

## Environmental Implications of Wireless Technologies: News Delivery and Business Meetings

MICHAEL W. TOFFEL

Haas School of Business, University of California, 545 Student Services Building, Berkeley, California 94720-1900

ARPAD HORVATH\*

Department of Civil and Environmental Engineering, University of California, 215 McLaughlin Hall, Berkeley, California 94720-1712

Wireless information technologies are providing new ways to communicate, and are one of several information and communication technologies touted as an opportunity to reduce society's overall environmental impacts. However, rigorous system-wide environmental impact comparisons of these technologies to the traditional applications they may replace have only recently been initiated, and the results have been mixed. In this paper, the environmental effects of two applications of wireless technologies are compared to those of conventional technologies for which they can substitute. First, reading newspaper content on a personal digital assistant (PDA) is compared to the traditional way of reading a newspaper. Second, wireless teleconferencing is compared to business travel. The results show that for both comparisons wireless technologies create lower environmental impacts. Compared to reading a newspaper, receiving the news on a PDA wirelessly results in the release of 32–140 times less CO<sub>2</sub>, several orders of magnitude less NO<sub>x</sub> and SO<sub>x</sub>, and the use of 26–67 times less water. Wireless teleconferencing results in 1–3 orders of magnitude lower CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub> emissions than business travel.

### Introduction

Since the Industrial Revolution, economic growth has required an ever-increasing amount of natural resources and has left a legacy of pollution and waste including toxic emissions, a degraded stratospheric ozone layer, and manifestations of global climate change. With the advent of the computer age, some have enthused that a new knowledge economy may break the trend that increasing wealth depends on increasing environmental exploitation. According to this view, moving information instead of physical resources will reduce the resource and pollution intensity of economic growth.

This article contributes to a nascent literature that compares the environmental impact of information and communication technologies (ICT) to the traditional products and services they may replace. Reflecting on the results of a recent special issue of the *J. Ind. Ecol.* on the relative

environmental impacts of ICT, the editor remarked, "The picture that emerges is ambiguous...[but] is also a cautionary tale for those who would posit IT [information technology] as a means of environmental salvation or an easy road to sustainable development" (1).

This paper compares the environmental effects of wireless technologies to the traditional applications for which they can substitute. Two comparisons are conducted. The first examines the impacts of reading newspaper content loaded onto a personal digital assistant (PDA) compared to the traditional way of reading a newspaper. Millions of people read news content online, and ICT is increasingly substituting for traditional hardcopy news. A study (2) notes, "The considerable information content of most newspapers, combined with high fixed costs and the subsidizing of content by advertising, makes them particularly vulnerable to electronic substitution". Another report (3) found that only half of the executives surveyed from 400 U.S. companies expect that they will obtain their news from traditional daily newspapers in the future.

The second scenario compares wireless teleconferencing to business travel. Increased use of telecommunications in lieu of business trips are often justified in tougher economic times and for employees who either already travel frequently or who are averse to travel. Video and teleconferencing technologies are substituting for business travel, especially internal meetings (4). Given continuous improvements in ICT's audio and visual quality and features, it is increasingly feasible that wireless telecommunication will substitute for time-consuming and both economically and environmentally expensive business travel. ICT may be particularly suitable to substitute for follow-up meetings among participants who have already met rather than serving as a forum for initial introductions.

**Related Research.** The Internet is expected to reduce the economy's energy intensity due to e-commerce reducing retail and warehouse space requirements, telework reducing work-related commute and office space requirements, and other structural changes (3). Several articles have compared e-commerce to traditional retailing (3, 5–11). Compared to conventional shopping, e-commerce has been found to require 16% less energy and to generate 36% less conventional air pollutants, 23% less hazardous waste, and 9% less greenhouse gases (8). The logistics to support Web-based book shopping in the United States have resulted in lower environmental impacts than logistics to support conventional retail book sales (8). The environmental burden of increased air shipments is more than offset by reduced personal shopping trips (7). However, a more recent study found that e-commerce book sales in the United States and in Tokyo require more energy than traditional retailing but found the opposite in rural Japan (12). Another study found that the relative environmental impact of conventional and online book purchasing was dependent on the customer's transportation method (10). Shopping by car—even when the book purchase represented only one of several purposes for the trip—required twice the energy as either traveling by bus or shopping online. Others have concluded that the two shopping methods require the same total amount of energy but quite different proportions from building, transportation, and packaging, which in turn have significant environmental implications (9). Compared to conventional grocery shopping, shopping electronically with home delivery services have been shown to reduce greenhouse gas emissions by

\* Corresponding author phone: (510)642-7300; fax: (510)643-8919; e-mail: horvath@ce.berkeley.edu.

18–87% (11). The extant literature on telework/telecommuting has looked at, for example, the travel-related energy and air quality implications of telecommuting (13), rebound effects (14), and potential energy consumption and related air emission implications from travel, the company, and the home office (15). While rebound effects may complicate the analysis, scenarios could be constructed where telework has the potential to reduce air emissions (15).

Several studies have compared the environmental impact of novel ICT products. For example, a centralized telephone recording service was found to require one-tenth of the life-cycle energy of a home answering machine (16). Online telephone directories may require less energy than both conventional phonebooks and those produced on CD-ROMs (17).

**Wireless Applications.** The few studies that have compared the environmental impacts of wireless technologies to applications they are replacing have concluded that wireless technologies impose a lower environmental burden. For example, several studies have shown that replacing traditional road toll plazas with electronic toll collection systems results in decreased mobile source emissions (18–22). Wireless computer local area networks (LANs) have been shown to require only 10% of the energy required by wired LANs (23).

