Routledge
Taylor & Francis Group

International Journal of Environmental Studies

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/genv20

A framework to estimate emissions from virtual conferences

Grant Faber

To cite this article: Grant Faber (2021) A framework to estimate emissions from virtual conferences, International Journal of Environmental Studies, 78:4, 608-623, DOI: 10.1080/00207233.2020.1864190

To link to this article: https://doi.org/10.1080/00207233.2020.1864190

INTERNATIONAL JOURNAL OF ENVIRONMENTAL STUDIES
2021, VOL. 78, NO. 4, 608–623
https://doi.org/10.1080/00207233.2020.1864190

Routledge
Taylor & Francis Group

ARTICLE

A framework to estimate emissions from virtual conferences

Grant Faber

Department of Mechanical Engineering, Global CO_2 Initiative at the University of Michigan, Ann Arbor, MI, USA

ABSTRACT
While virtual conferences emit far less greenhouse gas emissions relative to their physical counterparts, they still have a considerable impact on the environment arising from participant computer life cycle emissions, network data transfer energy use, server energy use, and other activities that would not have happened without the conference. This article proposes a modifiable framework for systematically measuring the emissions attributable to such conferences using data about participant computers, Internet energy intensity, network data transfer, server power ratings, and other relevant factors. Strategies to reduce emissions attributable to virtual conferences are also proposed based on the framework.

KEYWORDS
Videoconference; emissions; virtual; meeting; environmental; digital

Introduction

On 13 May 2020, the AirMiners carbon removal networking community held its first virtual conference, titled Foundations for a Carbon Negative Future. The growing urgency of addressing climate change, increasing opportunities in carbon capture, use, and sequestration (CCUS) technologies, and the global COVID-19 pandemic all inspired the organisers to create this event. The conference featured prominent scientists and entrepreneurs in the carbon removal space, including Dr. Klaus Lackner, Dr. Lisa Dyson, and Dr. Peter Eisenberger, along with hundreds of interested participants from nearly a dozen countries [1].

Organisers hosted the event as a series of large Zoom meetings over the course of the day, with links available on an associated webpage [2]. Zoom is a prominent video communications company, and use of their services has increased dramatically with social distancing measures because of the COVID-19 pandemic [3].

As the AirMiners community is concerned with using carbon removal technologies to mitigate and remove past carbon dioxide (CO_2) emissions from the atmosphere, one focus of the conference was the purchase of carbon removal offsets for any emissions generated by conference activities. These are the emissions generated by hosting Zoom meetings and engaging in other activities that would not have happened but for the conference. They would not have happened otherwise. This article explains the process for estimating these emissions and attempts to offer a more generalisable framework for doing so. Some have already used this framework to estimate emissions

CONTACT Grant Faber gfaber@umich.edu Department of Mechanical Engineering, Global CO_2 Initiative at the University of Michigan, Ann Arbor, MI, USA.

Supplemental data for this article can be accessed here.

Published online 11 Jan 2021

for other virtual conferences and general online activities. There is opportunity for other scholars to develop this framework further to increase its accuracy and applicability.

Many studies have already noted the significant emissions reductions from conducting virtual meetings relative to physical or 'face-to-face' meetings [4–10]. Internet communication still has a significant climate impact arising from energy use and attributable embodied emissions from equipment, among other factors. New social distancing measures that may be in place for years as of May 2020 [11] along with a rising global population that is increasingly connected to the Internet [12] will likely lead to continued growth in the number of virtual meetings, conferences, classes, and other social interactions. Estimating emissions that can be allocated to virtual meetings and associated behaviours will be increasingly important to help videoconferencing companies, Internet infrastructure providers, and users understand ways to reduce the climate impact of these activities. In the case of AirMiners, this information was necessary to purchase an amount of offsets that would make the conference 'carbon negative' – meaning it would result in the removal of more CO_2 from the atmosphere than it was responsible for emitting – with reasonable certainty.

There is also interest in the consideration of emissions associated with the increasingly technological world. For example, Microsoft, as part of their mission to become carbon neutral as well as to cancel out all of their historical emissions, released a sustainability calculator that will allow stakeholders in their value chain to measure emissions associated with usage of Microsoft services [13]. Apple, as part of their own climate goals, plans to make all of their products carbon neutral by 2030 [14], which will in turn help reduce the emissions attributable to virtual conferences. Apple's current, transparent greenhouse gas accounting for laptops was already useful for estimating embodied emissions in this model. Steps like these from significant technology companies demonstrate an increasing willingness to measure and mitigate the climate impact of digital technology use, to which this model will hopefully contribute.

The framework in this article estimates virtual emissions by considering a range of data sources and inputs, discussed throughout. To ensure that the final output captures the 'true' amount of emissions with a high degree of certainty, the framework uses conservative assumptions, estimates, and methods where applicable. This means that the worst-case scenarios, or the ones tied to higher emissions or energy use, are considered where appropriate.

Materials and methods

Literature review

A literature review was conducted to determine how others have already attempted to estimate emissions for virtual activities. The studies cited in the Introduction are all comparative as they compare the emissions from virtual meetings with those from physical meetings. The focus of these studies is on virtual *meetings* rather than virtual *conferences*. Conferences generally have far more participants than the meetings analysed by these studies, and the studies exclude other factors relevant to hosting virtual conferences, such as website visits, search engine queries, and more.

