Supporting Information

Reusable vs. Disposable Cups Revisited: Guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the U.S. consumer

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S.1 Background and Motivation

S.1.1 LCA and disposable cups

In 1991, the journal Science published Professor Martin Hocking's correspondence comparing paper cups to polystyrene cups (*1*). Hocking's study was not exhaustive, and his final conclusion was cautionary. Short of declaring plastic cups a better choice than paper, he called for "a much more even-handed assessment as regards their environmental impact relative to paper cups" in single-use applications. Respondents highlighted shortcomings in the study and provided alternative suggestions that encouraged broadening the scope and refining the input for a fairer comparison (*2*). The dialogue highlighted a need for a life cycle approach in the analysis with better resolved boundary definitions and more accurate material flow data.

Less well-publicized, yet equally valid, was a critique of Hocking's work citing the high publicity it had received but claiming, "methods developed to date do not provide the necessary analysis

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on which to base decisions about product choices (*3*)." Hocking's expanded study was published later the same year, minimally addressing some of the criticisms (*4*). The extended analysis reiterated the call for an "even-handed" approach and extrapolated results to packaging. Soon thereafter, in an article introducing the method and software for Carnegie Mellon University's environmentally extended input-output life cycle assessment, the authors cited Hocking's work as an example where accounting for indirect economic interactions is advised (*5*).

S.1.1.1 Using narrowed analysis with broader comparisons

In 1994, Hocking extended the study to include reusable cups while narrowing the evaluation to energy only, noting that the interest and misinterpretations of the 1991 publications prompted the study (*6*). He sought to find the break-even number for how many uses of a reusable glass or ceramic cup would be required to outperform the same number of single-use cups, a difficult determination given "the widely differing nature of the materials used and the conditions required (*6*)." Thus, he claimed energy as "the fundamental property common to each product system... to keep the scope of the paper manageable." He examined the fabrication energy and energy for commercial washing and sanitizing and briefly considered disposal options. The main conclusions in his work were that the energy to wash a reusable cup is about equal to the energy to manufacture a polystyrene foam cup and that, therefore, "one's choice of cup may be freely based on aesthetic and convenience criteria rather than environmental and energetic ones." Hocking's conclusion was based on cumulative energy consumption alone within the boundaries of analysis.

In the main report and in correspondence to Nature, Hocking made claims regarding social preferences, namely, "Most people prefer to use a ceramic, glass or hard plastic cup than any of the disposable varieties (*7*)." However, research into consumption patterns has shown, instead, a correlation to more practical matters than such an implied self-evident preference system. Such practical matters can be product placement, peer influence, or verbal cues (*8*, *9*). Moreover, consumption patterns are influenced by deference to authority or social norms, in some cultures more strongly than others (*10*). Such influences can have huge implications in developing, populous nations be-

ginning to resemble U.S. consumption patterns, where consumer choice is not necessarily based on aesthetics or personal values, but on expectations and norms. The refined theory of basic values differentiates how behaviors, including decision-making such as purchasing, derive from values forming a complex motivational continuum (*11*). In the industrial ecology literature, Hertwich has commented on consumption, stating, "Consumers have some leeway to make changes in their own lifestyles and product choices, and thus affect their own environmental footprint. The freedom to do so, however, is constrained by the infrastructure within which life needs to be organized, by habits and social expectations, and by products available (*12*)."

S.1.1.2 Scientific communities and popular literature 15-20 years later

In a discussion of what merits a healthy journal space, Suh cited Hocking's work and subsequent responses as having exposed LCA to broader audiences while also raising issues of credibility in LCA (*13*). Nonetheless, review of popular literature shows the publications by Hocking from the early 90's still persist as most cited sources regarding the environmental impact of choosing a cup for inquiring consumers (*14–27*). See Section S.2.2 for discussion.

There have been other studies in the time since Hocking's piece in Science, most notably a Franklin Associates, Inc. comparison of disposable options (*28*), a TNO report (*29*), and a joint Task Force study with Starbucks Coffee Company and Alliance for Environmental Innovation (*30*), each discussed below in a literature review for compiling less publicized works and their conclusions. First some context is provided on the advent of single-use cups in America.

S.1.2 Historical context

S.1.2.1 Disposable cups: a profitable response to public health

Paper mills in America were modeled after the European approach, located near populated areas for a ready supply of water and rags. While paper-makers experimented with local natural resources, the availability of mechanical wood pulp grinders made trees a viable feedstock, leading to the

first newspaper made from ground wood pulp in 1863 and the subsequent expansion of the paper industry (*31*).

Paper containers in America and machinery for forming them were developed as early as the 1860s for uses as spittoons, casks, and pails, with one of the earliest U.S. patents for a paper drinking cup filed in 1892 (*32–35*). What is most interesting about the paper cup's design of Figure S.1 is that it aims to exploit the ability to print on paper and targets the white space for local merchant advertising.

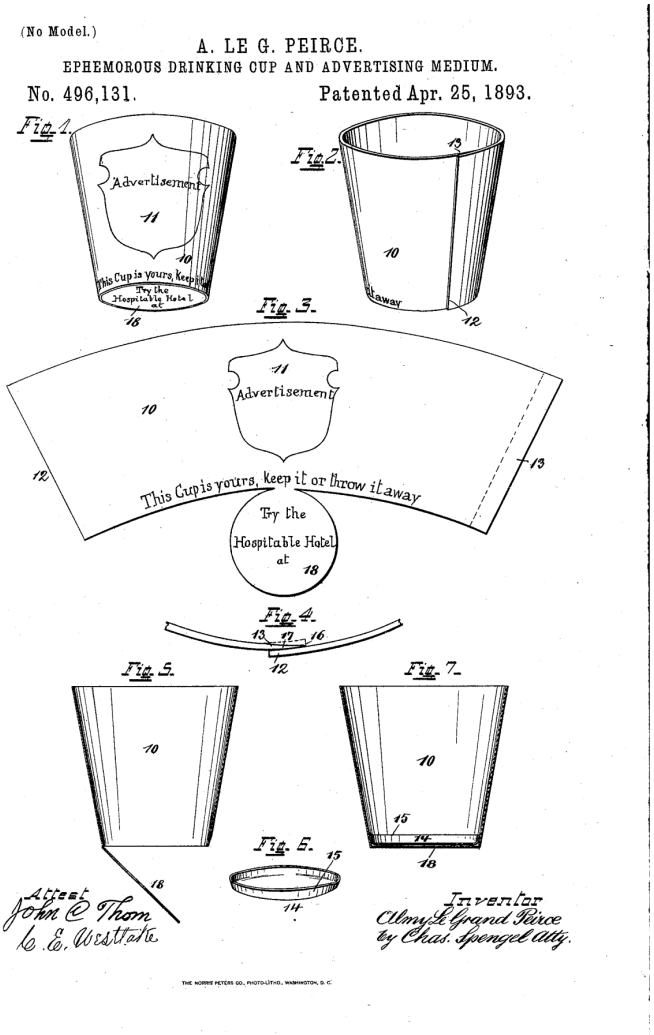


Figure S.1: Paper cup with advertisement, filed 1892, patented 1893.

More practical, however, is the reason behind the growth of paper cup use and subsequent vending machines that were in development as early as 1905 for water dispensing (*36*, *37*). The

following quote indicating sanitary conditions of the time is taken from a 1907 patent filing of a vending machine (*37*):

> The device is especially designed for dispensing water in measured quantities. In most places where water is dispensed to the public generally the same cup or glass is used by all persons who draw water from the apparatus. Where this is the case the cup is very apt to become unsanitary, and in many instances becomes a means of scattering contagious diseases.

With the wide-spread acceptance of disposable drinking cups and vending systems alongside advancements in materials and processing technologies, polystyrene became a competitive material for disposable cups. A patent of submission date 1956 declares a foamed polystyrene laminate for lining of paper cups to improve performance (*38*). A patent submitted in 1958 for the design of nestable cups to facilitate better vending specifically recommends high-impact polystyrene over paper cups for stated practical and aesthetic reasons (*39*). A filing in 1960 assigned to Phillips Petroleum Company described the use of blowing agents for forming foamed thermoplastic resins (*40*). In a filing of 1964 assigned to Monsanto Company, the development of a nested foam cup of polyethylene, polystyrene, polybutadiene, or modified polystyrene designed to overcome higher material coefficient of friction of these materials for easier dispensing in vending machines is described (*41*). Both latter patents indicate that vended beverages in polystyrene cups had come into wide use in America by 1960. In parallel, the electric dishwasher had only just begun to make its way into American homes by 1950, taking 30 years to reach a saturation point of 37% by 1980 (*42*, *43*).

S.1.2.2 Modern urban waterworks and social inertia

In response to developing knowledge of disease transmission and prevention through sanitary water supply and the need for fire protection in urban developments, the US has since the 1800s built one of the most reliable (although aging) water supply and waste treatment systems in the world.

From filtration, piping, pumping, and other industrial operations involved in provisioning water for consumption, one still requires serviceware, or cups, excepting brief stops at a water fountain.

Whether this serviceware should be of a disposable or reusable type and in what respective form is dependent on a number of variables, notwithstanding convenience. In Life magazine's 1955 article, "Throwaway living," disposable items are heralded as time-savers, liberators portrayed in a single photo of items claiming to save a "housewife" cumulatively 40 hours of cleaning (*44*). The article is itself placed in a magazine that has nearly 40% of page covering as advertisements, the remaining in articles, photos, headlines, and administrative notes.

Perhaps the marketing of the disposable lifestyle and sympathy to the labor that accompanies consumption speaks to a cultural mentality outside of but fully encompassing this analysis. Nonetheless, barring rules preventing the use of a personal cup for receipt of a beverage (whether in a perversion of order or a practical situation as medical facilities), there remains no conceivable barrier to the choice of cup belonging solely to the consumer in a free market so long as the consumer is willing and enabled to maintain possession of his or her own vessel in a suitable form for its use in a transaction.

S.1.2.3 Early investigations

In a precursor to LCA, the US Environmental Protection Agency in 1974 conducted a resource and environmental profile analysis (REPA) of 9 beverage containers (*45*). The study compared four materials in both one way and returnable systems, finding high rates of return associated with lowest impact. The report took a retailer and distributor perspective, concluding that a shift from "one-way" or "throw-away" containers to returnable systems would yield reductions in raw material and energy consumption and environmental pollution. The methods of REPA align well with the emergence of LCA in the decades to come, its authors noting the lack of impact assessment methodologies, making it essentially an inventory analysis over seven categories: raw materials, energy, water, industrial solid wastes, atmospheric emissions, waterborne wastes, and post-consumer solid wastes.

Hocking's papers seemed to thrust LCA into the public forum, beginning with the policy correspondence in Science in February 1991 (excerpted and updated in Consumers' Research Magazine in October with extended paper in Environmental Management in November), though it, too, was essentially an inventory analysis, not a relatively state of the art LCA (*1*, *4*, *46*).

S.1.3 The Public and polystyrene

At a time where polystyrene foam was under public scrutiny with bans being enacted in various townships, camps were forming on both sides (*47–49*). Many of the initial bans and those that persist were not necessarily enacted for reasons of life cycle energy consumption and such, but as a response to frequency of litter and the burden on marine systems. This is especially a concern with food service polystyrene, where cups comprised 18.4% of foamed plastic in the 1999 U.S. Coastal Cleanup Day (*50*). In general, food service items (cups, plates, forks, knives, spoons), caps/lids, and food wrappers/containers have been in the top five annually for number of items recovered in Cleanup Days from 1989-2011, alongside cigarettes/cigarette filters and bags (plastic and paper) (*51*).

For another viewpoint, stated on Dart company's website, "(L)itter is a people issue, not a product issue... (S)tudies found that people generally litter because it is easy to do so, they feel no ownership of the property, and often believe that someone is being paid to clean up after them (*52*)." Recycling was also beginning to become a point of contention (*53*, *54*). It is worth noting that narrow assessments such as energy analysis do not account for additional indicators of human and ecosystem health such as litter, though the inventory phase of life cycle assessment can capture end-of-life flows for impact assessment and interpretation.

S.1.4 The Public and paper

One thing Hocking's extended paper did was to make clear descriptions of the processes for papermaking, thus helping to disqualify inclination to think of paper products as fully renewable, highlighting non-renewable resource inputs. This was in a time when ecolabeling for forest products

was not widely applied or well-developed. As a sign of the times, the Forest Stewardship Council Founding Assembly for developing worldwide certification systems was not held until two years later, in 1993 (*55*). Hocking's initial papers were very fitting in terms of the social movement that had begun years earlier, starting with widespread boycotting of certain wood products and resulting in what we know of today as the market-friendly certification process (*56*).

S.2 Literature Review

S.2.1 Scientific literature

This section will lay out what has been published in terms of comparisons of reusable and disposable cups, beginning with Hocking's work in 1994 and continuing through less well-publicized works to determine the points of comparison and for establishing a reference set for this analysis, which applies a number of tools to the space. Table S.1 is provided with an overview of references discussed below.

