 by 50 % in 2030, compared to 2019 levels. This objective is aligned with the "Plan

430 Climat du MESR" published in November 2022 by the French Ministry of Higher
431 Education, Research, and Innovation.²⁹ Firstly, we review existing sustainability plans
432 or policies at the hosting university or research center. These plans often include
433 specific actions that could be implemented to reduce GHG emissions, such as the use
434 of renewable energy categories. We prioritized these actions as they are already planned
435 and endorsed by the hosting institution. Secondly, we conducted a review of existing
436 literature on GHG reduction solutions for research laboratories, including peer-
437 reviewed articles, government reports, and sustainability guides specific to
438 chemistry.^{51,52} Finally, we engaged in discussions with colleagues in the laboratories
439 and across the hosting institutions to gather their valuable perspectives and insights on
440 GHG reduction solutions.

441 **SUPPLEMENTARY INFORMATION** The electronic supplementary information is
442 available free of charge at <http://XXXX>. It includes details on the context of the study
443 (Table S1, Figure S1), details on purchase/equipment, including LCA case study on
444 acetone distillation (Tables S2-S4), additional figures for purchases (Figure S2), energy
445 (Figure S3, Tables S5, S6), travels/business trips (Table S7, S8, Figure S4), commutes
446 (Table S9, Figures S5-S7).

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455 **ABBREVIATIONS**

456 CF, Carbon Footprint; EF, Emission Factor, GHG, GreenHouse Gases; MS, Mitigation
457 strategy; LCA, Life Cycle Assessment; teqCO_2 : ton of equivalent CO_2

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462 **Author Contributions**

463 All the authors contributed equally to the manuscript and gave approval to its the final
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469

470 **REFERENCES**

- 471 1. Franta, B. Early oil industry knowledge of CO₂ and global warming. *Nat. Clim.*
472 *Change* **8**, 1024–1025 (2018).
- 473 2. Masson-Delmotte, V. *et al.* *Climate Change 2021: The Physical Science Basis.*
474 *Contribution of Working Group I to the Sixth Assessment Report of the*
475 *Intergovernmental Panel on Climate Change* *Climate Change 2021: The Physical*
476 *Science Basis.* 2391 10.1017/9781009157896. (2021).
- 477 3. Attari, S. Z., Krantz, D. H. & Weber, E. U. Statements about climate researchers’
478 carbon footprints affect their credibility and the impact of their advice. *Clim. Change*
479 **138**, 325–338 (2016).
- 480 4. Capstick, S. *et al.* Civil disobedience by scientists helps press for urgent climate
481 action. *Nat. Clim. Change* **12**, 773–774 (2022).
- 482 5. da Silva, L. A., Dutra, A. R. de A., Soares, T. C., Birch, R. S. & Guerra, J. B. S.
483 O. de A. Trends in research: carbon footprint reduction in universities as a way to
484 achieve a green campus. *Int. J. Sustain. High. Educ.* **24**, 584–601 (2023).
- 485 6. Valls-Val, K. & Bovea, M. D. Carbon footprint in Higher Education
486 Institutions: a literature review and prospects for future research. *Clean Technol.*
487 *Environ. Policy* **23**, 2523–2542 (2021).
- 488 7. Portegies Zwart, S. The ecological impact of high-performance computing in
489 astrophysics. *Nat. Astron.* **4**, 819–822 (2020).
- 490 8. Klöwer, M., Hopkins, D., Allen, M. & Higham, J. An analysis of ways to
491 decarbonize conference travel after COVID-19. *Nature* **583**, 356–359 (2020).
- 492 9. Jäckle, S. The Carbon Footprint of Travelling to International Academic
493 Conferences and Options to Minimise It. in *Academic Flying and the Means of*
494 *Communication* (eds. Bjørkdahl, K. & Franco Duharte, A. S.) 19–52 (Springer Nature
495 Singapore, 2022). doi:10.1007/978-981-16-4911-0_2.
- 496 10. Stevens, A. R. H., Bellstedt, S., Elahi, P. J. & Murphy, M. T. The imperative to
497 reduce carbon emissions in astronomy. *Nat. Astron.* **4**, 843–851 (2020).
- 498 11. Aujoux, C., Kotera, K. & Blanchard, O. Estimating the carbon footprint of the
499 GRAND project, a multi-decade astrophysics experiment. *Astropart. Phys.* **131**,
500 102587 (2021).
- 501 12. Burtscher, L. *et al.* Forging a sustainable future for astronomy. *Nat. Astron.* **5**,
502 857–860 (2021).
- 503 13. Berné, O. *et al.* The carbon footprint of scientific visibility. *Environ. Res. Lett.*
504 **17**, 124008 (2022).
- 505 14. Leon, I., Oregi, X. & Marieta, C. Environmental assessment of four Basque
506 University campuses using the NEST tool. *Sustain. Cities Soc.* **42**, 396–406 (2018).
- 507 15. Fry, J. *et al.* Assessing carbon footprints of cities under limited information. *J.*
508 *Clean. Prod.* **176**, 1254–1270 (2018).

