Exploring Sustainability Research in Computing: Where we are and where we go next

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ABSTRACT
This paper develops a holistic framework of questions which seem to motivate sustainability research in computing in order to enable new opportunities for critique. Analysis of systematically selected corpora of computing publications demonstrates that several of these question areas are well covered, while others are ripe for further exploration. It also provides insight into which of these questions tend to be addressed by different communities within sustainable computing. The framework itself reveals discursive similarities between other existing environmental discourses, enabling reflection and participation with the broader sustainability debate. It is argued that the current computing discourse on sustainability is reformist and premised in a Triple Bottom Line construction of sustainability. A radical, Quadruple Bottom Line alternative is explored as a new vista for computing research.

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Sustainability, critical reflection, discourse

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
There have been a number of surveys on sustainability appearing in the last five years in the computing community. Some of these have focused tightly on a particular approach or orientation, such as eco-feedback [26] and persuasion [12], or alternative, emerging possibilities for interacting with energy [66]. Others have explored the various computing outputs within a particular sub-community, e.g. 'Sustainable HCI' [20, 30] or 'Green IT' [60], to reflect on future directions for research. Our work explores the computing contribution to sustainability *as a whole*. Our analysis reveals that despite a historical lack of communication between the human-centered and engineering communities within computing, there is considerable overlap in areas of interest.

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Nothing has even dented the curve of exponential growth in carbon emissions since 1850 [5, 44], despite the efforts of many disciplines (computing included). Bearing this in mind, it makes sense to consider alternative approaches to the sustainability problem. In this paper, we use Dryzek's classifications [22] of environmental discourses to contextualize computing's understanding of, and contribution to, 'sustainability'. We combine this with a framework built around ten motivating questions that underpin sustainability research in computing, in order to reflect upon the possibilities for novel research inspired by alternative notions of sustainability not currently explored in computing.

We base our observations about our framework of motivating questions within this wider community, and what it means for the future of computing, on two corpora: the top one hundred most cited papers in computing related to sustainability ('Top 100'), and a collection of 122 sustainability-related papers published in the last three years in UbiComp and CHI ('Recent'). Unlike prior surveys, our Top 100 corpus provides a metric-based indication of where focus in computing has actually laid, as indicated by the acknowledgement paid by subsequent authors (i.e. number of citations). A significant number (51%) of the Top 100 papers are from the UbiComp/HCI community. The Recent corpus covers the period since the DiSalvo et al. [20] survey (i.e. 2010–2012), and shows that the broader trends have continued, with some important exceptions. As we discuss the motivating questions, we draw from references in both corpora to demonstrate this. The full citation information for the Top 100 and Recent are available as a supplement to this paper.

METHODS
Our methodological approach is philosophically aligned with postmodern developments in grounded qualitative analysis, such as situational analysis [15], which acknowledges the political nature of data interpretation, the biases and decisions involved in representations of these interpretations, and the role of analyst as 'acknowledged participant' in the 'production of always partial knowledges' [15]. While one of our aims is to generate a visual representation of the breadth of current and past sustainability research in computing (Figure 2), we argue that this representation should not be taken as a definitive classification, but rather that its real value lies in what it enables, i.e. a holistic understanding of the sustainability territory in computing that can then be further critiqued.

To arrive at our visualization, we employ an overarching methodology of thematic analysis [11] (TA), the phases of which are detailed below. Positional mapping techniques [15] are used as part of the refinement of these themes. The final ten-question structure represents major positions implicit in publications in this field, and offers a lens for critiquing the underlying discourse that gives computing research this structure.

Finally, we code two systematically selected corpora according to these ten motivating questions in order to provide insight into the relative attention paid to different areas.

Development of initial themes

TA phase 1: familiarization. We began by performing a general search for conferences and journals related to 'green' or 'sustainable' + 'computing' or 'technology'.

TA phase 2: initial codes. Topics of interest were mined from these venues and collated in a spreadsheet until the search reached saturation. An emerging range of topics were recorded.