One reason so few comparative studies have focused on wireless technologies is a paucity of life-cycle environmental data. Most of this research is quite recent, including assessments of the environmental impact of semiconductor wafers (24), computer memory chips (25), cellular telephones (26–29), city-wide mobile and fixed telecommunications systems (30), a pager (31), and teleworking (15, 32).

**Reading the News.** A few studies (33–36) that have compared the environmental impacts of online to printed publications have yielded mixed results. For example, one found that the creation and use of electronic and print journals consumed similar amounts of energy and that the results were highly dependent upon the scenario considered (35, 36). A Swiss study compared the environmental burden associated with producing and receiving news via a hardcopy newspaper, an Internet newspaper, and television broadcast (34). The results depended on the unit of analysis. When evaluating the entire newspaper, the Internet newspaper resulted in less environmental burden (approximately one-third) than the hardcopy newspaper. However, the reverse was true when considering a single news article, as the environmental burden of an Internet news item was nearly six times that of a newspaper cutting.

**Business Communication.** A few studies have evaluated the environmental impacts of various business communication methods. One study compared business travel methods to a videoconference and not surprisingly found that—except for short distances—a videoconference requires less energy than traveling to a meeting by rail, car, or air (10). For example, a videoconference requires 500 times less energy than a business trip requiring a 1000 km flight, and the disparity increases with distance. Another study compared videoconferencing to various travel methods between offices in Stockholm and Gothenburg and found that flying required at least 5 times more energy (37). Whether train travel required more or less energy than videoconferencing depended on how often the ICT equipment was used and left on. A Web-based tool recently developed to compare the environmental impacts of teleworking to conventional commuting (32) has the capability of demonstrating that there are plausible telecommuting scenarios that may reduce air pollution but that telework programs may also increase air emissions if not designed properly (15).

The following sections first calculate and compare the life-cycle environmental effects of reading newspapers to reading the news on a PDA and then compare conducting

a meeting via cellular teleconference to the travel required for a face-to-face meeting.

## Reading the News

With a total paid circulation of nearly 1.2 million on weekdays and 1.7 million on Sundays, the New York Times (NYT) has the largest circulation of any 7-day newspaper in America (38). The NYT also delivers articles to PDAs via AvantGo software. This content can be loaded onto a PDA in two ways: via a wireless connection to the Internet or via a PDA wired to a personal computer that is connected to the Internet. AvantGo estimates that about 1.5 million people subscribe to The Times Channel, 30% of AvantGo users actively read content, and 9% access content via a wireless connection (39). Below, life-cycle environmental effects are calculated for reading the news via a newspaper and via a PDA using the two alternative methods to load news content.

In comparing newspapers to PDA news delivery, the unit of analysis is one person reading the daily news for 1 year. An important consideration is that on average more than one person reads each NYT newspaper. The NYT daily readership has been estimated at 2.5–4.2 million (40, 41); the mean (3.35 million) is used in this analysis. Dividing this figure by the weekday- and weekend-weighted average daily circulation of 1.27 million suggests that a reasonable estimate of the average readership per newspaper is 2.6. The following section calculates the environmental effects of one daily newspaper over the course of a year.

**Newspapers.** In determining the incremental environmental effects of reading the NYT in Berkeley, CA, the life-cycle environmental effects of newsprint and ink, and the emissions resulting from the fuel consumption of delivery vehicles are calculated. This includes the burdens of manufacturing newsprint and of ink and the printing process as well as newspaper delivery and disposal. The impacts of manufacturing and operating the newspaper printing machinery and manufacturing delivery trucks in this case study were excluded from the discussion due to their long, multiyear life-cycle and intensive use. The same news content is assumed to be provided to consumers regardless of the medium of delivery, and thus the impact of producing content is excluded.

**Newsprint.** The environmental burden of fiber acquisition, paper manufacturing, and post-use transport to a recycling facility or a landfill are estimated. A year's worth of the NYT weighs some 236 kg (520 lb) (42). Two scenarios are created. In the *base case*, the newsprint is assumed to be comprised of 50% recycled newspaper and 50% virgin thermomechanical pulp (based on calculations from (43)). This is a higher ratio than used by the NYT, which is currently composed of around 28% recycled fiber (44), but it reflects the potential that the industry would move toward higher recycling levels. After being read, half of the newspapers are assumed to be recycled, and the other half landfilled. This is consistent with a recent U.S. Environmental Protection Agency (EPA) estimate that 58% of newspapers are recovered for recycling nationwide (45). A *best case* is also considered where newsprint is comprised of 100% recycled newspaper, and all newspapers are recycled. This alternative is presented as the most optimistic case given that paper fiber deteriorates with recycling, and thus at least some virgin material is a necessary input to producing recycled paper.