- 509 16. Güereca, L. P., Torres, N. & Noyola, A. Carbon Footprint as a basis for a cleaner
510 research institute in Mexico. *J. Clean. Prod.* **47**, 396–403 (2013).
- 511 17. Mariette, J. *et al.* An open-source tool to assess the carbon footprint of research.
512 *Environ. Res. Infrastruct. Sustain.* **2**, 035008 (2022).
- 513 18. Cooper, J. *et al.* The Carbon Footprint of a UK Chemical Engineering
514 Department – The Case of Imperial College London. *Procedia CIRP* **116**, 444–449
515 (2023).
- 516 19. Martin, P. *et al.* A comprehensive assessment of the carbon footprint of an
517 astronomical institute. *Nat. Astron.* **6**, 1219–1222 (2022).
- 518 20. Larsen, H. N., Pettersen, J., Solli, C. & Hertwich, E. G. Investigating the Carbon
519 Footprint of a University - The case of NTNU. *J. Clean. Prod.* **48**, 39–47 (2013).
- 520 21. Yates, J. *et al.* Can virtual events achieve co-benefits for climate, participation,
521 and satisfaction? Comparative evidence from five international Agriculture, Nutrition
522 and Health Academy Week conferences. *Lancet Planet. Health* **6**, e164–e170 (2022).
- 523 22. Tseng, S. H. Y., Lee, C. & Higham, J. Managing academic air travel emissions:
524 Towards system-wide practice change. *Transp. Res. Part Transp. Environ.* **113**, 103504
525 (2022).
- 526 23. Reyes-García, V., Graf, L., Junqueira, A. B. & Madrid, C. Decarbonizing the
527 academic sector: Lessons from an international research project. *J. Clean. Prod.* **368**,
528 133174 (2022).
- 529 24. Kilcoyne, J., Bogan, Y., Duffy, C. & Hollowell, T. Reducing environmental
530 impacts of marine biotoxin monitoring: A laboratory report. *PLOS Sustain. Transform.*
531 **1**, e0000001 (2022).
- 532 25. Howes, L. Can Laboratories Move Away from Single-Use Plastic? *ACS Cent.*
533 *Sci.* **5**, 1904–1906 (2019).
- 534 (26) De Paepe, M.; Jeanneau, L.; Mariette, J.; Aumont, O.; Estevez-Torres, A.
535 Purchases Dominate the Carbon Footprint of Research Laboratories. bioRxiv April 14,
536 2023, p 2023.04.04.535626. <https://doi.org/10.1101/2023.04.04.535626>.
- 537 27. Eurostat. Final energy consumption in households per capita.
538 https://ec.europa.eu/eurostat/databrowser/view/sdg_07_20/default/table?lang=en
539 (2023).
- 540 28. Emissions – Global Energy & CO2 Status Report 2019 – Analysis. *IEA*
541 <https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions>.
- 542 29. Ministère de l’enseignement supérieur et de la recherche. *Plan de sobriété*
543 *énergétique*. <https://www.ecologie.gouv.fr/sites/default/files/dp-plan-sobriete.pdf>
544 (2023).
- 545 30. Univ Bordeaux. Le plan de sobriété énergétique de l’université de Bordeaux.
546 <https://www.u-bordeaux.fr/actualites/plan-sobriete-energetique> (2022).

- 547 31. Mills, E. & Sartor, D. Energy use and savings potential for laboratory fume
548 hoods. *Energy* **30**, 1859–1864 (2005).
- 549 32. My green lab. <https://www.mygreenlab.org/>.
- 550 33. International Institute for Sustainable Laboratories. The Laboratory
551 Benchmarking Tool. <https://lbt.i2sl.org/>.
- 552 34. Posner, S., Stuart, R. & Thompson, G. A conceptual model for laboratory
553 ventilation greenhouse gas planning. *J. Chem. Health Saf.* **18**, 34–42 (2011).
- 554 35. Gumapas, L. A. M. & Simons, G. Factors affecting the performance, energy
555 consumption, and carbon footprint for ultra low temperature freezers: case study at the
556 National Institutes of Health. *World Rev. Sci. Technol. Sustain. Dev.* **10**, 129–141
557 (2013).
- 558 36. Drahl, C. A Matter of Degree. *ACS Cent. Sci.* **4**, 1294–1297 (2018).
- 559 37. Espinel-Ingroff, A., Montero, D. & Martin-Mazuelos, E. Long-Term
560 Preservation of Fungal Isolates in Commercially Prepared Cryogenic Microbank Vials.
561 *J. Clin. Microbiol.* **42**, 1257–1259 (2004).
- 562 38. SNCF. Information sur la quantité de gaz à effet de serre émise à l’occasion
563 d’une prestation de transport. Méthodologie générale.
564 [http://medias.sncf.com/sncfcom/pdf/co2/Information_CO2_des_prestations_de_trans](http://medias.sncf.com/sncfcom/pdf/co2/Information_CO2_des_prestations_de_transport_Methodologie_generale.pdf)
565 [port_Methodologie_generale.pdf](http://medias.sncf.com/sncfcom/pdf/co2/Information_CO2_des_prestations_de_transport_Methodologie_generale.pdf).
- 566 39. Shi, Y., Sorrell, S. & Foxon, T. The impact of teleworking on domestic energy
567 use and carbon emissions: An assessment for England. *Energy Build.* **287**, 112996
568 (2023).
- 569 40. Simon, S. & O’Brien, W. Pilot study to measure the energy and carbon impacts
570 of teleworking. *Build. Cities* **4**, 174–192 (2023).
- 571 41. Font Vivanco, D. The role of services and capital in footprint modelling. *Int. J.*
572 *Life Cycle Assess.* **25**, 280–293 (2020).
- 573 42. Kralisch, D., Ott, D. & Gericke, D. Rules and benefits of Life Cycle Assessment
574 in green chemical process and synthesis design: a tutorial review. *Green Chem.* **17**,
575 123–145 (2015).
- 576 43. Raccary, B., Loubet, P., Peres, C. & Sonnemann, G. Life cycle assessment of
577 sample preparation in analytical chemistry: a case study on SBSE and SPE techniques.
578 *Adv. Sample Prep.* **1**, 100009 (2022).
- 579 44. Wynes, S., Donner, S. D., Tannason, S. & Nabors, N. Academic air travel has
580 a limited influence on professional success. *J. Clean. Prod.* **226**, 959–967 (2019).
- 581 45. Mincigrucci, R. The carbon footprint of research papers. *Nat. Photonics* **17**,
582 375–375 (2023).
- 583 46. Labos 1point5. GES 1point5. <https://apps.labos1point5.org/ges-1point5>.

