Web for Sustainability

Tackling Environmental Complexity with Scale

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Abstract— **There are contrasting ways to understand the Web: as global technical infrastructure, the largest ever information construct, and as social new media. Existing communities of *ICT for sustainability*, such as *environmental informatics*, *Green ICT*, and even the more recent *sustainable HCI*, tend to focus on engineering and the individual user. However, the Web's full potential to advance environmental sustainability is contingent upon it capacity for *social communication*, its *content, massive scale and diversity*. This research explores the nature of *web for environmental sustainability* through qualitative analysis of data describing systems and companies. These have been called *cleanweb* companies, and the definition of *cleanweb* is discussed and an estimate found of the number of firms (at least 2000). Two major dimensions of web for sustainability are identified: the web *means* (more valuable *insight* or *relationships*) and the *complexity* of the environmental *ends* (narrow *resource-use* or *broad sustainability*). These demarcate a matrix of four domains of web for sustainability systems (*resource insight, sustainability insight, resource networks* and *sustainability networks*). Areas of current activity within each domain are identified, along with example systems. Each domain has a distinct and valuable role, and the complexity of environmental sustainability, and particularly rebound effects, create both congruities and interdependencies between them. The matrix highlights the importance of innovation in *broad sustainability* web systems, not just in *resource-use*. It spans from engineering to the humanities, illustrating the need for interdisciplinary research approaches, such as web science, in order to realise the transformative sustainability opportunities presented by the scale of the Web.**

Index Terms— **ICT for Sustainability; Web Science; Cleanweb; Web for Sustainability; Web Entrepreneurship; Environment; Climate Change; Complexity; Big Data; Information Visualization; Open Data; Human-Computer Interaction; Energy Efficiency; Sustainable HCI; Behaviour Change; Collaborative Consumption; Environmental Politics; Interdisciplinarity; Natural Resources.**

I. Introduction

The potential for the Web to advance environmental sustainability has received considerable recent attention, particularly under the epithet *cleanweb* which was coined in early 2011 as a portmanteau of *web* and *cleantech* (technology for environmental sustainability) [1]. Since then the term *cleanweb* has appeared in newspaper articles [2], European Union funding calls [3], White House communiqués [4], it has been adopted by national [5] and international community groups [6], and has been employed by software-creation "hack" events around the world. The word has been used to describe companies that have attained major success in recent months: Solar City has a market capitalisation of $6.75bn, Nest was bought for $3.2bn, Climate Corporation for $1.1bn, and Zipcar for $500m. In the UK the internet industry is estimated to be worth £82 billion (10^9) [7] whilst the cleantech industry is worth £122 billion [8]. The intersection of the two could comprise major economic and environmental value, and may even represent the emergence of a new industry.

There are contrasting ways to understand the Web: as global technical infrastructure, the largest ever information construct, and as social new media [9], [10]. The Web is enabled by information and communication technology (ICT) but it is not identical to it. Hence new interdisciplinary research approaches have arisen, such as web science, that go beyond computer science to compliment insights from engineering with those of social science and other areas. Existing communities of ICT for sustainability tend to focus on engineering and the individual user. These include environmental informatics, green ICT (either green *in* ICT that reduces the negative impacts of ICTs themselves or Green *through* ICT which uses ICT to advance sustainability beyond ICT [11], [12]), and more recently *sustainable human-computer interaction (HCI)* [13]. In order to understand how the Web can advance environmental sustainability, novel approaches are required that also acknowledge *social communication*, its *content*, and especially its *massive scale and diversity* [14]. Being orders of magnitude bigger is very different in kind. DiSalvo et al. [13] found that 70% of sustainable HCI papers focus on the individual user. But Web systems can connect millions of people, and some Web companies are famous for their rapid growth from garage startup to global corporation. This combination of scale and speed, interactivity and accessibility has disrupted many industries. Berners-Lee et al. [14] characterised these new entities that combine humans and ICTs on a large scale as *social machines*. It is precisely the scale, speed and breadth of uptake of these social machines that offers significant opportunities to tackle the urgent global challenges of sustainability, such as climate change, in viable timescales.