The most informative study for the review by Ong et al. [6] considered emissions from peripheral videoconferencing equipment such as cameras, sound systems, and so on, which companies now simply build into most laptops. As the vast majority of conference participants used laptops to participate, the framework captures emissions associated with such devices with an aggregate life cycle emissions figure for computers themselves.

As many contributing factors as possible were used to shape the rest of the framework. The following list details the factors discovered during the review along with their source(s). The studies measure the following and then generally tie emissions factors to them: energy use of network infrastructure [6,9,10], energy use of computers and peripheral equipment [6,9,10], embodied energy use of network infrastructure [6,9], embodied energy use of computers and peripheral equipment [6,9,10], actions performed when videoconferencing, such as using digital documents or drinking beverages [5,8], money spent on things that would not have been spent otherwise [5,8], and travelling to locations to allow for teleconferencing [7].

Relevant factors selected for inclusion in this framework were energy use from network infrastructure, computer energy use, computer embodied energy, and actions performed when videoconferencing (only those that would not have happened otherwise). Other aspects of the conference such as search engine queries and website visits were added. Embodied energy use of network infrastructure, money spent, and travel were excluded from this model.

While there are figures for the embodied energy, or emergy, of Internet network infrastructure, there are various factors that led to the decision to exclude them in this framework. Most importantly, there is a significant amount of uncertainty when calculating such figures [15]. A large portion of the figures in Raghavan and Ma [15] are also made up of the embodied energy in desktops and laptops, which are already included separately in the model. Servers and related equipment – another considerable portion of these emissions – are also considered as a separate category in this model. Separately, the figures are constantly in flux, given the ever-changing amounts of equipment and Internet traffic itself. It is difficult to allocate these emergy figures to Internet traffic in a useful way, as it is unclear how the supply of Internet infrastructure would realistically change with relatively minor changes in usage. Finally, based on a consultation with a representative from Zoom, it is also not entirely clear how much infrastructure any given session might use.

For money spent on things that would not have been bought otherwise, this factor was relevant only in studies that compared purchases that would and would not have happened with and without travel to a business meeting. Travelling to locations for teleconferencing was relevant only in the particular context of the study that proposed it, as it included having patients travel to their local doctor's office to teleconference with an off-site expert. Most if not all of the participants of virtual conferences do so from their homes or standard places of work. Based on survey responses and the extent of the COVID-19 pandemic at the time, most if not all of the participants of the AirMiners conference joined from home.

Direct software use emissions data

Computer emissions data

All conference participants had to use a computer to access the conference. Emissions associated with this usage can be calculated by allocating each computer's life cycle emissions to the percentage of its useful life spent participating in the conference. This method captures both the emissions arising from the energy use of the computer as well as the embodied, shipping, and end-of-life emissions. Many computer manufacturers already publish this information in the form of product carbon footprints. Formula 1 captures all of the relevant factors for estimating the total emissions arising from direct computer use among participants for the conference.

$$P_c * E_c * \frac{H_c}{Y * 365.25 * H_d} \tag{1}$$

P_c = number of participants (computer), E_c = computer emissions (kg CO_2-eq/computer), H_c = conference duration (hour), Y = years of useful life (year), H_d = daily hours of computer use (hour/day)

To understand the average computer emissions from conference participants, the organising team conducted an intake survey asking about computer usage. Only about 10% of registrants responded (45 out of ~400 who registered), but there was no reason to believe that this response set was not representative of participants of the overall conference. The vast majority of respondents planned to use laptops for the conference, and about 70% planned to use some kind of Apple laptop. Apple publishes product carbon footprints for all of their physical products [16]. This made lifecycle emissions data collection simple for the majority of laptops used for the conference. Dell [17], Lenovo [18], HP [19], Asus [20], and Sony [21] have all also published some level of carbon footprints for at least a sample of their products, which were used where appropriate in estimating computer emissions.

Once the lifecycle emissions for all computers were recorded, an average value was taken for the E_c variable in Formula 1. This process is recorded in the 'Participant Computers' worksheet of Supplementary Materials 1. Users of this framework could increase its accuracy by calculating and allocated the life cycle emissions of each participant's individual computer, assuming the data are available.

As for the other variables, P_c was 207, Hc was six given that the conference lasted for six hours, Y was four based on the expected useful life of the MacBook Pro 16-inch laptop that was used by many participants [22], and H_d, the average number of hours spent per day using the computer, was two based on Statista data [23]. While many do use their computers for far more than two hours per day, this value is likely balanced out by those who use their computers far less and those who have multiple computers that may on average only be used for this relatively smaller amount of time.

Network data transfer emissions data

The energy used by Internet infrastructure when transferring data between Internet users is a significant source of global emissions. One model claims that by 2030, electricity use from information and communications technologies could exceed 20% of the global total [24]. For the conference, this energy use ended up being a significant contributor to the overall conference emissions. Embodied emissions for the infrastructure that carries the data were excluded for reasons described in the Literature Review section.

$$P_c * E_e * I * D * H_c * \frac{3,600}{8,000} \tag{2}$$

P_c = number of participants (computer), E_e = electricity emissions (kg CO_2-eq/kWh), I = Internet energy intensity (kWh/GB), D = data rate (Mbps/computer), H_c = conference duration (hour)

According to Ong et al [6], Internet energy intensity (I in Formula 2) is a very important consideration when estimating the emissions that occur because of data transfer over the Internet. This intensity figure is represented by kilowatt-hours (kWh) per gigabyte (GB) of data transferred, and this value has varied and continues to vary significantly over time. Given the vastly different values of this variable over time, this study directly calculated the approximate current state of this variable by dividing the total energy used by the Internet by the current amount of Internet traffic. A 2019 report stated the annual amount of energy used by the Internet is around 2,000 terawatt-hours [25], and a site that tracks the amount of data being transferred over the Internet put it at about 98,600 GB per second [26]. Combined, these yield an average Internet energy intensity of about 0.64 kWh per GB. This number is expected to decrease with time as the efficiency of Internet infrastructure increases. Thus, it should be recalculated manually each time this framework is used. This number was checked against other estimates used in literature and was found to be within a reasonable range [27–29]. For calibration and verification purposes, newly calculated values should be checked against new literature if possible.

