Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings

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Abstract

While video conferencing is often viewed as a greener alternative to physically travelling to meet in-person, it has its own energy, carbon dioxide and time costs. In this paper we present the first analysis of the total cost of videoconferencing, including operating costs of the network and videoconferencing equipment, lifecycle assessment of equipment costs, and the time cost of people involved in meetings. We compare these costs to the corresponding costs for in-person meetings, which include operating and lifecycle costs of vehicles and the costs of participant time. While the costs of these meeting forms depend on many factors such as distance travelled, meeting duration, and the technologies used, we find that videoconferencing takes at most 7% of the energy/carbon of an in-person meeting. This comparison changes when the time cost is taken into account, with videoconferencing potentially costing more than in-person meetings in a worst-case scenario. We also analyse the sensitivity of the energy and carbon costs to various factors and consider trends in energy and carbon usage to predict how the comparison might change in the future.

Keywords
face-to-face meetings; green communication; remote virtual meetings; teleconferencing; telepresence.

Author's Note

Previously published in the *IEEE GreenCom 2012 Conference Proceeding*. In this paper we have broadened the scope to cover the time dimension, which is the third factor in addition to the previous two factors (energy and carbon cost) considered previously. We have also considered more cases, and enhanced the presentation by including graphs that demonstrate the impact of multiple factors on the results. We have attached a copy of the previous paper as part of our submission.

1 Introduction

Information and communication technology (ICT) is often seen as an attractive mechanism for reducing our environmental impact. In particular, ICT substitutes physical processes with virtual ones, thus providing a greener alternative to conventional activities. A good example is the increasing use of videoconferencing, which replaces physical travel with transferring information across a network. However, videoconferencing is not entirely green with zero environmental impact. The many devices involved in the capture, processing and transmission of information in a videoconference consume electricity, and the generation of electricity has a considerable carbon footprint. Significant environmental impact also arises from the lifecycle of these devices, including their production, deployment and disposal stages. Depending on the magnitude of these effects, the actual carbon savings of videoconferencing over in-person meetings might be reduced or even negated. Furthermore, meetings impose a time cost on participants, and while videoconferencing may save on travel time, videoconferences can take longer than in-person meetings in order to achieve the same outcome, so the overall time cost of the different ways of meeting is also uncertain.

This paper presents a comprehensive study to evaluate the actual energy, carbon and time savings of videoconferencing solutions over in-person meetings. The scope of our study includes the operating and lifecycle (embodied) energy cost of the end terminals, videoconferencing equipment, and network infrastructure. In addition, we also factor in the time overhead caused by the lower efficacy of video communication in completing tasks. These are then compared with the costs of the common modes of transportation taken by participants to attend meetings, such as the direct fuel consumption and the lifecycle energy cost of vehicles, corresponding transport infrastructure and travellers' time cost. We also evaluate how varying travel distance and meeting duration affect the overall carbon savings brought about by videoconferencing.

While claims that videoconferencing has lower carbon, energy and time costs than in-person meeting are often asserted and may seem "obvious" to many people, there is scant literature that tests these claims. To the best of our knowledge, our work is the first to provide a holistic estimate of the energy and carbon cost of a videoconference that includes both the direct and embodied energy of all devices involved in videoconferencing. While the results of our work are not particularly surprising, their value is in the fact that they provide evidence to confirm widely held opinions. This paper extends our previous work [1] in this area by also considering the time costs of the different meeting modes.

Our work focuses on substituting videoconferencing for travel for in-person meetings. That is only one use of videoconferencing, and videoconferencing is also widely used as a substitute for audio-only technology such as teleconference and phone calls. However, to limit the scope of this paper, we will not further consider the costs of audio-only meetings, and instead compare videoconferencing with in-person meetings.

This paper starts by reviewing literature that has examined the carbon costs of videoconferences and in-person meetings (Section 2). Because the carbon costs of running videoconferencing equipment arise from electricity consumption, and electricity generation systems (and so corresponding carbon costs) vary radically by geographical location, most of this paper (Sections 3-4) expresses running costs in terms of energy, and we translate these to carbon costs in Section 6. Considering energy as the unit for operating costs has the added benefit of facilitating comparison to other lifecycle costs (e.g. manufacture and disposal) which are typically expressed in terms of energy rather than carbon emission, enabling a total lifecycle comparison of the energy costs of videoconferencing versus in-person meetings. In Section 3 we consider the costs of videoconferencing, covering network operating costs (3.1), videoconferencing terminal operating costs (3.2) and lifecycle assessment of network and terminal equipment (3.3). We then consider the transportation costs of in-person meetings in Section 4, and time costs for both meeting modes in Section 5. Total costs of video conferencing and in-person meetings are calculated in Section 6. In Section 7 we extrapolate trends in energy/carbon usage to predict how these costs may change in the future, and offer conclusions in Section 8.

2 Literature review

Although video conferencing has been commonly advertised as a greener alternative to in-person meetings, surprisingly little research has been done in quantifying the actual energy savings and greenhouse gas reductions brought about by video conferences. In this section we review the few papers that have directly considered the carbon costs for videoconferencing, while in subsequent sections we refer to many other papers (e.g. [2, 3]) that provide data about energy and carbon costs of components of the complete meeting ecosystems.