To better understand these opportunities, this article analyses the space of possibilities through which the Web can promote environmental sustainability (equivalent to Green *through* ICT; the negative direct environmental consequences of ICT use are out of scope) [11]. Data has been sourced from the *CrunchBase* database of technology companies, and the cleanweb community itself, in which the researcher has actively participated. If *cleanweb* is a new industry, how should it be defined, and how big is it? What is it that the Web is enabling these companies to do, and what sets of activity are occurring that could advance sustainability?

II. Method

Potentially relevant companies were identified through secondary analysis of a large directory of technology companies, CrunchBase [15], created and maintained by TechCrunch, a leading technology news company from California. CrunchBase is ranked as the 1,289th most popular website globally [16]. Content is updated by users, and moderated by staff, to provide the size, coverage, rich content and timeliness, which is of particular value in the fast moving web industry with a high start-up and failure rate. Data on all 182,000 companies were downloaded from the CrunchBase API over a two-week period in October 2013.

A subset of 6000 possible web for sustainability companies was identified by searching the list for particular terms in the three major qualitative data fields (description, overview and user generated tags). Entries were selected that included *either*

- Both terms related to the Web (e.g. “online”) *and* to sustainability (e.g. “carbon”)
- Or terms of specific relevance to the use of web for sustainability (such as “ride-sharing”).

To do this, three lists of search terms were created (relating to the web, sustainability and web for sustainability). These were developed by gathering three sets of relevant documents, and selecting the search terms from the 500 most frequent words appearing in each set. Others terms were added from the researchers experience, including variations such as those due to dialect (“railroad”, “railway”). The search terms were constructed in regex – a flexible syntax for pattern-matching sequences of characters, allowing for word stemming and variations. By iteratively examining the results and updating the search terms, they could be refined to maximise effectiveness. This was influenced by theoretical sampling methods in grounded theory [17], and aided by a parallel analysis of sustainability open government data. The resulting search terms do depend significantly upon the judgement of the researcher, as environmental sustainability and the Web are complex, rapidly evolving phenomena with contested definitions.

The companies were then examined individually, in priority order of the number of relevant terms found for each, until 300 Web for sustainability companies were discovered. These were combined with a list of 100 cleanweb companies identified by Pascual [18] and the cleanweb community, as well as examples from the researchers own experience and from searching the Web, which was necessary for non-commercial systems not appearing in Crunchbase.

The descriptions of each company were coded using a methodology based on grounded theory, a leading qualitative social science research method that begins with data analysis and works towards a hypothesis or theory (in contrast to the traditional “hypothetico-deductive” scientific method) [17]. These open codes were then organised into similar concepts and then categories. Meanwhile theoretical memos were made to describe and develop the categories. Most categories corresponded to either the socio-technical approach taken or the sustainability or resource outcome. These two dimensions allowed the companies to be plotted on a matrix (Figure 1), with popular combinations of socio-technical approach and sustainability outcome representing active markets. The typical components and processes within systems in each market were then analysed to develop the model in Figure 2. Examining the similarities and contrasts between the processes within each system, and their sustainability outcomes, enabled the two dimensions (described in Sections V and VI below) to be identified.

III. Estimating the Number of Cleanweb Companies

In addition to the main qualitative analysis, a brief quantitative analysis was undertaken to find an approximate estimate of the number of cleanweb companies. An individual analysis of a random sample of 30 from the 6000 potential web for sustainability companies from CrunchBase found that 36% were actually using the web in ways with a potential environmental benefit. This suggests that there are at least 2000 Cleanweb companies worldwide. This is of low accuracy because of the fast-moving experimental and entrepreneurial environment of the Web, with a high turnover of companies. In addition, CrunchBase does not capture all companies in existence, especially in non-English speaking countries.

