

## Carbon footprint and mitigation strategies of three chemistry laboratories

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#### ▶ To cite this version:

André Estevez-Torres, Fabienne Gauffre, Guillaume Gouget, Chloé Grazon, Philippe Loubet. Carbon footprint and mitigation strategies of three chemistry laboratories. 2023. hal-04279713

## HAL Id: hal-04279713 https://hal.science/hal-04279713

Preprint submitted on 10 Nov 2023

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

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

#### 25 ABSTRACT:

As the global imperative for decarbonization gains momentum, the need for action in 26 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 teqCO<sub>2</sub>/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, collaborative resource management, as well as a limitation in the use of planes and 35 36 thermic cars. Such changes imply actions at the level of the government, the university and the individual. We suggest fostering a sustainable research environment in 37 38 chemistry laboratories by rationalizing experimental practices and dedicating time to 39 consider the socio-environmental implications of research.



#### 45 Introduction

Measurable proofs of the accumulation of carbon dioxide in the atmosphere and its relation with the combustion of fossil fuels for human activities were established by the chemist Charles Keeling, shortly before 1960. At 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 its Scientific Advisory Committee, predicted marked change in the climate by 2000.<sup>1</sup>

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 of the Intergovernmental Panel on Climate Change (IPCC).<sup>2</sup> Reducing greenhouse gas 56 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.<sup>3</sup> Many scientists have joined calls for urgent climate action, sometimes even through civil disobedience acts.<sup>4</sup> Since many 64 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 a strategic imperative. The sooner, the better. 67

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

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.<sup>17</sup> 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 first step in the construction of a rational strategy to tackle, at the lab scale, the human-96 97 induced impacts of research activities on the livability of Earth surface.

#### **Results & Discussion** 98

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 to 6 teqCO<sub>2</sub>/pers. with a standard deviation of 1 teqCO<sub>2</sub>/pers. The variability among 101 102 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, purchases dominate emissions followed by heating for Labs 1 and 3, while the order is 104 105 inversed 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 observed between Lab 1 and Lab 2, as well as a significant discrepancy in purchase-107 108 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 electricity share being the most variable (7-18 %), followed by travels (11-16 %) and 110 111 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 laboratory database of the GES 1point5.<sup>26</sup> In particular, heating and electricity 113 114 emissions are 60 to 190 % higher than the GES 1 point5 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.



117 118

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

#### 121 **Purchases**

Figure 2A display purchases emissions per capita broken down by sub-category. Lab 122 123 equipment and consumables dominate purchases emissions for the three laboratories. Additional information is provided in Table S3 concerning the most expensive 124 125 equipment acquired in Lab 2. Interestingly, the three laboratories have equivalent 126 emissions associated to equipment with an average 0.9 teqCO<sub>2</sub>, while consumables and 127 other purchases (including hosting, services and lab life) are 2 to 4 times higher for Lab 3, compared to Lab 1 and 2. The remaining maintenance and IT sub-categories 128 129 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 between laboratories. Especially, emissions associated to chemicals and lab supplies 132 133 are 3 to 5 times higher in Lab 3 compared to the two others.





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 CO<sub>2</sub>.

Purchases category is the most emitting in Labs 1 and 3 (**Figure 1**) and, therefore, 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 25 % (MS1) and further reduce by 25 % lab equipment by pooling (MS2), reduce by 149 150 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 imply an increase of maintenance, we apply an increase of their emissions by 50 %. As 152 153 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 154 (Table S4). The results (Figure 2D) reveal that the emissions resulting from the 155 156 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 associated with the production and disposal of acetone. In addition, a 50% recycling 158 rate yields 35% economic cost savings. These findings highlight the environmental and 159 economic benefits of recycling acetone, especially in laboratories where large 160 quantities are consumed. Implementing a recycling system requires organizational 161 162 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 solvent purposely. 163

164 The effectiveness of the mitigation strategies (Figure 2C and S2) is ranked similarly across all laboratories:  $MS2 \ge MS1 \implies MS5 \sim MS3 \implies MS4$ . Labs 1 and 2 reduce their 165 emissions by approximately 25 %, Lab 3 reduction being 15 %. This disparity is 166 primarily due to the differing distribution of purchases emissions, Lab 3 having a higher 167 proportion of emissions due to consumables. It is worth noting that the increase of 168 169 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 % 170 171 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 can refer to Howes' paper,<sup>25</sup> which discusses single-use plastics in biological 174 laboratories. It is crucial to assess and compare the impacts of potential solutions to 175 ensure that they do not cause burden shifting between life cycle stages. For instance, 176 177 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.