To calculate the life-cycle emissions associated with a year's worth of newspaper production and disposition, data from refs 43 and 46 are used. Hazardous air pollutants and volatile organic compounds are estimated based on processes associated with newsprint production, including thermomechanical pulp mill, groundwood pulping, thermomechanical pulping, deinked recovered fiber, and papermaking uncoated groundwood. The Economic Input-Output Analysis-

**TABLE 1. Environmental Burden Associated with a Daily NYT Newspaper Delivered 365 Days**

	A newsprint, base case	B newsprint, best case	C printing	D local truck delivery	E total per newspaper, base case (A+C+D)	F total per newspaper, best case (B+C+D)	G total per newspaper reader, base case (E÷2.6)	H total per newspaper reader, best case (F÷2.6)
<b>Air Emissions [kg]</b>								
greenhouse gas emissions [CO <sub>2</sub> equiv]	660	369	37	5	702	411	270	158
NO <sub>x</sub> (NO <sub>2</sub> for printing)	2.1	1.5		0.07	2.2	1.6	0.9	0.5
particulates (PM <sub>10</sub> for printing)	1.1	0.8	0.04	0.01	1.2	0.9	0.5	0.3
SO <sub>x</sub> (SO <sub>2</sub> for printing and truck)	3.6	2.7	0.1	0.01	3.7	2.8	1.4	1.0
<b>Hazardous Air Pollutants [kg]</b>								
methanol	0.01	0.01			0.01	0.01	0.004	0.004
formaldehyde	0.01	0.01			0.01	0.01	0.004	0.004
benzene	0.001	0.00			0.001	0.00	0.0004	0.00
<b>VOCs [kg]</b>								
acetone	0.003	0.002			0.003	0.002	0.001	0.001
terpenes	0.02	0.02			0.02	0.02	0.008	0.008
other VOCs	0.3	0.2			0.3	0.2	0.1	0.1
<b>Effluents [kg]</b>								
biological oxygen demand	0.5	0.6			0.5	0.6	0.2	0.2
chemical oxygen demand	3.7	2.9			3.7	2.9	1.4	1.1
total suspended solids	0.7	0.7			0.7	0.7	0.3	0.3
<b>Effluent Volume [L]</b>								
total effluent flow	11 900	11 500			11 900	11 500	4577	4423
<b>Solid Waste [kg]</b>								
total solid waste generation	210	120			210	120	81	46
<b>Wood Use [kg]</b>								
total wood use	240	0			240	0	92	0
<b>Water Use [L]</b>								
total water use	22 700	22 700			22 700	22 700	8731	8731

based Life-cycle Assessment (EIO-LCA) tool (47, 48) is employed to estimate water consumption associated with newspaper production. Based on an industry estimate of \$540 per ton (49), newsprint for a year's worth of NYT costs \$130, and its production consumes 22 700 L (6000 gal) of water. Since most of this water consumption occurs at the mills, this figure is used for both the base and the best case scenarios. Column A of Table 1 presents the effects associated with the base case, and column B presents the best case.

**Printing.** To estimate the environmental burden of printing, the cost of ink used in newspapers is estimated at \$0.45 per week (\$23.40 per year). The environmental burden of printing ink (48) is presented in column C of Table 1.

**Newspaper Delivery.** For customers in California's San Francisco Bay Area (where Berkeley is located), the NYT is printed in Concord, a 64 km (40 mi) round trip drive from Berkeley. Using average local truck emission factors (50, 51), the emissions resulting from local truck delivery of 236 kg of NYT are presented in column D of Table 1.

The environmental effects associated with newsprint, printing, and newspaper delivery are shown in columns E and F of Table 1. As the average NYT newspaper is assumed to be read by 2.6 people, the environmental effects of newspapers reported in Table 1 are divided by 2.6 in columns G and H for comparison to the PDA method.

**Reading News on a PDA.** The annual environmental effect of reading news on a PDA is estimated by considering the manufacturing and use of a PDA, the energy required to load news content via the wireless or wired telecommunications infrastructure, and the optional use of a personal computer (PC). The life span of a PDA is assumed to be 3 years, which is consistent with other studies (52). Users are assumed to read news content on their PDA for 1 h per day and use the PDA for its other features for another hour. Given these two assumptions, one-sixth of the environmental burden associated with the manufacturing of the PDA is allocated to

reading news during 1 year. For the PDA's usage, half of the energy burden is allocated to reading news.

**PDA Manufacturing.** A life-cycle assessment (LCA) study of a PDA has not yet been published. Thus the environmental effects of manufacturing a PDA are approximated by focusing on the production of its memory chip, processor, display, and battery. A recent study (25) found that the production of a 2-g 32 MB DRAM chip—including the silicon wafer, chemical production, fabrication, assembly process, and assembly materials—requires 41 MJ or 11.4 kWh (using 3.6 MJ/kWh) and 32 L of water. The Palm m500 PDA contains 12 MB of memory (8 MB RAM plus 4 MB ROM). Thus the manufacturing of the PDA's 12 MB of memory is estimated to use a proportional amount of energy and water (12/32, or 38%), 4.3 kWh and 12 L.

The Palm m500 contains a Motorola DragonBall VZ processor. Because most of the energy related to integrated circuit production is associated with the wafer fabrication process (53), the energy required to produce the DragonBall processor is estimated based on its silicon wafers. The Dragonball contains two dies each measuring 135.1 × 134.9 mils, or 0.343 × 0.343 cm, for a combined area of 0.236 cm<sup>2</sup>. Because wafer fabrication requires 1.4 kWh/cm<sup>2</sup> of energy and 5.9 L/cm<sup>2</sup> of water (53), similarly to other studies cited in (25), 0.3 kWh and 1.4 L are estimated to be needed to manufacture the wafers used in the DragonBall processor.