IV. Web for Sustainability Matrix

The web for sustainability matrix (Figure 1) organizes systems and companies along two dimensions described below, which were chosen after considerable experimentation from many identified alternatives. The two were selected as they clarify the interplay between the range of affordances offered by the underlying technologies (the web *means*), and the range of challenges presented by sustainability (the environmental *ends*). (This division is not the same as identifying the constituent markets.) Some companies and systems offer different sets of functionality that would sit at different locations on the matrix, and so have been placed at the average point.

The two dimensions were identified by developing this model of the components of web for sustainability systems, composed of large numbers of diverse participants (humans, organisations) and ICTs. It shows the simultaneous roles of the Web as technical infrastructure, information construct, and social performance and media.

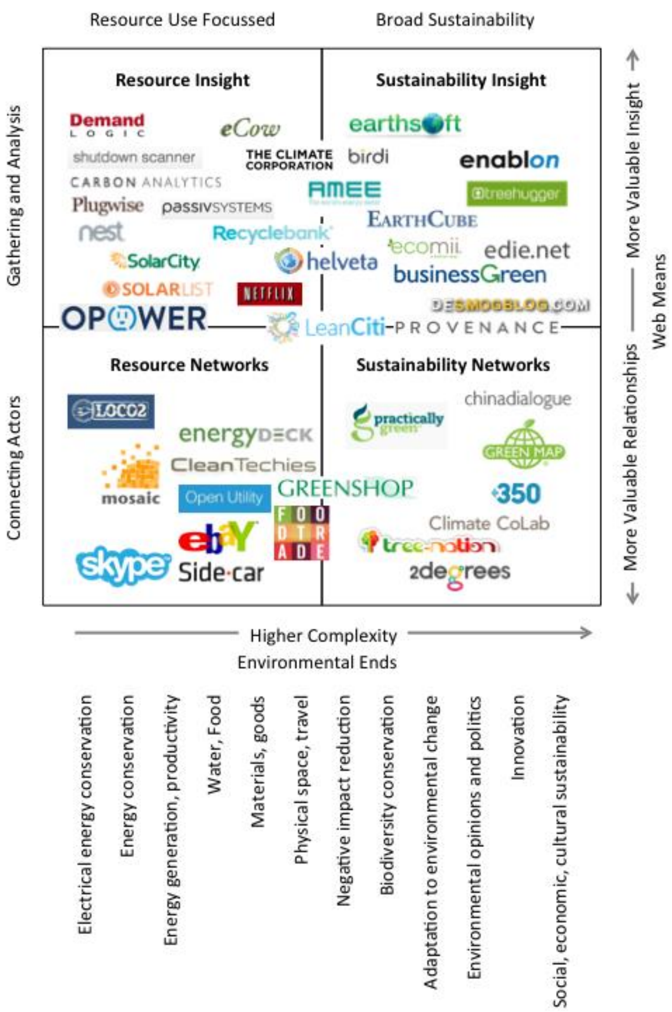

Fig. 1. Web for sustainability matrix, showing example systems and companies organised by web *means* and environmental *ends*.

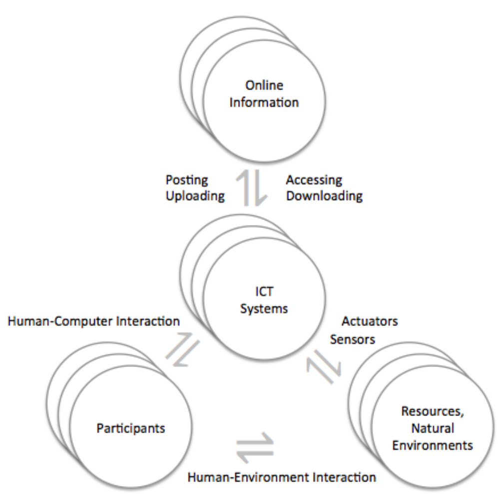

Fig. 2. Components of web for sustainability systems

V. Web *Means*: More Valuable Insight or Relationships?

All web for sustainability systems analysed were found to work in (at least) one of two ways that make up the first dimension of the web for sustainability matrix (Figure 1). These were found by considering the typical flows of information and interaction through the components of the model above.