TA phase 3: searching for themes. Sixty papers were selected to be read in depth, specifically chosen by keywords and abstract to represent this range of topics. While reading these papers, major themes, minor themes, and sub-themes within these were recorded as they emerged.

Mapping and themes development

TA phase 4: reviewing themes. In following with the positional mapping approach, instead of aiming to map differences in groups (e.g. trying to differentiate between existing sub-communities in sustainable computing), we looked for similarities and differences between themes. Three broad types of interests were found — pollution, resource management, and society and culture — which served to enable organization of lower-level themes.

TA phase 5: defining & naming themes. A final mapping solution was achieved by rephrasing emerging themes as questions (e.g. 'How can we reduce CO_2 emissions?') and spatially arranging these onto our three areas of interest such that neighboring questions reflected relative similarity — a process similar to grounded theory's axial coding [17].

Corpora formation and analysis

With this understanding of sustainability themes in computing, we wanted to know how the literature had attended to these areas.

Corpus 1: 'Top 100'

Since it was unrealistic to try to categorize this entire body of research, we targeted a representative and highly regarded slice of the corpus, namely the 100 most cited papers written in the last ten years (2002 to 2012) and available through the ACM Digital Library or IEEE Xplore archives (chosen for their reputations), or appearing in references of previous surveys [20, 30] (so as to include papers that have been deemed relevant, if not explicitly using these key search terms).

The Top 100 corpus was created using the following steps. (i) Searching ACM, IEEE and the references of prior surveys for papers matching search strings such as 'green computing', 'green IT', 'green ICT', 'sustainable IT', 'sustainable HCI' or 'sustainable interaction design'. (ii) Reading titles and abstracts of the results to ensure relevance to sustainability. (iii) Recording the highest cited (about 150 papers) in a spreadsheet. (iv) Ranking the list of papers in order of citation count according to Google Scholar. In the event of a tie, papers were ordered by citation count in ACM or IEEE, and if still tied, the number of Mendeley readers.

These 100 most cited papers were then coded according to the motivating research questions identified in the previous stage by reading the abstracts and conclusions of each paper (and where necessary, the entire paper). Intercoder reliability was 88% at a first pass, and all discrepancies were resolved through discussion. While we found that certain paper types spanned multiple motivating questions with largely equal weighting (in these cases we assigned fractional counts for the purposes of Figure 1), we did not discover any altogether new motivating questions in this phase. These findings suggested that the framework did not require structural modification.

Corpus 2: 'Recent'

As there is debate about the correlation of citation metrics to research impact [9], and because citation counts would not have had time to accrue for more recent papers which might expose emerging trends, we compiled the Recent corpus as follows. A search was done for papers in the UbiComp, Pervasive, CHI and DIS proceedings 2010–2012 (including extended abstracts and workshop papers, when these were accessible in the ACM archives), which contained any of the keywords 'sustainability', 'sustainable', or 'energy'. This resulted in 650 papers, which were individually browsed to ensure relevance, resulting in a corpus of 122. While there are many other reputable publication venues, we limited ourselves to UbiComp, Pervasive, CHI and DIS, commensurate with the communities we are presently writing for.

TEN MOTIVATING QUESTIONS IN COMPUTING

Below we describe the ten key questions that, from our analysis, are driving computing's current sustainability research (see Figure 2). By identifying these questions, we hope to expose the kinds of questions being asked — and by their omission, the kinds of questions not being asked — as indicators of a particular framing of the sustainability problem that researchers seek to address. To better explain the differences between these motivations, we provide examples of some of the approaches for answering these questions. The specific citations we mention are intended to be illustrative rather than exhaustive.