- 584 47. RTE. *Bilan électrique 2019*. [https://assets.rte-france.com/prod/public/2020-](https://assets.rte-france.com/prod/public/2020-06/bilan-electrique-2019_1_0.pdf)
585 06/bilan-electrique-2019_1_0.pdf (2019).
- 586 48. GES 1point5 & Lasire. BGES 2019 du Lasire.
587 [https://apps.labos1point5.org/ges-1point5-results/505787c5-3a5a-4b36-bf72-](https://apps.labos1point5.org/ges-1point5-results/505787c5-3a5a-4b36-bf72-244289b47b9e)
588 244289b47b9e.
- 589 49. GES 1point5 & ISM. BGES 2019 de l'ISM. [https://apps.labos1point5.org/ges-](https://apps.labos1point5.org/ges-1point5-results/ddbcca6e-8a6e-4e9e-93af-c746dbc4358b)
590 1point5-results/ddbcca6e-8a6e-4e9e-93af-c746dbc4358b.
- 591 50. GES 1point5 & ISCR. BGES 2019 de l'ISCR.
592 [https://apps.labos1point5.org/ges-1point5-results/9f8aa53f-ee22-424c-a136-](https://apps.labos1point5.org/ges-1point5-results/9f8aa53f-ee22-424c-a136-445de4697062)
593 445de4697062.
- 594 51. Durgan, J., Rodríguez-Martínez, M. & Rouse, B. Green Labs: a guide to
595 developing sustainable science in your organization. *Immunol. Cell Biol.* **n/a**.
- 596 52. Sustainable laboratories - practices to reduce the environmental effects of
597 research. *Royal Society of Chemistry* [https://www.rsc.org/new-](https://www.rsc.org/new-perspectives/sustainability/sustainable-laboratories/)
598 perspectives/sustainability/sustainable-laboratories/.

Electronic Supporting Information

Carbon footprint and mitigation strategies of three chemistry laboratories

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Context of the study

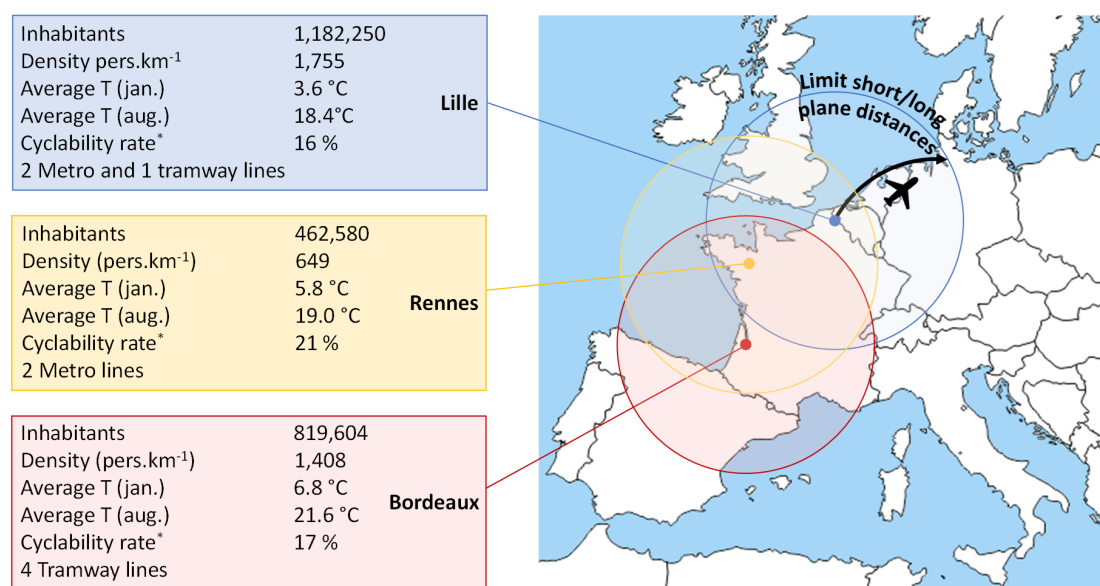


Figure S1. Geographic and demographic data of three city areas hosting the chemistry labs: lab1, LASIRE in Lille Métropole; lab2, ISM in Bordeaux Métropole; lab3 ISCR in Rennes Métropole. Sources: Wikipedia pages of the cities; * <https://www.velo-territoires.org/actualite/2022/05/11/indicateur-de-cyclabilite/>. Data mostly from 2020, Rennes metro line B opened in 2022.

Table S1. Chemistry laboratories investigated. Data correspond to year 2019.

Lab #	Name	Staff number	Surface m ²	Heating system	Hoods number	Publications
Lab 1	LASIRE ⁴⁷	76	3570	Cogeneration via natural gas	59	76
Lab 2	ISM ⁴⁸	222	10000	Natural gas	217	230
Lab 3	ISCR ⁴⁹	468	16447	Urban heating network (natural gas 91%, waste 9%)	315	568

Purchases/Equipment

Table S2. Carbon intensities for different purchases categories

Category	Subcategory	Carbon intensity (kgeqCO ₂ /€)
Purchases*		0.31
Consumables	All	0.44
IT**		0.14
Lab equipment		0.30
Lab life		0.51
Maintenance		0.23
Services		0.10
Hosting & transport***		0.37
Consumables	biochemistry	0.38
Consumables	chemicals	0.45
Consumables	gases	0.29
Consumables	glassware	0.23
Consumables	lab supplies	0.49
Consumables	solvents	0.45

Table S3. Top 5 most expensive equipment bought in 2019 in Lab 2.