Baliga et al. [4] studied the carbon savings provided by telecommuting as a function of the percentage of reduction in car and air travel. Their work focused on the energy consumed by the network infrastructure, in particular the carbon contribution for different access networks. However, they did not study the energy and carbon contribution of end systems such as videoconferencing equipment and LANs, and also omitted the lifecycle cost of the devices involved. Their calculations show that telecommuting and teleconferencing do substantially reduce carbon emissions; e.g., a mere 5% reduction in car travel will save between 50 to 160 $kgCO_2e$ (kilograms of carbon dioxide equivalent) per household (equivalent to 1% of the average household carbon emission), depending on the quality of the video call and the type of access network.

Guldbrandsson and Malmodin [5] studied the life-cycle CO_2 savings of three different videoconferencing configurations for a meeting between Stockholm and Dallas. The total active duration of the video conferencing systems is assumed to be 960 hours p.a. and 48 plane trips are assumed to be eliminated per year. For this specific case, they found that using the videoconferencing systems saved roughly 215 $tonCO_2e$/year, which is about 170 times the annual carbon emission of a videoconferencing system.

Another study by Quack and Oley [6] found that substituting meetings by videoconferences reduces carbon emissions by up to 90%. They also presented the tradeoffs between distance and the energy cost – longer travel distances leads to increased carbon savings. However, they did not present details of their derivation and intermediate values in terms of the energy and carbon emission for both meeting solutions. This makes it hard to scale their results to estimate the environmental impact for varying meeting dimensions (distance, duration, configuration of end terminals, number of participants and endpoints).

3 Videoconferencing energy cost

In this section we assess the energy costs of videoconferencing by examining the contribution of the operating expenses (opex) of the network (Section 3.1) and videoconference terminals (Section 3.2), as well as the lifecycle costs of network and videoconference equipment (Section 3.3).

3.1 Network operating expenses

Network opex cover the use-phase energy cost of the network infrastructure including all transmission and switching equipment in the Internet. For our purposes, the Internet does not include networking equipment at end sites (e.g. home routers) but includes ISP equipment. We will separately consider networking equipment at end sites because it can be measured using techniques similar to those used to measure the power requirements for other devices at end sites, which will be addressed in Section 3.2. A common measure for the network opex is the energy intensity of data transfer, which is the energy cost per gigabyte of data transmission (kWh/GB) [2].

The total active power of the Internet is estimated to be between 43 GW to 72 GW [7]. Also, the global Internet traffic was estimated to be 500 PB per day in 2010 [8]. This is consistent with the value extrapolated from the Minnesota Internet Traffic Studies [9], assuming the growth rate of the Internet data flow is 50% in 2009 [2]. Therefore, the Internet energy intensity is calculated by dividing the operating power of the Internet (Watts) by the Internet data flow (bits per second), as in [2]. The end result is an estimate of the average operating energy intensity of the Internet of between 2.17 kWh/GB and 3.61 kWh/GB in 2010. Videoconference data rates vary widely (as discussed further in Section 6), but typically range between 100 kb/s to 10 Mb/s (or equivalently 0.045 GB/h to 4.5 GB/h), which at around 3 kWh/GB equals 135 W to 13.5 kW to carry video traffic across the Internet.

As a sanity check, we compare our obtained values of the Internet energy intensity to the values estimated in [2]. The analysis of Internet advertising in [2] presented 3 separate estimates of the energy intensity: 24.9, 16.3 and 9.4 kWh/GB. They also found that the Internet energy intensity fell 10-fold in 6 years. Assuming this trend continues, the estimates of energy intensity would be 3.7, 2.4 and 1.4 kWh/GB in year 2010, which are consistent with our range of estimates.

3.2 Videoconference terminal operating expenses

Videoconference devices lie at the outer edge of the network, which include the home or office LAN devices (modems, switches and Wi-Fi access points), computers, displays, projectors and videoconferencing specific equipment and peripherals such as CODECs, microphones, sound systems and cameras. Unlike network equipment, the energy consumed by these devices correlates to their operating time rather than data volume [3]. So, we estimate the power consumption of these devices, representing the energy consumption per hour of use. Also, in our power consumption estimations we assume dedicated use of the devices for the duration of the videoconference. If a user performs some other task such as web browsing while videoconferencing, the power consumption attributed to the videoconference will be reduced. However, user activity varies and can be hard to predict, so we consider power consumption for dedicated use scenarios as conservative estimates.

Current videoconference systems vary widely in terms of their configuration. PC-based videoconferences only require a microphone, speaker, camera, display and a PC. On the other hand, top of the range telepresence systems such as the Cisco TelePresence System 3000 [10] include multiple large displays that can optionally be replaced by projectors, multiple high definition (HD) cameras and a sound system for spatial audio-video, a dedicated CODEC and custom lighting arrays. Therefore, we estimate the power consumption per device separately for a range of devices to enable calculation of the energy consumption of different setups.

Personal Computers (PC): Software-based videoconferencing systems rely on the processing power of a general PC to perform the functions of a CODEC. We estimate the power consumption of current laptop and desktop computers to be 40 W and 150 W respectively [7].

