Towards carbon neutral scientific societies: A case study with the International Adsorption Society

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Keywords: Scientifc conferences, CO_2 emissions and carbon footprint, Opinion surveys, Policy recommendations.

Synopsis: By considering a specific yet representative international conference, CO_2 emission analysis is combined with opinion surveys to propose recommendations for conferences more respectful of the environment.

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With increasing concerns over climate change, scientists must acknowledge their share in contributing to CO_2 emissions.[1,2] Considering the large emissions associated with scientific traveling – especially international conferences – initiatives to mitigate such impact are blooming.[2,3,4] With the COVID-19 pandemic shattering our notion of private/professional interactions,[5,6,7] the moment should be seized in its aftermath to reinvent science conferences and collaborations with a model respectful of the environment. Yet, despite efforts to reduce the footprint of conferences, there is a lack of a robust approach based on reliable performance indicators (emissions, carbon offsetting/removals, etc.) to support and accompany this shift of paradigm. Here, considering a representative scientific society, the International Adsorption Society,[8] we report on a case study as a typical manifestation of the challenge we want to tackle: making conferences carbon neutral while respecting the needs of scientists. We first provide a quantitative analysis of the CO_2 emissions for the IAS conference in 2022, related to accommodation, catering, flights, etc. Then, we conduct two surveys probing the view of our community on the carbon footprint of our activities. These surveys mirror each other and were distributed two years before and immediately after our triennial conference.

As the Intergovernmental Panel on Climate Change (IPCC) reports increasingly pessimistic scenarios for Earth's surface temperature by the end of the century,[9] there is an increasing drive to drastically decrease our greenhouse gas emissions – both at the individual and collective levels.[10,11] For many of us, such efforts already translate into small practical climate-positive actions in our daily life. Moreover, the fact that emissions from professional activities can largely surpass those from the private sphere has resulted in action to decrease CO_2 emissions in all fields relevant to the primary, secondary, tertiary, and quaternary sectors.[12] In the last few years, by analyzing their carbon footprint, many scientific communities, with both academic and industrial members, have also recognized the non-negligible impact of science-related traveling to attend conferences and to visit collaborators.[2,3,4,13,14,15,16,17,18] For some of these communities, acknowledging such negative impact is perceived as paradoxical, because their activities are specifically devoted to developing technologies that mitigate climate change and reduce carbon dioxide emissions. This is the case of the International Adsorption Society (IAS), which serves in the present paper as the model for a "real case study" to identify options to make carbon neutral scientific societies compatible with cutting-edge innovative research. With its activities centered on adsorption technologies to design processes for environmental, health and energy applications, the IAS is at the forefront of research and development on carbon capture and storage. Our international society, which gathers a few hundred researchers and engineers both from academia and industry, is strongly committed to reducing its carbon footprint as witnessed by the appointment of an IAS working group on carbon neutrality as early as 2019.

While evidence exists on the excessive carbon footprint of scientific conferences, solving the problem of such large CO_2 emissions cannot be as simple as making all scientific conferences on-line or continuing business as usual while financially compensating through available carbon offsets. The solution to this complex equation lies in finding the balance so as the undisputable benefits of scientific interactions are weighed against their associated CO_2 emissions. Any optimal, viable solution needs (1) to accurately account for the carbon footprint of scientific interactions (e.g., conferences, collaborations, visiting programs) and (2) to consider the benefits of such exchanges on the quality of scientific outcomes. One example is the stringent need for the generation of the younger scientists to meet physically with each other and with their more senior colleagues to form efficient professional networks for the next decades. In this regard, while some authors support that restrictions in scholarly travels would be detrimental to the scientific system,[19] other studies suggest that air travel has a limited impact on career success.[20] In any case, beside radical suggestions in the literature to switch to online conferencing only[21] and/or to restrict air travel to emergencies and life-saving projects,[22] the working hypothesis in the present paper is to envision an intermediate solution by finding the right tradeoff between carbon footprint and scientific interactions in this complex optimization problem.

The quantification of the carbon footprint of scientific and engineering research needs to rely on a robust and transparent strategy. Unfortunately, there is a lack of consolidated datasets and best practices, despite several interesting initiatives having already originated in other communities.[2,3,4,23] To fill this gap, this contribution proposes a rational and transparent approach based on the following two-step strategy. First, considering that the IAS carbon footprint is largely dominated by its international conference held every three years, we present a robust CO_2 emission assessment based on accurate attendance numbers and cross-checking of data from different reliable sources. Second, we analyze the results from two surveys that were distributed to assess the opinion of the IAS community regarding its carbon footprint and conferencing habits. While the first survey was distributed in summer 2020, the second survey was sent and analyzed in the aftermath of our latest international conference in Broomfield, USA in May 2022. By comparing the answers to the two surveys, which are analyzed in the light of our CO_2 emissions assessment, we are in the position to formulate practical recommendations with the goal to establish a transparent strategy to address this intrinsically complex problem shared by scientific communities regardless of their field, scope, size, geography, etc.