Apparatus	Emissions (teqCO ₂)	Cost (€)
MALDI spectrometer	47.9	199,500
Raman confocal microscope	27.2	100,784
NIR laser light source	15.0	50,000
Liquid-Phase Chromatography	13.2	55,000
UV-vis. spectrometer	11.5	48,000

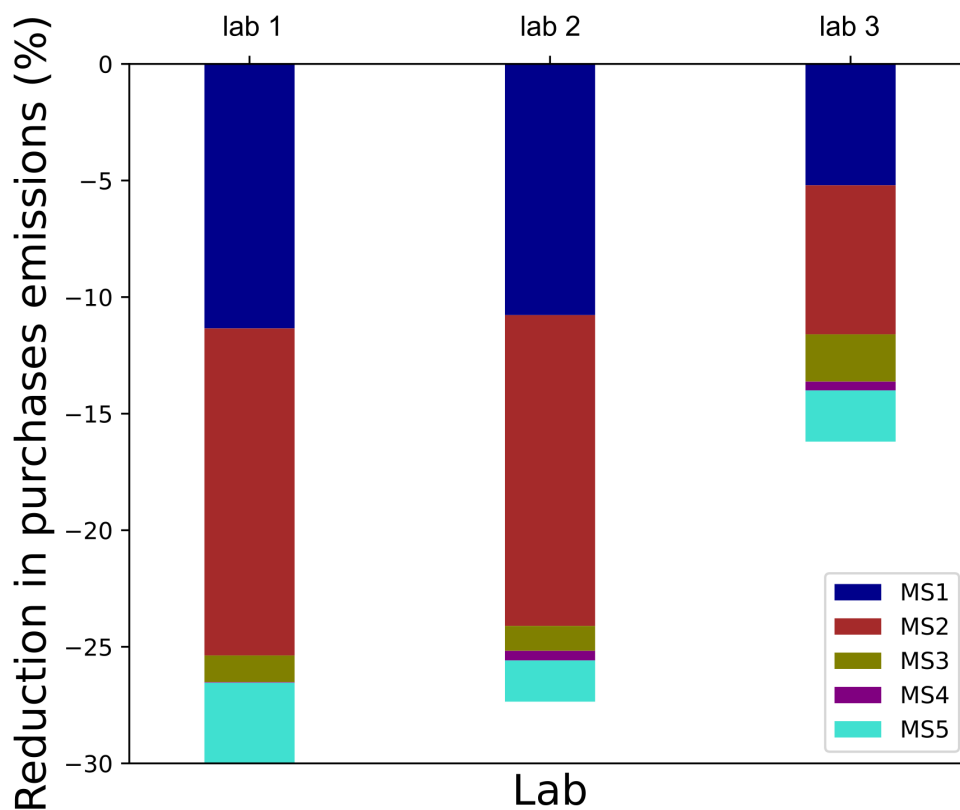


Figure S2. Relative reduction in purchases emissions induced by each mitigation strategy (MS) per laboratory. MS1: increase the lifetime of equipment by 25 %; MS2: and further reducing by 25 % lab equipment by pooling; MS3: reducing by 10 % the use of chemicals by pooling; MS4: reducing acetone purchases by recycling; MS5: increasing by 50 % the lifetime of IT equipment.

Acetone is one of the main solvents used in laboratories. For instance, Lab 2 and Lab 3 consume annually 3 700 and 10 000 liters of acetone, respectively. Their incineration induces the emission of 6.6 and 18.1 teqCO₂, respectively.

Table S4. Life cycle assessment conducted to compare the carbon footprint and cost related to three scenarios of acetone supply in Lab 2.

	Scenario recycling 0	Scenario recycling 0.1	Scenario recycling 0.5
Inventory data			
Yearly purchase of acetone (L)	3 710	3 346	1 892
Yearly purchase of acetone (kg)	2 909	2 618	1 454
Acetone recycling rate	0%	10%	50%
Yearly amount of recycled acetone (L)	-	371	1 855
Electricity consumption distiller/chiller (kWh)		285	1 425
GHG emissions (kgCO₂eq/year)	12 416	11 202	6 349
Acetone production	5 535	4 993	2 823
Waste transport	336	302	168
Waste incineration	6 544	5 890	3 272
Electricity distiller/chiller	-	17	85
Manufacturing distiller/chiller		123	123
Acetone evaporation and degradation	-	17	84
Cost (€/year)	6 245	6 407	4 121
Acetone purchase	5 194	4 685	2 649
Waste treatment	1 051	946	526
Electricity distiller/chiller	-	43	214
Purchases distiller/chiller		733	733

Unitary cost and emission factors	€	kgCO ₂ eq per	Source
Electricity (FR)	0.15	0.0599 kWh	ADEME
Acetone production	1.4	1.492 L	ecoinvent 3.9 + IPCC
Acetone incineration	0.36	2.25 kg	stoichiometric combustion
Lorry transport		0.21 tkm	ecoinvent 3.9 + IPCC
Distiller manufacturing	7000	1589 unit	ecoinvent 3.9 + IPCC
Chiller manufacturing	3500	260 unit	ecoinvent 3.9 + IPCC

Other data		
Evaporation rate of acetone during distil.	2%	
Acetone density	0.784	kg/L
Waste treatment plant distance (Bdx/Lyon)	550	km
Power of the chiller	0.52	kW
Power of the distiller	2.04	kW
Cadence distiller per run	4.5	h
Volume distiller per run (up to 30L)	15	L
Life time of the distiller	15	yr
Life time of the chiller	15	yr

The life cycle assessment (LCA) is conducted in order to compare the carbon footprint and costs of three acetone recycling scenarios in Lab 2. The functional unit of this comparative LCA is “to provide 3 710 L of acetone to Lab 2”, which is equivalent to the yearly demand of this solvent. The assessed scenarios are: 1) business-as-usual 0% recycling, 2) 10% recycling, and 3) 50% recycling.

The boundaries are “cradle-to-grave” and include the production and transport of acetone, distillation of the solvent (manufacture and use of the distillation/chiller unit), evaporation of acetone during distillation, transport and incineration of the waste solvent. Emission factors for the different elements have been calculated with ecoinvent 3.9 life cycle inventory database + IPCC life cycle impact assessment method, and directly from GES1point5 for electricity.

Inventory associated to the manufacture of the distillation/chiller unit has been built through an estimation of the metal/plastics/electronic content of the machines.