The rate of data transfer to and from Zoom users during the conference – D in Formula 2 – is also required to understand the total energy use and thus emissions burden from network data transfer. According to Zoom's system requirements as of May 2020, the maximum bandwidth required for receiving and sending the highest-quality video possible – 1080p HD – during group calling is 5.5 megabits per second (Mbps) [30]. Zoom users can monitor this value in real-time, and throughout the conference, observations of the bandwidth showed that it both never crossed ~2.3 Mbps and was at a far lower value for the vast majority of the conference, given that many had turned off their video and audio while listening to speakers. To be conservative, the model assumes that all participants were using the highest possible bandwidth value for the entire conference. If a more accurate calculation is desired, recording bandwidth values throughout the duration of the Zoom meeting and averaging them could provide one. If Zoom were to add a feature that records and shares the total data transfer during meetings, then users could conduct this calculation more precisely as well. Certain tools that track network data transfer, such as the Activity Monitor on Mac computers, could also be of use here.

As for the other variables in Formula 2, H_c was kept constant at six and P_c was kept constant at 207 from the previous section. The remaining variable E_e, electricity emissions, was 0.4322 kilograms carbon dioxide equivalent (kg CO_2-eq) per kWh based on March 2020 EPA Emissions & Generation Resource Integrated Database (eGRID) data [31]. This value represents the average CO_2 emissions per unit of electricity averaged across the United States, along with CH_4 and N_2O emissions converted to CO_2-eq based on 100-year Global Warming Potential values from the IPCC [32]. While there were participants from nearly a dozen countries at the conference, the vast majority were in the US allowing this average figure to be used. To increase accuracy, specific emissions intensity values for given participant localities could be used along with factoring in any potential personal purchases or use of renewable energy.

Server energy use emissions data

A representative from Zoom helped confirm the overall methodology of this study as well as how many servers would likely be used on the backend for the conference. The representative noted the high level of complexity of routing Internet traffic but noted also that only a single server is necessary to host a Zoom meeting with hundreds of people. In order to be conservative, the framework assumes that one fully dedicated server is used to host the conference, although this is a point to be verified in further studies if possible. The lack of specificity here was found to be acceptable given the ultimately minor contribution to overall conference emissions from servers.

$$E_e * S * W_s * H_c \tag{3}$$

E_e = electricity emissions (kg CO_2-eq/kWh), S = servers (server), W_s = power rating of servers (kW/server), H_c = conference duration (hour)

The emissions estimation technique for server use looks primarily at the emissions arising from the servers' energy use. There are also embodied emissions as well as shipping and end-of-life emissions associated with servers, but these are likely negligible considering the lifetime of servers as well as the sheer amount of Internet traffic that they handle [15]. The aforementioned issues with embodied emissions of Internet infrastructure are generally applicable to servers as well. Combined with the ultimately low contribution to the conference's overall emissions and the lack of data, these embodied emissions were excluded. However, this does pose a modest opportunity to increase the accuracy of the model.

As the servers could be located anywhere in the United States according to the Zoom representative, the average emissions rate from electricity generated in the US – the same value used for the network data transfer emissions calculations – was used for the energy that powers the server. One server and the previously established conference duration were also used in Formula 3.

Finding W_s, the power rating of all of the equipment for the server, proved more challenging. One of the articles reviewed is a study of the energy performance of scholarly journals in both print and digital forms, and it contains a graphic representing the network through which a digital server can be accessed [33]. The 'host server' involves a router, hub, switch, and the server itself, and the article offers power ratings for each of these devices. Table 1 shows the names and power ratings for each.

Table 1. *Server components and power ratings* [33].

Name	Power Rating (W)
Sun Enterprise 3500 server	484
Cisco 800 hub	20
Cisco Catalyst 1700 switch	30
Cisco 3620 LAN router	60

When added together, the values above yield a total power rating of 0.594 kW for W_s.

Emissions from other sources

Organiser meetings

The conference itself led to a substantial amount of emissions as calculated by the model. The conference organisers also held about 30 one-hour Zoom meetings, each with about 10 people, which would not have happened otherwise. Thus, for completeness, the methodology above was used to calculate the emissions generated by these meetings to be added to the total. This framework assumes that these meetings use the same virtual meeting platform and general types of computers, so only the total number of participants and the duration of the meetings to be altered in the prior formulas. The result also needs to be multiplied by the total number of organiser meetings. Formula 4 demonstrates how to calculate this aspect of conference emissions.

$$O * \left(\left(P_o * E_c * \frac{H_o}{Y * 365.25 * H_d} \right) + \left(P_o * E_e * I * D * H_o * \frac{3,600}{8,000} \right) + (E_e * S * W_s * H_o) \right) \tag{4}$$