Q1. How can we support more responsible disposal of electronic waste? There is a growing humanitarian concern not just about the volume of electronic waste being produced and its environmental toxicity, but also about whether current disposal practices (which tend to involve sending e-waste to the poorest nations) are unjust [57, 72]. One approach for mitigating these problems is to produce less of this waste, for example by overcoming the technological challenges of reusing components [63]. Another is to ensure that the waste that is being produced is less toxic. While this is often practically in the remit of legislators, many publications address the implications of recent (and potential future) e-waste legislation on technological practice, articulating criteria and implications of compliance [13, 77]. And a third approach is to better manage the waste that is being produced, for example by using pervasive sensing technology for tracking purposes [10].

On the whole, this research tends to address the *symptoms* of unsustainable patterns of consumption but does not address or attempt to critique this consumption (as does *Q10*, below). Instead, research motivated by this question tends to begin with an awareness of a problem that needs cleaning up, but does not attempt to intervene at the source of the problem.

Q2. How can we reduce CO_2 emissions? Growing public literacy about climate change is evident in an awareness of carbon footprints. This manifests itself within computing in two ways; firstly, in the development of technologies aimed at helping reduce individuals' carbon footprints (many of which are persuasive technologies, and were in these cases coded as *Q4* rather than *Q2*); and secondly, through research into ways of reducing the carbon footprint of the technology itself [83]. Within the latter, some research aims to reduce emissions from the highest-footprint technologies, including data centers [2].

The vast majority of research motivated to help reduce CO_2 emissions deals with the *consumption* stage of the IT product life-cycle — i.e. reducing the amount of energy consumed during the use of technology. By comparison, embodied carbon of IT (the *production* stage) is largely omitted from the problem domain (in comparison to *Q6*).

Q3. How can we better monitor the state of the natural environment? Given that protecting the environment requires, to some extent, understanding where and how the environment is currently being damaged, some computing research explores the use of technology for monitoring the environment — e.g. air quality [45, 51] or water supplies [49]. Frequently this research focuses on developing more refined and more durable pervasive sensing technologies [75, 76, 79]. But also related to this research question is work that has been described as 'citizen sensing' [30] — technologically enabling public engagement with issues related to the state of the environment [48, 68, 84].

Q4. How can we use technology to foster environmentally responsible behavior? A great deal of research aims to develop technologies that 'support sustainable lifestyles and decision-making' [58]. Overwhelmingly, these interventions aim to promote *conservational* behavior [12], and energy usage — a common proxy for environmental impact — is the most popular target for change. Common approaches include ambient awareness [50], persuasive technology [25, 34, 46, 52], eco-feedback [26] and gaming [7].

Q5. How can we make better use of renewable resources? There has been much publicity surrounding industrial strides toward data center innovation — e.g. integrating solar (Apple) and hydroelectric (Yahoo!) power. In addition to the environmental wins associated with these developments, there is a popular consensus that non-renewable energies are likely to become increasingly (perhaps prohibitively) expensive in years to come. One active research area focuses on developing techniques for integrating renewable energies into smart grids [27, 54]. Other approaches include energy harvesting techniques and human-powered technology [66].

Q6. How can we make more efficient use of resources? Given the environmental costs of production, consumption and waste of physical objects and technologies, digital versions of products are often considered less environmentally costly. For example, dematerialization of media (i.e. books and compact discs to eBooks and music downloads) is ostensibly 'greener' (that is, if we ignore potential rebound effects [4]). Related to this, two key strategies for addressing this question are virtualization and cloud services, and the technical challenges involved in these solutions is the subject of much research [3, 55]. Other means include algorithmic or robotic controls to reduce system inefficiencies [6, 71] or to bypass user-generated inefficiencies [19, 32], and other technologies that introduce new sensing techniques, machine learning or behavior prediction which could be applied to automated control [47, 56, 73].

Q7. How can we improve operational and process efficiency? A large research area deals with the development of energy-efficient and energy-aware technologies, which aim to reduce energy usage by eliminating waste. These same techniques are also used by researchers attempting to reduce CO_2 emissions *(Q2)*, though the difference in motivation is significant. Here, many of these technologies are offered as a means of reducing cost (overwhelmingly, though not exclusively, this refers to *business* cost) [23, 64]. Importantly, this research is only indirectly related to any environmental discussion within computing; the fact that waste reduction is also environmentally beneficial is a bonus.