Also, the mitigation strategies considered here are demand-driven only, 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 does not enable to differentiate suppliers. and therefore considering supply-driven strategies. As a result, it is not possible to take into account supply-driven strategies include purchasing more sustainable lab equipment, lab supplies, and chemicals.

#### 186 Energy

The energy consumption related to electricity and heating categories are comparable in all three labs (details in **Figure S3**) and ranges from 14 300 kWh/pers. (Lab 3) to 17 000 kWh/pers. (Lab 2). Such amounts are 2 to 3 times higher than the average individual French houses consumption, which is approximately 6 850 kWh/pers/year.<sup>27</sup> The main building of Lab 2 consumes around 10 times more electricity than a similarlysized education building within the hosting university, indicating that electricity 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 190 heating compensation.

201 Energy-associated emissions (Figure 3) range from 1.6 teqCO<sub>2</sub>/pers (Lab 1) to 202 2.3 teqCO<sub>2</sub>eq/pers. (Lab 2). Electricity generates less emissions than heating because 203 France has a low-carbon electricity mix (60 geqCO<sub>2</sub>/kWh in 2019). In comparison, the world electricity mix generated 475 geqCO<sub>2</sub>/kWh in 2019.<sup>28</sup> If the laboratories 204 205 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 geqCO<sub>2</sub>/kWh), whereas Lab 1 and 3 are furnished through a district heating 211 network based on natural gas and cogeneration (206 and 184 geqCO<sub>2</sub>/kWh resp.).



Emission (teqCO<sub>2</sub>/pers.)
 Figure 3. GHG emissions associated with energy use per lab in 2019 (top) and mitigation strategies for
 2030 (bottom) 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).

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 sufficiency launched in 2022, which aims to achieve a 40 % reduction in energy 218 consumption by 2030.<sup>29</sup> Examples of generic solutions taken at the scale of the 219 University of Bordeaux<sup>30</sup> (host of Lab 2) include daily-life operations and 220 infrastructures, as detailed in Table S5. Alongside general measures, chemistry labs 221 have several levers that are specific to their activity, such as management of fume 222 hoods<sup>31–34</sup>, cooling systems (*e.g.* ultra-low temperature freezers),<sup>32,35–37</sup>, and equipment 223 224 (e.g. lasers). These examples are further discussed in **Table S6**. To prioritize efforts, a precise electricity monitoring system is needed. Although it is absent in the studied 225 Labs, data from the Laboratory Benchmarking Tool<sup>33</sup> indicates ventilation uses 35 %, 226

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

Figure 3 illustrates the potential reduction by implementing energy savings of 40 % and transitioning to renewable energy sources for heating systems. The results indicate a significant decrease in emissions, ranging from 65 % in Lab 3 to 78 % in Lab 2. 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  $geqCO_2/pers./km$  depending on the type of train)<sup>38</sup>. Interestingly, in one of the 239 240 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

offers convenient train connections to Paris, Belgium, the Netherlands, and the UK.



 Emissions (teqCO<sub>2</sub>/pers.)
 Figure 4. GHG Emissions associated with professional travels per lab in 2019 (top) and mitigation strategies for 2030 (bottom) with: short distance plane trips (< 600 km) replaced by train trips and 30 % long distance trips replaced by remote attendance.