O = number of organiser meetings (meeting), P_o = number of organiser meeting participants (computer), E_c = computer emissions (kg CO_2-eq/computer), H_o = organiser meeting duration (hour), Y = years of useful life (year), H_d = daily hours of computer use (hour/day), E_e = electricity emissions (kg CO_2-eq/kWh), I = Internet energy intensity (kWh/GB), D = data rate (Mbps), S = servers (server), W_s = power rating of servers (kW/server)

Search engine queries

There were many search engine queries, from both organisers and participants, that would not have happened but for the conference. It was infeasible to gather information on the exact number of searches, but approximate estimates were made. Two queries during registration for the 400 registrants (one for the conference itself and another for their virtual calendars) were assumed, and 15 queries during the conference for each of the 200 participants were assumed based on an assumption of three per hour for five hours of attendance. These add up to 4,000, and on the part of the organisers, 500 queries per person for each of the 10 organisers were assumed. This estimate is significantly higher than the number of queries for participants given the significant amount of time, effort, and planning that went into the conference. This rounds out to 9,000, which was rounded to 10,000 in order to be conservative. Each search generates about 0.2 grams (g) of CO_2 [34].

$$Q * E_q \tag{5}$$

Q = queries (query), E_q = query emissions (kg CO_2/query)

There is some debate about whether the 0.2 gram per search figure is accurate, as some researchers estimate figures in a range of 1 to 10 g/search [35]. Google – the most commonly used search engine – itself now claims to have completely carbon neutral operations, despite not owning all Internet infrastructure [36]. In order to compensate for this disparity in claims in the model, full transparency and modularity is recommended to allow users to adjust this assumption as needed. These queries had a minor impact on the overall emissions figure, which will likely continue to fall as Google and other search engine operators continue to decarbonise their operations.

Monitor usage

The intake survey suggested that a fair amount of participants planned to use a monitor separate from their laptop or in addition to their desktop computer during the conference. Based on the survey results, it was assumed that 20% of participants planned to use such a monitor. As no specific monitors were specified within the survey, an average life cycle emissions value for a common Dell monitor – 626 kg CO_2-eq from the AW2518H monitor [37] – was taken and manipulated in a similar way to the computer emissions to yield an amount of emissions attributable to monitor use during the conference.

$$M * E_m * \frac{H_c}{Y * 365.25 * H_d} \quad (6)$$

M = monitors in use (monitor), E_m = monitor emissions (kg CO_2-eq/monitor), H_c = conference duration (hour), Y = years of useful life (year), H_d = daily hours of monitor use (hour/day)

Desk lamp usage

The intake survey also indicated that a certain fraction of conference participants would be using desk lamps during the conference for general lighting purposes. Based on survey results, it was assumed that about 20% of participants would use desk lamps with 100 W bulbs. This data was used to calculate the total amount of energy used by these desk lamps, which was then multiplied by the US emissions factor for a total amount of desk lamp-related emissions. Embodied emissions were excluded because of a lack of data and the comparatively small amount of emissions contributed by desk lamps overall. More specificity in future studies would be ideal.

$$L * W_l * H_c * E_e \quad (7)$$

L = lamps in use (lamp), W_l = power rating of lamp (kW/lamp), H_c = conference duration (hour), E_e = electricity emissions (kg CO_2-eq/kWh)

Website visits

Two websites were in use as part of the conference, which included the EventBrite registration site as well as an AirMiners-affiliated site that hosted Zoom links for the day of the conference. The Website Carbon Calculator [38] was used to determine the amount of CO_2-eq generated from a visit to each of these sites, and actual backend visitor data was used to find the number of times the websites were visited. The CO_2-eq values were multiplied by the number of visits for each site in order to find the total CO_2-eq generated by all website visits. Future calculations should take into account all websites that are created and visited as part of the virtual conference or event, thus the summation notation in Formula 8.

$$\sum_{i=1} V_i * E_{V_i} \quad (8)$$

V_i = visits of website i (visit), E_{Vi} = website i visiting emissions (kg CO_2-eq/visit)

Results and discussion

Adding the results of Formulas 1 through 8 will yield the total amount of emissions attributable to the virtual conference. Table 2 lists the results of each individual formula from the AirMiners conference calculation. Figure 1 shows a visualisation of the

Table 2. See supplementary material 1 excel sheet for full calculations.

Formula	Emissions (kg CO_2-eq)
1: Allocated Computer Life Cycle	145
2: Data Transfer Energy Use	854
3: Server Energy Use	2
4: Organiser Meetings	249
5: Search Engine Queries	2
6: Allocated Monitor Life Cycle	51
7: Desk Lamp Energy Use	10
8: Website Visits	11
Total	**1,324**