Perhaps the main reason to distinguish this question from *Q2* is the marked difference in discourse between them — *Q2* appeals to people's sense that the environment is inherently worthy of protection, and *Q7* appeals to a view of the environment as a store of resources — which work to very different psychological and political ends. And while papers of this type often employ similar techniques as *Q6*, success, here, is couched in terms of cost-saving.

Q8. How can we use technology to make society more efficient? Compared with many of the other key research questions — which target individuals, businesses, and/or technology as opportunities for environmentally beneficial change — some research targets society's infrastructure as a pathway toward more coordinated action toward environmental wins. Perhaps the most publicized example of such work is IBM's Smarter Planet, though a great number of other researchers are contributing to the development of smart grid technology [40, 59]. Another popular target of intervention is improvements in transportation efficiency [24, 28, 41].

Q9. What is the role of technology in making society sustainable? Somewhat more philosophical and future-oriented than other questions, this question deals with a) the possibility for new targets for sustainability intervention [16, 36, 69], b) political aspects of the debate [21], and c) the potential tension between sustainable living and a technology-rich society. Within the latter of these, researchers are exploring the appropriateness of technological solutions to sustainability [1, 61], and are conducting research into sustainable lifestyles as inspiration [85].

Q10. How can we promote less destructive and more satisfying patterns of consumption? Lastly, there is a growing corpus of research that expands on the ideas of sustainable interaction design [8], addressing what are perceived as unsustainable patterns of technological consumption: rapid obsolescence cycles, preoccupation with 'newness', 'design for the dump', etc. Some researchers interested in this problem are attempting to address design production [43, 80]; others are attempting to address social practices [67, 74]; and yet others are attempting to uncover knowledge about what drives current consumption behavior in order to accommodate perceived needs in less environmentally destructive ways [29, 31, 39, 62].

Results of coding

Our coding reveals a highly disproportionate distribution of research across the different motivating questions and between disciplines. The most frequently cited papers (perhaps, but not necessarily indicative of a greater number of publications in this area) were those that explore technological means of changing behavior (*Q4*), focus on operational and process efficiency (*Q7*), or explore automated controls to increase efficiency (*Q6*). Notably, research in these areas tended not to span disciplines. *Q4* was the concern of the sustainable HCI and UbiComp communities; and while *Q7* and its surrounding questions were of clear interest to the remainder of computing, they tended not to be explored within HCI and UbiComp.

Analysis of our Recent corpus reveals that work in HCI and UbiComp has largely maintained this shape in the last three years, albeit with an approximate quadrupling in commentaries on the role of technology in making our societies sustainable (*Q9*), and an even greater domination by behavior change research (*Q4*). This suggests that although there are new contributions in these areas, the framing of the sustainability problem remains largely unchanged, despite the critiques of this framing in recent years (e.g. [12, 20, 21, 30]).

DISCUSSION AND IMPLICATIONS

As mentioned above (TA phase 4), we identified broad types of interest which tied subsets of the questions together: pollution, resource management, and society and culture. During our positional mapping process, we spatially ordered these within an advanced Venn diagram, in order to relate the broad types of interest to the ten questions, where grouped