S.2.1.1 Hocking 1994 (*6*)

Hocking compared cups of approximately eight ounce capacity. As for representativeness of input, a study in 2003 in The Journal of the American Medical Association determined trends for increasing portion sizes from 1977-1998 for home, fast food, and restaurant settings (*60*). For 1994-1996, soda and juice portions served at home averaged 17 and 14.7 ouces, respectively, with averages higher in fast food and restaurant establishments. Note, too, that coffee chains have moved towards sizes larger than 8 oz. Starbucks Coffee Company does offer still a "short" size, which is 8oz, but it is not listed on the stores' menus, which list cup sizes 12 oz ("tall") and higher. This factor is nontrivial as Hocking's results are highly dependent on the total mass of the disposable cups, whereas the reusable cups are dependent on washing assumptions, which are not relatively sensitive to a 50% or higher increase in the size of a cup.

Hocking concedes that factors other than energy consumption lead to differing break-even

Table S.1: Overview of reviewed studies' boundaries and analyses

reference	materials[a]	inventory detail	impact assessment	results
1994 Hocking (*6*)	EPS PE-paper ceramic glass	process-level reasonably detailed	inventory analysis: energy	cup size: 8 oz breakeven ceramic vs. EPS : $>$ 1000 uses breakeven ceramic vs. paper: $>$ 39 uses breakeven glass vs. EPS (paper): 393 uses (15)
1995 Lave et al. (*5*)	EPS paper	U.S. economic sectors aggregated	inventory analysis: toxic releases electricity demand	not intended for decision-making demonstrated magnitude of indirect economic impacts
1998 Denison (*57*)	EPS paper ceramic	process-level reasonably detailed	inventory analysis: energy some air/water emissions solid waste	cup size: 16 oz breakeven ceramic vs. EPS : 260 uses breakeven ceramic vs. paper: 120 uses
2000 Starbucks (*30*)	PE-paper PET ceramic glass	process-level reasonably detailed	inventory analysis: water GHG solid waste	cup size: 16 oz breakeven ceramic vs. PET and paper: 70 uses breakeven glass vs. PET and paper: 36 uses
2006 Franklin Assoc. (*28*)	EPS PE-paper	process-level high detail industry collaboration Gabi4 LCA software	inventory analysis: energy solid waste GHG	cup size: 16 oz (EPS and PE-paper only)[b] energy: inconclusive solid waste (weight): EPS lower solid waste (volume): inconclusive GHG: inconclusive
2006 Vercalsteren et al. (*58*)	PC (reusable) PP PE-paper PLA	process-level high detail stakeholder input Ecoinvent v1.01 database	Eco-indicator 99 (H/A)	cup size: 250 mL (8.5 oz) mixed results dependent on participation (return rate)
2007 Garrido and del Castillo (*59*)	PP (reusable) PP (one-way)	process-level reasonably detailed BUWAL 250 database IDEMAT 96 database	Eco-indicator 95	cup size: 200-300 mL (6.8-10.1 oz) weighted results reported 10 uses to breakeven washing impacts correlate to nuclear-heavy electrical mix
2007 TNO (*29*)	porcelain cup/saucer earthenware mug TPS PE-coated paper	process-level high detail industry-specific data Ecoinvent v1.01 database	CML2 baseline shadow pricing	cup size: 180 mL (6.1 oz) results report earthenware mug "most environmentally polluting system" for 7 of 10 categories

[a]EPS = expanded polystyrene PE-paper = polyethylene-coated paper PET = polyethylene terephthalate PC = polycarbonate PP = polypropylene TPS = thermoformed polystyrene PLA = polylactic acid

[b]Summarized results listed here are for EPS vs PE-paper without sleeve.

points and defers to a Dutch study (referred to as TAUW study), noting that the study found "very high" return rates are required for the reusable cup to outperform in three of four categories (air, landfill volume, energy consumption) and no point for a more favorable impact on water with reusables when washed once with every use. The TAUW study evaluated cups of 180 mL (6.1 oz). The 2007 update to the TAUW study is discussed below in Section S.2.1.8.

Hocking's main conclusions are that the washing energy dominates the impacts per use of reusable cups. Specifically, he concludes, "The wash energy alone is as much or more than required to make a polystyrene cup in the United States and more than half that required to make a paper cup." He encourages reuse of either type cup before disposal or washing. Hocking does not give explicit merit to the factor of serving size and representativeness in his discussion.

S.2.1.2 Lave et al. 1995 (*5*)

The study presented the environmentally-extended input-output LCA (EIOLCA) software, using Hocking's 1991 work as an example to merit boundary extension through the EIOLCA method (*5*). Through this method at its early stage of development, the authors concluded that for paper and plastic producing sectors, indirect suppliers' toxic discharges are substantially greater than direct suppliers and, therefore, must not be neglected in the decision process. The example included only the two disposable cup scenarios and was meant to be demonstrative, not comprehensive.

S.2.1.3 Denison 1998 (*57*)

This briefing, in conjunction with the Alliance for Environmental Innovation, presented a comparison of ceramic mugs, PS foam, and paperboard. It is an inventory analysis with the following categories considered: energy use, material inputs, some air and water emissions, and solid waste. For these categories, the most number of uses required for a ceramic mug to break even with polystyrene was 260 and with paper was 120 (*57*).

This study cites the 1992 TAUW study (discussed in Section S.2.1.8 below) for its ceramic mug data, a 1992 Franklin Associates report for polystyrene data (discussed in section Section S.2.1.5),

and an Environmental Defense Fund 1995 report for paper data. This study assumes use of a commercial washer and so implies centralized facilities such as provided in some office buildings. The briefing assumed 16 oz beverage sizes, and refers to the Franklin study for the polystyrene cup mass and personal communications with Starbucks Coffee Company for the mass of reusable and paper cups.

S.2.1.4 Starbucks Coffee Company and Alliance for Environmental Innovation 2000 (*30*)

Partnered in a Joint Task Force, the expressed goal of this study was to both increase use of reusable cups provided for in-house service and to develop a new single-use cup to replace the frequently used nested paper cups for hot beverages (*30*). Pilot-scale tests using visual and verbal cues to encourage reusable cups for in-house consumption were well-received and subsequently implemented across the national network of stores. Before this study, about 20% of stores provided reusable ceramic cups for hot drinks, and none carried glassware for cold service. Test stores showed increases from 18% to 57% in average use of reusable cups, and some evidence was found to correlate with higher consumer satisfaction.

The Joint Task Force produced an inventory analysis determining a breakeven point of 70 and 36 for ceramic and glass cups, respectively, versus disposable cups, but the report does not detail the boundaries and inputs for much of the analysis, including washing phase assumptions. The economic analysis determined significant savings in packaging costs with nominal labor cost increases. Based on study results, the Task Force proposed incentives to promote individual users of personal take-out cups. It is noted in the study, "(t)he majority of Starbucks' beverage business is take-out, with most of those drinks sold in disposable cups."

S.2.1.5 Franklin Associates 2006 (*28*)

In 2006 Franklin Associates, Ltd. released a peer-reviewed life cycle inventory of polystyrene foam, bleached paperboard, and corrugated paperboard foodservice products. This was an update to an earlier report in 1992; the 2006 report was updated in 2011 addending the inventory to

include polylactic acid foodservice products without modifications to the paper and polystyrene datasets (*28*, *61*, *62*). The study was scoped to analyze foodservice products most competitive with polystyrene foam products. For comparing cups, 16 oz and 32 oz sizes were evaluated. Competing scenarios of coated paper cups included cardboard sleeves and "double-cupping." It did not, however, address reusable cups.

The Franklin report includes aspects of secondary packaging, energy analysis, and disposal scenarios concomitant with current trends. Unfortunately, detailed process flow diagrams and supporting information is located in the appendices of the report that are not publicly available, as confirmed by personal communication. Results are presented in accordance to ISO standards in a 236 page report. It is an inventory analysis with attention given to energy, solid waste, and GHG emissions. It has been found in popular literature that the Franklin analysis lended more credence to proponents of polystyrene foam in the choice of single-use cups. Much of the results were inconclusive between the two types of cups, but leaned towards PS over paper. All data was reviewed for accuracy and currency, all sets having been updated in 1997 or later.

S.2.1.6 OVAM 2006 (*58*)

OVAM, the Public Waste Agency for the Flemish Region, commissioned the Flemish Institute for Technological Research to perform a study of both reusable and disposable plastic cups at both small and large events, citing the majority of waste at large events being discarded drink cups. The full report was presented in Februrary 2006; a summary publication appeared in 2010 (*58*, *63*). Reusable polycarbonate cups were compared to three disposable types: polypropylene, polyethylene-coated cardboard, and polylactide; impact analysis was performed using EcoIndicator 95. The size assumed is 250 mL or 8.5 oz.

For small events, under the assumptions, the reusable PC cup never had the highest impact, but showed lowest impact for five of nine impact categories with one-way PP holding lowest impact for the remaining four. The results differ for large events with more interchange among PC, PP, and paper cups for lowest impact.

Sensitivity analysis showed much greater variation for assumptions in reuse of the PC cups than for other senstivitites tested. Specifically, the return rate for the PC cups at the events had the largest impact on the results with respect to the variables considered. The impacts for the one-way cups showed similarity across the three cups and for both types of events and much less respective variability, such as end-of-life treatment and transport distances. This indicates less technical and more structural, social influences that ultimately impact the environmentally comparative performance, erring on the side of the reusable PC cups in events having high participation of consumers.

S.2.1.7 Garrido and del Castillo 2007 (*59*)

In a similar context, a Spanish study assumed reusable plastic cups for public events and determined that 10 uses were needed to be more environmentally preferrable (*59*). This figure is drawn from use of the Eco95 weighting leading to a single-score output, but the results are mixed for individual impacts. One-way cups were assumed 200 mL (6.8 oz) while the reusable cups were assumed 300 mL (10.1 oz) with the functional unit of delivery of 1000 L draught beverages, or 5000 disposable cups versus 3,333 uses of the reusable cups. Both cups types were polypropylene with the reusable cup having about 14 times the mass of the cup for single-use, and thus meant to hold up to reuse.

S.2.1.8 TNO 2007 (*29*)

A Dutch study from the early nineties referred in literature as the TAUW study was determined to be the predecessor of the TNO report. By 2007, TNO analysts were commissioned to update the TAUW study with more modern assumptions and LCA methodologies, conforming to ISO 14040 and 14044 standards (*29*). The functional unit is the dispensing of 1000 units of hot drinks from a drinks vending machine or dispenser in an office or factory environment. The cups' sizes were assumed 180 mL (6.1 oz), which arguably represents European communities moreso than American.

The study considered two reusable systems: a porcelain cup and saucer combination and an

earthenware mug. The one-way cups compared are thermoformed PS cups, lightweighted thermoformed PS cup inserts in a reusable cup holder, and PE-coated paper cups. As trending, the highest sensitivites are for energy use in washing, mass of the disposable cups, and number of uses before disposal or washing. The porcelain cup and saucer scenario assumes a centralized commercial-scale washing unit where the porcelain dishes are provided by the employer, while the earthenware mug scenario assumes handwashing with use of a kitchen boiler. Arguably, neither of these scenarios adequately represent average users and facilities.

In conclusion, the TNO report states very strongly the user-behavior dependency of environmental outcomes, stating that conclusiveness may only be answered with specific reference to the user's operating choices. Yet, a second part of the study's analysis called "shadow pricing," not in conformance with ISO standards, was applied concluding results "clearly point in the direction that disposable (coffee) drinking systems being the least environmentally burdening." The commissioning company, Stitching Disposables Benelux, and Plastics Europe have cited the report with headlines, "Single use Cups are the winners! from an environmental perspective" and "Single-use cups win every time!"(*64*, *65*).

The CML2 method employs the USES-LCA model for ecotoxicity potentials. While the method is thorough and rigorous, there are considerable uncertainties in ecotoxicity, as discussed by Huijbregts et al. (*66–68*), and these should be included in interpretation of LCA results. It should be noted that the largest contributor to the shadow price results for the earthenware mug is from the category Marine Aquatic Ecotoxicity Potential (MAEP), accounting for 33% of the shadow price. The uncertainty of the underlying impact assessment model was not addressed in communication of the conclusions of the shadow price method, though senstivity analyses were shown.

Moreso, in the same report is the following statement: "Ecotoxicity of metals, in particular, has been found not to be satisfactorily modelled by the CML2 method. Especially high and unrealistic scores often occurred for freshwater and marine ecotoxicity (*29*)." The statement is made in reference to the Apeldoorn Declaration, where experts agreed that speciation, persistence, es-

sentiality, bioavailability, characterization, compartments in multimedia model, and spatial aspects are important in these indicators and not modeled comprehensively enough for lowered uncertainty and applicability. The declaration states, "business or policy decisions should not without further discussion be made on the results of the currently available (deficient) methods for assessing eco-toxicity in LCIA." (*69*). The declaration makes other useful clarifications on how to approach inventory and impact assessments. Of note, it states, "LCA is designed to compare different products and systems and not to predict the maximal risks associated with single substances." Therefore, the final aggregated conclusions in application of the shadow pricing method are questionable in terms of a fair analyses of the relevant systems.

S.2.2 Popular literature

Interestingly, as recapped in ref *70*, at the workshop Hofstetter pointed out that environmental coverage in the mass media is more important than modeling since the coverage will influence how and to what extent we develop preferences.