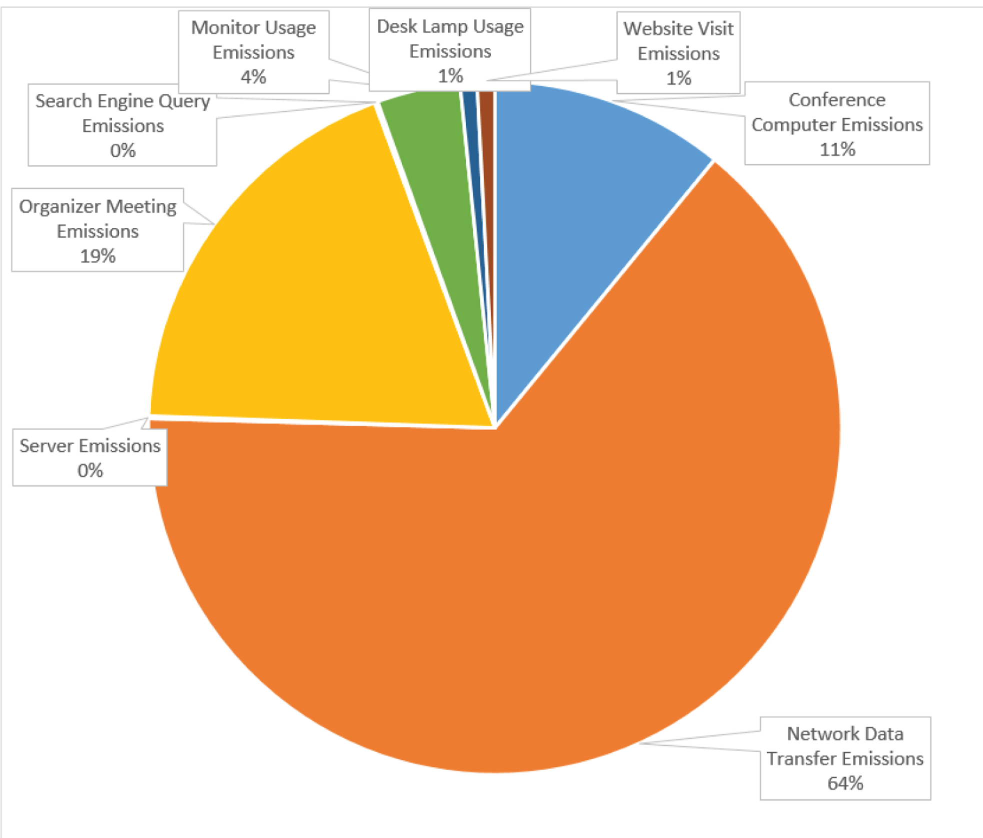

Figure 1. Distribution of contributing factors to conference emissions.

distribution of these results. The underlying calculations can be observed in Supplementary Material 1, which can also act as a general tool to perform similar calculations.

To the great surprise of the organisers, this virtual conference was responsible for emitting over 1.3 metric tons of CO_2-eq. The primary contributors included the energy use from a large amount of data transfer during the conference, allocated emissions from each participant's computer, and the many organiser meetings, which required a substantial amount of data transfer and computer use. The organiser meeting emissions in this framework largely depend on the same variables as the computer emissions and energy use from data transfer. Basic sensitivity analysis was conducted on variables for these 'hotspot' factors to identify areas for potential emissions reduction for virtual meetings and conferences.

Reducing variables such as total participants and conference duration reduces emissions in a mostly linear fashion. Most of the contributing emissions factors vary linearly with these variables. Changing variables such as life cycle computer emissions, average expected life for computers, hours of daily computer use, electricity emissions, Internet energy intensity, and the Zoom data rate all had notable effects on the overall conference emissions figure as well. Analysis of these is split into two sections below.

Computer emissions sensitivity

Allocated emissions from computer usage for virtual conferences can be reduced by decreasing the overall computer life cycle emissions, extending the expected useful life of the computer, and increasing the daily hours spent using the computer assuming this can happen independently without reducing the expected useful life. Computer manufacturers can reduce overall computer life cycle emissions with measures such as using less energy overall or less emissions-intensive energy during manufacturing, sourcing raw materials with lower embodied emissions, figuring out logistical ways to reduce shipping distances and emissions, and making the computer itself more energy efficient so that it consumes less energy during its service life. They may be able to extend the expected useful life of their computers by increasing the durability of the computer, working to mitigate planned and perceived obsolescence, and allowing for modularity and reparability. Hours of daily use are the responsibility of the user, and more hours within an equivalent useful life will distribute the life cycle emissions over more hours. Figure 2 shows how overall conference emissions change with corresponding changes in each of these variables.

Network data transfer sensitivity

Emissions related to Internet data transfer can be reduced by decreasing average electricity emissions, decreasing Internet energy intensity, and decreasing the Zoom data rate. Average electricity emissions can be reduced by using a variety of lower emissions energy sources, including but not limited to wind, solar, nuclear, geothermal, hydropower, tidal power, and even natural gas with carbon capture and sequestration. Solar electricity applied throughout the model, for example, could reduce the electricity emissions from the current value of 0.43 kg CO_2-eq/kWh to as low as 0.04 based on