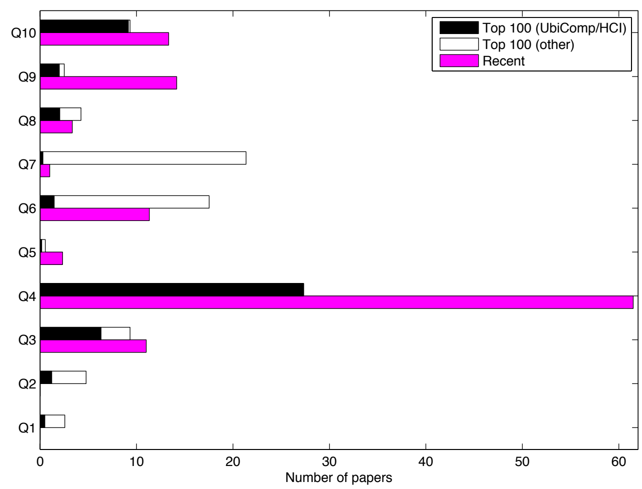

Figure 1. The comparative emphases of the motivating questions in sustainability research in computing. Fractions were used for papers with multiple motivating questions.

questions indicate a common broad interest (such as pollution), and where a particular question might be seen to contribute to two of the broad interests.

Having visualized the questions this way, it occurred to us that the intersection of these areas of interest could be seen as representing concerns about environmental needs, social needs, and economic needs: the three pillars of Sustainable Development, as outlined in the well-known 1987 Brundtland report [86]. While we do not suggest that there are clear divisions between economic, environmental, and social concerns, so hesitate to quote definite percentages, it does seem that despite the sustainability community's assumed association with the environment (cf. [30]), *economically*-driven questions are at least as prevalent in computing as environmentally-driven questions. Socially-driven questions, less surprisingly, represent no more than one-fifth of the Top 100 corpus.

Imposing this Triple Bottom Line superstructure (Figure 2) is only one possible, partial view, but we put forth that it is a potentially useful lens for understanding (a) our current and future research efforts, (b) the relations between various communities within computing, and (c) its relation to competing discourses on sustainability.

As to the first of these, results indicate that the locus of concern for HCI and UbiComp has tended to lie at the intersection of pollution and resource management — in other words, the focus has been on *environmental* needs. While there has also been interest in the intersection between pollution and society and culture (i.e. *social* needs) in the past decade, the Recent publications have demonstrated a significant increase in society and culture concerns *(Q9)*.

In contrast, there is a second locus of concern at the intersection of resource management, and society and culture concerns, namely a concern for *efficiency*, which is closely

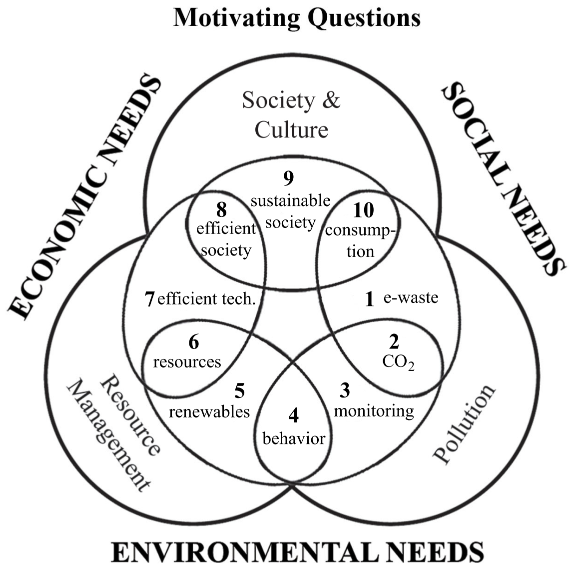

Figure 2. Computing's motivating questions in a Triple Bottom Line framework.

related to *economic* needs. This helps illuminate a difference in focus between sustainable HCI and other communities such as Green IT. Interestingly, UbiComp appears to act as a bridge between these two camps, with strong emphasis on both environmental needs (e.g. *Q4* and *Q3*) and economic needs (*Q6*).

So far our analysis has been primarily descriptive. We have shown that certain questions are well covered (e.g. *Q4, Q6, Q7*), and that others are less so and could perhaps benefit from greater exploration. We have also shown that this research arguably maps onto a Triple Bottom Line agenda.

But while a Triple Bottom Line understanding of sustainability has gained significant traction in popular culture, it is by no means politically uncontested. Indeed, it is only one of many competing environmental discourses. In the next section we recap some of these competing discourses in order to provide greater context for computing's orientation to sustainability, and to reflect on what this Triple Bottom Line framing both *enables* as viable targets for research and *excludes* from our problem space.