Ref *14* recounts a local coffee shop's reference of Hocking's 1991 figures as justification for the small business' choice of polystyrene over paper cups. In consumer queries on the merits of disposable versus reusable cups in highly respected and widely circulated periodicals as "The Guardian" and "Chicago Tribune," Hocking's 1994 work is cited as recently as 2011 (*20–22*), though ref *21* defers conclusion to suggestions by a senior editor of the Natural Resources Defense Council after citing Hocking's oft-repeated figures.

Some sites bring to the discussion improvements in dishwasher efficiencies in the nearly 20 years passed (*23*, *24*). Ref *20* cites a Dutch study (discussed in the article as TNO report) finding "the energy burden of washing (a ceramic) cup even more significant (than Hocking's figures)." Ref *25* indicates email correspondence in 2007 with a concerned consumer and Professor Hocking, where he had provided the interested party his publications and is quoted as warning that a chipped mug at a church function is equivalent to the energy cost of 1,000 polystyrene foam cups.

In fall 2012, chemistry professor David Tyler has been giving interviews and talks also sharing

what seem to be counterintuitive insights on the reusable versus disposable cup issue (among others), calling the idea of ceramic mugs being environmentally better "basically an urban legend" and apparently also referring to Hocking's study or the TNO report, though the reports of his interviews and talks lack citation (a point that reader comments highlight at the online publication sites) (*71–73*).

A disposable cup company, Mirkem, has two references, summaries of Hocking's 1994 study and the TNO report, to support the use of single use drinking cups (*6*, *29*, *74*). At cup manufacturer Dart's website, on Environmental Questions and Answers page, there is a link to downloadable literature (*52*), where regarding reusable versus disposable cups, the only reference in this matter is a summary of Hocking's 1994 paper (*26*).

It is not uncommon for popular sites claiming reusable cups perform better than disposable cups to be criticized for lacking comprehensive data on wash cycles and then to be referred to Hocking's 1994 study (*27*). Such sites tend to compile some data making the case for reusable cups and occassionally refer to a study done by Starbucks in 2000 (discussed in Section S.2.1.4) (*75*, *76*). The references are not exhaustive, but representative of trends in popular and consumer literature.

S.3 TNO Comparison

First, efforts were made to duplicate the results of the TNO study for the disposable cups by aligning assumptions, boundaries, and inputs as described in the report, especially given the level of public reference the report has received. Since no uncertainty information was made available, the mean values reported were checked against the results of Monte Carlo analysis for the duplicated inventory. Nine of the ten reported means for the paper cups and five for thermoformed PS cups were within the 95% confidence intervals calculated. Figure S.2 shows the results of the duplicated study at the 180 mL size with the TNO results indicated. An extrapolation of the results to the 16 oz size is provided. A range of sensitivities are shown for the ceramic and glass cup results with

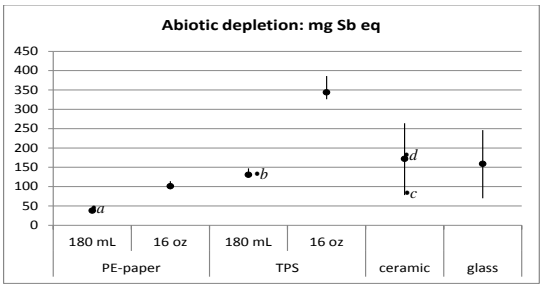
the TNO study results for the earthenware mug and porcelain cup and saucer indicated.

Taking the same approach as the TNO study, liquid packaging board (LPB) serves as a proxy inventory for paper cup base material. LPB is used in food packaging applications, and a detailed inventory is provided in the Ecoinvent database. A coating of 6.7% by mass of polyethylene is assumed. Nonetheless, this updated study assumes low density polyethylene coating while the TNO study assumed high density, which is not typically used in paper cup linings. Furthermore, the LPB inventory has aluminum foil production for embossing packages; this inventory component was removed in this study for lack of relevance to paper cup manufacturing. Also, since printing on either disposable cup is not in this analysis' scope, inventory components for printing process in LPB production were removed here as well.

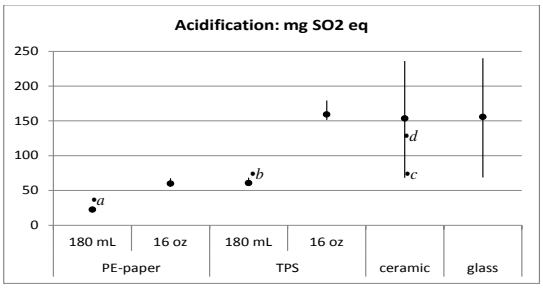
S.4 Midpoint Model Background

In presenting the expanded study results to include midpoint impacts, the CML, TRACI, and ReCiPe methods were selected. The CML method was released originally in 1992 with the original Dutch guide on LCA methodology and updated in 2001 after much development in the LCA community, including fate and exposure models for toxic releases based on USES-LCA (*66*, *77*, *78*). Its release was regarded as "a breakthrough in the scientific foundation of LCA methodology (*79*)." The baseline method had been well-received for policy and decision-support.

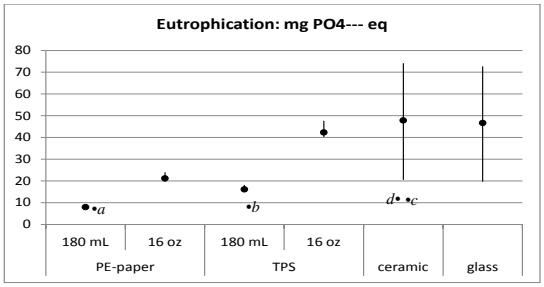
Following CML release was development of the US Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) for consistency with US policy and regulations (*80*, *81*). Bare et al. have provided a thorough discussion of midpoints, endpoints, damages, and areas of protection, which is recommended for further understanding of midpoint and endpoint methods (*82*). Most US practitioners had previously used the CML method (*81*). In TRACI, impact categories considered universal or traditional were included initially, while the human toxicity category was subdivided into carcinogens, non-carcinogens, and respiratory effects; smog formation was kept independent and not modeled aggregately into human



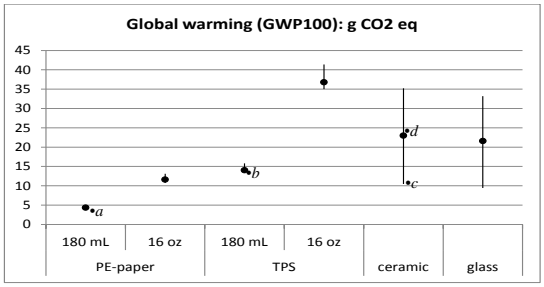
(a) Abiotic depletion potential.



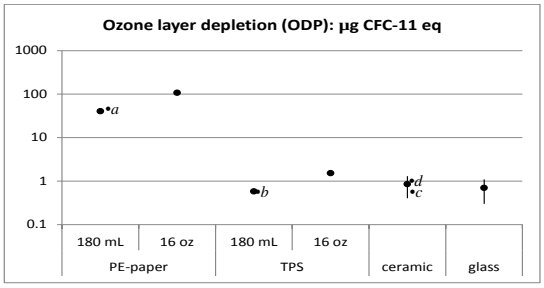
(b) Acidification potential.



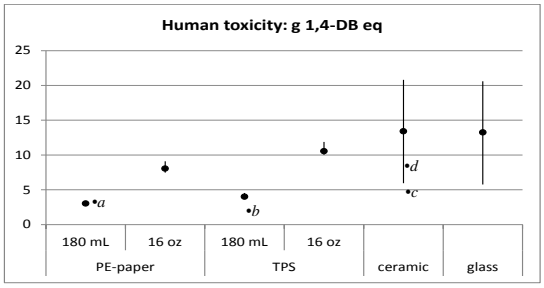
(c) Eutrophication potential.



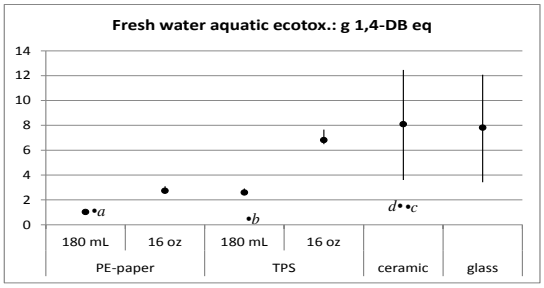
(d) Global warming potential.



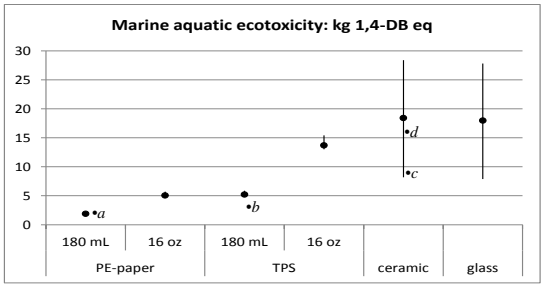
(e) Ozone depletion potential.



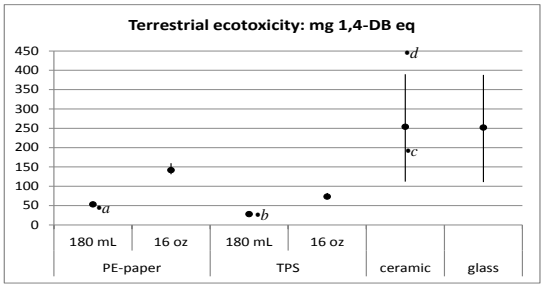
(f) Human toxicity potential.



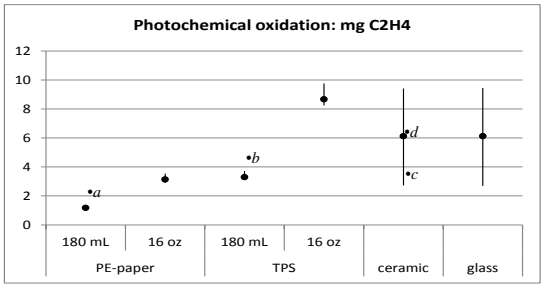
(g) Freshwater aquatic ecotoxicity potential.



(h) Marine aquatic ecotoxicity potential.



(i) Terrestrial ecotoxicity potential.



(j) Photochemical oxidation potential.

Figure S.2: CML2 results (per use). Disposable cup results are reproduction of the TNO study (180 mL) with extension to larger cups (16 oz). TNO results are superimposed, where *a* is the reported figure for the 180 mL paper cup, *b* is for the 180 mL thermoformed PS cup, *c* is for the porcelain cup and saucer set, and *d* is for the earthenware mug.

health categories (*81*). Models for ozone depletion and global warming are global in perspective, while the human health categories, smog, eutrophication, acidification, and ecotoxicity impacts are modeled for US specificity, with capability to model some indicators regionally.

In 2000, a workshop of 50 LCA specialists was held to come to consensus on the strengths and weaknesses of baseline methods like CML and methods like Eco-indicator 99, which focus on impacts using the endpoint approach (*70*, *79*). The developers of TRACI, CML, and (later) ReCiPe were included in the workshop, which helped to draw on the experiences of specialists to determine how best to communicate LCA results transparently, robustly, and effectively, whether midpoint, endpoint, weighting, valuation, normalization and combinations of these approaches to impact assessment and interpretation had more or less merit. The ReCiPe method since developed is regarded as the next generation of LCA process modeling for a comprehensive approach to midpoint and endpoint characterization to assess impact at different places in the environmental effect chain, born out of and co-developed by originators of two different impact assessment models: Ecoindicator 99 (endpoint) and the LCA Guide 2001 (CML midpoint). ReCiPe models include updates to the fate, exposure, effect and damage part of USES-LCA, referred to as USES-LCA 2.0 (*79*). Table S.2 shows the tools used in the iteration of the analysis.

Table S.2: LCA tools employed

SimaPro v7.2.4 with Ecoinvent v2
cumulative energy demand (CED)
CML 2 baseline and extended v2.05*
TRACI2 v3.03
ReCiPe(H): Midpoint v1.04**

* based on CML v3.1 spreadsheet (November 2009)

S.5 Additional Modeling Information

Table S.3 is a summary of the cup mass, packaging, and end-of-life values. The disposable cup masses are from the Franklin Associates study (*28*, *62*). Low values for reusable cups are from Hocking's 1994 study (*6*). To get a value that reasonably captures the heaviest typical 16 oz

ceramic or glass cup, retail samples were weighed during the study period with the maximum sample value recorded. Midpoint values are the average of these two endpoints. It has been found that cup mass in this range has little effect overall relative to energy consumption in washing. Ceramic mugs were chosen in part due to higher impact than comparable reusable cups such as glass and durable plastics designed for reuse. Packaging assumptions are conservative and were

Table S.3: Cup manufacture and end-of-life assumptions

	mass, *g*			
material	low	mid	high	end-of-life treatment
EPS[a]	4.4	4.7	5.0	landfill (88.3 %); incinerate (11.7 %) with energy recovery
PE-paper[b]	12.3	13.3	15.0	landfill (88.3 %); incinerate (11.7 %) with energy recovery
ceramic	292	496	700	landfill (100 %)
glass	199	440	680	landfill (100 %)
corrugated cardboard	% product mass[c]			recovery (76.6 %); 50% avoided production

[a] expanded polystyrene
[b] polyethylene-coated paperboard
[c] 10% and 20% for PE-paper and EPS, respectively

determined through a survey of shipping weights for 1000 units per box. By subtracting the cups' mass from the shipping mass, 16 oz EPS cups were found to have 20 to 27% added mass while paper cups had 11 to 14% added mass, indicating shipping boxes ranging from 2 to 5 kg. These values are much lower than the masses determined in the Franklin Associates study on EPS and paper cups (*28*). Shipping pallets, lids, and sleeves were not included in the analysis.