Results and Discussion

CO_2 emissions assessment. Every third year, the IAS organizes the international conference on the Fundamentals of Adsorption (FOA) – a one week meeting that brings together experts from across the world (**Figure 1**). With approximately 300 participants from more than 30 different countries, it is the most important conference in the field of adsorption and covers all areas from fundamentals to industrial applications. A rotating location with venues in the USA, Europe, and Asia-Pacific is consistent with the international nature of the conference. Participation is only to a small degree dictated by proximity to the venue, and about three quarters of the participants travel from across the world regardless of the location. This results in long (10,000 km) or ultra-long-haul flights (> 10,000 km) for approximately 2/3 of the participants to attend FOA. Such intercontinental travel results in significant CO_2 emissions (1-6 t CO_2/delegate) that will be difficult to sustain in a net-zero emissions world. Here, we emphasize that it was decided to include all non-local CO_2 emissions such as those related to travelling despite the fact that flights do not operate specifically to convey FOA attendees to the conference location. Indeed, considering the urgent need to decrease the carbon footprint of science conferences, it is essential to acknowledge their overall climate impact and act accordingly.

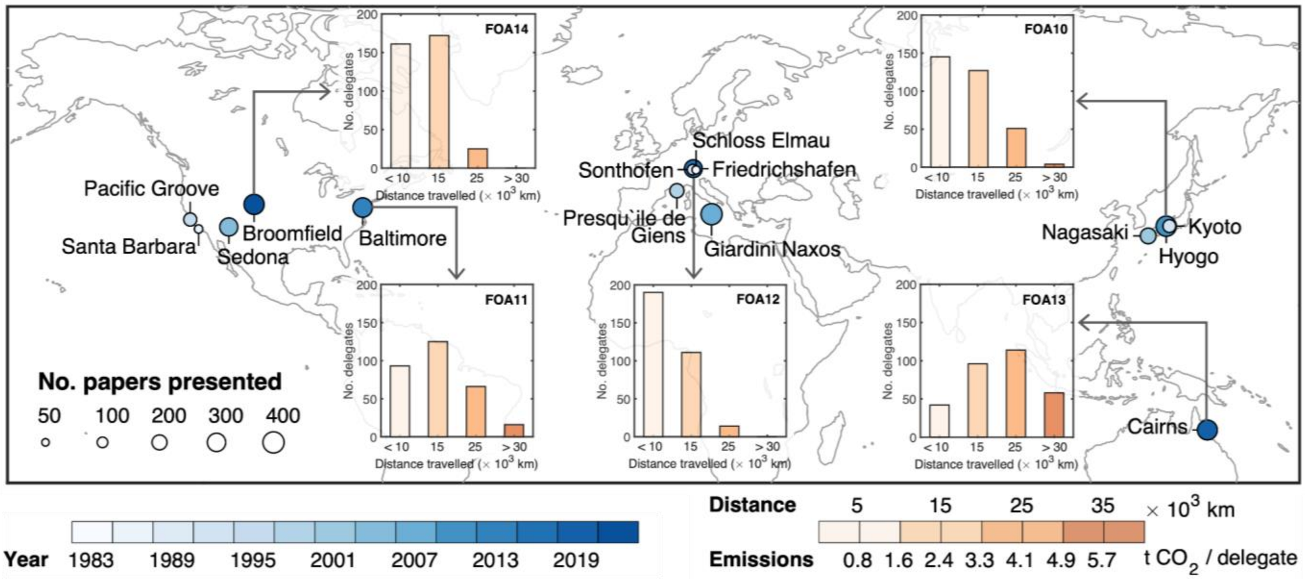

Figure 1. World map indicating the location of the International Conference on the Fundamentals of Adsorption (FOA) – the premier international conference in the field of adsorption organized by the IAS. The FOA series of conferences is held every three years, rotating in an alternating manner between the USA, Europe, and the Asian/Pacific area. Since its establishment in 1983, the conference has grown substantially (as quantified by the number of papers presented) and gathers nowadays approximately 300 delegates from 35 different countries. The four insets indicate the average distance traveled by the delegates to reach the conference venue for the last four meetings (FOA 11, Baltimore, USA, 2013; FOA 12, Friedrichshafen at Lake Constance, Germany, 2016; FOA 13, Cairns, Australia, 2019; FOA 14, Broomfield, USA, 2022) and the associated emissions (t CO_2/delegate, *see text*). Note that the data for FOA 14 in Broomfield, USA are affected by the lack of attendees from Asia due to COVID-related travel restrictions. On the other hand, for this conference, there was a substantial increase in US attendees with respect to the previous edition in the USA.

In addition to air travel, several other factors add to the CO_2 footprint of the conference, albeit to a lesser degree. By selecting FOA 14 as a case study (May 22–27 2022, Broomfield, CO, USA), a detailed analysis was carried out to estimate the average CO_2 emissions per participant resulting from the attendance to the conference. The analysis accounts for transportation, accommodation, on-site mobility as well as emissions related to the venue itself, such as those resulting from catering and energy use (**Figure 2**). All details on our CO_2 emission assessment can be found in the corresponding section in the Supplementary Information (including the main approximations and assumptions used to assess such data). As described there, the exact attendance distribution to our conference was taken into account, and several tools were used and compared to obtain a consistent and reliable picture of CO_2 emissions. Moreover, we also note that our initial estimates regarding CO_2 emissions were revised and updated to reflect the exact attendance distribution to our conference.