Energy

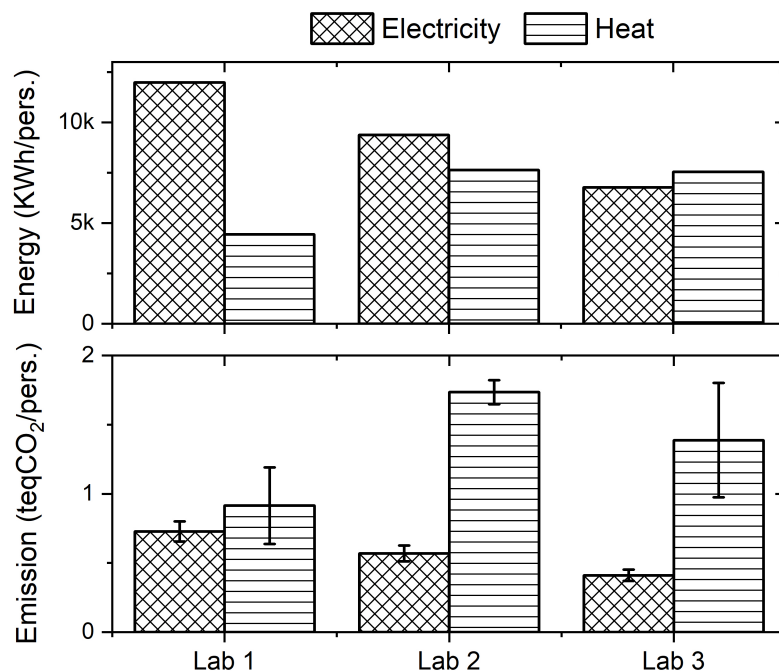


Figure S3. Energy consumptions for year 2019 of the three labs (top) and associated emissions (down). Note that in France the electricity is mainly produced by nuclear fission.

Table S5. Measures for the reduction of heat-related GHG emissions, from reduction plan of the University of Bordeaux¹, host of Lab 2.

<i>Daily-life operations</i>	<ul style="list-style-type: none"> ■ removal of hot water for sanitary purposes (except showers), ■ removal of auxiliary electric heaters in favor of a collective regulation, ■ optimization of outdoor lightning (e.g., turning off parking lot lightning from 1.00 to 5.00 AM), ■ reduction of heating at night, on weekends and for summer and winter breaks, ■ schedules of heating times accorded to room booking tools, temperature at 19° C in winter when the buildings are occupied and 16° C when not, ■ end of comfort air-conditioning, ■ minimum 26 °C air-conditioning when necessary.
<i>Infrastructures</i>	<ul style="list-style-type: none"> ■ switch from natural gas to biomass and geothermy for heating systems, ■ installation of photovoltaic panels, ■ insulation of buildings.

¹ Univ Bordeaux. Le plan de sobriété énergétique de l'université de Bordeaux. <https://www.u-bordeaux.fr/actualites/plan-sobriete-energetique> (2022).

Table S6. Measures for the reduction of electricity-related GHG emissions that are specific to chemistry activities.

<i>Fume hoods management</i>	The work from Posner <i>et al.</i> indicate that a clever use of the fume hoods could reduce the electrical consumption of the extraction system by 30 % (direct reduction by less air pumping and indirect reduction by air compensation, possibly heated or cooled in winter/summer), ² which is in line with previous estimations. ³ Since 2023, the recommendations given to all chemists in Labs 2 and 3 are the following: (i) <i>fume hoods must have their sash down in the absence of operator</i> , which is also a safety requirement, and (ii) <i>fume hoods must be turned off when all containers stored underneath are closed</i> .
<i>Ultra-low temperature freezers</i>	Regular cleaning/defrost of the freezers and their maintenance and location in a room at less than 25° C allow to decrease their energy consumption down to 25 % and increases their life time. ⁴ In addition, following the recommendations of MyGreenLab ⁵ , shifting ultra-low freezer from - 80° C to - 70° C reduces the energy consumption of those machines by 30-40 %, without damaging the cell lines. ^{6,7}
<i>Lasers</i>	Replacing gas lasers with diode lasers in spectroscopy devices, such as Raman and infrared spectrometers, is a significant step towards achieving energy savings for equipment. Diode lasers offer higher electrical-to-optical conversion efficiency, resulting in reduced energy consumption and lower operating costs. In Lab 2, two gas lasers with power outputs of 15 kW and 21 kW, along with a water consumption rate of 10 L/min, were recently replaced by two diode lasers with power outputs of 30 W and 63 W, eliminating the need for water consumption entirely. This transition allows for a remarkable 99 % reduction in both energy and water usage for these specific applications. However, further LCA studies must be conducted to ensure the avoidance of any potential burden shifting during manufacturing of diode lasers. One main issue is that diode lasers lifetime might be reduced compared to gas lasers.

² Posner, S., Stuart, R. & Thompson, G. A conceptual model for laboratory ventilation greenhouse gas planning. *J. Chem. Health Saf.* 18, 34–42 (2011).

³ International Institute for Sustainable Laboratories. The Laboratory Benchmarking Tool. <https://lbt.i2sl.org/>.

⁴ Gumapas, L. A. M. & Simons, G. Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health. *World Rev. Sci. Technol. Sustain. Dev.* 10, 129–141 (2013).

⁵ My green lab. <https://www.mygreenlab.org/>; Drahl, C. A Matter of Degree. *ACS Cent. Sci.* 4, 1294–1297 (2018).

⁶ Espinel-Ingroff, A., Montero, D. & Martin-Mazuelos, E. Long-Term Preservation of Fungal Isolates in Commercially Prepared Cryogenic Microbank Vials. *J. Clin. Microbiol.* 42, 1257–1259 (2004).

⁷ Biological Samples Stored Long Term at -70 C or Warmer database. <https://docs.google.com/spreadsheets/u/1/d/13UvBeoXAhwSHshSYoUDHwcxWiW7qYLnUbeLwxJbCYs/pubhtml>.