S.6 Grid Information and Cumulative Energy Demand (CED)

Figure S.3 provides CED results according to power generation type. This is more insightful for considering climate change or ozone depletion, for example, in regions with higher coal or nuclear power generation in contrast to those with higher renewable energy penetration. Table S.4 gives the utility subregion names along with the acronyms used in reporting. Discussion regarding interstate transmission and regional groups is in the main article. Figure S.4 provides the eGrid 2009 figures for utility mixes and a reference map (*83*).

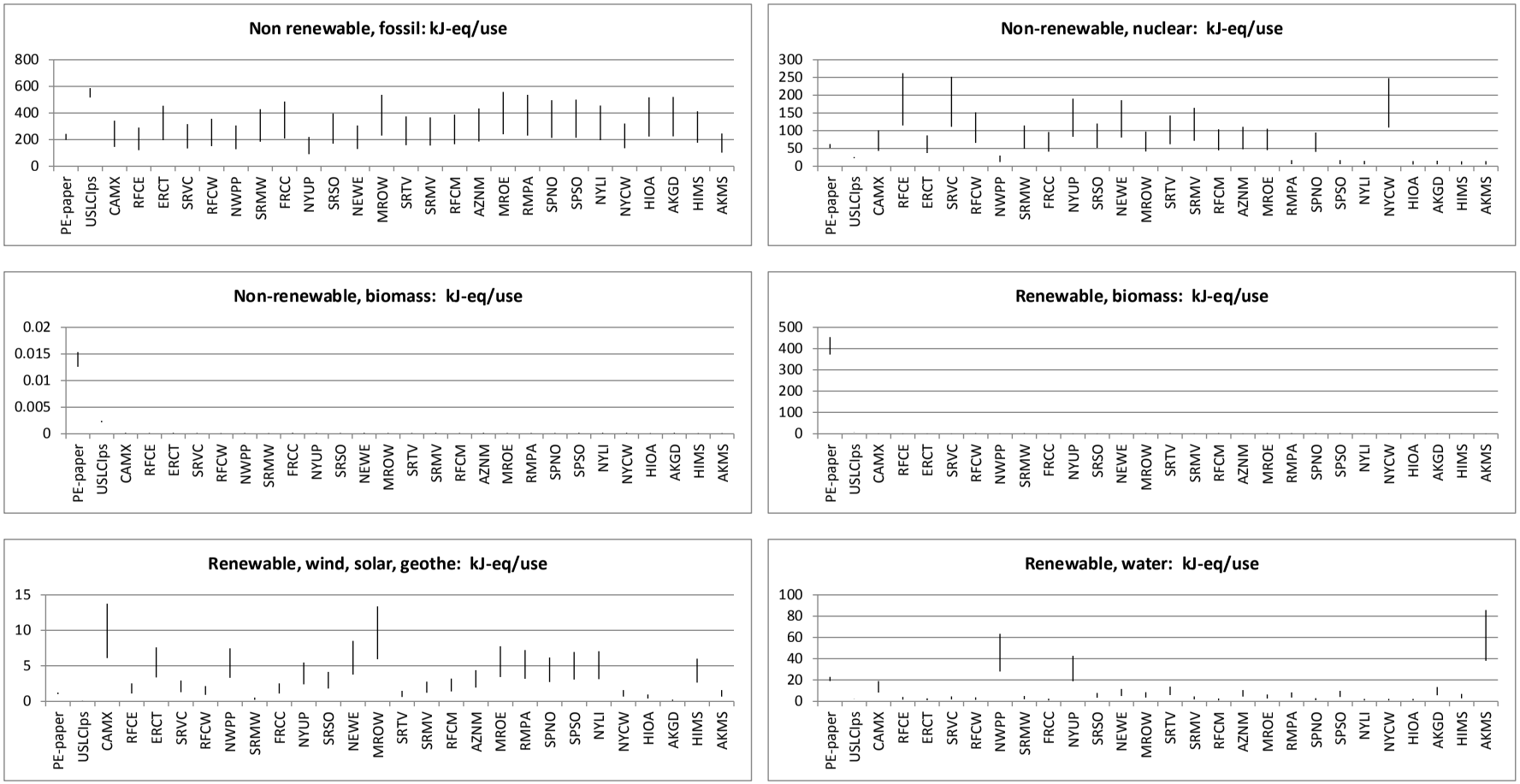
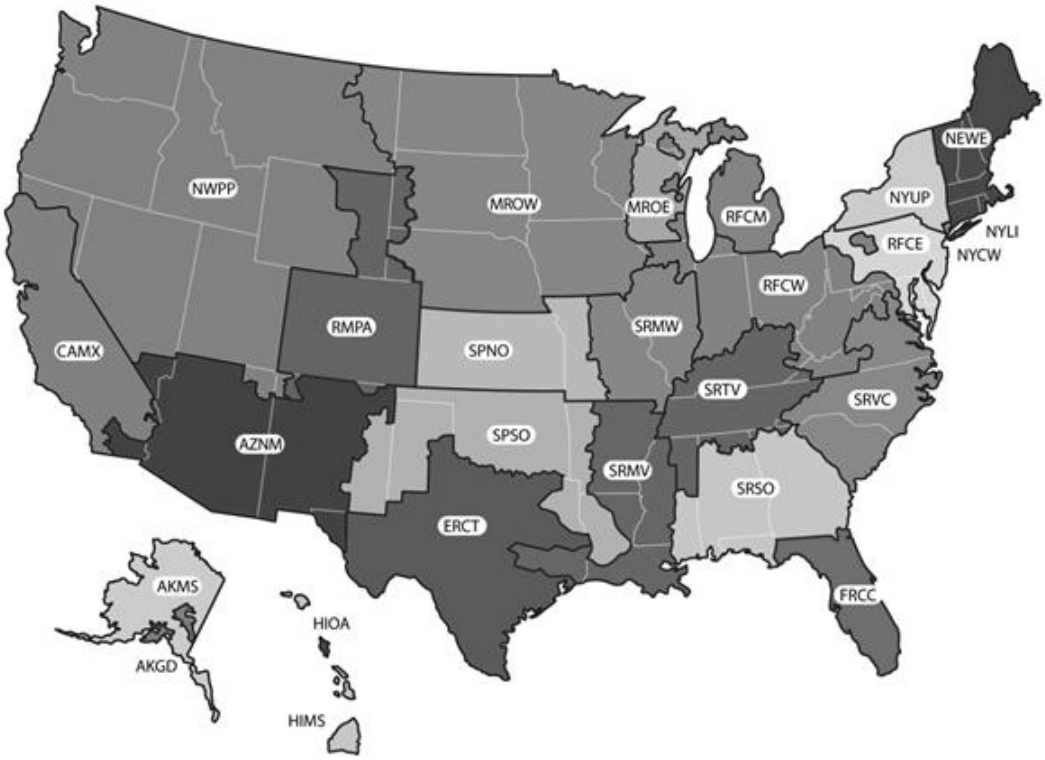


Figure S.3: Cumulative energy demand disaggregated across six types: fossil, nuclear, non-renewable and renewable biomass, hydroelectric power, and other renewable sources - as described in ref (*84*).

Table S.4: US regional utilities

Abbreviation	**Council Name**
SRMW	SERC Reliability Corporation - Midwest
SRMV	SERC Reliability Corporation - Mississippi Valley
SRSO	SERC Reliability Corporation - South
SRTV	SERC Reliability Corporation - Tennessee Valley
SRVC	SERC Reliability Corporation - Virginia/Carolina
CAMX	Western Electricity Coordinating Council - California
NWPP	Western Electricity Coordinating Council - Northwest
RMPA	Western Electricity Coordinating Council - Rocky Mountain region
AZNM	Western Electricity Coordinating Council - Arizona and New Mexico
RFCE	Reliability First Corporation - East
RFCM	Reliability First Corporation - Michigan
RFCW	Reliability First Corporation - West
NYLI	Northeast Power Coordinating Council - New York: Long Island
NEWE	Northeast Power Coordinating Council - New England
NYCW	Northeast Power Coordinating Council - New York City/Westchester
NYUP	Northeast Power Coordinating Council - New York: Upstate
ERCT	Electric Reliability Council of Texas
FRCC	Florida Reliability Coordinating Council
MROE	Midwest Reliability Organization - East
MROW	Midwest Reliability Organization - West
SPNO	Southwest Power Pool - North
SPSO	Southwest Power Pool - South
HIMS	Hawaiian Islands Coordinating Council - remaining parts of Hawai'i
HIOA	Hawaiian Islands Coordinating Council - Oahu
AKGD	Alaska Systems Coordinating Council - South/Central Alaska
AKMS	Alaska Systems Coordinating Council - remaining parts of Alaska



Region	Subregion	Renew-able	Hydro-electric	Nuclear	Fuel oil	Natural Gas	Coal
SERC	SRMW	0.2	1.8	17.1	0.1	1.0	79.8
	SRMV	1.9	1.7	26.0	1.5	45.1	22.7
	SRSO	2.9	4.1	18.1	0.3	22.3	52.2
	SRTV	0.9	8.6	22.1	0.9	8.6	58.8
	SRVC	2.0	1.6	41.3	0.6	9.0	45.1
WECC	CAMX	10.1	12.7	14.9	1.4	53.0	7.3
	NWPP	5.4	46.5	2.5	0.3	15.2	29.8
	RMPA	5.2	4.3	0.0	0.0	22.6	67.8
	AZNM	3.1	6.1	16.5	0.1	35.7	38.6
RFC	RFCE	1.7	1.2	43.0	0.7	17.1	35.4
	RFCM	2.2	0	15.3	0.4	9.5	72.0
	RFCW	1.4	0.8	23.6	0.4	3.5	69.9
NPCC	NYLI	5.1	0	0.0	13.0	77.3	0.0
	NEWE	6.2	7.0	29.8	1.5	42.0	11.9
	NYCW	1.0	0	40.8	1.8	55.9	0.0
	NYUP	3.9	30.8	30.6	0.9	18.9	14.5
ERCOT	ERCT	5.5	0.2	12.3	1.1	47.8	33.0
FRCC	FRCC	1.7	0	14.0	4.4	54.8	23.7
MRO	MROE	5.6	2.7	15.3	2.4	5.0	68.9
	MROW	9.8	4.4	13.9	0.2	2.4	69.1
SPP	SPNO	4.4	0.1	13.5	0.3	7.8	73.8
	SPSO	5.0	5.5	0	0.2	33.9	55.2
HICC	HIMS	17.3	3.7	0	69.9	0	2.0
	HIOA	2.2	0	0	77.6	0	18.0
ASCC	AKGD	0	8.5	0	13.7	66	11.8
	AKMS	1.0	63.9	0	31.3	3.9	0

Figure S.4: eGrid 2009 subregional utility mixes (percentage) (*83*)

S.7 Number of Uses

Previous studies focused on a breakeven number of uses (*6*, *30*, *57–59*), but all agree user behavior and washing energy are dominant in the impact for reusable cups. While number of uses is non-trivial, it has been shown that figures as Hocking's, claiming more than 1,000 uses are necessary to break even, are based on myopic environmental assessments that are neither temporally nor geographically relevant. To address any concern over breakeven points, Table S.5 is provided, giving the approximate number of uses where the ceramic mug has similar or less climate change impact than the 16oz EPS cup. The case has been made in the main article for the mean as a

Table S.5: Approximate number of uses for equal or better climate change impact.

Region	Subregion	2004AP	2007AP	2013MC	2013ES	2013BAT
SERC	SRMW	na	na	na	550	110
	SRMV	160	130	120	110	70
	SRSO	670	270	210	190	90
	SRTV	580	260	210	180	90
	SRVC	170	140	120	110	80
WECC	CAMX	110	100	90	90	70
	NWPP	120	100	100	90	70
	RMPA	na	na	na	na	120
	AZNM	420	230	190	170	80
RFC	RFCE	140	110	110	100	70
	RFCM	na	na	490	360	100
	RFCW	na	440	300	240	90
NPCC	NYLI	230	160	160	130	80
	NEWE	110	90	90	90	70
	NYCW	100	90	90	80	70
	NYUP	80	160	70	70	60
ERCOT	ERCT	490	250	200	170	90
FRCC	FRCC	na	350	250	210	90
MRO	MROE	na	na	na	na	130
	MROW	na	na	na	na	130
SPP	SPNO	na	na	na	na	120
	SPSO	na	na	na	na	140
HICC	HIMS	290	190	160	140	80
	HIOA	na	na	na	610	110
ASCC	AKGD	na	390	280	230	90
	AKMS	80	80	70	70	60

measure of central tendency for climate change. Thus, Table S.5 was constructed by comparing sample means for increments of 10 uses.