Display Devices: We consider three display technologies which are commonly used in current PC videoconferencing solutions – plasma display panels, light emitting diode backlit liquid crystal displays (LED-LCDs) and projectors. The active-mode power consumption of plasma and LCD displays generally correlates with their screen area, with additional overhead attributed to non-display components [11], given by:

$$P_{TV(on)} = AP_{screen} + P_{base} \tag{1}$$

where A represents the screen area, P_{screen} and P_{base} represents the operational power consumption of the screen and non-display components respectively.

Because videoconferencing systems can differ markedly in screen size, we consider screen area in our power estimation. The average value of P_{Basic} is 20 W [12]. We also estimate P_{Screen} to be 203 W/m^2 for plasma and 172 W/m^2 for LED-LCD, based on data for the average on-mode power and the average screen area of TV displays in 2010 [12].

Projectors are used as a display device in some videoconferencing systems (e.g., the Cisco TelePresence System 3000 provides an optional projector [10]). We estimate a projector to consume 135 W based on measurements in [13].

CODECs: Some videoconferencing solutions use dedicated hardware for encoding and decoding video, rather than a general purpose PC. Constable [13] performed controlled experiments to measure the actual power consumption of multiple videoconferencing CODECs. He found that newer CODECs generally consume more power (due to their increased versatility), which is contrary to the trend of modern IT equipment where newer equipment consumes less power despite having more computing power [13]. Also, CODEC power consumption tends to be independent of the data rate of the call [13].

In order to obtain the upper and lower bound on the power consumption of CODECs, we present separate estimates for high-end and entry level CODECs. For high-end CODECs, we estimate a power consumption of 80 W, representing the average power consumption among top-of-the-range CODECs from the main manufacturers (Polycom HDX 9000, LifeSize Room 220 and TANDBERG C90) [13]. Likewise, average active power consumption for entry-level CODECs (LifeSize PassPort and TANDBERG C20) tested in [13] is 26 W.

Videoconferencing Peripherals: Although the power consumption of peripherals is relatively low, we include them here for completeness. We estimate that cameras consume 9.5 W [13], while sound systems take 4.1 W [14]. We also estimate a power consumption of 2.5 W for a microphone, based on the operating power of a studio quality microphone [15].

Home/Office Network: Here we consider the power consumed by the devices at the edge of the network, including modems, switches and Wi-Fi access points. While we would expect the power profile of such equipment to vary depending on the number of connections, currently deployed network devices actually draw about the same power when idle as they do when transmitting large amounts of data at high rates [16]. Therefore we use 20 W as a conservative indication of the LAN’s power consumption [7], regardless of the number of active connections. If more sophisticated networking devices that are capable of scaling power according to bandwidth usage or number of connections were deployed in the future, videoconferencing traffic’s share of the home or office network will then have to be analysed.

The left column of Table I summarizes the power consumption of different devices involved in videoconferencing.

3.3 Lifecycle Analysis (LCA) of network and video-conferencing terminal equipment

The operating energy is only part of the total energy cost. A holistic estimate should consider the entire lifecycle emissions of videoconferencing solutions, including the manufacture, deployment, operation and disposal phases. In this section, we estimate the embodied energy cost involved in videoconferencing.

TABLE I. LIFECYCLE AND OPERATING COSTS OF END POINT DEVICES

	Operation	Other Lifecycle Phases		Lifecycle Phases Included^
	Power Consumption (W)	***Embodied Energy (MJ/unit)***	***Carbon Emission ($kgCO_2e$)***	
PC				
Desktop	150	2100*	350	M D O E
Laptop	40	1362	227*	M D O E
Display				
Plasma	203 W/m^2 + 20W	5096 MJ/m^2	849 $kgCO_2e$ /m^2*	M D O E
LED-LCD	172 W/m^2 + 20W	3218 MJ/m^2*	536 $kgCO_2e$ /m^2	M D O
Projector	135	384*	64	M D O E
CODEC				
High End	80	1120	187	M D O E
Entry Level	26	364	61	M D O E
Video-conf. Peripherals				
Camera	9.5	120	20*	M D O E
Sound System	4.1	374*	62	M
Microphone	2.5	187*	31	M
Home/ Office LAN	20	1000	167*	M

^ M =Manufacture, D=Distribution & Deployment, O=Operation, E=End-of-life (disposal & recycle)

* Value derived from source based on a conversion factor of 0.6 $kgCO_2e/kWh$.

We consider the full lifecycle energy consumption for the types of devices where data is available. For the other devices, we use the manufacturing energy cost as a rough estimate of the lifecycle cost, since the manufacturing and operation energy constitute a major part of the lifecycle cost while the deployment and disposal phases make relatively small contributions. For example, the majority of the studies on consumer electronics evaluated in [17] show that manufacturing and operating energy cost constitute over 95% of the overall product lifecycle cost.