Travels/business trips

Table S7. Distribution of transportation uses for professional travels in the three chemistry laboratories. Bottom lines: distance ratio made by long distance flights or train over the total distance travelled. Long distance: > 600 km.

		Lab 1	Lab 2	Lab 3
distance (km/pers.)	plane (long dist.)	2464	4418	5390
	plane (short dist.)	50	268	190
	car	50	152	119
	train	678	1011	844
distance ratio	plane (long dist.)	0.76	0.76	0.82
	train	0.21	0.17	0.13

Table S8. Duration of several trips by train, according to the French Railway Service SNCF. Other tools (example <https://www.chronotrains.com>) enable to estimate the duration of train trips from one city to another.

Departure	Arrival	Geodesic distance (km)	Duration (hh:mm)
Lille	Brest	600	05:30
Lille	Hamburg (DE)	560	07:30
Lille	Geneva (CH)	570	05:20
Bordeaux	Valencia (ES)	590	10:30
Bordeaux	Marseille	500	06:10
Bordeaux	Geneva (CH)	540	06:20
Rennes	Antwerp (BE)	570	05:30
Rennes	Liverpool (UK)	590	09:00
Rennes	Grenoble	650	05:40

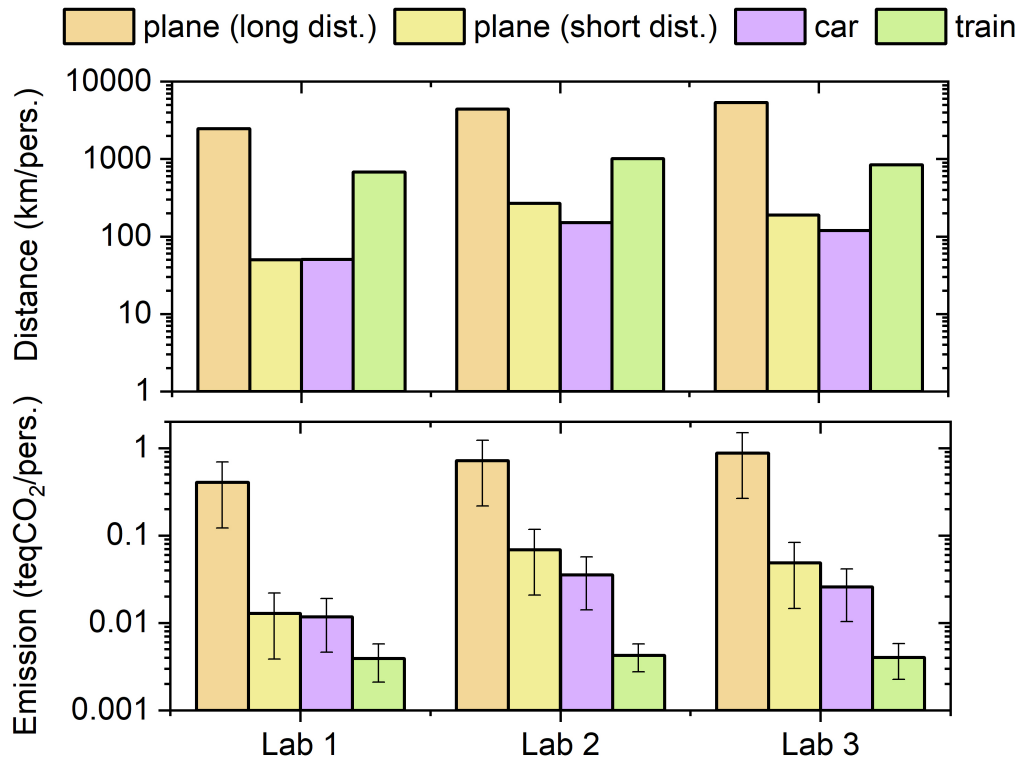


Figure S4. Modes of transportation used during business trips (conferences, seminars, PhD committees...) for the three labs (top) and associated GES (down). Data are normalized per persons. Amplitudes are represented on a logarithmic scale.

Commuting

In order to know the mode of transportation of the employees of the different laboratories, an online survey (managed via the GAS 1point5 tool)⁸ was sent to all the staff (PhD, post-doc, techs., researchers/teachers).

The questions were the following:

1. In 2019, on average, when you were not on vacation, how many days per week did you go to your workplace?
2. What modes of transportation did you use on the most frequent typical day in 2019? (Possibility to enter a 2nd typical day later if you have very different trips in the same week). (Choose between: walk, bike, electric bike, electric scooter, moto, car, city bus, long-distance bus, tramway, train, metro).
3. What were the total distances you traveled to and from on the most typical day in 2019?
4. Do you have another frequent typical day to report in 2019? (yes→go back to question 2 / no→question 5)
5. Simulation answer

Table S9. Answers of the commuting survey. Category are: Researchers/teachers (α), technical staff/engineers (β), PhD and Post-doctoral fellows (γ)

Category	Lab 1			Lab 2			Lab 3		
	α	β	γ	α	β	γ	α	β	γ
total	27	17	32	78	51	93	204	80	180
answers	24	10	8	46	35	26	113	61	46
% answers	90%	57%	25%	59%	69%	28%	55%	76%	26%

⁸ Mariette, J.; Blanchard, O.; Berné, O.; Aumont, O.; Carrey, J.; Ligozat, A.; Lellouch, E.; Roche, P.-E.; Guennebaud, G.; Thanwerdas, J.; Bardou, P.; Salin, G.; Maigne, E.; Servan, S.; Ben-Ari, T. An Open-Source Tool to Assess the Carbon Footprint of Research. *Environ. Res.: Infrastruct. Sustain.* **2022**, 2 (3), 035008. <https://doi.org/10.1088/2634-4505/ac84a4>.