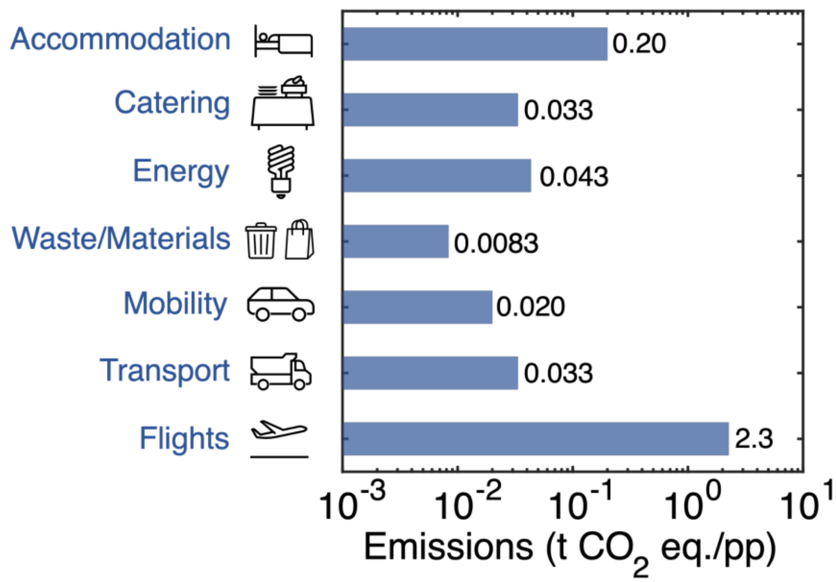

Figure 2. Estimated cumulative emissions (t CO_2 eq.) associated with the attendance to FOA 14 in Broomfield, CO, USA (May 22–27, 2022). Note the use of a log scale to better visualize the orders of magnitude difference between the CO_2 emission components. Emissions from flights have been calculated using a detailed flight calculator from myclimate.org,[24] by assuming the same composition of delegates of the previous USA-based conference (FOA 11, Baltimore, MD, USA). Flights were assumed to be all economy and to depart from the capital of each country, or for the US from the respective state capital. For accommodation, the average of a 6-nights hotel stay in Denver was calculated based on hotel footprints using hotelcarbonfootprints.org which relies on the 2021 Cornell Hotel Sustainability Benchmarking (CHSB) index.[25] The remaining emissions for onsite mobility, catering, energy consumption, conference materials, waste and transport of goods to/from the venue are based on myclimate.org.[26] All data were cross-checked by considering additional information sources. Additional details on all calculations can be found in the Supplementary Information.

Pre and post conference surveys

In the framework of the present study, two surveys were distributed to the IAS community to obtain feedback on the carbon footprint of our scientific activities. These surveys contained specific questions to probe the community's view before and after our last FOA meeting but we note that they are similar in spirit to previous initiatives in other scientific fields.[11,18] The first IAS survey was distributed in spring 2020 to the IAS community while the second IAS survey was sent in summer 2022 immediately after the FOA conference in Broomfield, Colorado. For the second survey, an additional section was added to assess how conferencing habits changed between the first and the second survey (pre and during/post COVID times). We also added questions to receive feedback regarding the online attendance experience, which was implemented for the first time for this conference series on the occasion of FOA 14. In practice, online attendance included access to presentation recordings and poster files (available on the first day of the conference and for 3 weeks thereafter) as well as to live stream sessions of the plenary lectures. Finally, for the second survey, questions related to emission estimates and awareness about CO_2 compensation were removed. The other questions were repeated from the first survey. The number of participants (~120) and the split between academia and industry (2/3 versus 1/3) were similar in both surveys. More students and postdocs responded to the second survey with an increase from 20% to 32% of the responses from academia, which may be related to the timing of the second survey (directly after the conference) and to announcements made during the conference. For the second survey, 65 % of survey participants attended the conference, 8% attended online, and one third already participated in the first IAS survey from 2020.

For both surveys, after a few general questions regarding their position and knowledge on CO_2 emissions related to conference attendance, each survey participant was asked two groups of questions dealing with the following aspects: (1) Carbon footprint reduction through different initiatives such as hybrid conferences combining both on-line and on-site participation, satellite regional (i.e. less impacting) conferences, combined events, etc. together with actions leading to diminished CO_2 emissions for on-site physical conference attendance. (2) Use of carbon offsetting actions through reliable organizations ensuring high standards in carbon reduction to compensate for the CO_2 emissions caused by the FOA conference. The questions asked in each survey as well as detailed data analysis can be found in the Supplementary Information. When calculating averages and percentages, we only considered participants that actually responded to the question (therefore discarding for a given question survey participants that did not answer).

► *FOA carbon footprint, conference attendance, and satisfaction of participants.* As shown in **Fig. 3(a)**, in both surveys, between 70% and 80% of the survey participants consider it important/very important to reduce FOA carbon footprint (less than ~10% consider it not important/not important at all). Regarding the estimated carbon footprint in the first survey, the answers are broadly distributed with a median of 2 t CO_2/participant to attend FOA – a value close to our estimate, as described above. Similarly, on average, the participants believe that flights largely contribute to overall CO_2 emissions – with a value close to that estimated from our carbon footprint assessment [87%]. In the second survey distributed about 2.5 years after the COVID outbreak, 58% of respondents indicated that they were planning to attend a similar number of conferences as before the COVID pandemic. Almost half of the participants indicated that they are planning to attend less conferences on site (42%), favor conferences with shorter travel distances (47%), and combine different events (49%). Approximately 58% plan to attend more conferences online than pre-Covid. Importantly, 93% of all survey participants who attended FOA were either satisfied or very satisfied with the social and scientific interactions, however all the online participants were dissatisfied or very dissatisfied with the experience.