The lifecycle expenditures should be amortized across active hours of the product lifetime. However, the total operation time of devices varies widely for different organizations, depending on the frequency of usage, duration of meetings and also the total lifetime of the videoconferencing system before being replaced. As such, instead of neglecting the time dimension, we present the total embodied energy (MJ) and the equivalent environmental cost ($kgCO_2e$) over the lifecycle for each type of device, which can later be scaled appropriately to obtain the per hour cost for different videoconferencing setups.

It is also important to note the fundamental distinction between the total and marginal costs of devices: Devices such as PCs and displays are used for purposes other than videoconferencing, so their lifecycle costs would likely be incurred even if videoconferencing was not used. It is only the marginal operating costs of those devices that increase when they are used more in order to support videoconferencing. In our later case study (Section 6), we address this distinction by considering upper and lower bound cases. For the upper bound case, we assume dedicated videoconferencing equipment to provide a high definition telepresence service so videoconferencing includes the full lifecycle costs of devices, and in the lower bound case we consider using a multi-purpose platform such as a laptop device, in which only part of the device’s use is attributed to videoconferencing, and scale its lifecycle cost accordingly.

Where data on the embodied energy are not provided, we infer the embodied energy from the carbon emissions by assuming a conversion factor of 0.6 $kgCO_2e/kWh$. This factor is based upon the International Energy Agency’s figure on the CO_2 emission arising from the world electricity generation of 0.5 $kgCO_2/kWh$ [18], with an additional 0.1 $kgCO_2e/kWh$ attributed to the fuel supply chain, infrastructure for energy distribution, losses in distribution and waste management [7]. Table I summarises our estimates of the embodied energy in the devices commonly used in a videoconference. A column on the carbon emissions is included to show the original value from data sources before our conversion factor is applied.

Personal Computers (PC): We estimate the embodied energy of a desktop PC to be 2100 MJ, derived from Fujitsu's lifecycle assessment of the ESPRIMO E9900 Desktop PC [19], which has a hardware configuration that is common in current office PCs. As for the embodied energy of laptops, a value of 1362 MJ is estimated [20]. Both of these embodied energy estimates for desktop and laptop PCs include all lifecycle phases from cradle-to-grave excluding the use phase.

Display Devices: We derive the embodied energy for the three different display devices included in our scope - plasma [21], LED-LCD [22] and projector [23]. These studies base their assessment on a single screen size (42" for plasma in [21] and 15.4" for LED-LCD in [22]), which does not allow for a fair comparison of the different lifecycle energy for the different display technologies. Therefore, for the purpose of this study, we assume that the embodied energy in plasma and LED-LCD displays scales linearly with respect to the screen area, since a larger display would involve a higher material, transport and waste management energy cost. To this end, we estimate the embodied energy to be 5096 MJ/m^2 for plasma displays, 3218 MJ/m^2 for LED-LCDs and 384 MJ for projectors.

CODECs: To the best of our knowledge, data on the lifecycle energy of videoconferencing CODECs are not available. Therefore, we estimate this from the embodied energy for desktop PCs, by scaling it according to the ratio between the operating energy of a desktop and a CODEC. The resulting values are 1120 MJ for high end CODECs and 364 MJ for entry level CODECs.

Videoconferencing Peripherals: The lifecycle cost of a camera is estimated to be 120 MJ [24] from the lifecycle assessment of a night camera with the same form factor as typical videoconferencing cameras. As for the sound system and microphones, we estimate their embodied energy to be 374 MJ and 184 MJ respectively, which were converted from the carbon emission of these devices measured in [5].

Home/Office Network: The LAN is estimated to have an embodied energy of 1000 MJ [7]. Note that this value represents the average aggregated embodied energy of all devices in a LAN instead of the embodied energy of a single LAN device.

Internet: The low and high estimates of the Internet's embodied energy intensity are summarized in Table II, which are 1.61 and 3.33 kWh/GB respectively. This is obtained by dividing the Internet's embodied power of 33.2 GW (minimum) and 70.7 GW (maximum) [7] by the global Internet traffic in 2010 of 500 PB per day [8], which is similar to the method used previously in Section 3.1.

TABLE II. INTERNET LIFECYCLE AND OPERATING COSTS

	Operating Energy Intensity (kWh/GB)	**Embodied Energy Intensity (kWh/GB)**	**Lifecycle Phases Included^**
Minimum Estimate	2.17	1.61	M O
Maximum Estimate	3.61	3.33	M O

^ M = Manufacture, O = Operation

4 In-person meeting costs

4.1 Transportation costs

The transportation used to get participants physically together significantly contributes to the carbon footprint of in-person meetings. To this end, we evaluate the energy consumption and carbon emission of the transportation here to enable a comparison of the difference in environmental impact between a virtual meeting via videoconferencing and a physical meeting. We evaluate three common modes of transportation, which are plane, train and private car. Since the distance travelled affects the energy consumption (and the carbon emission) of transportation, the measurement unit for transportation is the energy involved in ferrying 1 passenger over the distance of 1 kilometer (kWh/pkm).

The estimated energy costs for transportation are summarized in the left column of Table III. Our estimates are mainly based on research by Lenzen [25]. That study considered both the direct energy from the fuel and electricity consumption, as well as the indirect emissions from the production of fuel, vehicle lifecycle, generation of electricity, maintenance cost and the construction of related infrastructure (roads, railways, stations, airports etc.).