The energy and water required to manufacture a PDA screen is estimated based on an LCA of a 15-in. liquid crystal display (LCD) monitor. The upstream (materials acquisition and production), manufacturing, and end-of-life phases of a 15-in. LCD computer monitor (12 × 9 in. screen) requires 1989 MJ and 2395 L of water (54). Having identified no published research that characterizes the relationship between the amount of energy required to manufacture LCD screens and the size of the screen, the PDA screen's production effects are assumed to be proportional to those

of the 15-in. LCD screen. Thus manufacturing the PDA's 2.3 × 3.3 in. LCD screen is estimated to require 140 MJ, or 39 kWh of energy, and 168 L of water.

Lithium-based rechargeable battery cells have been assessed in the range of 26–46 g, 1.5–5.5% of which is lithium (55). The midpoints of these ranges, 36 g and 3.5%, are employed in the current analysis. A recent LCA found that 700 MJ is required to produce 1 kg of lithium (56). Therefore, the energy required to produce the lithium in the PDA battery is calculated to be 0.3 kWh.

In summary, the total energy and water required in the manufacturing of the PDA's memory chip, processor, display, and battery are 44 kWh and 181 L. This does not include the transportation of the PDA to the customer and the end-of-life fate of the device. Over the PDA's 3-year lifespan, loading and reading the news are allocated 7.3 kWh of energy and 30 L of water per year from manufacturing.

**PDA Usage.** The PDA consumes energy in three ways. First, it consumes energy while recharging in its cradle. Second, the PDA continues to draw energy while in the cradle even after it is fully charged. Third, the charger continues to draw energy even when the PDA is not in the cradle. It is assumed that the user places the PDA in the charger every day for 10 h (e.g., overnight from 9 p.m. to 7 a.m.) and always leaves the charger plugged in.

Having found no published data pertaining to the energy consumed by PDA chargers, the power consumption of a charger for a Palm m515 was measured. This charger draws 3.5 W while actively recharging the PDA, 0.7 W maintaining the battery charge while the PDA remains in the cradle, and 0.5 W while the cradle is empty (57). Assuming the battery requires 1 h per day to actively recharge, the charger consumes 0.017 kWh per day or 6.2 kWh per year. Because half of the PDA's use is allocated to reading news, this translates into 3.1 kWh per year for this task. The manufacturing of the charger is not assessed due to lack of data.

**Loading Content via a Wireless Device.** To estimate the electricity consumption associated with wireless loading of content onto a PDA, the focus here is on the energy consumed by a Palm device during the upload. (The network infrastructure is considered further below.) The Palm m500 can communicate via a telephone line or a wireless telephone if it is attached to the PalmModem Connectivity Kit, which includes an analogue 56K modem. This modem requires two AAA 1.5 V batteries, which are expected to provide 150 min of use (58). Connecting and uploading news content takes about 1 min, thus the batteries enable 150 uploads. Therefore, the PalmModem consumes six AAA batteries per year. A recent LCA of dry and wet primary batteries concluded that manufacturing \$100 of batteries requires 63 kWh and 3100 L of water (59). If six AAA batteries cost \$10, the PalmModem annually consumes approximately 6.3 kWh and 310 L of water. The manufacturing of the modem is not assessed due to lack of data.

**Loading Content via a PC.** The environmental effects of loading news content onto a PDA using a PC result from the manufacture and use of the PC and its communication devices. Because the Palm m500 connects to a PC using a USB port, uploading data on the PDA is fast. The user turns on the PC, connects to an Internet service provider (ISP) via a dial-up modem, loads the news content from the Internet via the PC to the PDA, and then turns off the PC. Allowing for the PC's operating system to start, this entire operation takes about 5 min.

The environmental burden of a PC's manufacturing is estimated based on an LCA of a typical 1998 computer (60). Total primary energy consumption including the materials production, manufacturing, distribution, disposal, and recycling of the central processing unit (CPU), the keyboard, and the monitor is 951 kWh (3422 MJ), and water use is 13 400

**TABLE 2. Energy Associated with Uploading Daily NYT Content to PDA over 365 Days**

	wireless uploading [kWh/yr]	wired uploading [kWh/yr]
PDA manufacturing	7.3	7.3
memory chips	0.7	0.7
processor	0.05	0.05
LCD screen	6.5	6.5
battery	0.05	0.05
PDA usage	3.1	3.1
uploading via wireless device	6.3	
uploading via PC		10.7
telecommunications infrastructure	8.0	2.9
internet operation	0.001	0.001
<b>total</b>	<b>24.7</b>	<b>24.0</b>

L. Assuming a PC has a useful life of 3 years and is used 4 h per day, the PC's manufacturing energy burden is 0.0036 kWh per minute of PC usage. This is a similar calculation used by others (9) and is generally aligned with alternative estimation approaches (33). Thus, the five-minute process is allocated 0.018 kWh per day or 6.6 kWh of energy and 93 L of water per year for PC manufacturing.

The power requirement of a Pentium desktop PC during active use has been estimated at 50–55 W (33, 61) and 70 W (62). Herein the average of these estimates, 60 W, was used. The average power requirement of a monitor sold in 2001 has been estimated at 65 W (62), a number also reported by others (33). The total, 125 W, is in line with a 1999 estimate that a PC and a monitor consume 150 W (3). A PC modem has been estimated to require 10 W (63). Thus, the energy required by the PC and modem is 135 W, and the five-minute upload requires 0.011 kWh or 4.1 kWh per year. (The manufacturing of the modem is not assessed due to lack of data.) Adding the allocation from PC manufacturing, a PC consumes 10.7 kWh per year to upload news to a PDA.