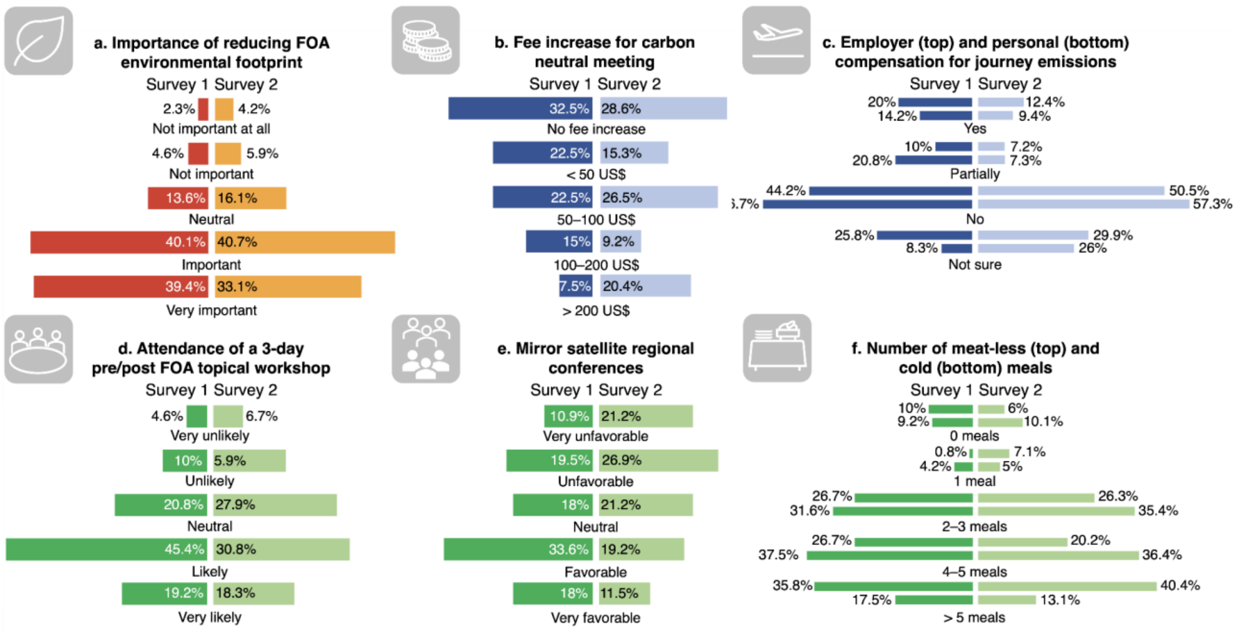

Figure 3. Selected results from the two IAS surveys conducted in spring 2020 (Survey 1, dark colored bars on the left-hand side of each histogram) and in summer 2022 (Survey 2, light coloured bars on the right-hand side of each histogram), respectively. Each panel (a to f) refers to a question that was asked in both surveys (with the exact same wording, see Supporting Information). They belong to the three different groups of questions in the surveys, namely *General position and knowledge on CO_2 emissions related to conference attendance* (Panel a); *Carbon offsetting initiatives* (Panels b and c); *CO_2 emission reduction initiatives* (panels d–f).

► *CO_2 emissions reduction.* The survey indicated that 65% of the participants of the first survey are at least somewhat likely to attend a pre/post FOA school/workshop. Similarly, 49% of the participants are likely to very likely to attend such events in the second survey [**Fig. 3(d)**]. The all-inclusive cost judged as acceptable for such events of ~75–175$/day (survey 1: median 125, IQR 75-175; survey 2: median 125, IQR 125-175) remains stable between the two surveys (note that these numbers only consider answers by survey participants, who indicated that they were neutral or likely to attend pre/post conference events). In the second survey, only 31% of participants are (highly) in favor of satellite FOA conferences – conferences that would occur in different places but with the same on-line common sessions – compared to 51% in the first survey. Moreover, 48% of the participants are against this option compared to only 30% in the first survey [**Fig. 3(e)**]. If FOA were broadcasted on-line (on-site attendance combined with possible remote access), most participants indicate that several people around them (including them) would attend online, with a median of 3 (survey 1: IQR 2-5; survey 2: IQR 1-5). As for an acceptable on-line access fee, answers vary broadly from 10 to 400$ with an average of ~100-120$. Interestingly, the number of participants that indicated that nobody would attend such events increased from 9% in the first survey to 20% in the second. In both surveys, the participants supported having several of the seven conference meals served vegetarian (median 4, IQR 3-7) or cold (median 4, IQR 3-5) [**Fig. 3(f)**]. Moreover, ~65 % of participants are (highly) in favor of more informal gala dinners and welcome receptions.