The UK Department for Environment, Food and Rural Affairs (DEFRA) also provides data on the energy and carbon emission for different modes of transport [26]. Unlike Lenzen's study which considered the embodied energy in the vehicle and infrastructure, DEFRA only included the direct emissions and the lifecycle impact of fuel that arise from fuel extraction, refinement, storage and transportation. However, we include data from DEFRA here as a check on the lower bounds of the transportation energy to increase the reliability of our data. As DEFRA presented results in terms of the carbon emission rather than the energy consumption, we include the figures on carbon emission from both studies in Table III.

TABLE III. WHOLE LIFECYCLE (INC. OPERATING) COSTS OF TRANSPORT

	Lenzen [25]		**DEFRA** [26]
	Lifecycle[a] Energy (MJ/pkm)	***Lifecycle[a] Carbon Emission ($kgCO_2e/pkm$)***	***Lifecycle[b] Carbon Emission ($kgCO_2e/pkm$)***
Plane (International)	3.1	0.25	0.13
Plane (Domestic)	5.7	0.49	0.20
Train	1.9	0.17	0.06
Private Car	4.4	0.34	0.24

a. Includes lifecycle for fuel, vehicle and corresponding transportation infrastructure

b. Includes lifecycle for fuel only

5 Time cost

Other than having different carbon and energy costs, videoconferencing and in-person meetings both have different costs in terms of participants' time. Travel time is one of the largest costs of distant in-person meetings, and the travel time reduction enabled by videoconferencing is often touted as one of its major benefits over in-person meetings [27].

5.1 Time cost for in-person meeting

For in-person meetings, the time cost represents the opportunity cost lost by participants while travelling. Travel time unit costs vary depending on trip type, travel conditions, and traveler. The trip type can be classified into "on-the-clock" business travel (journeys taken as part of an employee's job, in which the business pays for the excess time cost) and personal or leisure travel. Research has shown that these two trip types have different time values, e.g. business travel is valued at the rate of an employee's hourly income, while personal travel is valued at 50% of that person's hourly income [28]. Since travelling to and from in-person meetings is generally considered as part of a business trip, we restrict our time cost analysis to only consider "on-the-clock" business travel.

In our analysis, we utilise data from the U.S. Department of Transportation on the "on-the-clock" business travel [28], which suggests that the time cost for business travel is equivalent to the traveller's income as the excess time spent for meeting travel are generally borne by business. Besides, an important distinction in terms of the time cost should be made depending on the mode of transport and the required attention, whether a person is driving a vehicle or travelling as a passenger. Time spent driving cannot be used for productive work, but time spent travelling on a train or bus can generally be used to perform some work like working on a mobile device or reading a book. Most travellers value such time spent [29], especially for business travel. As such, the time cost for passenger that does not have to maneuver the vehicles (e.g. plane and trains) should be offset against the actual cost per unit time spent for the journey. We take this factor into account in our case study (Section 6), scaling the time costs of plane and train travel by 0.75 which is the adjustment value adopted by Transport Canada [30] and UK Department of Transportation [31].

These values represent the recommended average values, while often there are substantial differences in the time value between individuals, due to the different income, distance travelled, comfort levels and traveller preferences. For example, people with a higher income level are usually willing to pay more for travel time savings, and so travel time for them has a higher unit cost. Currently videoconferencing equipment is usually used by employees with a higher-than-average income like higher executives or professionals, which should have a higher time cost. However we do not account for this in the values we used. This method is also in-line with the US DOT's report, which found that in the situation where there are wide and overlapping income ranges, the use of a single value is more preferable than using different time cost estimates based on different travellers' income [28].

5.2 Time cost for videoconferencing

Videoconferencing has no travel time cost. However, it is usually less efficient to perform a task via videoconferencing compared to in-person meetings. Remotely located groups suffer from weaker social ties and feeling of co-presence between participants [32]. In particular, spatial cues are lost in videoconferencing, which affects the conversation flow and turn taking between participants. This is particularly true in conventional desktop videoconferences, e.g. Skype, in which audio/video fidelity is sacrificed in order to reduce the required bandwidth to a level that can pass through communication links. This lower fidelity can disrupt the interaction between parties at each remote end, which slows down the meeting.

Past research has shown that participants who meet remotely using video communication technology take longer to complete the same task than those who meet in-person. However, the results have a large degree of variance (e.g. time cost of 110% [33], 150% [34], 160% [35] and 215% [32]) which are expected because of the large degree of freedom in the possible experiment setups and research methodologies. These factors include the different task types, videoconferencing equipment, video quality (bitrate, resolution, loss rate), number of remote endpoints, participants etc. In this study we consider a lower bound time overhead (versus in-person meetings) of 100% and an upper bound time overhead of 250% for videoconferencing. The lower bound value represents the higher task efficacy achieved by high end telepresence-based meetings with high quality reproduction of video and spatial cues, while the lower end value represents the lower task efficacy brought by conventional desktop videoconferencing.