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- 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 (**Figure 4**) which, we believe, combine the quality of international exchange and research dissemination with 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</li>
  257 600 km are detailed in **Table S8**.
- 258 Combining both measures leads to a  $\sim 30$  % reduction of the travel emissions. To 259 promote train versus plane, French institutions ruled that train should be imposed for trips less than 3 to 4 h. To improve the acceptability of long train journeys, the use of 260 first class would enable staff to work remotely in a comfortable space not afforded in 261 planes. Other incentives may be implemented, such as an extra hotel night to adapt to 262 train schedules, and specific support such as children care for single parents. The train 263 264 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 and care for the environment, evaluating researchers on the basis of the number of 266 conferences they attend per year (e.g., ERC applications) has become inappropriate. 267

#### 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 is the subway. The three labs are directly connected to bus, tramways, metro and or 272 273 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. Cars are responsible for 91, 82 and 86 % of the emissions due to commutes, and they 278

- emit 0.3, 0.4 and 0.6 teqCO<sub>2</sub>/pers. for Labs 1, 2 and 3, respectively (**Figure 5**). This is because cars are the primary mode of commuting, while France's decarbonized
- 281 electricity leads to low-GHG public transport.



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Figure 5. GHG Emissions associated with commutes per lab in 2019 (top) and mitigation strategies for
 2030 (bottom) with 0-5 km: trips made by thermic car are made by bicycle or walking; 5-10 km: trips
 made by thermic car are made by electric bike or subway/train; +10km: trips made by thermic car are
 made either by electric car or by carpooling (2 person/car) + people work from home 1 day per week on
 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 relocating or increased heating expenses for home-based work.<sup>39,40</sup> These effects have 294 295 not been taken into account because we considered the emissions of staff at home to be 296 outside the scope of the study.

- We center commutes mitigation measures on replacing cars with strategies that depend on the home-to-work one-way distance (**Figure 5**):
- 299  $-0 \le 5 \text{ km}$ : trips made by thermic car are substituted by bicycle or walk
- 300  $5 \le 10$  km: trips made by thermic car are substituted by electric bike (50 %) or 301 subway/train (50 %)
- + 10km: trips made by thermic car are substituted by electric car (33 %) or by
  carpooling with 2 persons/car (33 %). In addition to this, 33 % of people work from
  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

**Figure 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 40-50% for the three laboratories. If we consider absolute reductions by source, heating represents 40-50% of the reduction effort, followed by purchases (15-25%) and electricity, then travels and commutes (5-10% each). In this scenario, half of the reduction efforts depend on the institution (heating) while the other half is directly controlled by the laboratory. When we look at

- 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.



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

#### 320 **Conclusion & outlook**

Our calculations of the 2019 carbon footprint for the three laboratories yield an average 321 322 carbon footprint per researcher of ca 5.6 teqCO<sub>2</sub>. This ranks chemistry laboratories slightly higher than the median of 5.0 teqCO<sub>2</sub>, calculated on the basis of 100 323 324 laboratories from all disciplines using the same methodology.<sup>26</sup> 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 teqCO<sub>2</sub>/pers. emission for an astronomical institute.<sup>19</sup> 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 teqCO<sub>2</sub>/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 teqCO<sub>2</sub>/pers. which is close to our results.<sup>20</sup> 333

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

production costs are small relative to research & development ones.<sup>26,41</sup> As a result, a 338 339 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 most concerned one. It is also important to recognize that assessing the carbon footprint 342 343 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 LCA can help chemists to identify the most impactful stages and materials in their 350 research and product development.<sup>42,43</sup> 351

352 Altogether, our mitigation strategies show a possible reduction of 40 to 50 % for the three laboratories, which is very encouraging. However, this implies a combination of 353 actions at the level of the government (e.g. public transportation), the university (e.g. 354 355 thermal isolation of buildings) and the individual (e.g. proper use of the sashes). Collective actions are generally difficult to implement, unless strong incentives are 356 357 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 environmental burden of research. Indeed, a number of works identified how 360 professional success is associated to international travels.<sup>13,44</sup> International 361 collaborations, invitations to international conferences or as invited professor are 362 363 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 research<sup>45</sup> (by identifying useless experiments and oversized analysis) should lead to a significant decrease of the environmental impact of research. Additionally, 372 373 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.