**Telecommunications Infrastructure.** Regardless of whether a PDA is using a wireless news upload or a wired news upload through a PC, loading is estimated to require 1 min. As calculated below, the cellular infrastructure is estimated to require 0.014 kWh per minute, and the wired telecommunications infrastructure is estimated to require 0.008 kWh per minute. Therefore, loading news wirelessly onto a PDA (which uses both infrastructures) consumes 8.0 kWh per year and via the wired infrastructure 2.9 kWh per year.

**Internet Operation.** For either the wired or the wireless connection, the PDA accesses an ISP. An ISP modem has been estimated to require about 1 W and be shared across 12 subscribers (52). ISP modems are estimated to be used at 50% capacity, thus 0.17 W is allocated to this task. At 1 min per day, this consumes 0.001 kWh per year.

**Summary and Environmental Effects.** Table 2 summarizes the PDA analysis and shows that the wireless PDA news method requires 24.7 kWh of energy and 340 L of water per year, while the wired method requires 24.0 kWh and 123 L. For this scenario, emission factors pertaining to the average fuel mix for electricity generation in California are used (64). Thus, wireless uploading for a year results in the release of 5 kg of CO<sub>2</sub>, 0.01 g of CH<sub>4</sub>, 4 g of SO<sub>2</sub>, and 4 g of NO<sub>x</sub>, essentially the same as wired uploading.

Therefore, compared to reading the news loaded onto a PDA using a wireless or a wired method, reading the NYT as a newspaper results in the release of 32–140 times more CO<sub>2</sub>, several orders of magnitude more NO<sub>x</sub> and SO<sub>x</sub>, and the use of 26–185 times more water depending on whether a newspaper is read by 1 or 2.6 readers and the level of recycled content used in the newsprint. The choice of whether news content is loaded onto the PDA via a wireless versus wired

**TABLE 3. Environmental Burden of Meeting Scenarios, Per Person**

business travel		CO <sub>2</sub> [kg]	CH <sub>4</sub> [g]	SO <sub>2</sub> [g]	NO <sub>x</sub> [g]
drive Berkeley to SFO, round trip		18			15
flight between SFO and O'Hare, round trip					
two takeoff and landing cycles		47	0.7	15	200
cruise cycle		535		170	2220
total flight		581	0.7	185	2420
light rail between O'Hare and downtown Chicago, round trip		8	0.05	69	25
<b>total</b>		<b>608</b>	<b>0.75</b>	<b>254</b>	<b>2460</b>

wireless meeting	kWh	CO <sub>2</sub> [kg]	CH <sub>4</sub> [g]	SO <sub>2</sub> [g]	NO <sub>x</sub> [g]
cellular telephone manufacture	0.43				
cellular telephone usage (charger)	0.0056				
cellular telephone infrastructure	1.7				
wired telephone infrastructure	0.95				
<b>total</b>	<b>3.1</b>	<b>1.3</b>	<b>0.01</b>	<b>9</b>	<b>3</b>

connection has little bearing on the air emissions, but the wireless method uses three times more water.

The analysis was based on the assumption that the energy required to produce a 12 MB chip is directly proportional to the amount required to produce a 32 MB chip, i.e., 12/32, or 38%. To test the sensitivity of the results to this assumption, an alternative assumption is made here that the energy required to produce a 12 MB memory chip is the same as that required to produce a 32 MB memory chip. Recalculation on the new basis added only 1.2 kWh per year (5%) to the PDA scenario. Also, if the useful life of the PDA were taken to be only 2 years (instead of 3), this would add 3.8 kWh per year to the PDA scenario. This change only slightly reduces the advantage of the PDA method, as newspapers would still result in the release of 26–117 times more CO<sub>2</sub>.

**Travel versus Wireless Communications**

In the second scenario, the environmental implications of substituting business travel with a wireless teleconference call are considered. Business travel generates a wide array of environmental burdens such as the emissions of greenhouse gases and toxic chemicals. Not the least because of rapid advances in wireless telephone and teleconferencing services, foregoing business travel for a teleconference has especially been embraced in the latest economic downturn and amidst the post-9/11 travel slump.

**Business Travel.** The environmental burden of a round-trip travel between Berkeley and Chicago, IL is calculated. For the business trip, the individual drives 40 km (25 mi) to San Francisco International Airport, takes a scheduled flight, rides the light-rail train 31 km (19 mi) from O'Hare International Airport to downtown Chicago, walks to a downtown hotel and to the meeting place, and then takes the same transportation modes in reverse to get home.

This analysis focuses on the emissions associated with the fuel consumed by the trip and excludes the impacts of vehicle manufacturing and building and operating the roads and airports. The difference between the energy consumed by a one-night hotel stay is assumed to offset the energy savings from a night away from home, thus the environmental burden of lodging was also excluded from the analysis. This analysis used average rather than marginal values for travel, hence switching modes may not be accurately accounted for.

**Automobile Journey.** Emissions are calculated based on the assumption that the automobile meets California Low Emission Vehicle requirements (65). To estimate CO<sub>2</sub> emissions, the vehicle is assumed to consume 9.4 L gasoline per 100 km (25 mpg) and thus uses 7.6 L (2 gal) for the 80 km (50 mi) round trip drive. Resulting emissions are calculated

based on emission factors (66) and are presented in Table 3.