S.8 Statistical methods

The mean of a lognormal distribution is $\mu_{LN} = e^{\mu_n + \sigma_n^2/2}$ with variance $\sigma_{LN}^2 = \left(e^{\sigma^2} - 1\right) e^{2\mu_n + \sigma_n^2}$, where unbiased estimators for μ_{LN} can be constructed using maximum likelihood estimators of $\hat{\mu}_n$ and unbiased estimators of σ_n^2, shown in Equation (Eq. (1b)).

$$\hat{\mu}_n = \frac{1}{n}\sum_{i=1}^{n} \ln X_i \tag{1a}$$

$$S_n^2 = \frac{1}{n-1}\sum_{i=1}^{n} (\ln X_i - \hat{\mu}_n)^2 \tag{1b}$$

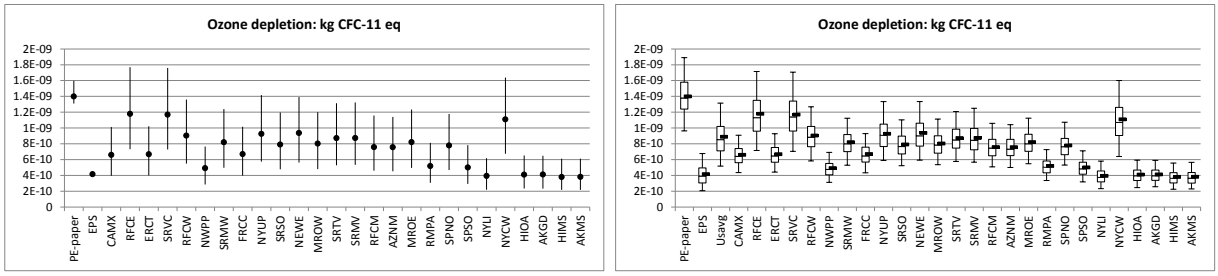
This background is described thoroughly with respect to construction of the Z-score by Zhou et al. (*85*).

In SimaPro, where an approximately lognormal distribution may result as in this study, the mean and standard deviation reported in the Monte Carlo analysis are not the log-transformed parameters. Thus, using the upper bounds (UB) and lower bounds (LB) of reported confidence intervals reported, the Cox method for estimating confidence intervals (*86*), shown in Equation (Eq. (2)), is applied to to calculate the estimators, $\hat{\mu}_y$ and S_y^2:

$$LB = \exp\left(\hat{\mu}_n + \frac{S_n^2}{2} - Z_{\alpha/2}\sqrt{\frac{S_n^2}{n} + \frac{S_n^4}{2(n-1)}}\right) \tag{2a}$$

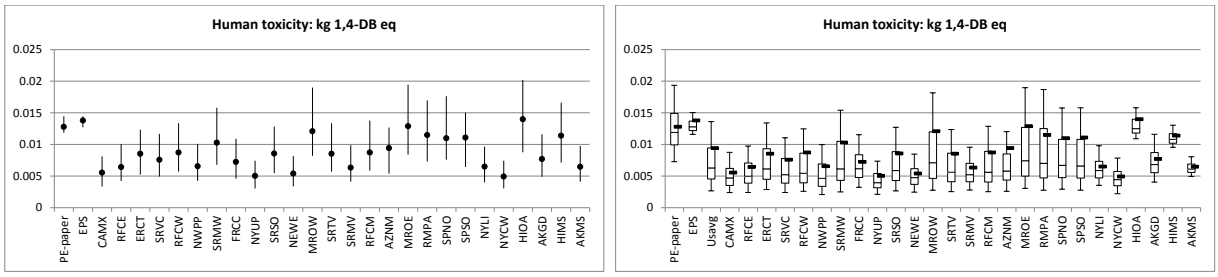
$$UB = \exp\left(\hat{\mu}_n + \frac{S_n^2}{2} + Z_{\alpha/2}\sqrt{\frac{S_n^2}{n} + \frac{S_n^4}{2(n-1)}}\right) \tag{2b}$$

Figure S.5 to Figure S.17 demonstrate measures of central tendency, discussed in the main article, where the sensitivity plot show a range of scenario uncertainties from assumptions in cup size and energy and user efficiencies. The circle is the mean from one set of assumptions and correlates to the sideways hash on the box plots with underlying distribution.



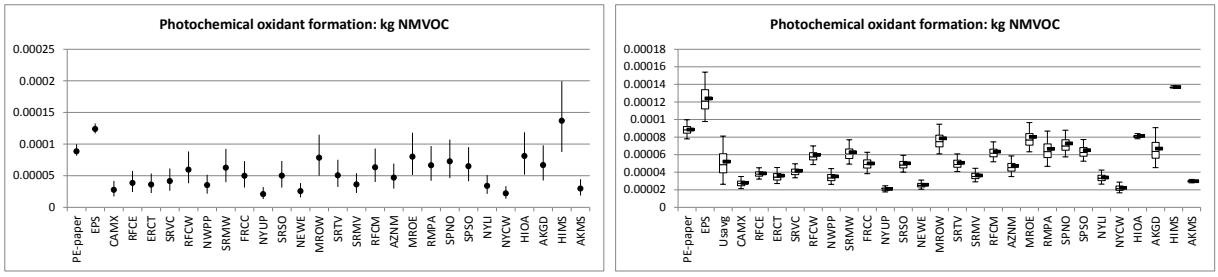
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.5: Ozone depletion (OD); kg CFC-11-eq per use.



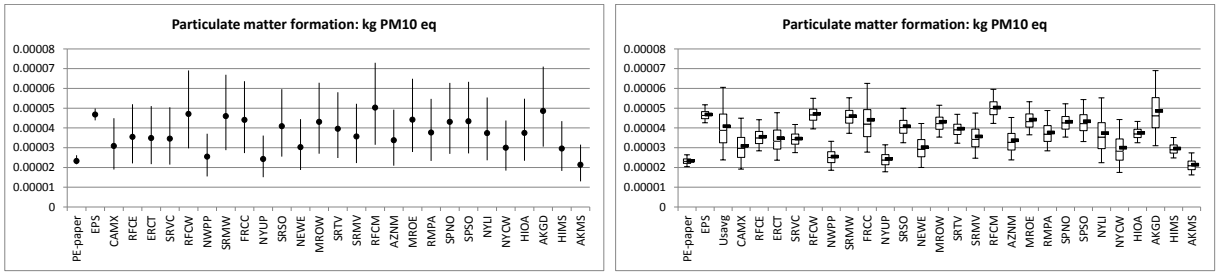
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.6: Human toxicity (HT); kg 1,4-DB-eq per use.



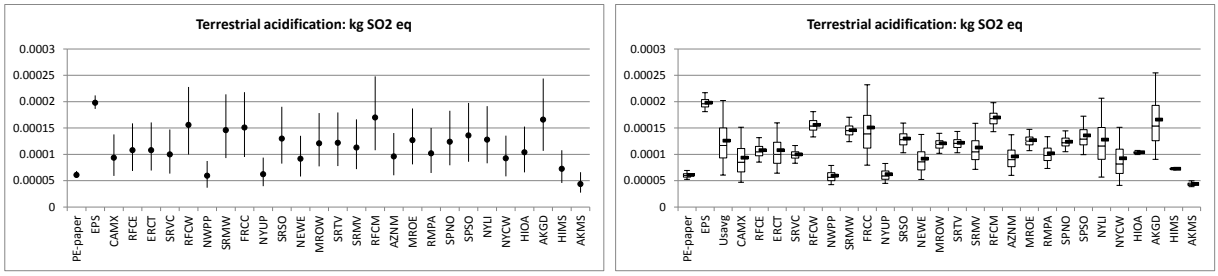
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.7: Photochemical oxidant formation (PCOP).



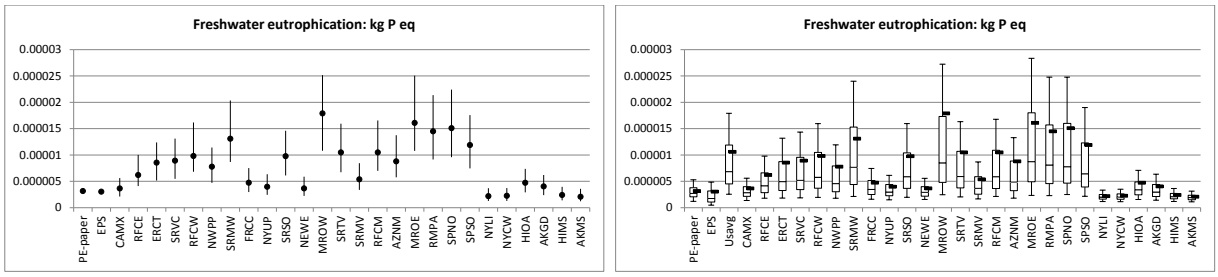
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.8: Pariculate matter formation (PM).



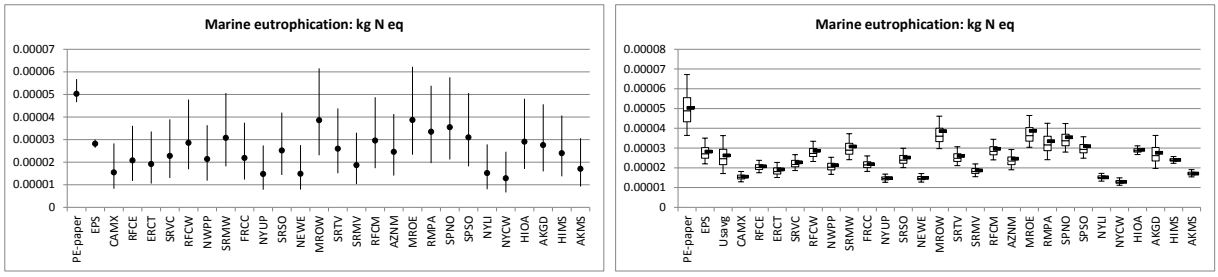
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.9: Terrestrial acidification (TA); kg SO_2-eq per use.



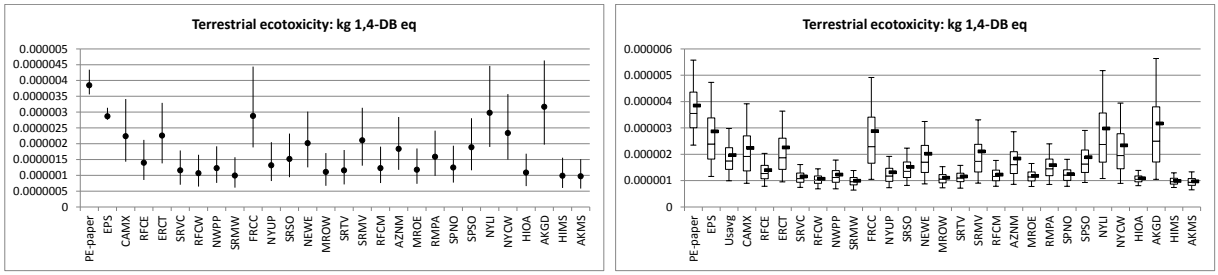
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.10: Freshwater eutrophication (FE); kg P-eq per use.



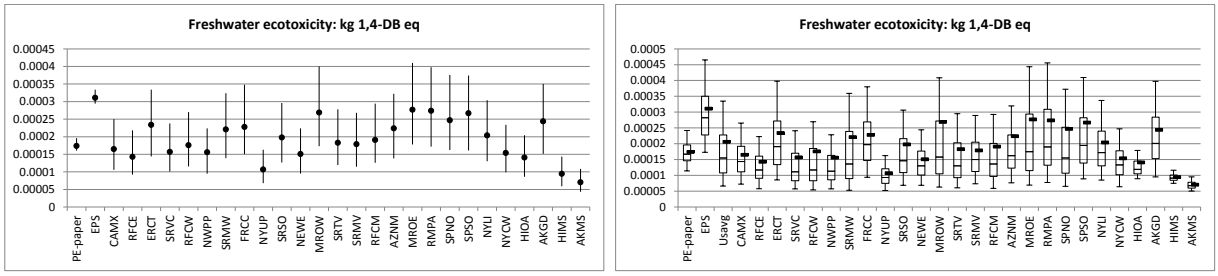
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.11: Marine eutrophication (ME); kg N-eq per use.



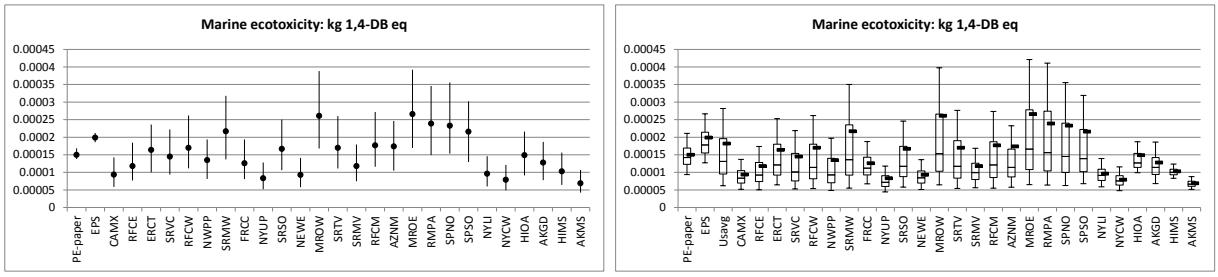
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.12: Terrestrial ecotoxicity (TET); kg 1,4-DB-eq per use.