Competing environmental discourses

In his 2005 book [22], Dryzek surveys the various recognizably distinct environmental discourses that vie for political dominance. He argues that all of these discourses emerge as reactions to Industrialism, and that these reactions diverge along two dimensions. Reactions can be *reformist* or *radical*, the latter being characterized by a desire to move further away from the conditions created by and supporting Industrialism. Reactions can also be *prosaic* or *imaginative*. Prosaic approaches assume the basic 'rules' of Industrialism are unchangeable, whereas imaginative approaches deconstruct and seek to redefine these 'rules'.

Using these categories, Sustainable Development can be described as an *imaginative/reformist* discourse. It is imaginative in comparison to what Dryzek calls 'Problem Solving' approaches, — e.g. Administrative Rationalism, Democratic Pragmatism, Economic Rationalism — which advocate policy adjustments to account for emergent environmental problems within the political-economic status quo. More imaginatively, Sustainable Development challenges the 'rule' that economic growth is necessarily antagonistic to environmental protection and social justice, and instead proposes that these could be understood as being mutually reinforcing pursuits [22, p. 155].

Sustainable Development is also reformist in comparison to what Dryzek calls 'Green Radicalism' approaches (e.g. deep ecology, eco-theology, eco-feminism, and others) which propose that the solution to our environmental problems lies in re-aligning the relationship between humans and nature that, proponents argue, has been warped by Industrialism [22, p. 193]. Sustainable Development is less radical in that it does not seek a major overhaul of the dominant worldview, and instead seeks a solution that fits within our familiar mode of instrumental rationality.

Our literature survey has revealed important parallels between Sustainable Development and HCI. Just as Sustainable Development proposes guidance of economic growth in ways that are 'environmentally benign and socially just' [22, p. 153], HCI's sustainability research seeks to guide technological development toward these same ends. In both cases, 'growth' is not in itself the problem — rather, when guided responsibly, it is seen as a solution. In Sustainable Development, this manifests as the commitment of nations and organizations to a framework of growth that aligns with environmental and social responsibilities; and in Sustainable HCI, this manifests in large part as the development of technologies (i.e. the growth of the digital economy) that enable more responsible practices on the part of individual consumers *(Q4)*, but also as a desire to move away from choreographed obsolescence *(Q10)* [8], which can generate profits at the expense of the environment.

A lesser-known, but more readily implemented discourse that shares Sustainable Development's *imaginative/reformist* approach is Ecological Modernization. This approach is dominated by efforts to mitigate environmental damage through targeted efficiency improvements throughout society. Compared to Sustainable Development, Ecological Modernization more enthusiastically proclaims the economic benefits of 'greening' practices, including, for example, the business opportunity to be found in providing 'green' products and services. Ecological Modernization is premised in corporatism, which assumes that businesses and governments can work together toward ends that benefit the state and its people. Excluding HCI and the UbiComp contribution to environmental concerns, much of the remainder of sustainability research in computing (including the remainder of UbiComp's efforts) appears to be contributing to an Ecological Modernization agenda, as evidenced by the efforts to improve technological and societal efficiency *(Q7, Q8)*, reduce CO_2 emissions *(Q2)* and integrate renewables *(Q5)*.

While potentially reductive, we suggest it might be useful as a launching point for further discussion to think of HCI as discursively similar to Sustainable Development, compared to the more engineering faction of this computing research which is discursively similar to Ecological Modernization; meanwhile UbiComp, which straddles these camps, displays similarities with both. All of these discourses are rooted in the three pillars of environmental, social, and economic needs. They are all imaginative, in the sense that they explore a mutual relationship between these three pillars. They are also reformist. The fact that computing offers a reformist discourse is evidenced by the motivating questions — e.g. rather than exploring alternatives to what has been argued as an inherently unsustainable digital economy, or challenging the instrumentalization of the sustainability problem, computing seeks sustainability wins that can be found within the dominant ideology of our technological era.