**Flight.** The flight from San Francisco to Chicago is 2980 km (1850 mi) each way. A typical aircraft used for this flight is an Airbus 320 (with two cf6–80a type engines) that operates at a cruise speed of 730 km per hour (454 mph) (67). It is assumed that the plane, which is typically configured with 146 seats, is filled to 75% capacity. For the cruise cycle, emission factors for SO<sub>2</sub> and CO<sub>2</sub> are from the “simple method” (68), and the fuel consumption and the emission factor for NO<sub>x</sub> are from ref 69. For the landing and takeoff cycle, the fuel consumption and emissions factors are from ref 70. The emissions per passenger resulting from this trip are presented in Table 3.

**Light Rail Journey.** On average, light rail consumes 0.208 kWh per passenger km (0.336 kWh per mi), calculated by dividing 4.50E+08 kWh consumed by light rail in 2000 (71) by 2.16E+09 passenger km (1.34E+09 mi) ridden on light rail that year (72). Emission factors pertaining to the average fuel mix for electricity generation in Illinois are used (64).

**Cellular Communication.** The environmental effects of a 1-h cellular conference call between two parties is estimated by examining the manufacture and use of a cellular phone and the use of the cellular and wired telephone infrastructures. Calculations are based on two 1-h calls (one by each party).

**Cellular Telephone Manufacturing.** Few LCA data pertaining to microelectronics products have been published. Nokia has reported that the energy embodied in mobile phone components dominates raw materials, assembly, transportation, and use (73). However, no numbers are available. Ericsson researchers have reported the electricity consumption associated with the manufacturing of various cellular phone components and the operation of a 3G system for 1 year (27) but had not normalized the results to the useful basis of a user, telephone, call, or call minute. The lack of LCA data and normalization numbers (e.g., subscribers, system usage) has been attributed to confidentiality concerns among component suppliers, cellular telephone manufacturers, and system operators (27).

Lacking LCA data for a specific cellular phone, the EIO-LCA software (48) was used to determine that the energy required to manufacture a \$100 cell phone (communication equipment sector) requires approximately 39 kWh. A cell phone is assumed to have a 3-year lifespan. Studies have estimated the average number of minutes cell phone subscribers use each month as 255 min (74), 320 min, and 335 min (75). The mean of these (303) is employed herein, resulting in 3636 min per year. Thus the energy required to manufacture a cell phone is allocated at 0.0036 kWh per

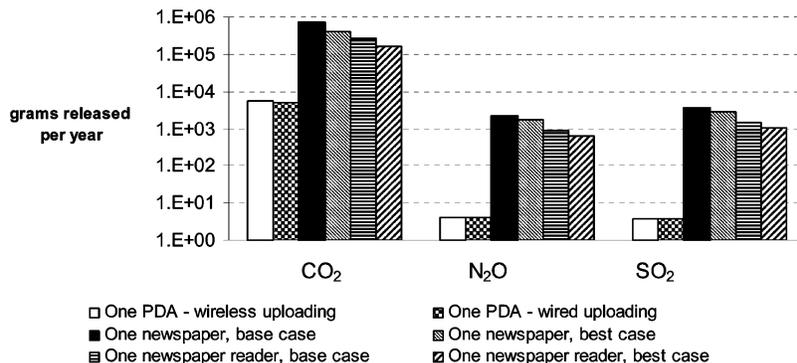


FIGURE 1. Environmental effects of three news scenarios.

minute, or 0.43 kWh for the two 1-h calls.

**Cellular Telephone Usage.** Prior studies provide relatively consistent estimates of cell phone energy consumption. One study reports 110.22 kJ per day (26), which equates to 0.031 kWh per day. Another study estimates that a charger consumes 3 W while charging the phone, and 1.5 W while the charger remains plugged in all day but sits empty (52), suggesting daily consumption of 0.0375 kWh if the battery is charged in an hour. Calculations based on values from ref 28 indicate that chargers consume 0.055 kWh per day but that new “smart” chargers require only 0.0027 kWh per day.

For the current study, the power consumption of a Nokia charger for the Nokia J-MN02 cell phone was measured to ensure charger energy consumption is based on current technology. This charger draws 3.5 W during the 1 h that it actively recharges the phone and less than 0.1 W (the measurement instrument’s threshold value) after it automatically shuts off for the other 23 h. Assuming it draws 0.09 W while not actively charging a phone, the charger consumes 0.0056 kWh per day (57). This is on the same order of magnitude of another study that estimated that new “smart” chargers would require only 0.0027 kWh per day (28). Assuming a charged cell phone battery provides 2 h of talk time, one-half of the energy required to charge the phone is allocated to the 1-h telephone call. With two cell phones used for the call, the 1-h call requires 0.0056 kWh.

**Cellular Telephone Infrastructure.** A few studies have reported the total energy consumed by the use of wireless telecommunications systems, including infrastructure and devices. One of these studies calculated the energy consumed by the current cellular infrastructure in California, including radio base stations, switching equipment, mobile phones, the operator use of equipment, heating, cooling, service, administration, and the energy consumed by the fixed (wired) networks (28). This study found that the existing system consumed the equivalent of 31 L of petroleum per subscriber-year but that new equipment that is less energy-intensive would require the equivalent of 17 L of petroleum per subscriber-year (28). Another report noted that energy consumption associated with the use of the wireless telecommunications system dominates other life-cycle stages and that it results in the release of 50 kg of CO<sub>2</sub> emissions per subscriber-year (76). A third study estimated that the cell phone system in Sacramento, CA consumed 17 976 MWh per year (30). At the time, the system serviced 350 000 cell phone subscribers (77), which implies that a typical Sacramento cell phone subscriber consumed 51.4 kWh per year from the telephone infrastructure.