► *Carbon offsetting.* 66% of the participants are aware of carbon compensation by financially supporting emission reduction projects (first survey data, not asked in the second survey). In the first survey, 29% of the participants indicate that their employer is compensating (at least partially) for their flight/trip emissions – this number dropped to 19% in the second survey. A similar decrease was found for compensation on a personal level, with only 17% compensating their personal emission at least partially at the time of the second survey compared to 35% in the first survey [**Fig. 3(c**)]. In both surveys, ~70% of participants support an increase in registration fee to compensate for the CO_2 emissions [**Fig. 3(b**)]. In the first survey, when asked about how to apply a registration fee increase to compensate for the carbon footprint [~78$/participant as initially estimated for FOA 14 in Broomfield, CO, USA], approximately half indicated that they prefer such increase to be applied to every participant, with the other half being either against such increase or preferring an optional increase. In the second survey, when answering the same question, ~51% of the participants preferred such an increase to be applied as a general added fee to every participant, while ~28% advocated for an optional fee, and 20% are against. In both surveys, answers about a reasonable fee increase to achieve carbon neutral meetings vary broadly between a few 10$ to a few 100$ for those in favor of a fee increase, resulting in an average of 135$/participant (survey 1, median 100, IQR 50-200) to 220$/participant (median 100, IQR 75-250). When including all participants, values are significantly lower with an average of 91$/participant (survey1) - 130$/participant (mean 50, IQR 0-100 in both cases) [**Fig. 3(b**)].

Overall, the first and second survey data show that reducing their conference-related CO_2 footprint is important to the IAS community. Remote conferencing is seen as a good option to achieve this, whereas satellite in-person conferences are perceived as increasingly unattractive. Here, 'remote conference' is meant as solely online attendance to a conference[21] while 'satellite in-person conference' corresponds to a multi-site conference where a participant attends the closest conference site to their professional or personal location.[27] In the latter case, considering time zone differences, the multisite conference includes both common broadcasted sessions, and specific on-site sessions with their own program (which are recorded for remote watching available to every participant). For FOA 14, the conference was experienced as significantly inferior by online attendants compared to onsite attendants (see above for a description of the registration package corresponding to online access). Thus, even though remote conferencing is seen in principle as a good approach for emission reduction, its implementation in practice is often disappointing, and a high-quality experience for remote attendants must be ensured to maintain the interest in remote conferencing. Moreover, most participants are in favor of reducing on-site emissions, for example via vegetarian or cold or less fancy meals, shared taxis, less waste, etc., and many comments of survey participants regarding suggestions for making FOA carbon neutral were directed at on-site emission reduction actions. Furthermore, 70% of the attendees are in favor of emission compensation, but only ~50% think that such compensation should be compulsory; despite this, only 10% of the FOA attendees opted out of a $70 CO2 offset fee included in the conference registration. Few people and institutions compensate for their flight/trip emissions. Comments by participants indicate that this is related to their skepticism regarding meaningful compensation actions, and because they favor reduction over compensation. Finding suitable compensation mechanisms at an acceptable price thus is a major challenge and a key bottleneck at the moment for making compensation a viable solution for conference attendees.

Discussion

Based on the different elements presented in this study, we propose recommendations to help design future conferences that are more respectful of the environment, while taking into account the need for younger generations of scientists to keep running at least some conferences with physical attendance. Because reducing the carbon footprint of conferences is important to all scientific communities, we believe that the strategy proposed below applies not only to IAS. We do not claim that the proposed strategy is better than other initiatives that have already been proposed in other scientific communities (see references provided in the introduction). Yet, we think that our analysis of carbon emissions together with the helpful feedback from the community have helped us propose a possible, acceptable route, which is a compromise between the two asymptotic solutions (business as usual in conferencing habit and on-line conferencing only). It is worth underlining that the best compromise between these two limits may differ for different scientific societies.

While we are advocating for a shift of paradigm to reinvent conferences as climate neutral, there are important constraints. First, despite all efforts to mitigate the carbon footprint of scientific conferences, the fact that such events are dominated by flight-related greenhouse gas emissions has severe implications. Their climate impact can be reduced by (1) eliminating them or reducing their number, (2) switching to mostly online conferences,[21,27] or (3) fully compensating the emissions due to air travel associated with conferences. There are obvious drawbacks with all approaches. The scientific community acknowledges that a healthy science requires regular in-person exchange at meetings. The years of anti-Covid measures have made everybody experience how unsatisfactory and ineffective online conferences are. Second, effective emission compensation through real carbon removals (i.e. using negative emission technologies) is not a trivial solution as the associated costs are a moving and increasing target that make them somewhat prohibitive. For instance, the current Compensaid[28] price is ~700 €/t CO_2 for immediate compensation through Sustainable Aviation Fuels as compared to the ~30 $/ton CO_2 applied on a voluntary basis to the FOA delegates.

In view of these elements, *sobriety in scientific traveling* remains and will remain for quite some time a key component in any realistic strategy to mitigate the impact of conferences on climate. We believe that policymakers at different levels (e.g., government, institution, university) should enforce carbon neutrality by establishing strong rules monitoring the environmental impact of scientific travel. In parallel to setting CO_2 avoidance targets, a change of mentality in the scientific communities is mandatory to modify our current mindset about traveling. In particular, one needs to find a better compromise between quantity and quality of the conferences that one attends, without neglecting the vital need for scientists, particularly early career ones, to attend conferences. In this context, considering that conference organizers cannot control travel habits of conference attendees, it is important to acknowledge that they should set CO_2 emissions targets, define selection criteria for conference venues to minimize emissions, and establish strategies for low-carbon and low-waste behaviors with the goal to meet IPCC's recommendations (45% emission reduction by 2030 relative to 2010 levels and 100% by 2050). Therefore, considering the large CO_2 emissions related to scientific conferences, organizers must strive to reach such objectives while offering solutions to allow every participant to benefit from scientific exchanges at conferences regardless of their origin (distance to the conference location).