- *Insight.* An ICT system gathers information by sensing resource use, or the natural environment, or accessing information from the Internet (or some combination). This information is usually analysed to yield insight. It can then be acted upon by the ICT system, or presented to the user who reacts, possibly using further ICT, with an ultimate effect on resource use or the natural environment.
- *Networks*. Multiple participants use their devices and the internet to find and communicate with each other, leading to an effect on resource use and/or the natural environment. They are generally composed of larger numbers of smaller participants interacting with each other, compared to the unidirectional information flows common in *insight* systems.

Essentially, the Web is allowing 1) much greater quantities and diversity of information to be gathered and analysed, enabling more valuable insights to be garnered and disseminated 2) more participants to connect, creating more valuable relationships. These correspond to the “information” and “communication” in “ICT”, as they have been used for both connecting people and gathering and analysing information since their historic inception. However Moore’s law and the vast scale of the Web leads to a profound increase in the power of these approaches, as substantiated by the sudden emergence of large corporations like Google built upon *insights* forthcoming from “*big data”*, and that of companies like Facebook and eBay based upon *networks* of social media or marketplaces. Shirky describes how the Web enables us to connect together in new ways, and a great distances, “organizing without organizations” to form *networks*, thanks to hugely reduced transaction costs of communication [19]. Strong recent interest in the concept of *big data*, and related trends such as *linked data*, *broad data*, *open data*, *real-time data*, and the *quantified self* show the high present interest in the power of web-mediated *insight*.

This investigation of web for sustainability systems identified the following ways in which *insights* generated from the gathering and analysis of data are being applied:

- Managing resource use, the environment or related financing through analysis of real-time data, including problem diagnosis, algorithmic optimisation and feedback for behaviour change. Also enabling digital control by the user to facilitate management.
- Planning resource, or sustainability enhancements and similar measures to facilitate adoption.
- Gathering and disseminating knowledge and news for planning, education and behaviour change.

- Composing guides or ratings to facilitate sustainable consumption and behaviour change.
- Distributing information that substitutes for physical products.

In contrast, these are the ways that the relationships between participants forged on web *networks* are being applied:

- Exchanging more resource efficient or sustainable products, including underused resources and those that substitute information for physical products.
- Crowd-funding resource or sustainability enhancements.
- Group development or sharing of ideas, opinions or opportunities.
- Group action and political organising.
- Incentivising behaviour change through peer comparison and competition.

VI. Complexity of Environmental *Ends*: Resource Use Focus or Broad Sustainability?

The second dimension of the web for sustainability matrix emerged from the variety of sustainability *outcomes* identified, which were then organised onto a spectrum. At one extreme lie the many systems that focus on the efficient use of electrical power. The following succession of intervening stages was developed, of increasing *breadth* and *complexity*, leading to the other extreme of broad sustainability, considering even social, economic and cultural objectives:

- Energy conservation (including heating, fuels)
- Behaviour change for energy conservation
- Sustainable energy generation and productivity
- Water, food as resource (the "resource nexus")
- Materials, goods, physical space, travel
- Reducing the negative impacts of consumption
- Environmental quality (air, water)
- Biodiversity conservation
- Adaptation to environmental change
- Environmental opinions and politics
- Technical, economic, social and political innovation

This constructed scale illustrates the great contrast between, on the one hand, narrow reductionist views of ICT for sustainability as increasing efficiency of resource use, and on the other, more holistic understandings that recognise the social and physical complexities of the challenges. Whilst the former takes a positivist approach that engineers technology, the latter must consider more normative questions.

VII. Contrasting Literature on the Environmental Ends

Most of ICT for sustainability has emerged during the two decades of the Web's existence, and so the Web has been an element of ICT for sustainability research. This paper shifts the focus onto the Web itself, building upon that work and the swath of relevant literature from computer science to public policy.