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

#### 382 Methods

We investigate three laboratories located in three French metropoles: Lille, Bordeaux and Rennes (**Table S1** and **Figure S1**). The laboratories cover a wide range of chemistry 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 388 GES 1point5,<sup>46</sup> a web application specific to the research sector.<sup>17,26</sup> The data are 389 390 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, petrol), 6.3 % wind, 2.2 % solar, 1.8 % bioenergies,<sup>47</sup> corresponding to 60 397 398 geqCO<sub>2</sub>/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 §Commutes in SI for details)<sup>17</sup> submitted to the following staff members: PhD students, 402 postdocs, administrative and technical staff, assistant professors, professors and 403 404 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 emission factors of the GES 1point5 EF database<sup>26</sup> (Table S2). This hybrid EF database 411 412 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 (including technicians and lab administrative support staff). Uncertainties are 421 calculated according to the GES 1point5 tool.<sup>17,26</sup> The following emissions are not 422 423 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 on the GES 1point5 website: Lab 1: LASIRE;<sup>48</sup> Lab 2: ISM;<sup>49</sup> Lab 3: ISCR.<sup>50</sup> 426

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

Climat du MESR" published in November 2022 by the French Ministry of Higher 430 Education, Research, and Innovation.<sup>29</sup> Firstly, we review existing sustainability plans 431 or policies at the hosting university or research center. These plans often include 432 433 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.<sup>51,52</sup> 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).

#### 447 ACKNOWLEDGMENT

CG and PL acknowledge the members of the ISM environment group 2022, especially
Karine Ndiaye, Murielle Berlande, Karine Heuze, Pascale Godard, Valérie Ravaine for
collecting data and suggesting mitigation strategies. AET acknowledges Aymeric
Serazin for collecting data for Lab 1 and Laurent Jeanneau, Marianne De Paepe, Olivier
Aumont and Jérôme Mariette for insightful discussions. FG et GG thanks Elsa Caytan,
Olivier Jeannin, Gwendal Le Bars, Pierrick Ménez, Corinne Perier, Karine Robin,
Louise-Anne Cariou and Rémi Marchal for their help in collecting data.

#### 455 ABBREVIATIONS

456 CF, Carbon Footprint; EF, Emission Factor, GHG, GreenHouse Gases; MS, Mitigation
 457 strategy; LCA, Life Cycle Assessment; teqCO<sub>2</sub>: ton of equivalent CO<sub>2</sub>

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#### 465 **Funding**

- 466 This work was conducted as part of the research network GDR Labos 1point5, funded
- 467 by ADEME, CNRS and INRAE. It was further funded by Bordeaux INP and Université468 de Rennes.
- 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 ChangeClimate 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).
- da Silva, L. A., Dutra, A. R. de A., Soares, T. C., Birch, R. S. & Guerra, J. B. S.
  O. de A. Trends in research: carbon footprint reduction in universities as a way to
  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).

Jäckle, S. The Carbon Footprint of Travelling to International Academic
Conferences and Options to Minimise It. in *Academic Flying and the Means of Communication* (eds. Bjørkdahl, K. & Franco Duharte, A. S.) 19–52 (Springer Nature
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).
- Leon, I., Oregi, X. & Marieta, C. Environmental assessment of four Basque
  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 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).
- S26 23. Reyes-García, V., Graf, L., Junqueira, A. B. & Madrid, C. Decarbonizing the
  academic sector: Lessons from an international research project. *J. Clean. Prod.* 368,
  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).
- (26) De Paepe, M..; Jeanneau, L.; Mariette, J.; Aumont, O.; Estevez-Torres, A.
  Purchases Dominate the Carbon Footprint of Research Laboratories. bioRxiv April 14,
  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
  565 port\_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).
- Kralisch, D., Ott, D. & Gericke, D. Rules and benefits of Life Cycle Assessment
  in green chemical process and synthesis design: a tutorial review. *Green Chem.* 17,
  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).
- 44. Wynes, S., Donner, S. D., Tannason, S. & Nabors, N. Academic air travel has 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/2020-585 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-bf72588 244289b47b9e.
- 589 49. GES 1point5 & ISM. BGES 2019 de l'ISM. https://apps.labos1point5.org/ges590 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-a136593 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-598 perspectives/sustainability/sustainable-laboratories/.