We are careful to point out that 'radical' should not be interpreted to mean 'better' or 'stronger'. The distinction between reformist and radical discourses is principally about differences in the way 'sustainability' is understood, which in turn prescribes different solutions. Our argument is simply that in adopting a Triple Bottom Line framing of 'sustainability', computing does not address other, equally valid (if somewhat less populist) interpretations of what we ought to be aiming for with our sustainability efforts. As a case in point, in the next section we borrow one alternative understanding of 'sustainability' from the radical *design for sustainability* discourse in order to explore new opportunities for sustainability research in computing to be found by engaging with other competing environmental discourses.

From reformist questions to radical questions

At the heart of reformist environmental discourses is an assumption that the goal of sustainability is to ensure *continuance* of a way of life that is preferable to that of earlier ages and imagined future states. This notion of continuance is, for example, embedded in the Brundtland definition of Sustainable Development, which seeks continuance of the current standard of living to future generations. Yet, while a Triple Bottom Line approach to sustainability helps in formulating instrumental goals for the continuance of the status quo, it does not address questions about why we might *want* to sustain the world as is, or what ought to be sustained to make our continued existence meaningful and fulfilling [65].

In contrast, the radical *design for sustainability* understanding is premised in the notion that we negotiate three levels of meaning as a condition of being human, namely 1) physical meaning —- the satisfaction of basic survival needs; 2) social meaning — the satisfaction of our needs as social beings; and 3) 'spiritual' (a.k.a. 'personal') meaning — the satisfaction of our need to find some higher order and significance in our existence [35]. In recognition of this, sustainability can been understood as a problem of how to enable human fulfillment. A competing framework, known as

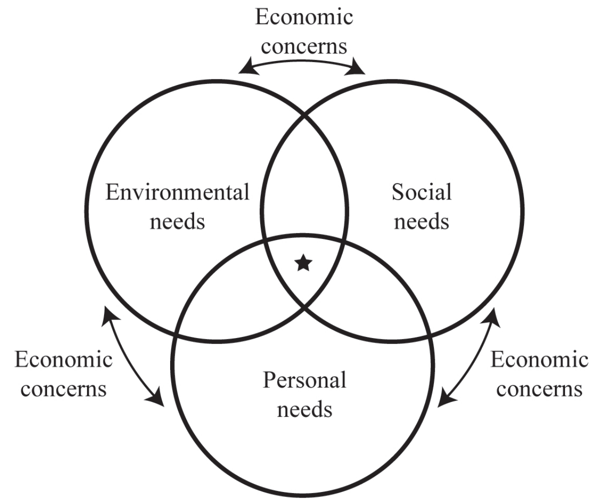

Figure 3. Quadruple Bottom Line framework for alternative sustainability questions in computing [82].

the Quadruple Bottom Line (QBL), has been proposed [82] to account for this understanding of sustainability as human fulfillment. As visualized in Figure 3, the core elements of sustainability relate to *environmental*, *social* and *personal* needs; meanwhile *economic* concerns (a human construct rather than a natural condition of being human) are understood to mediate our ability to satisfy these primary needs [82]. According to this QBL, sustainability is achieved at the point of intersection of these four concerns (indicated in Figure 3 by a star), meaning that any sustainability issue must be investigated as a four-fold problem.

What kinds of questions might computing explore within this framework of sustainability? In the space remaining, we provide preliminary examples.

It has been estimated that in order to actually stop climate change, individuals in developed countries will need to limit their carbon footprints to about three tonnes per year (an 80% reduction) by the year 2050 [4] (see also the United Kingdom's 2008 Climate Change Act). Bearing this in mind,

- *How can we design for the 3-tonne carbon lifestyle?* This entails, as a starting point, a calculation of the typical carbon footprint attributable to digital technologies [4], which may in itself exceed three tonnes per person per year in developed nations.