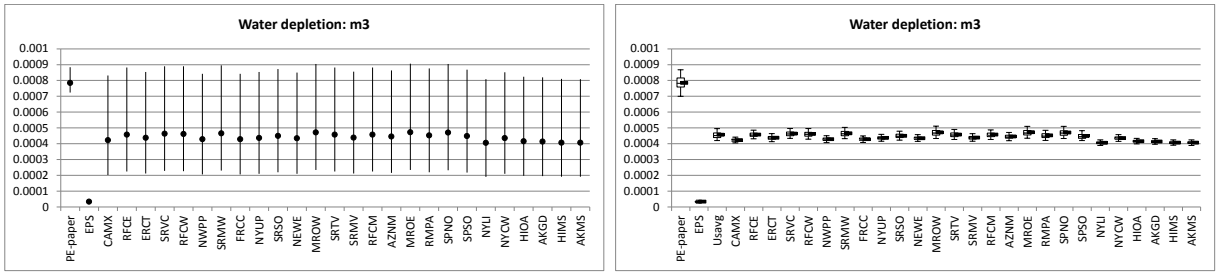
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.13: Freshwater ecotoxicity (FET); kg 1,4-DB-eq per use.



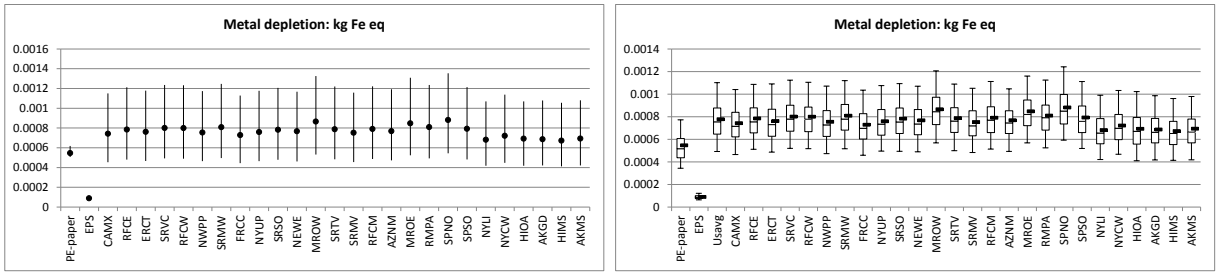
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.14: Marine ecotoxicity (MET); kg 1,4-DB-eq per use.



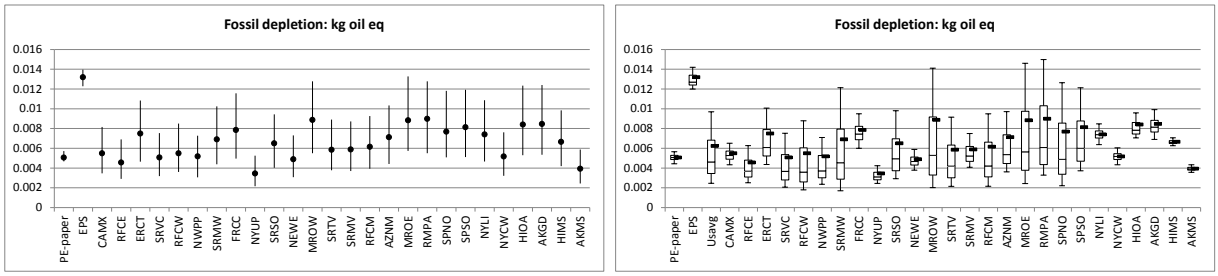
(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.15: Water depletion (WD); m^3 per use.



(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.16: Metal depletion (MD); kg Fe-eq per use.



(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Figure S.17: Fossil depletion (OD); kg oil-eq per use.

Figure S.18 to Figure S.28 are the remaining midpoints compared with climate change and particulate matter in the main article. Land use was considered outside of the study scope. Water depletion, which correlated not to energy use but from tap water draw, and metal depletion, both discussed in the main article, are shown in Figure S.29.

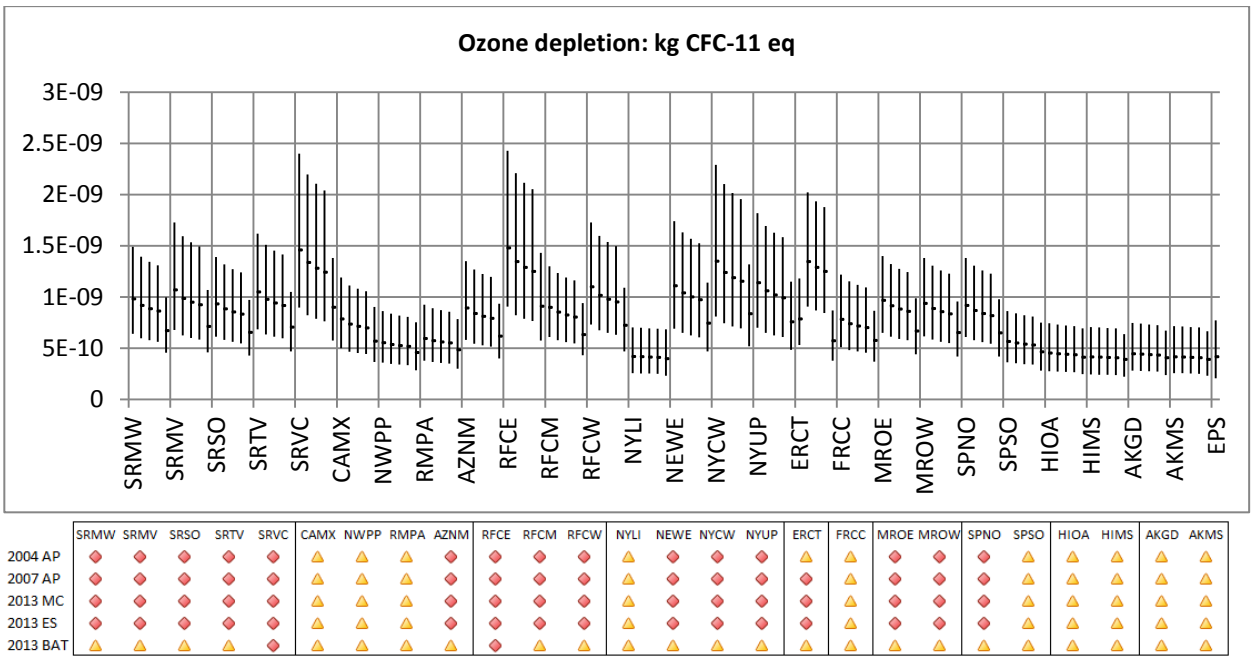


Figure S.18: Results across five models for ozone depletion (kg CFC-11-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

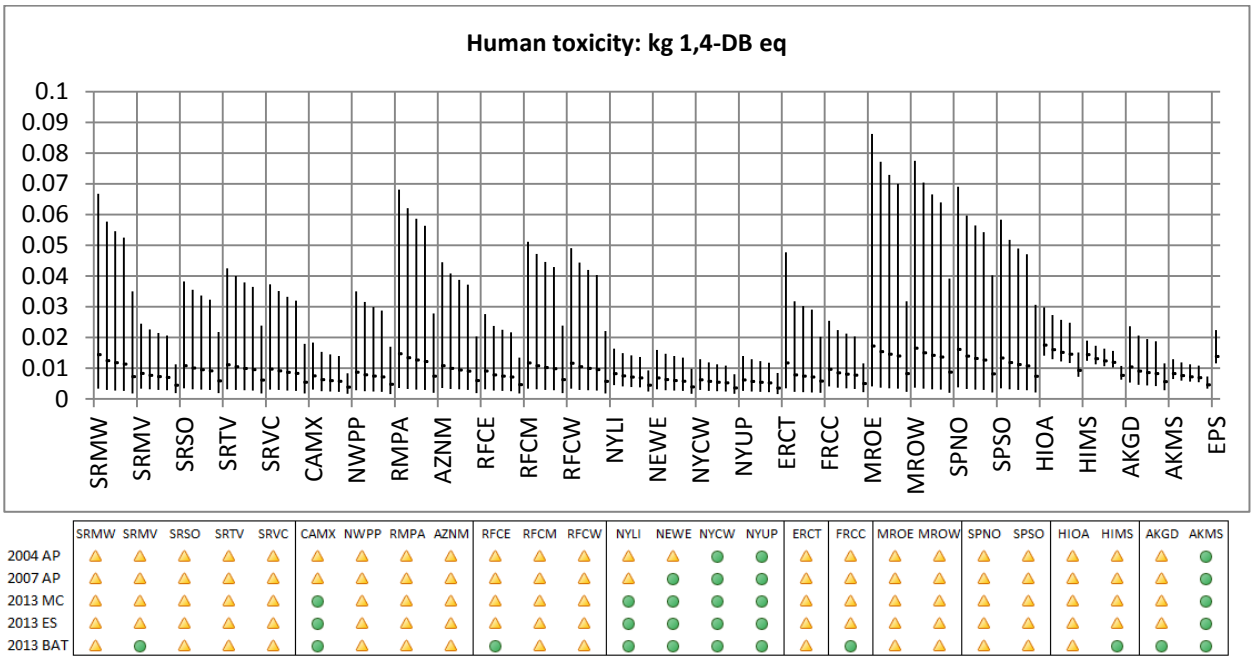


Figure S.19: Results across five models for human toxicity (kg 1,4-DB-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

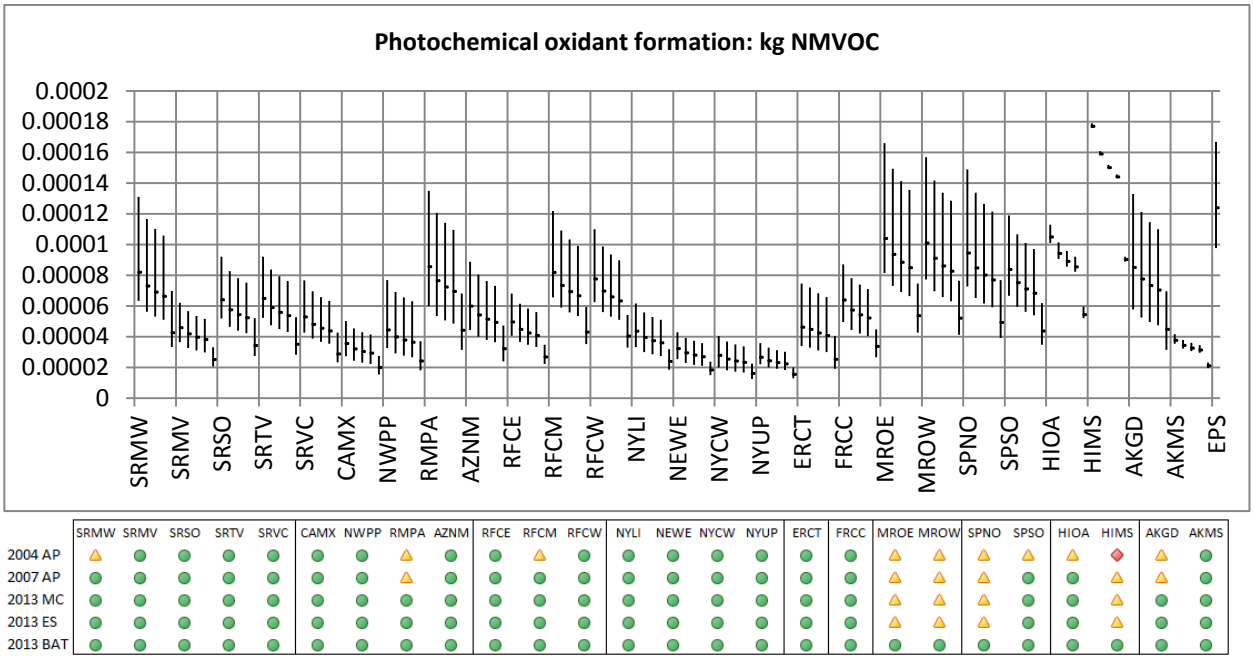


Figure S.20: Results across five models for photochemical oxidant formation (kg NMVOC-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