6 Total cost comparison

We begin this section (Section 6.1) by comparing videoconferences and physical meetings in terms of energy consumption and carbon footprint (including both the operation and embodied cost). As highlighted previously, current videoconferencing solutions have widely varying configuration using different types and number of devices. Besides, the meeting duration, meeting frequency and replacement time-span of the devices are different for different users. Therefore, we consider two different configurations - a high-end telepresence setup and a laptop-based videoconference - to obtain an upper and lower bound estimate of the energy and carbon expenditures. For the conversion of energy into the equivalent carbon emissions, we applied a conversion factor of 0.6 $kgCO_2e/kWh$ as described in Section 3.3. In the later part of this section (Section 6.2), we factor in the time cost and repeat the comparison of the overall cost for both meeting modes.

6.1 Energy and carbon cost comparison

The total power (energy per unit time) cost for a videoconference solution is the sum of its operational and embodied energy. We define the overall operating power as an aggregate of the active power contribution for all components,

$$P_{op} = \sum_{i=device} n_i k_i P_i + I_{NW(op)} R \tag{2}$$

where n_i represents the number of devices of type i deployed; P_i represents the power consumption of device type i; $I_{NW(op)}$ is the operational network energy intensity; R is the average data rate or bandwidth of the videoconference and k_i represents the *use factor*- the percentage of the device's use dedicated to videoconferencing for the duration of the videoconference (e.g. $k_i < 1$ if the user multitasks while videoconferencing). In this paper we assume that the user is dedicated to the videoconference and does not multitask (k_i=1) for most cases unless otherwise specified. Similarly, the embodied power is the aggregate of the power contribution for all other lifecycle phases of the devices,

$$P_{em} = \sum_{i=device} n_i k_i \frac{E_i}{U_i} + I_{NW(em)} R \tag{3}$$

where n_i, k_i and R are as defined previously for equation *(2)*. E_i represents the embodied energy for device type i; U_i represents the total number of operational hours of the device over its lifetime and $I_{NW(em)}$ is the embodied network energy intensity. We next apply the equations on two different teleconference configurations to estimate the lower and upper bound power consumption for videoconferencing.

Upper Bound: The high-end telepresence system evaluated is assumed to consist of 3 65-inch plasma screen, 3 HD cameras, 3 microphones, a sound system and a CODEC at each endpoint, using the Cisco TelePresence System 3000 as a model [10]. The system is assumed to be used 5 hours per business day (representing the average utilization of Cisco TelePresence solutions worldwide [36]), with 260 business days per annum, and an active lifespan of 4 years.

We first calculate the operating energy involved per hour of active use. Based on the upper bound value of the network energy intensity of 3.61 kWh/GB and the average telepresence bandwidth of 7 Mbps [10], the network opex is estimated to be 11.4 kW. As for the end-point equipment, we sum the contribution of each device involved accordingly to estimate the equipment's power (energy consumed per hour) to be 909 W. Summing these values yields a total operating power per endpoint of 12.3 kW.

Similarly, the embodied energy involved can be calculated by summing the lifecycle energy contribution of each individual device. All devices involved except the LAN devices are assumed to be dedicated to videoconferencing, so the embodied energy cost should be uniformly amortized over the active hours of the product lifespan. We assume that LAN devices operate for 10 hours per business day, with 5 hours dedicated to videoconferencing. We obtain a per-hour embodied energy of 11.6 kW for each endpoint including 10.5 kW attributed to the lifecycle cost (excluding opex) of the Internet.

Thus, the total per-hour energy consumption, including the direct energy consumed by the generation of electricity and the embodied energy from the lifecycle of devices involved in the videoconference for each endpoint is 23.9 kW. Note that the total energy involved in a video conference is highly dependent on the bandwidth of the video call. If the call bandwidth is high, the contribution from end user equipment is less significant (8.4% of the total power in our upper bound estimation). On the other hand, when the average bandwidth of a videoconference is low, the energy contribution of end-user systems becomes significant (as we shall see shortly: 36% of the total power in our lower bound estimation). In either case, the network's direct and embodied energy dominates the overall energy cost (64% to 91%), as compared to the energy consumed by the home or office end terminals.

Lower Bound: To obtain a lower bound on the total energy involved in a videoconference, we consider a laptop-based videoconference which has minimal device overhead. The laptop is assumed to have internal microphone, speakers, camera and display, which are used in the video call. However, a laptop is generally used for other purposes over its lifespan rather than being dedicated for videoconferencing only. Therefore, we assume that both the LAN and laptop are used for other activities for 5 hours per day.

We calculate the network energy opex by considering the minimum bandwidth required for a video call of 128 kbps [37] and the lower bound Internet energy intensity estimate of 2.17 kWh/GB. This gives us 125 W for the network energy opex. In terms of the per-hour operating energy consumed by end-user devices, only the laptop and home/office network are considered here, giving a sum of 60 W. Likewise, the total embodied energy of the laptop and home/office network is 2362 MJ, or 63 W when the cost is amortized over the active lifetime when the laptop is used for videoconferencing. The minimum estimate of the embodied energy intensity of the Internet is 93 W. The sum of the operational and embodied energy cost yields an estimate of the total per-hour lifecycle energy of 341 W consumed by each endpoint.