A. On Resource Use

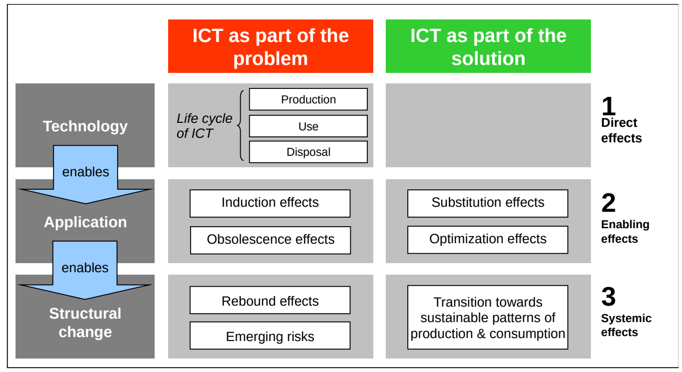

Fig. 3. Hilty's model of ICT for sustainability (reproduced with permission of L. Hilty) [12].

Hilty's model of ICT for sustainability (Figure 3) is a matrix showing the potential positive and negative consequences of ICT use for sustainable production and consumption [12]. Like Gartner's high-profile report on Green IT, it distinguishes three levels of impact [20]. The direct, or first order, impacts of the technology are entirely negative (and outside of the scope of our paper). Through the second order, enabling effects, ICT-based processes can induce, optimise, or substitute for the use of products and services. The third order, systemic effects include the negative consequences of rebound (discussed below) and the positive *transition towards sustainable patterns of production and consumption*, which is further broken down into either i) the generation of insight about environmental processes and ii) establishing dematerialised business models and life styles in which ICTs can organise a closed-loop or circular economy of comprehensive substitution.

Whilst Hilty's model contains little on the social and political complexities of the transition to sustainability, it details the progression of complexity from the relatively measurable and predictable first two levels, to the knotty challenges of the third such as rebound effects. In contrast, the Smarter 2020 report just ignores rebound effects to claim that 16.5% could be saved from global greenhouse gas emissions across a number of industries [21].

Persuasive technology that promotes behaviour change sits in the second tier of Hilty's model, and has been a central preoccupation of sustainable HCI, as detailed by DiSalvo et al. [13]. Behaviour change technology can be narrowly resource-use focussed, or it can tackle issues of broader sustainability, especially when it engages with users' values.

B. On Broad Sustainability

In her doctoral thesis, Bran Knowles critiques the "overwhelming majority of work" in ICT for sustainability for its modernist worldview, its preoccupation with self-enhancement, and its low impact. Knowles states that it does not address: rebound effects; the externalities of the direct effects of ICTs; the counterproductive promotion of consumerism during behaviour change interventions of marginal impact; the overwhelming scale of the required change; nor the deeply contested nature of sustainability. She argues that the narrow focus of ICT for sustainability research should give way to the promotion of environmental values and frames.

So what are some of the alternative ICT approaches beyond a narrow focus on resource-use? O'Neill & Boykoff see the Web as "socially constituted new media" building upon the rich heritage of traditional media, in which "struggles of social beliefs and meanings" take place [22]. Tomlinson sees the role of ICT as mitigating "the disconnection between the broad scales of time, space, and complexity across which environmental issues take place and the relatively narrow horizons of human understanding and action." and highlights its use in education, personal change and collective action [23]. Souter et al. [24] value the internet's role in connecting a wide range of actors to progress sustainability, whilst Easterbrook [25] promotes its use for collaborative science and collective decision making. Zapico celebrates the importance of the "hacker ethic" of openness and hands-on creativity [26], [27] and the value of web-mediated open knowledge [28], [29]. Knowles herself proposes an "imaginative/radical cyber-sustainability" based instead on the Quadruple Bottom Line model of sustainability [30].