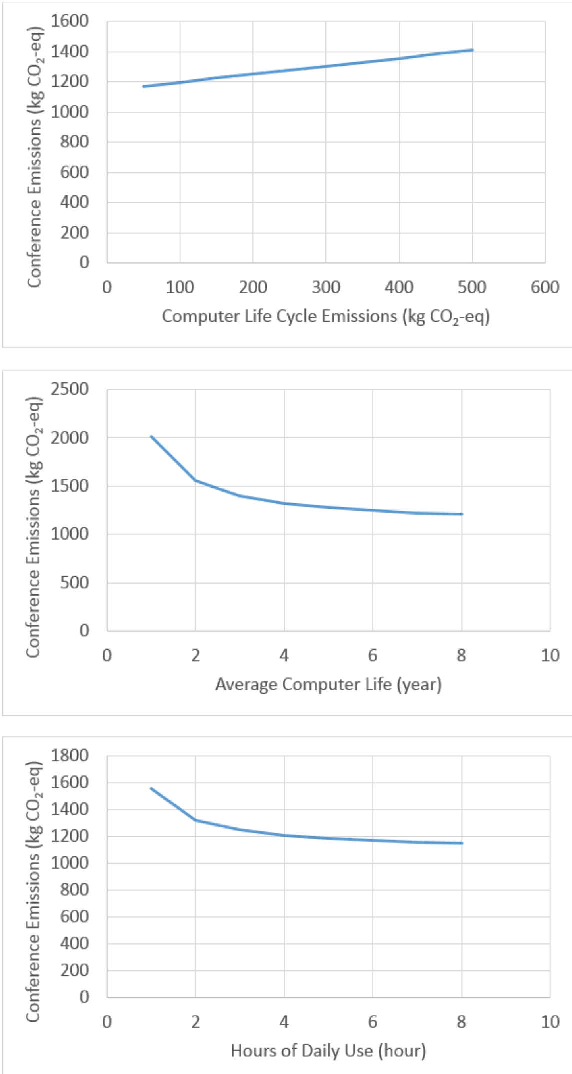

Figure 2. Sensitivity analysis for computer emissions. These charts demonstrate how overall conference emissions change with corresponding changes in variables related to computer emissions, altering only one variable at a time.

solar life cycle emissions data from an NREL study [39], which would lead to overall conference emissions of only 344 kg CO_2-eq, 26% of the current figure. Reducing transmission losses, if done in a low emissions manner, could also help reduce the emissions burden per kWh.

Internet energy intensity can be reduced by increasing the general energy efficiency of the infrastructure that enables the Internet through either software or hardware innovations. Zoom may also be able to decrease their data rate for the same quality service through updates to their own software or servers. Users can directly reduce the data transferred during a meeting or conference and corresponding emissions by not using gallery view, not using video or audio functionality, minimising time spent screensharing, and disabling HD video. Figure 3 shows how overall conference emissions change with corresponding changes in each of these variables.

Comparison to physical conference

As noted in the Literature Review, many scholars have demonstrated that physical meetings and conferences generate a much larger amount of greenhouse gas emissions relative to their virtual counterparts. In the case of the conference examined here, it most certainly would have generated far more emissions if it had been in-person. Analysis of the attendee list indicates that roughly 21% of the attendees live in the Bay Area in

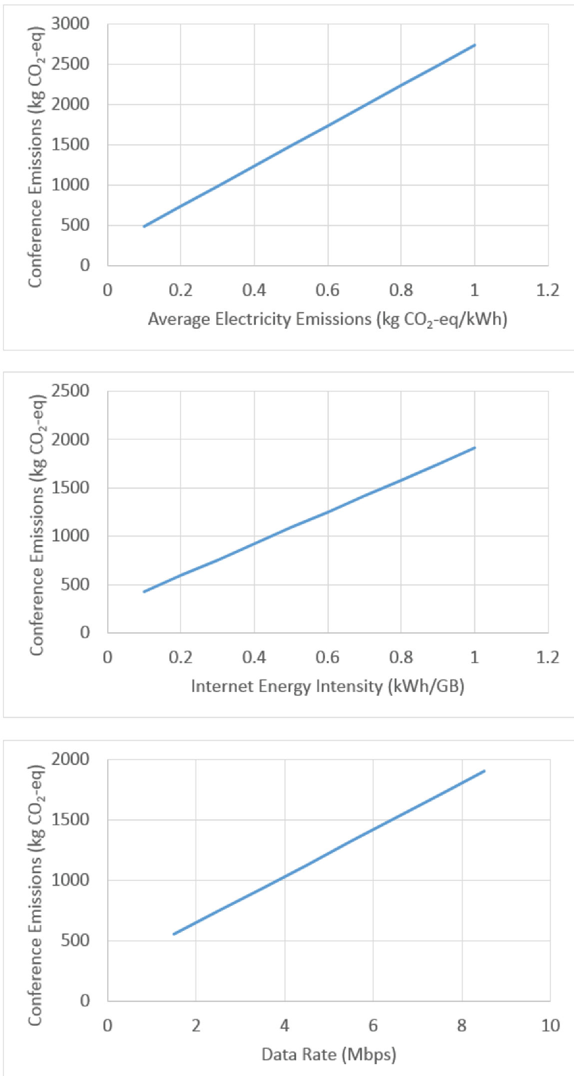

Figure 3. Sensitivity analysis for network data transfer emissions. These charts demonstrate how overall conference emissions change with corresponding changes in variables related to network data transfer emissions, altering only one variable at a time.

California [1], where a physical version of the conference would have likely been held. This means that 79% of the 207 participants – or about 164 people – would have likely had to fly to attend. While it is unlikely that this number of participants would have attended if the conference had been physical, a comparable analysis must hold the number constant. By the International Civil Aviation Organisation's carbon emissions calculator [40], if these 164 participants flew an average of 4,800 miles each (the distance between Detroit and San Francisco and back), emissions from this component of the conference alone would be roughly 88 metric tons of CO_2. This value is larger than the entire amount of emissions generated by the virtual conference by a factor of over 66, and this is before measuring all of the other relevant factors of in-person conferences, such as local travel, food consumption, electricity consumption at the venue, and so forth. Thus, while it is important to measure, mitigate, and offset virtual emissions, particularly in a time of increasing usage, it is also important to acknowledge the significant environmental burdens of physical travel and interactions.