Starting from these elements, our working strategy is simple: we intend to provide guidelines for researchers as well as for institutions to design a model for carbon neutral conferences. We consider that scientific conferences are central to the life of science communities so that they deserve to be maintained but in a sustainable format. To reach such an ambitious goal, we propose here a strategy with stringent yet realistic actions that can be implemented without major obstacles (**Fig. S1** in the Supporting Information). The targeted initiatives listed below are grouped into different categories: (1) carbon footprint reduction, (2) CO_2 emissions compensation, and (3) awareness and advocacy actions. Additional discussion can be found in the Supporting Information.

► **Carbon footprint reduction.** Despite their environmental impact, there is a general consensus that scientific conferences should be maintained – albeit in a more carbon neutral form. By fostering vivid exchanges among its members and ensuring the training of the next generation, the majority of participants acknowledges the role of conferences in promoting high quality achievements in a science community. Yet, to maintain conferences, already identified as large CO_2 emission contributors, it is also recognized that we should raise the bar in terms of reducing their carbon footprint. Here, our approach attempts to follow the recommendations from the UN IPCC: "*Non-state actors cannot focus on reducing the intensity of their emissions rather than their absolute emissions or tackling only a part of their emissions rather than their full value chain*".[29] Considering that all CO_2 emissions contribute to global warming, we focus on reducing emissions from the FOA conferences (with the final goal to reach net zero emissions in a reasonable short time). In this context, FOA meetings are already following a reasonable approach since they are not held every year but every 3 years (we note that recommendations in the literature have been made to make conferences biannual instead of annual[2,16]).

● *Relative and absolute targets.* While the urgency of global warming calls for very stringent targets, we believe that both relative and absolute CO_2 objectives should be set. Even if the acute climate crisis is striking everyone on Earth, broad variations among continents and countries are obvious and should be taken into account. In other words, considering local habits and practices, it is difficult – not to say unrealistic – to set the same absolute emissions (CO_2 ton/capita) for everybody. However, by setting the same relative target (e.g. share of the national CO_2 emissions/capita), we can create a virtuous circle in which every conference organization team will commit to do at least as well as the others.

● *Conference site selection.* We advocate to use CO_2 emissions as a stringent selection criterion for conference sites. The specific site location for a conference is often selected for its convenience (e.g. train/plane access) or attractivity (e.g. sightseeing). In the context of global warming, while the organizing team should always be selected for its competence, the conference site selection should also additionally consider carbon footprint. Such criterion, which should be seen as a mandatory point to address in a conference hosting bid, should be formulated to include both local (i.e. on-site) and global CO_2 emissions.

● *Local venue.* Universities or research centers are ideal conference venues. In addition to being much cheaper than conference centers, they provide most commodities and facilities for a low carbon footprint. Moreover, such venues offer great video-conferencing possibilities (software, rooms, networks) with IT support. With the numerous students and staff enrolled in universities, they are optimized for conference hosting with sufficient catering and accommodation capacities (universities are also well-equipped for internet access). Organizing events at universities is also virtuous as it fosters the training of future generations. We support that on site access to the conference should be free for all students to trigger vocations – a key aspect to ensure the continuity of any research field. We acknowledge that University-based solutions may only be applicable to small and mid-sized societies.

● *Local carbon footprint.* Carbon footprint at the conference site is far from negligible (~15% of overall emissions). Considering that local emissions are easier to control (compared to flight-related emissions for instance), they should be as close to zero as possible. As discussed below (see *compensation*), we propose to fully remove all local CO_2 emissions through financial support to negative emissions solutions. Several measures can be easily taken to reduce the local CO_2 emissions, including use of reusable materials, reduced cooling of the venue, shared accommodation, shared taxis, facilitated use of public transport, low-carbon catering including vegetarian food and less sophisticated galas, no printed materials, etc. As an example, the FOA conference organizers utilized a webpage 'Reducing your carbon footprint while at the conference".

● *Global carbon footprint.* The large share of travel-related emissions makes the reduction potential through measures that target other emission sources limited. Thus, as long as air travel is required, any model for carbon neutral conferences should be accompanied by strong policies to decrease the footprint of travel. Since conference organizers do not control travel habits of the participants (which vary broadly), it is in practice unfeasible to leave it to the local team to deal with this enormous problem. However, in any case, for the sake of transparency, all emissions should be estimated as they must be considered when selecting any conference site (so doing will also automatically decrease the overall impact of the organized event).

● *Carbon intensity.* While CO_2 emissions are an extensive indicator, carbon intensity is an intensive parameter that describes the impact of an event per day, per capita, etc. Initiatives to decrease carbon intensity do not reduce emissions but make traveling more worthwhile. For instance, organizing hybrid events with both on-site and on-line attendance reduces carbon intensity at constant (or slightly larger) absolute emissions (for the FOA conference, on-line access led to a ~50% increase in attendance, which reduces the carbon intensity of the FOA meeting when considering both on-site and on-line participants). Regarding the combination of events, while this decreases the carbon intensity de facto, we note that there is an associated risk of increasing attendance and, hence, absolute air travel emissions. Finally, while receiving less support from the community, other means to decrease carbon intensity include organizing satellite conferences (on different continents at the same time with joint sessions) and reducing the frequency of meetings. In this regard, we note that such conferences with regional satellite locations would largely decrease the carbon footprint (since participants would choose the closest site, therefore introducing a cut-off in the distribution of travel-related CO_2 emissions with only short to medium haul flights).