As discussed above, a typical cell phone subscriber is estimated to consume 3636 min per year. Lacking any data about the relative energy burden on the infrastructure of a phone in use versus standby, all cellular infrastructure energy is allocated across only cellular call time, though this implicitly assigns no infrastructure energy to phones on standby and

thus exaggerates the infrastructure energy assigned to calls. Dividing the annual 51.4 kWh usage by 3636 min indicates that the cellular infrastructure requires 0.014 kWh per cellular call minute. Thus, two 1-h cellular calls require 1.7 kWh from the cellular infrastructure. Note that cellular calls also rely on the wired telephone infrastructure.

**Wired Telephone Infrastructure.** Sacramento’s wired telephone system has been estimated to consume 36 051 MWh per year (30). At the time of the study, the system serviced 512 000 wired telephone subscribers (77), suggesting that a typical wired telephone subscriber consumed 70 kWh per year from the wired telephone infrastructure.

To allocate wired infrastructure energy consumption per telephone call minute, total call minutes were estimated. In 2001, 83 billion Inter-Local Access and Transport Area (Inter-LATA) toll calls were originated in the United States, while the total originating and terminating Inter-LATA calls resulted in 746 billion minutes (78). Avoiding double counting by dividing the latter figure in half, this implies that the average Inter-LATA calls lasted 4.5 min. In 1999, 5 billion international calls were originated in the United States, and 28 billion international call minutes were completed (79). Assuming that two-thirds of the latter were outbound calls (because outgoing U.S. calls are often cheaper), the average international call lasted 3.7 min. The 15 billion intra-LATA calls and 515 billion local calls in 2001 (78) were assumed to last an average of 4 min, implying 60 billion intra-LATA call minutes and 2060 billion local call minutes. Thus, the total originating call minutes in the United States during this period were estimated at 2060 billion local, 60 billion intra-LATA, 373 billion Inter-LATA, and 18 billion international, or a total of 2511 billion. Dividing this figure by 281 million, the U.S. population in 2000 (80), the average American made 8936 min worth of telephone calls per year (24 min per day).

Assuming that Sacramento residents’ call patterns are typical of American telephone consumers, Sacramento’s annual wired infrastructure energy requirement per subscriber (70 kWh) is divided by the nationwide average annual usage of 8936 min. This results in the wired infrastructure requiring 0.008 kWh per call-minute. Thus, two 1-h calls require 0.95 kWh from the wired infrastructure.

**Summary and Environmental Effects.** As illustrated in Table 3, a 1-h wireless teleconference incurs a total of 3 kWh of electricity. Since this call is meant to replace travel between Berkeley and Chicago, half of the energy was allocated using emission factors pertaining to the average fuel mix of California, and the other half to the average fuel mix of Illinois (64). Thus, two 1-h wireless calls result in the release of 1.3 kg of CO<sub>2</sub>, 0.01 g of CH<sub>4</sub>, 9 g of SO<sub>2</sub>, and 3 g of NO<sub>x</sub>.

## Discussion

Figure 1 illustrates a comparison of the environmental effects for which data are available in both news scenarios. Obtaining

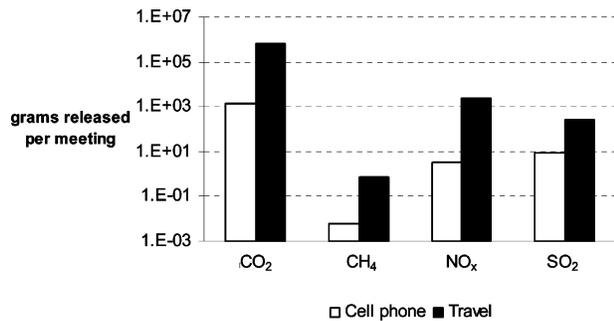


FIGURE 2. Environmental effects of travel versus wireless communication.

the news via newspapers incurs a greater environmental burden than loading news onto a PDA. This conclusion is robust to the choice of uploading news content to a PDA via wireless or wired Internet access and to whether a newspaper

is read by one person or shared among 2.6 people. Reading newspapers printed in conventional ways results in the release of 32–140 times more CO<sub>2</sub>, several orders of magnitude more NO<sub>x</sub> and SO<sub>x</sub>, and the use of 26–67 times more water. The choice of wireless versus wired PDA Internet access has little bearing on the air emissions of the PDA method as the estimated energy burdens of these methods were similar. However, wireless uploading of the news was found to have three times the water demand of wired uploading.

Nearly 56 million newspapers were sold every day in the United States in 2001 (81). Based on the current analysis, this resulted in 23 Tg (best case) to 39 Tg (base case) of CO<sub>2</sub> emissions per year. Nationwide, newspapers average 2.2 readers per copy, for a total of 123 million daily newspaper readers (81). If a quarter of these readers were to switch from newspapers to obtaining the news on their PDA, the 30.8 million PDA users would generate 0.17 Tg of CO<sub>2</sub> per year, a mere 2–3% of the 6–10 Tg of CO<sub>2</sub> per year that would have