VIII. Example Systems in the Web for Sustainability Matrix

This section details the areas of activity found by their position in the matrix, example systems in square brackets, and describes one archetypal example in more detail:

A. Resource Insight

- Managing resource use or requisite financing through analysis of real-time data [*Carbon Analytics* providing corporate carbon accounting], including problem diagnosis [*Demand Logic* who diagnose issues with commercial building heating management], algorithmic optimisation [*Nest* who increase efficiency of home heating with a smart thermostat], and feedback for behaviour change [*Opower* who help utility companies empower home customers to manage their use to reduce bills]. Also enabling digital control of resource use by the user to facilitate management [*PassivSystems* online control for home heating].
- Planning resource enhancements and other measures to facilitate adoption [*Solar City*, *Solar List* plan home solar panel implementations].
- Gathering and disseminating knowledge and news for planning, education and behaviour change [*RecycleBank* educate users to recycle more].
- Composing guides or ratings to facilitate sustainable consumption and behaviour change [*AMEE* which rates companies' environmental performance].
- Distributing information that substitutes for physical products. [*Netflix* dematerialised film distribution]

Demand Logic (https://www.demandlogic.co.uk/) offer a web-based system for real-time monitoring of heating and air conditioning system performance in commercial buildings, allowing opportunities for energy saving to be identified. Commercial buildings can waste much energy simultaneously heating and cooling space due to poorly configured equipment. Demand Logic provides a real-time dashboard and regular performance reports. Users are able to log in at any time and access live and historic data. Demand Logic provides a single point of contact where those engaged in improving the building's performance can share data and schedule improvements. It was founded in 2007 in London.

B. Resource Networks

- Exchanging more resource efficient products, including underused resources [collaborative consumption companies such as ridesharing site *SideCar*] and those that substitute information for physical goods or services [voice-over-internet communications provider *Skype*].
- Crowdfunding resource enhancements [domestic solar panel financing company *Solar Mosaic*].
- Group development or sharing of ideas, opinions or opportunities [cleantech industry social networking site *CleanTechies*].
- Incentivising behaviour change through peer comparison and competition [*Opower* who help utility companies empower home customers to manage their use to reduce bills].

Mosaic (https://joinmosaic.com/) is a solar energy project finance company, which lets individuals invest as little as US$25 in specific solar projects while earning an annual interest. Mosaic uses the network-enabling affordance of the Web to build financial relationships between those with sites for potential solar development and those with an interest in funding it. Mosaic has been referred to as "the Kickstarter for Solar", aiming to democratize the social and environmental benefits of clean energy. It was founded in 2010 in Oakland, California.

C. Sustainability Insight

- Data collection and analysis to manage the natural environment [*EarthSoft*, online environmental data management], the human environment [*birdi* networked air quality sensor], and sustainability performance [corporate social responsibility tracking software *Enablon*].
- Gathering and disseminating knowledge and news for public understanding and opinion, planning and behaviour change [environmental news website *Treehugger*, climate change blog *DeSmogBlog*].
- Composing guides or ratings to facilitate sustainable consumption and behaviour change [sustainability lifestyle guides site *ecomii*].

The *Climate Data Initiative*, (http://www.data.gov/climate/) within the US federal government open data programme, is releasing data, initially to help companies, communities, and citizens understand and prepare for the impacts of coastal flooding and sea level rise [31]. *Open data* is free for anyone to use, reuse, and redistribute [32]. Gathering together and releasing open data, is intended to unleash reuse, insight-generation and innovation, supporting sustainability in myriad ways. Launched in March 2014, the site is planned to grow to include more datasets, web services, and tools, as well as other themes such as the vulnerability of the food supply and the threats to human health from climate change.

D. Sustainability Networks

- Group development or sharing of ideas, opinions or opportunities [collective climate change innovation platform *Climate Colab*].
- Group action and political organising [web-based climate change campaign group *350.org*].
- Exchanging more sustainable products [green products marketplace *GreenShop*].
- Crowdfunding sustainability enhancements [tropical tree planting network *tree-nation*].
- Incentivising behaviour change through peer comparison and competition [social sustainable behaviour change platform *PracticallyGreen*]

Climate Colab (http://climatecolab.org) is a system designed to harness the collective intelligence of thousands of people from all around the world to address global climate change. It uses the network-enabling affordance of the web to recruit interested people and connect them with each other. It is a crowdsourcing platform where citizens work with experts and each other to create, analyze, and select detailed proposals for what to do about climate change. Policy proposals compete with each other in contests. In the most recent round of activity, there were 18 contests on a range of topics, from how to reduce emissions from electric power generation to how city governments can adapt to changes brought on by climate change. Almost 400 proposals were submitted, and there were 28 winning proposals. Colab was created by the MIT Centre for Collective Intelligence, and has 11,000 registered members.