# 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; \* <u>https://www.velo-territoires.org/actualite/2022/05/11/indicateur-de-cyclabilite/</u>. Data mostly from 2020, Rennes metro line B opened in 2022.

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

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

## Purchases/Equipment

Category	Subcategory	Carbon intensity (kgeqCO <sub>2</sub> /€)
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 S2. Carbon intensities for different purchases categories

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

Apparatus	Emissions (teqCO <sub>2</sub> )	Cost (€)
MALDI spectrometer	47.9	199,500
Raman confocal microscope	27.2	100,784
NIR laser light source	15.0	50,000
Liquid-Phase	13.2	55,000
Chromatography		
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 teqCO<sub>2</sub>, respectively.

		Scenario	Scenario
	Scenario	recycling	recycling
Inventory data	recycling 0	0.1	0.5
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
E lectricity consumption distiller/chiller (kWI	n)	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 5 4 4	5 890	3 272
E lectricity 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
E lectricity distiller/chiller	-	43	214
Purchases distiller/chiller		733	733

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

Unitary cost and emission factors	€	kgCO2eq	per	Source
E lectricity (FR)	0.15	0.0599	kWh	A D E ME
Acetone production	1.4	1.492	L	ecoinvent 3.9 + IPCC
Acetone incineration	0.36	2.25	kg	stoechiometric combustion
Lorry transport		0.21	tkm	ecoinvent 3.9 + IPCC
D is tiller manufac turing	7000	1589	unit	ecoinvent 3.9 + IPCC
C hiller 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 particular and the second secon	lan of the
University of Bordeaux <sup>1</sup> , host of Lab 2.	

~ ~ ~	
Daily-life	removal of hot water for sanitary purposes (except
operations	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.
Infrastructures	■ switch from natural gas to biomass and geothermy for
	heating systems,
	■ installation of photovoltaic panels,
	■ insulation of buildings.

<sup>&</sup>lt;sup>1</sup> Univ Bordeaux. Le plan de sobriété énergétique de l'université de Bordeaux. https://www.ubordeaux.fr/actualites/plan-sobriete-energetique (2022).

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

chemistry activitie	es.
Fume hoods management	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), <sup>2</sup> which is in line with previous estimations. <sup>3</sup> 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 <i>(ii) fume hoods must be turned off when all containers stored underneath are closed</i> .
Ultra-low temperature freezers	Regular cleaning/defrost of the freezers and their maintenance and location in a room at less than $25^{\circ}$ C allow to decrease their energy consumption down to 25 % and increases their life time. <sup>4</sup> In addition, following the recommendations of MyGreenLab <sup>5</sup> , 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. <sup>6</sup> ,
Lasers	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.

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

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

<sup>&</sup>lt;sup>4</sup> 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).

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

<sup>&</sup>lt;sup>6</sup> 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).

<sup>&</sup>lt;sup>7</sup> 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
	plane (long dist.)	2464	4418	5390
distance	plane (short dist.)	50	268	190
(km/pers.)	car	50	152	119
	train	678	1011	844
distance	plane (long dist.)	0.76	0.76	0.82
ratio	train	0.21	0.17	0.13

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

Departure	Arrival	Geodesic distance	Duration
		(km)	(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)<sup>8</sup> 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

% answers

	Lab 1			Lab 2 L		ab 3			
Category	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

59%

69%

28%

55%

76% 26%

57%

25%

90%

**Table S9.** Answers of the commuting survey. Category are: Researchers/teachers ( $\alpha$ ), technical staff/engineers ( $\beta$ ), PhD and Post-doctoral fellows ( $\gamma$ )

<sup>&</sup>lt;sup>8</sup> 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 %.