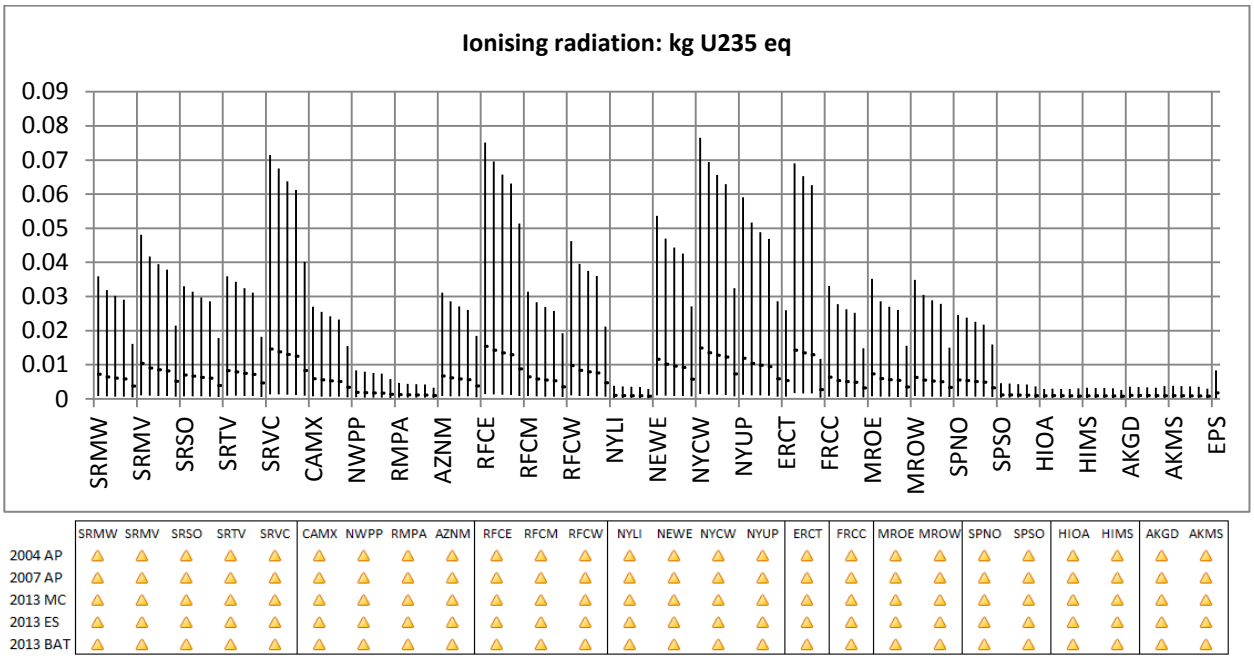


Figure S.21: Results across five models for ionising radiation (kg U235-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

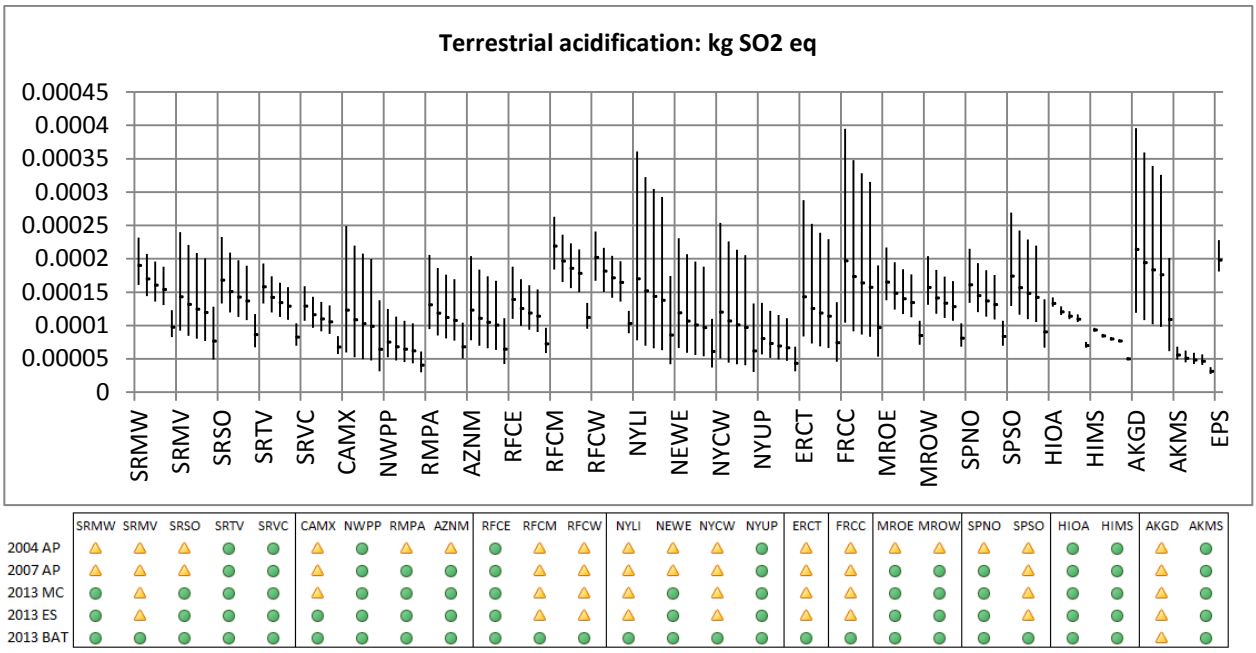


Figure S.22: Results across five models for terrestrial acidification (kg SO_2-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

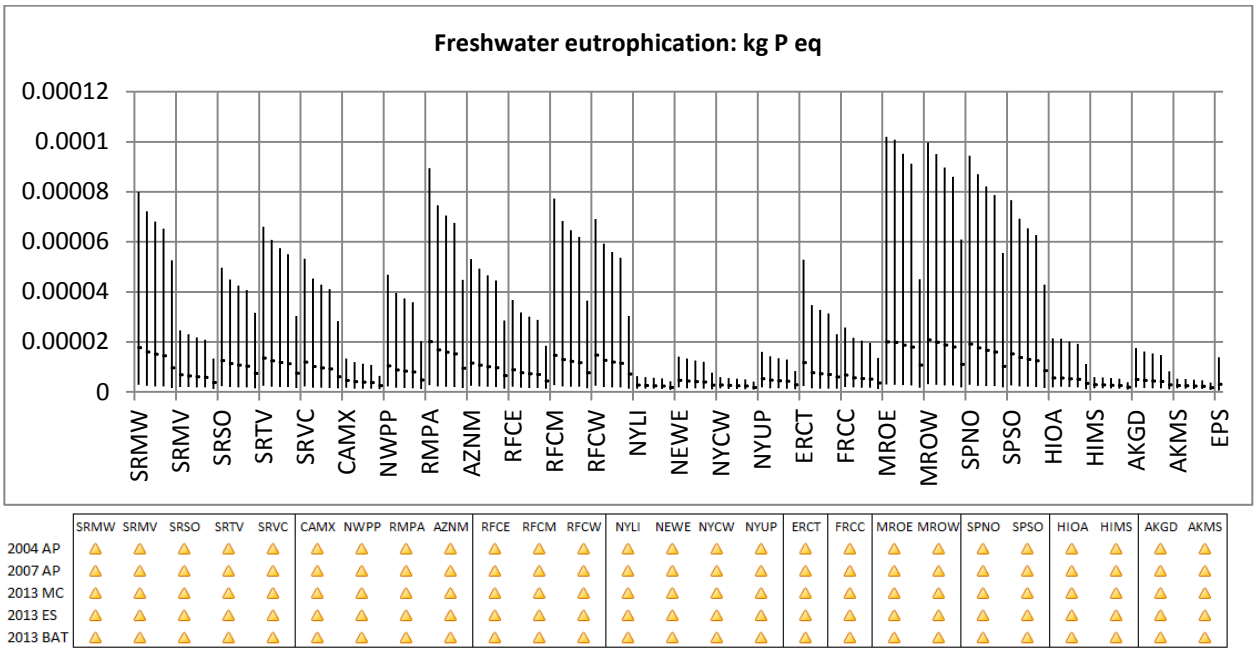


Figure S.23: Results across five models for freshwater eutrophication (kg P-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

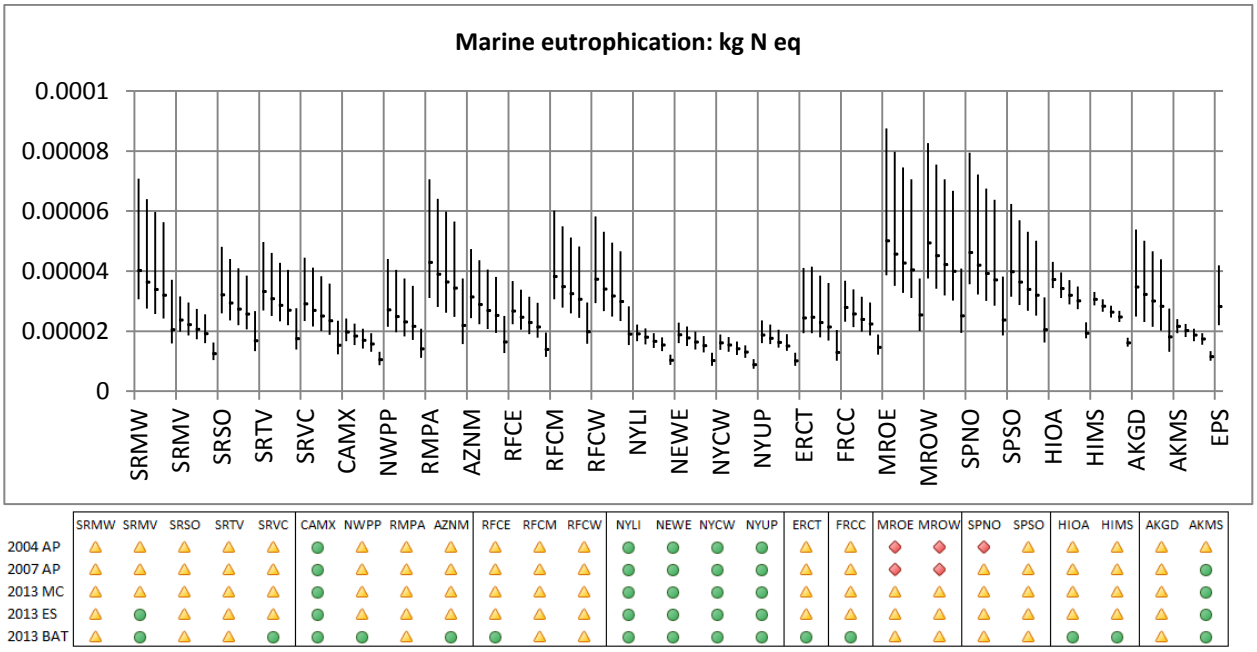


Figure S.24: Results across five models for marine eutrophication (kg N-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

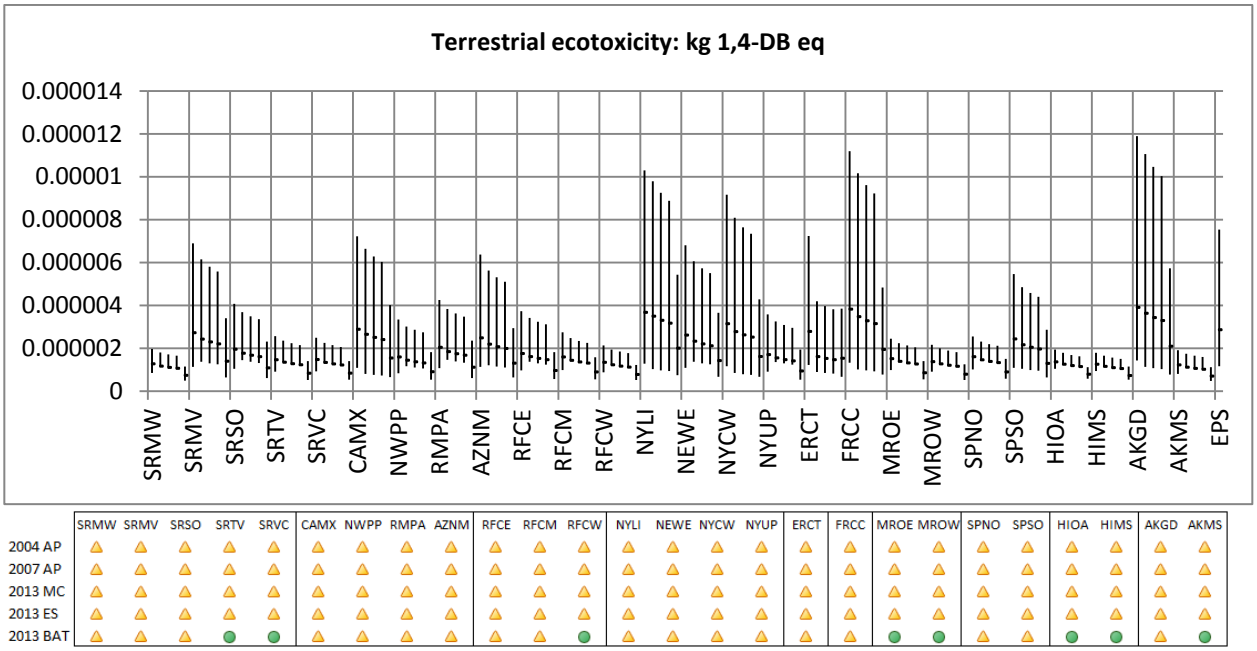


Figure S.25: Results across five models for terrestrial ecotoxicity (kg 1,4-DB-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