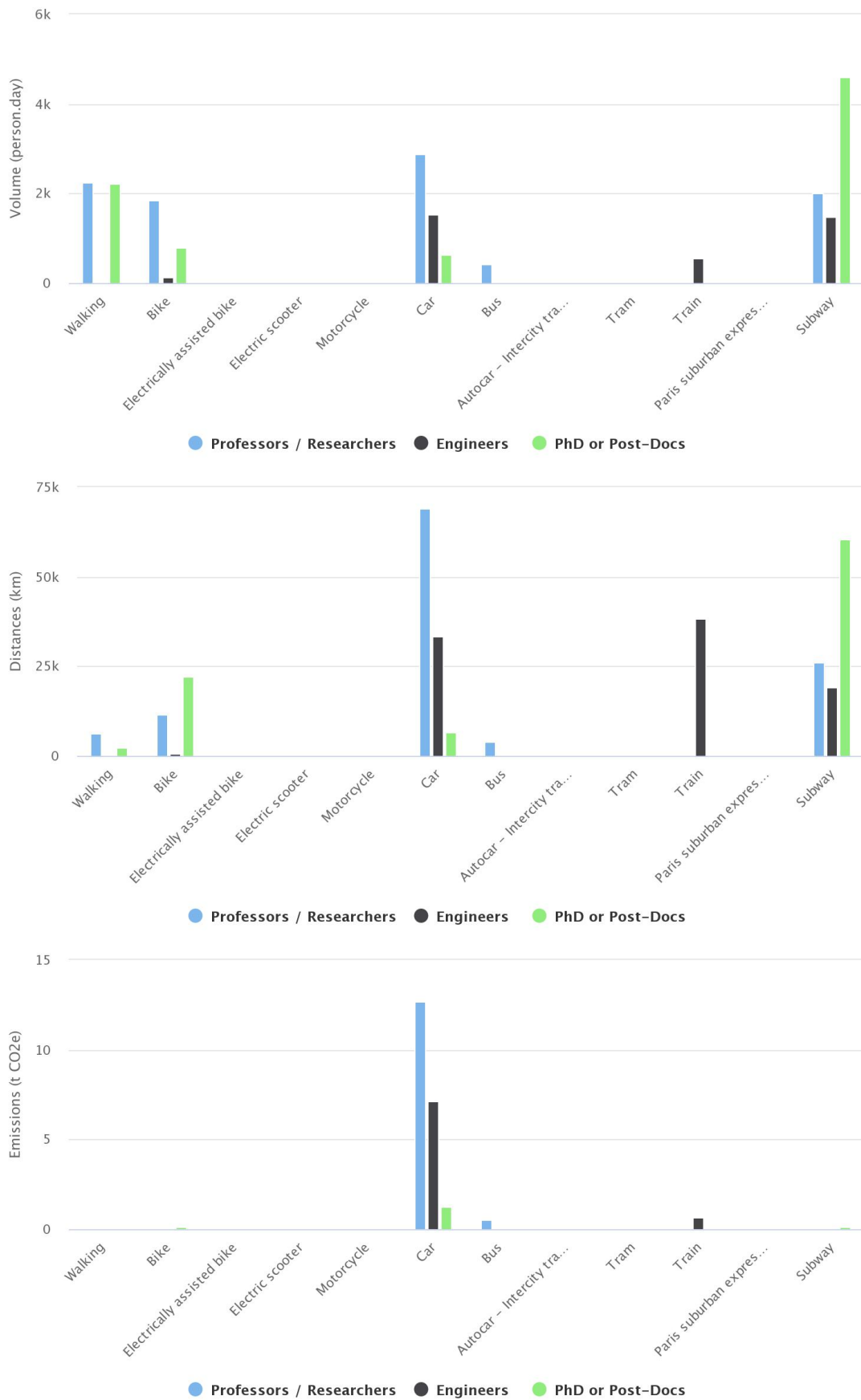


Figure S5. Lab 1 commute survey results (year 2019). Answers rate: 55 %.