Case Study: We consider the case of a 5 hour meeting with 2 local participants (who need not travel), 1 domestic participant (who travels 1000 km) and 1 international participant (who flies 5000 km). We consider three different cases where the domestic participant travels by plane, train and private car. Utilizing the transportation lifecycle energy data in Section 4.1, if the meeting is held in-person, the travel cost would be 21.2 GJ (domestic-plane), 17.4 GJ (domestic-train) and 19.9 GJ (domestic-car) for the different modes of transport taken by the domestic participant. On the other hand, if the meeting was held via a videoconference, the same meeting will cost 0.025 GJ (lower bound) or 1.3 GJ (upper bound) taking into account the lifecycle energy for all end user and network devices. Note that the number of endpoints is assumed to be 4 for the lower bound calculations (individual terminal for each participant), while it is assumed to be 3 for the upper bound case (as the two local participants should use the same telepresence studio).

In terms of the carbon emissions, the lifecycle carbon footprints for the in-person meetings are 3533 kgCO_2e (plane), 2900 kgCO_2e (train) and 3317 kgCO_2e (car), while the carbon emissions of the same meeting via videoconferencing is between 4 kgCO_2e (lower bound) and 215 kgCO_2e (upper bound). Hence, considering the full lifecycle energy and environmental cost of both meeting modes, videoconferencing only takes an upper bound value of 7% of the cost for a physical meeting, as shown in Figure 1.

Fig. 1. Comparison of the energy cost for videoconferencing versus the different modes of transportation for in-person meetings

As a sensitivity analysis, we first evaluate the effect of the meeting time on the resulting energy savings (Fig 2). Regardless of the total meeting time, the lifecycle energy (and thus the corresponding carbon footprint) for a physical meeting would stay constant as no additional travel is involved. However, the lifecycle energy from a videoconference scales linearly with the duration of use. For example, if the meeting time increases to 10 hours, the total energy involved in videoconferencing increases to 0.05 GJ (lower bound) and 2.6 GJ (upper bound), which are twice the values for a 5-hour meeting. In other words, if the meeting duration is the only variable, the breakeven point in which both meeting solutions incur the same energy cost is when the total meeting duration is 75 hours (roughly 10 working days). Thankfully most meetings are not this long!

Fig. 2. Energy curve for all meeting modes as the meeting duration is varied

If the distances change, the carbon emissions from travel will vary accordingly. However, this should have little impact on the energy cost of a videoconference. This is because a large proportion of the Internet's opex lies in the access networks rather than the core network (access networks consume about 10 times the energy of core networks per bit of data transferred [38]). If the distance between the endpoints increases, this should only increase the number of core router hops without affecting the access router hops. Since the energy consumption of the core network is relatively small, in this study we assume that the videoconferencing cost stays constant with varying meeting distances. If the travel distances from our case study are halved, such that the domestic participant travels 500 km and the international participant travels 2500 km, the overall energy contribution from the in-person meeting will fall by half to give 10.6 GJ (plane), 8.7 GJ (train) and 10 GJ (car). The travel distances will need to be shortened 15-fold (e.g. to a miniscule 67 km for the domestic participant and 333 km for the international participant) to reduce the lifecycle energy cost of the in-person meeting such that it matches the cost of videoconferencing. However, these results show that there are certain conditions in which having an in-person meeting is still better than videoconferencing environmentally, especially for high-end telepresences that have a higher energy profile. The effect of varying travel distance on the overall energy consumption is shown in Figure 3.

Fig. 3. Energy curve for all meeting modes as the aggregated travel distance is varied

6.2 Overall cost comparison including time cost

In this section we derive the overall cost of meeting via videoconference versus in-person, which now includes the time cost in addition to the energy/carbon cost for the case presented in Section 6.1. This comparison is non-trivial due to the different units involved in the energy dimension versus the time dimension, with both of them being orthogonal to each other. Our solution is to perform the comparison in terms of monetary cost, by putting a price on energy of 10 cents/kWh [39] based on US Energy Information Administration data. Time costs are also expressed in monetary terms based on the average National US wage in 2013 of $43/hour. The per-participant dollar cost for videoconferencing can then be expressed as the sum of the time and energy cost,

$$cost_{vc} = k_{time} c T_{meet} + k_{energy} c T (P_{op} + P_{em}) \tag{4}$$

where k_{time} and k_{energy} represents the time and energy to dollar conversion factor respectively (10 cents/kWh and $43/hour); c is the time overhead factor, which accounts for the different task efficacy between both meeting solutions (discussed previously in Section 5); T_{meet} represents the meeting time; P_{op} and P_{em} are the operational and embodied power consumption. Likewise the per-participant cost for in-person meetings can be defined,

$$cost_{ip} = k_{time}(q T_{travel} + T_{meet}) + k_{energy} E \tag{5}$$

where q represents the time cost adjustment for different modes of transportation (e.g. car drivers are unable to work in transit while plane travellers can, which was further discussed in Section 5.1); T_{travel} and T_{meet} is the transit and meeting time; while E is the energy cost for transportation as calculated in the previous section.