TABLE 4. Matrix Used for Data Quality Assessment<sup>a</sup>

indicator score acquisition method	1 measured data	2 calculated data based on measurements	3 calculated data partly based on assumptions	4 qualified estimate (by industrial expert)	5 nonqualified estimate
independence of data supplier	verified data, information from public or other independent source	verified information from enterprise with interest in the study	independent source, but based on nonverified information from industry	nonverified information from industry	nonverified information from the enterprise interested in the study
representativeness	representative data from sufficient samples of sites over an adequate period to even out normal fluctuation	representative data from smaller number of sites but for adequate periods	representative data from adequate number of sites, but from shorter periods	data from adequate number of sites but shorter periods	representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
data age	less than 3 yrs of difference to yr of study	less than 5 yrs difference	less than 10 yrs difference	less than 20 yrs difference	age unknown or more than 20 yrs of difference
geographical correlation	data from area under study	average data from larger area in which the area under study is included	data from area with similar production conditions	data from area with slightly similar production conditions	data from unknown area or area with very different production conditions
technological correlation	data from enterprises, processes, and materials under study	data from processes and materials under study but from different enterprises	data from processes and materials under study but from different technology	data on related processes or materials but same technology	data on related processes or materials but different technology

<sup>a</sup> Source: Based on refs 83 and 84.

TABLE 5. Results of Data Quality Assessment<sup>a</sup>

	acquisition method	independence of data supplier	representativeness	data age	geographical correlation	technological correlation	average
newsprint	2	1	1	2	1	2	1.5
printing	3	1	3	3	2	2	2.3
newspaper delivery	2	1	2	3	2	1	1.8
PDA manufacturing	3	1	4	2	2	4	3.2
PDA usage	1	1	4	1	2	1	1.6
wireless uploading	2	1	1	3	2	1	1.7
PC uploading	1	1	1	1	2	1	1.2
internet ISP modem	2	1	2	1	2	2	1.7
utility electricity emissions	2	1	1	1	2	1	1.3
automobile travel	2	1	2	1	1	1	1.3
light rail travel	2	1	2	1	2	3	1.8
aircraft travel	2	2	1	1	3	1	1.7
cell phone manufacturing	4	4	4	3	3	4	3.7
cell phone usage	1	1	1	1	2	1	1.2
telecommunications infrastructure	2	2	2	1	2	2	1.8

<sup>a</sup> Maximum quality = 1, minimum quality = 5. Each value within each category is defined in Table 4.

resulted from the 14 million newspapers they no longer require.

Figure 2 illustrates that cellular telecommunications results in 1–3 orders of magnitude less CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions than travel even though the cell phone scenario used a few assumptions that may have overestimated its impacts. If new “smart” chargers become ubiquitous, they would consume only 1 kWh per year (28), half the amount used in our analysis. In addition, new cell phones may require a fraction of the life-cycle energy of the current technology (82). To get a sense of the magnitude of the results, a company that converts 100 meetings a month to wireless teleconferences would reduce its CO<sub>2</sub> emissions by 720 Mg per year.

**Data Quality Assessment.** Data quality assessment deals with uncertainty related to the data employed in this analysis. The quality of data was evaluated using a six-dimensional estimation framework based on refs 83 and 84, presented in Table 4. Each of the six elements is rated on a five-point scale, with a score of 1 representing the highest data quality. The results of assessing the quality of the data employed in the current study are presented in Table 5. The majority of data quality indicators are scored 1 or 2.

The indicator score that represents the most uncertainty in the news analysis is the representativeness of the value for PDA manufacturing, especially of the screen. The next highest level of uncertainty stems from 5 to 10 year old data sources that were used in calculating newspaper printing and delivery as well as uploading wirelessly. To determine the sensitivity of the study’s results to this uncertainty, three parameters that were directly compared between reading newspapers versus news on PDA were examined (Figure 1). PDAs generated lower emissions across all three of these parameters. The closest ratio of the three parameters is in CO<sub>2</sub> emissions: when a newspaper is shared by 2.6 readers, each reader is responsible for the emission of 30–50 times more CO<sub>2</sub> than if the person reads the news on a PDA (depending on the extent to which the newspaper comprised of recycled content and is itself recycled). Thus, the results of the comparison are robust in the face of uncertainty.

In the travel scenario, the indicator scores that illustrate the most uncertainty correspond to cell phone manufacturing. Lacking LCA data, the environmental impacts associated with manufacturing cell phones were estimated based on an allocation of energy consumed by the communication equipment sector. This estimate resulted in cell phone manufacturing constituting 14% of the total environmental burden of the 1-h wireless call. However, because cellular telecommunications were found to result in 1–3 orders of magnitude lower emissions than travel (Figure 2), the comparison can be viewed as robust to the uncertainty in estimating the environmental effects of cellular telephone manufacturing.

**Results in Context.** The presented results are aligned with prior research that found ICT to have lower environmental impacts than the applications they are replacing, including comparisons of e-commerce to traditional commerce (6–8), centralized recording services to home answering machines (16), wireless road toll collection to traditional toll plazas (18–22), and wireless LANs to wired LANs (23).

A few recent studies have suggested that ICT may complement rather than substitute for older technologies (85, 86). For example, many PDA users continue their newspaper subscription while loading news from different content providers onto their PDA. In addition, many travelers are avid cellular phone users. Future research that evaluates the environmental impact of ICT would benefit by considering how they both substitute and complement the use of other technologies to calculate incremental burdens. This is not an easy task as many studies comparing the short-term environmental impacts of telecommunications to travel have

found substitution effects but have been criticized as being “incomplete and likely to miss the more subtle, indirect, and longer-term complementary effects that are typically observed in more comprehensive studies” (86). Nonetheless, this represents an important component of future research.

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