Conclusion

With an increasing number of people using the Internet each year, more virtual interactions with others around the world, and the COVID-19 pandemic that prevents physical meetings, usage of digital communications software is on the rise, with companies like Zoom offering video communication services to millions of people every day. In an attempt to reduce emissions and other burdens associated with travel and boost attendance, many conference organisers are turning to these products to conduct virtual conferences as well. Many studies have shown that emissions from virtual meetings are far lower than those generated by in-person meetings, but there can still be a considerable impact from conducting such conferences that ought to be measured and mitigated over time. This study offers a framework for estimating these emissions and analysis on the most effective levers to reduce them.

The accuracy of the framework can, of course, be improved. One particularly useful way would be gathering exact data on the type of computer used by each participant of a given conference, asking how long they expect to use it for, and measuring the time they spend at the conference, all to get a better idea of the life cycle emissions from that computer to allocate towards the conference. Getting specific data usage from each participant would help make the network data transfer figures more accurate as well. Understanding the location of each user as well as the specific fuel mix for their electricity supply would help users of the framework find energy use emissions for desk lamps and possible computers, if the use phase can be broken out of the overall life cycle emissions figure. There may be opportunities for the creation of online tools, maybe through a video communications service or as an add-on, that measure some of this information to allow for rapid and accurate greenhouse gas accounting of these kinds of digital activities.

The framework offered here is meant to capture all things that happen because of conferences that would not have happened otherwise, but users must still draw a reasonable system boundary that this analysis attempts to capture. At a certain point, it is impossible to understand the counterfactual, which is what would have happened if the conference had not occurred. For example, the AirMiners conference may have triggered new connections or new businesses, and if that business goes on to remove a great deal of CO_2 from the atmosphere, should associated emissions reductions be allocated to the conference? It is difficult to say; the conference may have been the incremental factor that led to the formation of that business, but this situation could have occurred regardless. The list of these kinds of indirect effects would be virtually infinite, but this framework focuses on the factors that are the most direct, the most certain, and for which it is easiest to gather data. These factors are more controllable by conference organisers, technology companies, and software users, but more social and indirect factors may be out of everyone's direct control.

Finally, the method offered here of using allocated computer emissions, network data transfer energy use, and server energy use may be applicable to other online activities. At least one group has already used a modified version of the framework described here to estimate emissions from a virtual tour, for example. Others may want to expand on this framework to encourage reductions of the environmental impact of online activities that have come to occupy so much time and attention.

Acknowledgments

The initial research did not receive any specific grant. The University of Michigan Global CO_2 Initiative funded the preparation of this article. The author would like to thank Professor Volker Sick for recommending preparation of and providing feedback on the initial draft.

Disclosure statement

No potential competing interest is reported.

ORCID

Grant Faber http://orcid.org/0000-0002-2546-2872

References

[1] AirMiners, 2020, AirMiners conference attendees. Available online at: https://airtable.com/shrdfZuC1pkjpGoAH/tblcX0yPyYmJfekkQ (accessed 15 August 2020).
[2] AirMiners, 2020, AirMiners virtual conference. Available online at: https://conference.airminers.org/(accessed 15 August 2020).
[3] Warren, T., 2020, Zoom grows to 300 million meeting participants despite security backlash. Available online at: https://www.theverge.com/2020/4/23/21232401/zoom-300-million-users-growth-coronavirus-pandemic-security-privacy-concerns-response (accessed 15 August 2020).
[4] Guerin, T., F., 2017, A demonstration of how virtual meetings can enhance sustainability in a corporate context: Quantified benefits of virtual meetings through video conferencing. *Environmental Quality Management* **27**1, 75–81.
[5] Matsuno, Y., Takahashi, K.I., Tsuda, M., Nakamura, J., and Nishi, S., 2007, Eco-efficiency for information and communications technology (ICT): The state of knowledge in Japan. *IEEE International Symposium on Electronics and the Environment* **2007**, 1–5