► **Carbon footprint compensation.** Financial support to specific actions to acquire carbon offsets is often invoked to compensate for CO_2 emissions. Carbon compensation includes very different strategies: from carbon offsetting obtained by supporting projects through which someone else is avoiding emitting the same amount of CO_2 somewhere else, to carbon removals obtained by investing in negative emission technologies. To achieve net-zero CO_2 emissions, CO_2 must be removed from the atmosphere. CO_2 avoidance offsets and re/afforestation do not provide this either: not at all in the former case or unreliably in the latter case.[30,31,32,33] As discussed in the preceding section, the priority should be to reduce emissions. Emissions (local and global) cannot be completely reduced to zero until the whole of society is powered by zero-emissions technologies (e.g., fully electrified by renewables). In the interim, fully virtual conferences are the only way to minimize emissions. We have received clear feedback from the IAS membership that fully virtual conferences are not desired, and as such, some form of CO_2 emissions compensation is currently required. The use of CO_2 avoidance offsets and re/afforestation are not our first preference, due to the aforementioned reasons. However, as discussed below, they are likely what will be opted for until the membership is willing to bear the cost of atmospheric CO_2 removal with permanent storage.

To define an acceptable compensation strategy, we list here potential guidelines.

● *Offset versus removal.* Roughly, carbon offsetting is significantly cheaper than carbon removal (tens versus hundreds US$ per t CO_2), but is less permanent. These numbers seem to be increasing rapidly as convenient options – the so-called low hanging fruits – are exploited. It seems fair to assume that the cost difference between offsetting and removal should not change much as the latter solutions are necessarily more complex. Under these circumstances, it seems unrealistic to remove all CO_2 emissions related to a scientific conference (~2.6 ton CO_2/capita) without rendering such events unaffordable. In contrast, the following dual mechanism seems to be transparent and sustainable: fully remove all CO_2 emissions produced locally at the conference site (after minimizing them as much as possible), while offsetting all travel-related emissions.

● *Compensation monitoring.* To get support from the scientific communities, any carbon compensation must be transparent. We propose to appoint a CO_2 fund in each scientific community to monitor and decide any actions performed using the funds raised for compensation. Such panels do not substitute for compensation organizations, whose business is dedicated to such programs, but ensure that high standard carbon offsettings/removals are utilized. Typically, compensation actions should be available to purchase immediately and the associated permanence (i.e. duration) well specified to maximize environmental benefit.

● *Zero emission certificates.* External verification and validation of the carbon compensation initiatives should be sought. This would provide independent, unbiased assessment of the compensation strategy as a part of the overall approach to carbon neutrality. Such evaluation would allow obtaining a zero emission certificate for a given scientific conference. Such labels, which are required to ensure full transparency towards the scientific community and the scientific institutions, would create a virtuous circle by providing reliable numbers on science event-related carbon footprint. In particular, by providing detailed figures about local/global CO_2 emissions and carbon compensation actions, such zero emission certificates would serve as a quality label when organizing science events. While we advocate for such verifications, we also acknowledge that the quality of these certifications, ecolabels, etc. is difficult to assess and sometimes questionable as discussed by Strick and Fenich.[34] The cost and use of many certifications can also be seen by organizers, customers, etc. as confusing.[12]

● *Compensation funds.* Compensation should be seen as a secondary means to achieve carbon neutrality behind carbon footprint reduction. Yet, considering that zero CO_2 emissions are difficult to achieve currently (even locally at the conference site), it is recommended to raise funding for compensation. Optional/mandatory additional registration fees, fundraising through "green" sponsoring, or financial support from institutions can be used to raise funds. Scientists could also request funding for such compensation when applying to funding agencies (we advocate that requested fundings for open access science could be used for carbon compensation instead since preprint servers are available). As an inspiring example, through an optional registration fee (70 US$), the FOA organizers raised 25,000 US$ which exceeded the 23,400 US$ estimated to make this conference carbon neutral through offsetting.

► **Awareness and advocacy.** Actions should be taken to increase the sensitivity of a given community (and beyond) towards the importance of reducing the carbon footprint of science events. All communities should be committed to this fight but some of them must act as role models as their activities are relevant to the climate crisis mitigation. This is the case of the International Adsorption Society whose research field is central to carbon capture and storage; among the many techniques to mitigate CO_2 emissions, adsorption processes are mature and viable technologies to remove CO_2 from the atmosphere (i.e. negative emission technologies as implemented by e.g. Climeworks AG, Global Thermostat). In this context, in addition to emission reductions, carbon dioxide removals (CDR), i.e., the net-removal of CO2 or other greenhouse gases from the atmosphere will likely be needed at large scale of around few Gt CO_2 equivalent removed per year in 2050 in order to achieve net-zero by mid century (IPCC 2022 WG III report-mitigation of climate change, 1.5°C report IPCC). In addition to reducing greenhouse gas emissions, CDR can also balance difficult-to-avoid emissions and remove historical emission from the atmosphere in case of an overshoot. Different technological as well as nature-based solutions are currently evaluated for CDR that vary in their scale, maturity, timescale of CO_2 removal (IPCC AR6). Whereas it has been shown that both technological as well as nature-based solutions can result in a net-removal of carbon dioxide from the atmosphere, many challenges remain. These include the current small-scale of frequently discussed technological solutions like bioenergy coupled with carbon capture and sequestration (BECCS) or direct air capture coupled with permanent carbon storage (DACCS), and higher cost compared to many CO_2 reduction options. In the case of successful scale up, there will be a competition for renewable energy between DAC and other applications, or land-use competition in the case of BECCS (the energy-water-land nexus, e.g.[35]). Nature-based solutions also face difficulties in correctly monitoring the amount removed and in assessing the duration of the removal. Hence, just like for CO_2 emissions reduction, CDR will also likely require a portfolio of solutions that are combined. Moreover, in parallel to the continued development and scale-up of both technological as well as nature-based solutions to better understand their potential, a co-development of monitoring, regulation, and verification (MRV) of CDR services is essential to ensure proper accounting.