We first calculate the time cost for both meeting modes, with average travel speeds of 700 km/h for planes, 100 km/h for trains and 80km/h for cars. As discussed earlier, we also scale the time cost for trains and planes by 0.75 to embody the fact that passengers can engage in other activities when travelling. For in-person meetings, no travel time cost is incurred by the two local participants. The international passenger who travels 5000 km will incur a time cost of $230, while the time cost for the domestic passenger who travels 1000 km is $46 (plane), $339 (train) and $538 (car) respectively for the different possible transportation modes. As described previously in Section 5, we assume that the meeting time does not expand when meeting via videoconference for the lower bound case. The upper bound scenario however considers that videoconferences require 2.5 times longer to achieve the same functionality as a corresponding in-person meeting. This means that for videoconferencing, the 5-hour meeting considered will be extended to 12.5 hours, with a time cost of $1290 associated with the 7.5 hours of time overhead. Note that because we are comparing the differences between meeting in-person and via videoconference, we do not include the base duration of the meeting time (5 hours) in calculations because it is the same for all cases.

We then convert the energy cost obtained in our previous calculation and express them in terms of dollars. This results in an energy dollar cost of $589 (domestic-plane), $483 (domestic-train) and $553 (domestic-car) assuming the meeting is held in-person. Alternatively, the same meeting held via a videoconference will have an energy dollar cost of $0.69 for the lower bound scenario. The calculation of the upper bound videoconferencing energy cost is not as straightforward due to the extended meeting time, such that the videoconference consumes more energy than calculated previously (3.25 GJ instead of the previous 1.3 GJ). This results in an upper bound energy dollar cost of $90 for videoconferencing.

Combining both the energy and time cost yields an overall cost of $865 (domestic-plane), $1052 (domestic-train) and $1321 (domestic-car) for in-person meetings, and widely ranging cost of between $0 and $1380 for videoconferencing. The results demonstrate that when time costs are taken into account, videoconferencing might become a less attractive meeting mode. In this scenario, videoconferencing has an upper bound cost that is higher than in-person meetings. The main cause of this is the lower task efficacy of videoconferencing, which makes the meeting unnecessarily longer and therefore incurs a higher time cost for participants. Therefore, for the common case where the efficacy of videoconferencing is lower than an in-person meeting, our results show that it is important to evaluate the meeting versus the total participants' travel time required for in-person meeting. Longer travel time does not necessarily translate into a higher overall cost, especially if the meeting duration is long.

We note that expressing all costs in monetary units is simplistic; in particular merely expressing carbon costs in dollar terms make them seem inconsequential compared to time costs. While that may have been necessary in order to reduce the problem to a single dimension, it does not reflect current concerns about the potentially fatal implications of global warming.

7 Future trends

What of the future? As noted, the Internet's bandwidth is rising faster than its power consumption. This implies that the energy intensity of data transfer is decreasing, with one estimate being that the decrease is 1.65-fold/18-months [40]. If we consider an upper-bound telepresence setup, which is likely to become more common in the future because it offers a higher level of immersion, the Internet constitutes approximately 90% of the overall videoconferencing energy use, so the decline of Internet power consumption should make it even more attractive environmental-wise. Even in the worst case where the embodied energy intensity of the Internet is assumed to remain constant in coming years, the network opex still constitutes 50% of the videoconferencing energy cost, thus we can estimate that the energy cost of videoconferencing will fall by 20% every 18 months.

However, these energy reductions do not necessarily translate into the equivalent energy savings of videoconferencing over in-person meetings. One can similarly argue that transportation will also become greener, leading to reduced energy and carbon emissions from travelling. Transport has historically improved in efficiency by a compound rate of about 3% p.a. since 2004 [41], which is almost an order of magnitude less than the decrease in Internet energy usage. As a best case consideration, we assume that in the future all transportation is electrically powered since this is the most efficient means of transport available in terms of its energy consumed and emissions, e.g. an electric car uses 0.87 MJ/km whereas a petrol fueled car uses 3.57 MJ/km well-to-wheel [42]. Even in this best case situation which reduces carbon emissions from transportation by 75%, videoconferencing, at current efficiency levels will only contribute up to 27% of the energy/carbon cost of in-person meetings, which is a moderate rise from the present upper bound value of 7%, but still well below the energy/carbon cost for physical meetings.

8 Conclusion

This study has compared the life-cycle energy, carbon and time costs of videoconferences and in-person meetings. We evaluated both the direct and embodied energy contribution for both meeting solutions, which is the impact from the manufacturing, deployment, opex and end-of-life handling for all end-user and network devices for videoconferences, and also for the vehicles and transportation infrastructure involved for in-person meetings. We also evaluated the time cost for both these meeting modes. Our results show that without factoring in the impact of time costs, videoconferencing currently takes at most 7% of the energy/carbon of an in-person meeting, and this economy of videoconferencing in terms of energy/carbon cost is likely to persist into the future. However, when time costs are considered, the cost benefit that videoconferencing has over in-person meeting is reduced because of the time overhead required to achieve the same functionality as a corresponding in-person meeting. Future work could consider the complex relationship between the efficiency of using video for communication (i.e. time overhead in videoconferencing), travel time and meeting duration to enable a more detailed analysis of the cost differences for both meeting modes.

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