In addition to the obvious environmental implications, this question requires thinking about further implications of such drastic change, for example:

- Social: *How can we enable less carbon-intensive social practices?*
- Personal: *Which digital products and services contribute the greatest meaning to our lives and should be prioritized?* For that matter, who gets to decide such things, and how is 'meaning' measured?

- Economic: *As new economic models are investigated, how might the digital economy adapt to one that is not based on a growth economy?* Alternatives such as natural capitalism [33] and steady state [18, 42], for example, have yet to be explored with respect to implications for digital artifacts and services.

Many contend that globalized society is inherently unsustainable, and that a sustainable future will necessarily be characterized by localization [38, 81]. This raises several questions for computing, for example:

- Environmental: *How can we enable the delivery of best practice knowledge for efforts such as local farming, local building, etc?*
- Social: *How can we help foster cohesion in local communities?*
- Personal: *How can we enhance values that are conducive to teamwork in order to enable local initiatives by communities?*
- Economic: *How can we enable the viability of local currencies?*

Current thinking in computing proposes that in addition to supposed environmental wins, technologies such as cloud services and smart grids enable localized or individual resilience, in the sense that one's personal IT can 'go down' without disastrous results. The flip side of this, however, is that the technological interdependence they require (e.g. centralized systems) simultaneously decreases large-scale, societal resilience. This vulnerability has *sustainability* implications [70], since resilience is often considered a key component of a sustainable society [37, 38]. In the future, computing may have to consider questions such as:

- Environmental: *What should we 'unplug' in an effort reduce our environmental impact?* Again, as a starting point, we would need to know the relative environmental impacts of various technologies, which suggests a need for collaboration between computing and environmental studies.
- Social: *How can this 'unplugging' be managed in such a way as to mitigate the worst of the societal disruption?*
- Personal: *How can we develop a new narrative about the role of computing in a responsible, resilient society?*
- Economic: *How might this project be leveraged into new research and business opportunities within computing?*

It has also been suggested in radical discourses that the root of our current unsustainability is a loss of meaning that encourages unfettered consumerism and shallow forms of socialization [14, 53, 78], which will ultimately 'corrode our desire to sustain it and the belief that humanity is worth sustaining' [65]. To attend to this problem, computing might ask questions such as:

- Personal: *How can we contribute to a notion of 'progress' that are more conducive to sustainability?* [70]
- Social: *How can we support more profoundly satisfying forms of social engagement that differ qualitatively from current social media?*
- Environmental: *How can we foster a sense of connectedness to the environment?*
- Economic: *Can we develop new economic models to underpin the digital economy that internalize relevant factors, such as environmental, social and spiritual impact?*

While it is tempting to propose practical solutions to these questions, or outline various means of addressing them, we suggest that doing so would be premature at this stage, and would function to narrow research possibilities at the very moment we aim to widen them. We present these broad questions to illustrate the difference in inquiry inspired by alternative conceptions of 'sustainability', and to seed a discussion within the computing community about its implications for the future of sustainability research.

CONCLUSION

We have surveyed the collective contribution of sustainable computing research in order to gain strategic insight into alternative pathways forward. A comparison has been made between computing and Triple Bottom Line notions of sustainability (e.g. Sustainable Development and Ecological Modernization), which is grounded in wide analysis of the body of literature emerging from computing over the last decade. We have argued that computing has unwittingly narrowed its solution space, and that even greater opportunities for research might be discovered by going *beyond* the Triple Bottom Line to embrace more contemporary, more holistic, and more *radical* understandings of sustainability. We have offered several initial ideas for radical research questions, which we intend to expand upon in subsequent publications. Finally, while we have provided a slice-in-time analysis of computing research — from 2002 to 2012 — we anticipate significant re-shaping and re-structuring of the field as more comprehensive understandings of sustainability, developed in other fields, continue to penetrate and influence developments in computing.

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