● *Communication.* Gaining support from the science communities but also from the society in general is a key objective when fighting the climate crisis. Communication aspects are therefore important to disseminate transparent and unbiased facts to broad audiences; the numerous articles written in specialized and general journals as well as presentations, reports, websites dedicated to the impact of science-related activities are therefore important initiatives. Surveys probing the feedback from either small, well focused communities or broad pans of the society – such as those that were distributed in the pre and post COVID pandemics within the International Adsorption Society membership – also contribute to increasing awareness.

● *Scientific coalition to advocate.* As discussed above, with the current state of the art, a provisional conclusion should be reached: *sustainable science requires climate-neutral aviation*. Here, we clearly acknowledge the limitations of alternative fuels such as hydrogen and synthetic or bio fuels as discussed in several important documents.[36,37,38] Of particular concern, while hydrogen fuel raises the question of its storage and design changes of aircraft, synthetic and bio fuels pose problems related to their low energy density. Moreover, a recent study has also discussed that climate-neutral aviation will only fly if air traffic is reduced to limit the impacts to mitigate.[39] Yet, in view of the need for urgent action to tackle the climate crisis, we argue that scientific societies and academic institutions should not wait passively for the aviation industry to realize carbon neutral operations. We need to take a proactive role beyond that of (for some of us) doing research on new and better solutions. We envision *a scientific coalition of the international scientific societies and academic institutions*, which argue and advocate for climate-neutral flights today, at both the international and the national levels. Such coalitions should serve as science ambassadors on the following topics, among others: (1) climate-neutral aviation, (2) the techno-economic potential and the deployment timeline of sustainable synthetic aviation fuels, (3) the need for carbon-free energy to power their synthesis, (4) the role of CO_2 removal solutions to close the carbon cycle associated to flight CO_2 emissions, (5) the need of CO_2 removal measures to compensate for climate non-CO_2 effects and for extra-flight CO_2 emissions. Such a coalition should request that standards be established for the calculation of the carbon footprint of everyone’s flight, and it should verify that these are consistent with the up-to-date climate science, including about the role of non-CO_2 effects. We believe in the power of the scientific community, and in the strengths of its scientific arguments, hence in the role that it can and must play in making aviation climate neutral and research sustainable for the benefit of the society.

Glossary

● *Carbon compensation.* Carbon compensation is a voluntary action taken by an entity to mitigate the impacts of carbon dioxide released to the atmosphere (directly and indirectly) as a result of their actions.
The compensation takes the form of a carbon offset or carbon credit, and is thereby also commonly called 'carbon offsetting'.

● *Carbon offset.* A carbon offset or carbon credit is generated and sold by an entity who operates a certified project. Certification is available from several third party bodies, however, they are not all necessarily aligned in their certification standards. A carbon offset can be generated by either reducing or avoiding carbon dioxide emissions ocurring elsewhere (avoidance offset), or removing carbon dioxide directly from the atmosphere (removal offset). The latter is now typically referred to as carbon dioxide removal (CDR). A key requirement of any project generating offsets is to prove that they are additional. That is, the project is only operational because carbon offsets are being sold, and not because of any other economic efficiencies or legislative requirements.

● *Carbon intensity.* Carbon intensity is the total amount of greenhouse gases released to the atmosphere (directly and indirectly), per unit of a good or service delivered. Greenhouse gases that are not carbon dioxide are converted to a carbon dioxide equivalent using a conversion factor, the global warming potential (GWP).

● *Relative and absolute carbon footprints.* The absolute carbon footprint is the total amount of greenhouse gases released to the atmosphere (directly and indirectly) as a result of a person or entity's actions, an event, or product. Carbon intensity data for goods and services are used in the calculation of this quantity. The relative carbon footprint is where the absolute carbon footprint is normalised to a per unit basis, e.g., per person in the case of events, or per unit revenue in the case of a business. However, in the context of this paper, relative carbon footprint refers to the ratio between the absolute carbon footprint per event participant and a country's total greenhouse gas emissions per capita.

Acknowledgments. The authors were appointed by the International Adsorption Society (IAS) to form a working group to evaluate its carbon footprint and propose/elaborate mitigation actions. The authors are grateful to the past and current IAS presidents for their trust and support (P. A. Monson, A. Seidel-Morgenstern, and P. Webley). The authors also thank the IAS secretary – D. Siderius from NIST – for his help and all the IAS community for its feedback and support.

Author contributions. All authors conceived the study, analyzed the data, interpreted the results, and contributed to the writing of the manuscript.

Supporting Information. The Supporting Information is available free of charge at XXX. Additional data and discussions.

Notes. The authors declare no competing interest.

Data availability. The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information file. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Ethical Approval. Not applicable.

Funding. No funding was used to conduct the research.

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