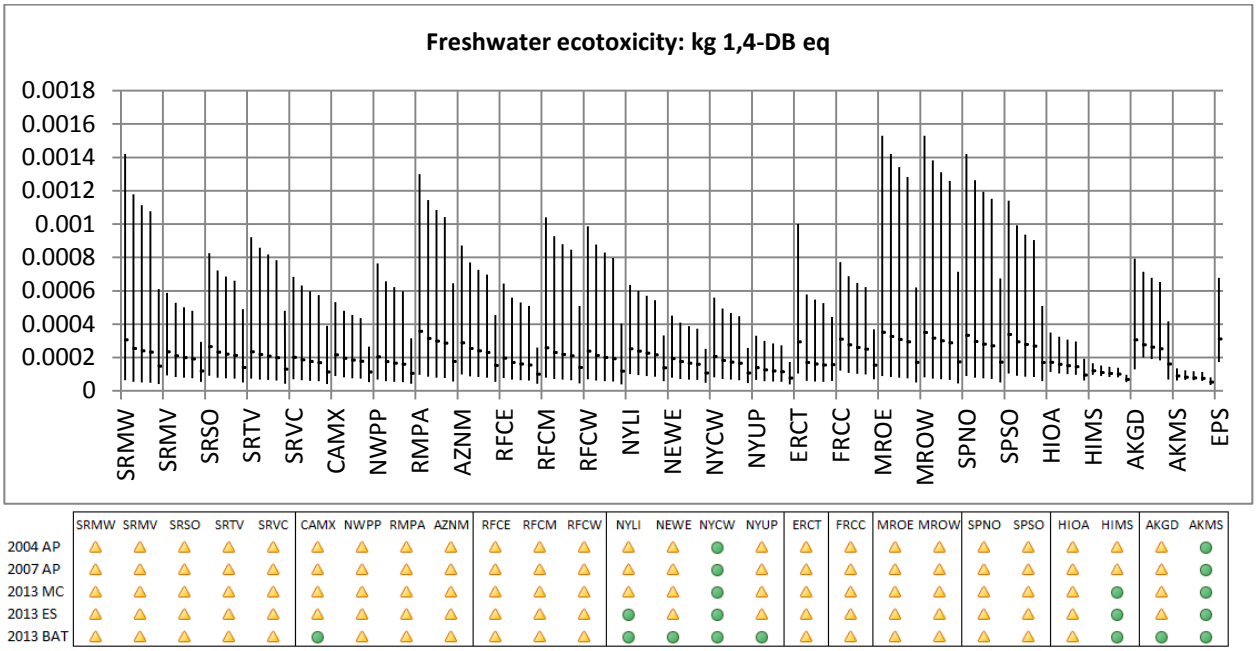


Figure S.26: Results across five models for freshwater ecotoxicity (kg 1,4-DB-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

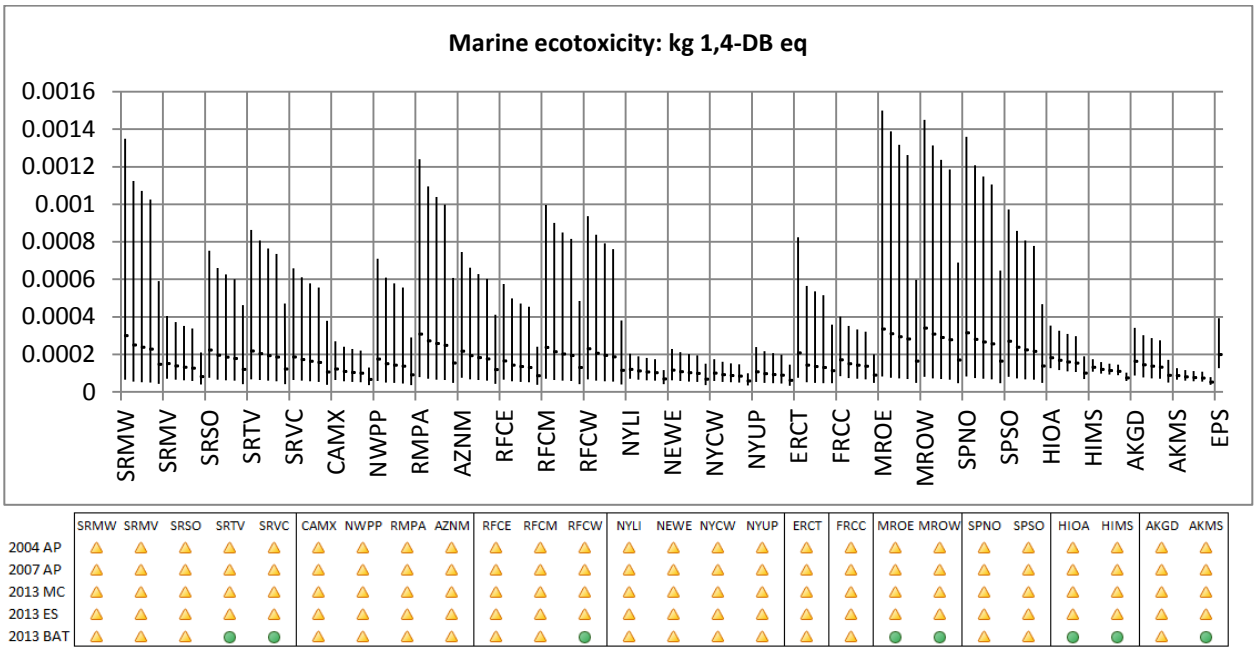


Figure S.27: Results across five models foR marine ecotoxicity (kg 1,4-DB-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

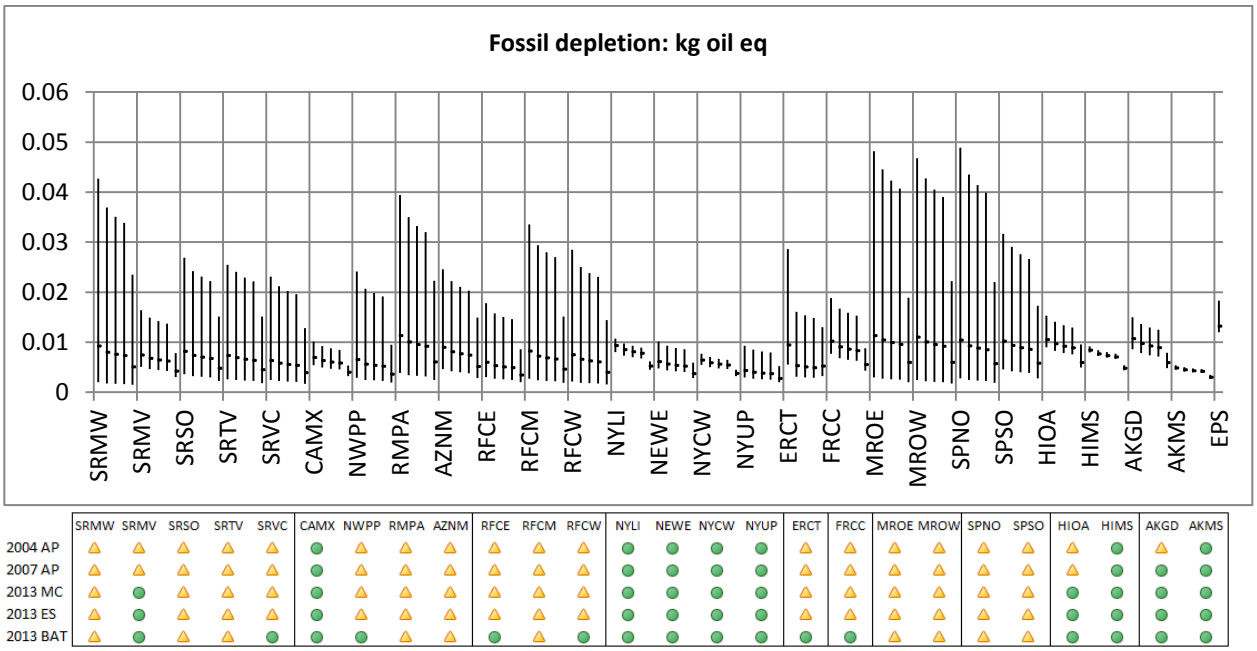


Figure S.28: Results across five models for fossil depletion (kg oil-eq per use): Mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions.

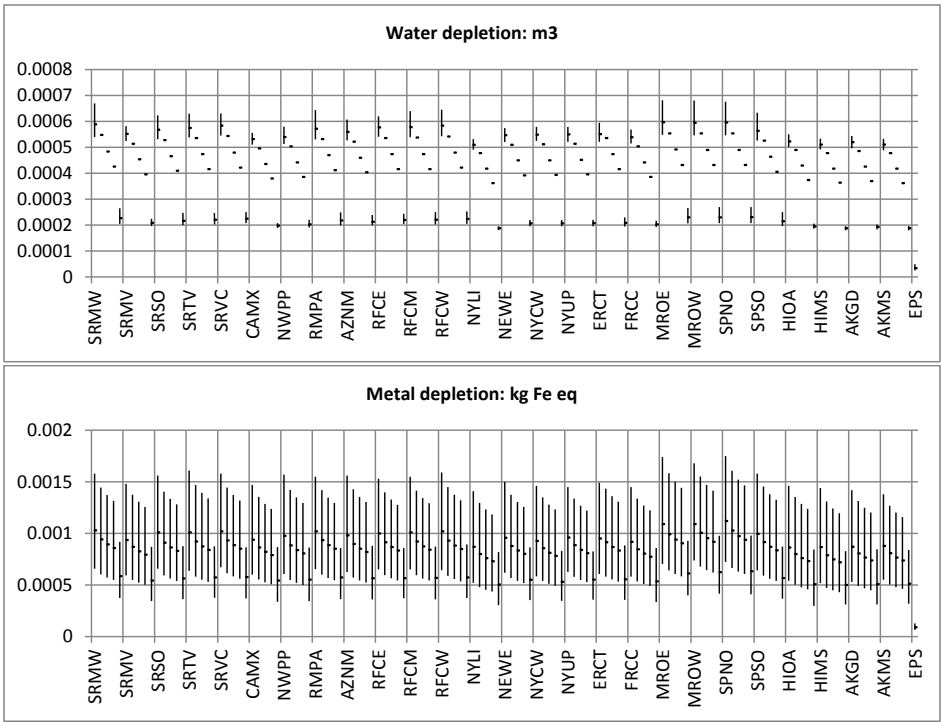


Figure S.29: Results across five models for water depletion (m^3 per use) and metal depletion (kg Fe-eq per use)

S.9 Extensions

To close the analysis, it was necessary to investigate implications of recent shifts in power generation, discussed in the main article. In Figure S.30, the 2009 eGrid score is shown alongside the score for the Energy Information Administration end of 2012 scenario (*87*). Also shown is the scenario of two uses of the ceramic mug for every wash on average. There are implicit assumptions regarding upstream natural gas production through hydraulic fracturing. Preliminarily, the 2012 inventory reflects conventional natural gas developments and has not factored benefits or drawbacks in comparison to rapidly developing policy and technology surrounding shale gas plays in the United States. The region SRMW was a focus as it has shown a marked changed in the grid mix with a decrease of approximately seven percentage points in coal-fired grid percentage and an increase in natural gas and renewable energy by five and one percentage points, respectively.

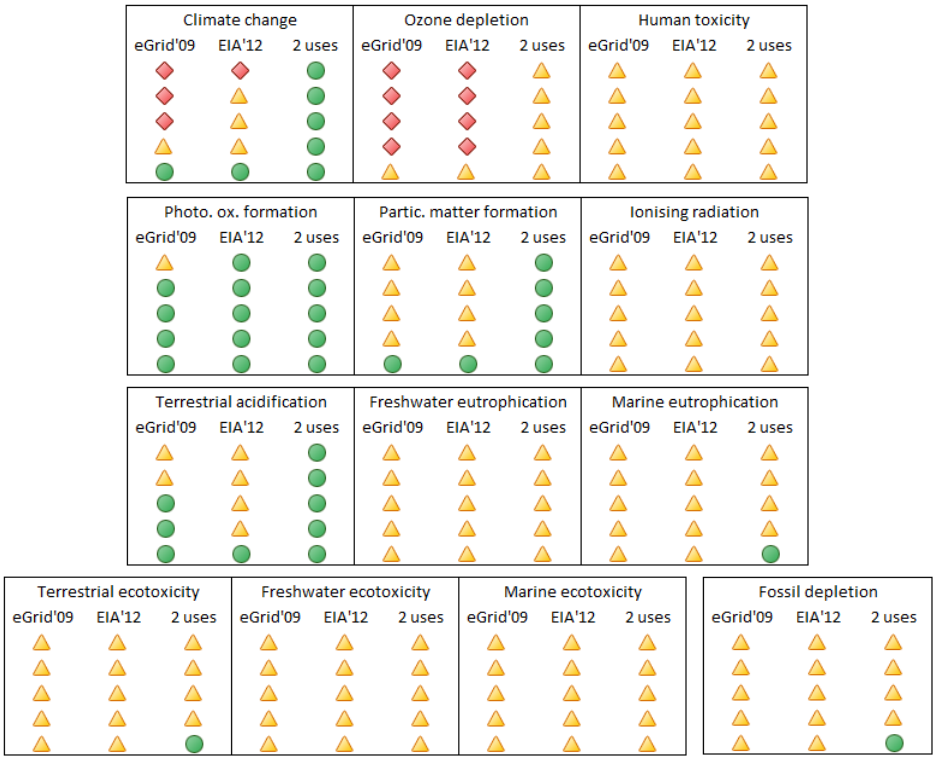


Figure S.30: Extension to SRMW: eGrid 2009 = basis scenario (*83*), EIA'12 = 2012 scenario (*87*), 2 uses = two uses per wash

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