[6] Ong, D., Moors, T., and Sivaraman, V., 2014, Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings. *Computer Communications* **50**, 86–94. doi: 10.1016/j.comcom.2014.02.009
[7] Oliveira, T.C., Barlow, J., Gonçalves, L., and Bayer, S., 2013, Teleconsultations reduce greenhouse gas emissions. *Journal of Health Services Research & Policy* **18**(4), 209–214. doi: 10.1177/1355819613492717
[8] Takahashi, K.I., Tsuda, M., Nakamura, J., and Nishi, S., 2006, Estimation of videoconference performance: Approach for fairer comparative environmental evaluation of ICT services. *IEEE International Symposium on Electronics and the Environment* **2006**, 288–291
[9] Quack, D. and Oley, M., 2002, Environmental advantages of video conferencing systems - results from a simplified LCA. *Environmental Communication in the Information Society* **2**, 446–500.
[10] Toffel, M.W. and Horvath, A., 2004, Environmental implications of wireless technologies: News delivery and business meetings. *Environmental Science & Technology* **38**(11), 2961–2970. doi: 10.1021/es0350350
[11] Kissler, S.M., Tedijanto, C., Goldstein, E., Grad, Y.H., and Lipsitch, M., 2020, Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. *Science* **368** (6493), 860–868. doi: 10.1126/science.abb5793
[12] Roser, M., 2018, The internet's history has just begun. Available online at: https://ourworldindata.org/internet-history-just-begun (accessed 15 August 2020).
[13] Microsoft, 2020, Microsoft sustainability calculator. Available online at: https://www.microsoft.com/en-us/sustainability/sustainability-guide/sustainability-calculator (accessed 15 August 2020).
[14] Apple, 2020, Apple commits to be 100 percent carbon neutral for its supply chain and products by 2030. Available online at: https://www.apple.com/newsroom/2020/07/apple-commits-to-be-100-percent-carbon-neutral-for-its-supply-chain-and-products-by-2030/ (accessed 15 August 2020).
[15] Raghavan, B. and Ma, J., 2011, The energy and emergy of the internet. *Proceedings of the 10th ACM Workshop on Hot Topics in Networks, HotNets-10*, doi:10.1145/2070562.2070571
[16] Apple, 2020, Your product's environmental report card. Available online at: https://www.apple.com/environment/(accessed 15 August 2020).
[17] Dell, 2020, Select product carbon footprint assessments. Available online at: https://www.dell.com/learn/us/en/uscorp1/corp-comm/environment_carbon_footprint_products (accessed 15 August 2020).
[18] Lenovo, 2020, Regulatory Compliance ECO Declarations. Available online at: https://www.lenovo.com/us/en/compliance/eco-declaration (accessed 15 August 2020).
[19] HP, 2020, Product carbon footprint reports: Notebooks. Available online at: https://h22235.www2.hp.com/hpinfo/globalcitizenship/environment/productdata/ProductCarbonFootprintnotebooks.html (accessed 15 August 2020).
[20] Asus, 2020, Product environmental information. Available online at: https://csr.asus.com/english/article.aspx?id=1736 (accessed 15 August 2020).
[21] Sony, 2020, Environmental Information. Available online at: https://www.sony.net/SonyInfo/csr_report/environment/data/(accessed 15 August 2020).
[22] Apple, 2019, Product environmental report: 16-inch MacBook Pro. Available online at: https://www.apple.com/environment/pdf/products/notebooks/16-inch_MacBookPro_PER_Nov2019.pdf (accessed 15 August 2020).
[23] Clement, J., 2020, U.S. daily media usage time via computer 2018–2022. Available online at: https://www.statista.com/statistics/469995/time-spent-desktop-laptop-media-type-usa/(accessed 15 August 2020).
[24] Jones, N., 2018, How to stop data centres from gobbling up the world's electricity. *Nature* **561**(7722), 163–166. doi: 10.1038/d41586-018-06610-y
[25] Jensen, V., 2019, Internet uses more than 10% of the world's electricity. Available online at: https://www.insidescandinavianbusiness.com/article.php?id=356 (accessed 15 August 2020).

[26] Stats, I.L., 2020, GB of internet traffic in 1 second. Available online at: https://www.internetlivestats.com/one-second/#traffic-band (accessed 15 August 2020).
[27] Coroama, V.C. and Hilty, L.M., 2014, Assessing internet energy intensity: A review of methods and results. *Environmental Impact Assessment Review* **45**, 63–68. doi: 10.1016/j.eiar.2013.12.004
[28] Schien, D. and Preist, C., 2014, A review of top-down models of internet network energy intensity. *Proceedings of the 2014 Conference ICT for Sustainability*, doi:10.2991/ict4s-14.2014.10
[29] Aslan, J., Mayers, K., Koomey, J.G., and France, C., 2018, Electricity intensity of internet data transmission untangling the estimates. *Journal of Industrial Ecology* **22**(4), 785–798. doi: 10.1111/jiec.12630
[30] Zoom, 2020, System requirements for Windows, macOS, and Linux. Available online at: https://support.zoom.us/hc/en-us/articles/201362023-System-Requirements-for-PC-Mac-and-Linux (accessed 15 May 2020).
[31] Environmental Protection Agency, 2020, eGRID summary tables 2018. Available online at: https://www.epa.gov/sites/production/files/2020-01/documents/egrid2018_summary_tables.pdf (accessed 15 August 2020).
[32] Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., and Dasgupta, P., 2014, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC), p. 87. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf
[33] Gard, D.L. and Keoleian, G.A., 2002, Digital versus print: Energy performance in the selection and use of scholarly journals. *Journal of Industrial Ecology* **6**(2), 115–132. doi: 10.1162/108819802763471825
[34] Google, 2009, Powering a Google search. Available online at: https://googleblog.blogspot.com/2009/01/powering-google-search.html (accessed 15 August 2020).
[35] Quito, A., 2018, Every Google search results in CO2 emissions. This real-time data viz shows how much. Available online at: https://qz.com/1267709/every-google-search-results-in-co2-emissions-this-real-time-dataviz-shows-how-much/(accessed 15 August 2020).
[36] Radio, C.B.C., 2018, The surprising carbon footprint of a Google search. Available online at: https://www.cbc.ca/radio/spark/episode-399-1.4676973/the-surprising-carbon-footprint-of-a-google-search-1.4676976 (accessed 15 August 2020).
[37] Dell, Dell AW2518H Monitor. Available online at: https://i.dell.com/sites/csdocuments/CorpComm_Docs/en/carbon-footprint-AW2518H-monitor.pdf?newtab=true (accessed 15 August 2020).
[38] Wholegrain Digital, 2020, Website Carbon Calculator. Available online at: https://www.websitecarbon.com/(accessed 15 August 2020).
[39] NREL, 2012, Life cycle greenhouse gas emissions from solar photovoltaics. Available online at: https://www.nrel.gov/docs/fy13osti/56487.pdf (accessed 15 August 2020).
[40] International Civil Aviation Organization, 2016, ICAO carbon emissions calculator. Available online at: https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx (accessed 1 December 2020).