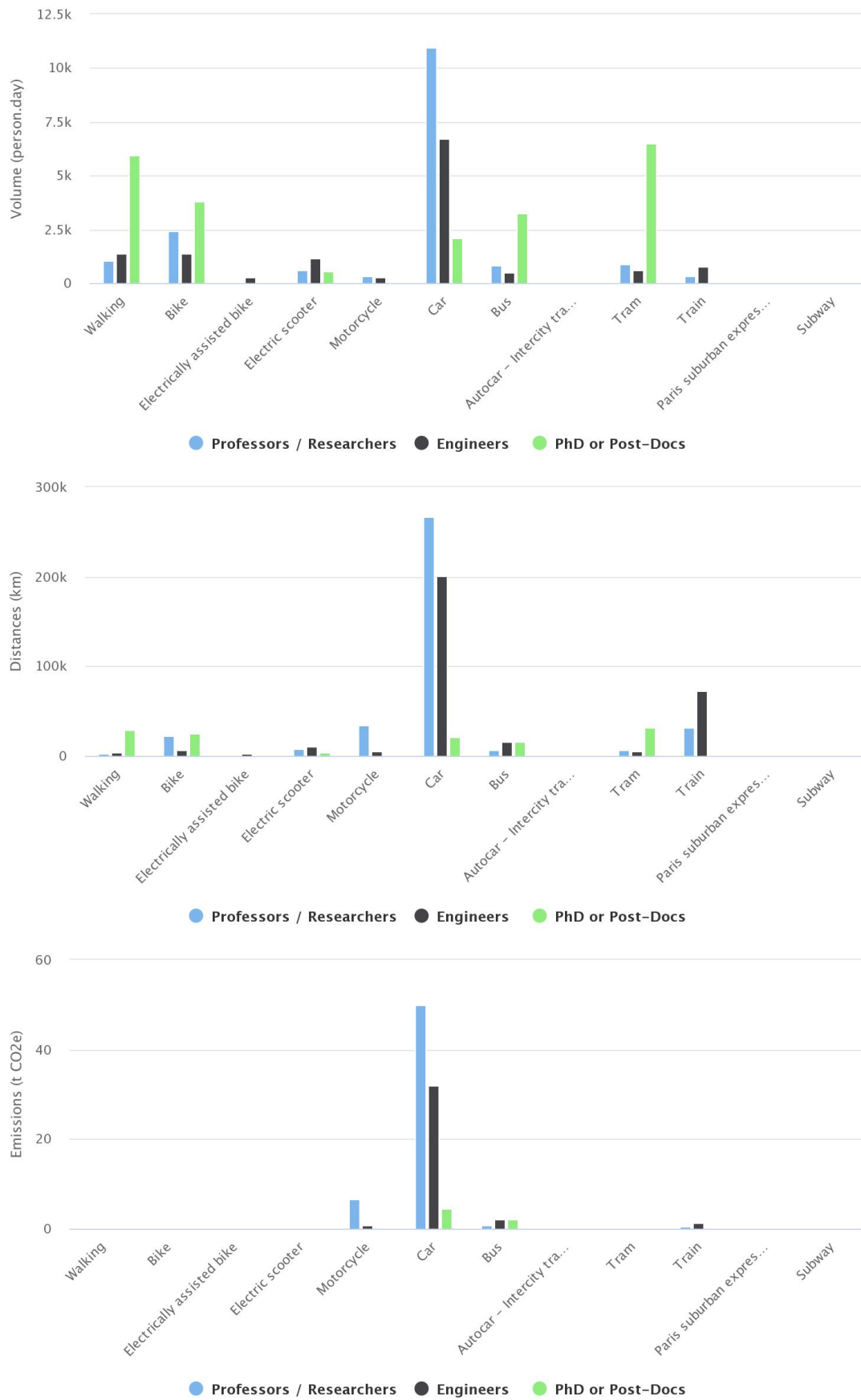


Figure S6. Lab 2 commute survey results (year 2019). Answers rate: 48 %.

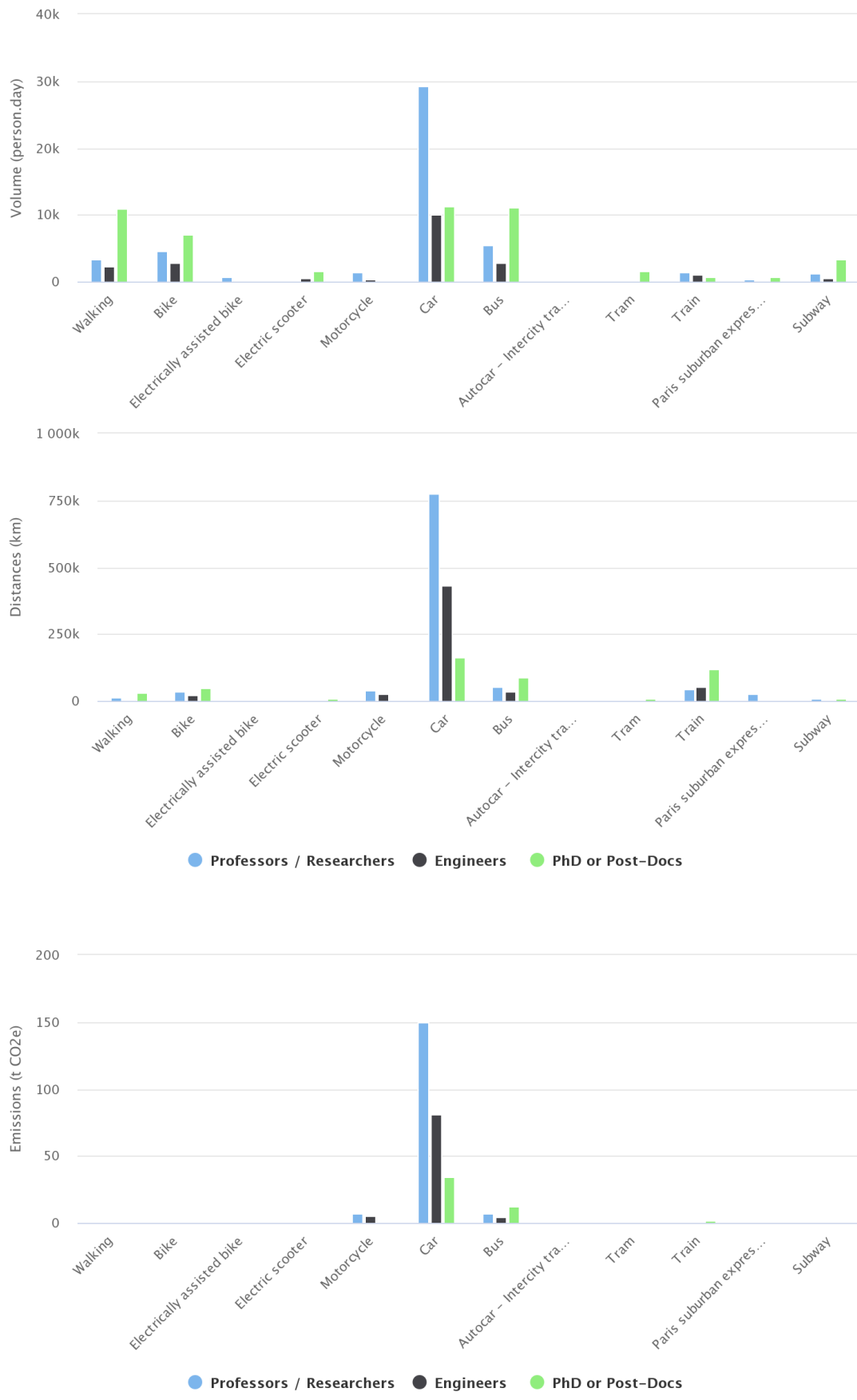


Figure S7. Lab 3 commute survey results (year 2019). Answers rate: 47 %.