IX. Resource-Use, Revenue Generation for Scaling, and Defining Cleanweb

The ability of web systems to rapidly scale in size to global levels at low cost is of great value to entrepreneurs, and has similar potential for the urgent global challenges of sustainability. Although the cost of scaling web technologies is relatively low, growth can be amplified by the ability to generate revenue. The predominant sustainability outcome of web for sustainability companies was found to be improving resource-use. Whilst this is partially driven by the particular affordances of the technology, it is the intrinsic source of revenue provided by the saving or generation of resources that incentivises resource-use improvements and supports their adoption. For instance, the *Nest* smart thermostat system and the *Demand Logic* building management diagnosis systems enable users to heat or cool their buildings more efficiently, reducing energy costs whilst also improving comfort. In contrast, broader sustainability with its inclusion of social and political goals lacks a primary source of revenue generation to support business models for growth. A larger proportion of the examples found rely on external sources of funding such as charitable donation, or, like much of the Web, advertising revenue. However, there are a diversity of commercial opportunities on this right side of the matrix, driven by, for instance: user's concern for a healthy local environment (home environmental quality sensors *birdi*); the needs of the scientific and regulatory bodies (online environmental data analysis *EarthSoft*); concerned consumers demand for sustainability news (journalism site *businessGreen*); sustainable goods (marketplaces *Provenance*, *GreenShop*); and the needs of sustainable businesses (business network *2degrees*).

The international Cleanweb community takes its name from the portmanteau of *cleantech* with *web*. Cleantech has been defined as technologies that "provide superior performance at lower costs, while greatly reducing or eliminating negative ecological impact, at the same time as improving the productive and responsible use of natural resources" [33]. This definition mixes financial, environmental, and resource requirements. The author is working with international community members to develop a definition of *cleanweb*, and the current working definition is *connected information technology solutions that address resource and sustainability challenges.* Whilst the resource-use-focussed left half of the web for sustainability matrix predominates amongst cleanweb companies, and amongst conceptualisations of cleanweb, the working definition specifies both resource and sustainability challenges, so that *broad sustainability* systems on the right half of the matrix are not excluded.

X. Complexity, Rebound Effects and Interdisciplinarity

There is much alignment between a focus on resource use and broader environmental sustainability, but there are significant discords too. Measures to increase efficiency of resource use are often subject to rebound effects that reduce their effectiveness. At their most extreme they can even lead to a great increase in the overall use of the resource (Jevon's paradox). Rebound effects are often organised by increasing levels of complexity: direct, indirect and economy wide [34]. Berners-Lee and Clark [35] identify four effects: firstly, that it makes the resource cheaper so it's used more; secondly, that money saved is spent with negative environmental consequences; thirdly, that others absorb any slack in the resource; and fourthly, the myriad ways in which the global economy is effected by the change. Spreng has shown that, whilst the introduction of ICTs enables the saving of energy or time, people generally chose to save time at the cost of expending energy, so overall energy use increases as the economy speeds up and grows [36]. Essentially, the global economy is a highly complex system and the implications of a particular intervention are manifold and of limited measurability or predictability.

Berners-Lee and Clark argue that similar effects even apply to renewable energy [35], so "to tackle climate change we'll need to focus our attention on slowing the flow of fossil fuels into the global economy. That will require global politics. [So]…investing much more in research and development for clean power sources and energy-efficient technology will make it more politically feasible to constrain oil, coal and gas since it will allow cuts in fuel use to go in tandem with alternative ways of achieving the same levels of utility…[but] bottom-up progress can help unlock top-down action, but it won't be enough." Similarly Hilty observes "Harnessing ICT in the service of sustainability… only succeeds when the enormous efficiency potential of these technologies is not used under conditions of seemingly unlimited resource availability, but rather under exogenously imposed framework conditions thus turning natural limits into man-made policies." [11]

What can be done to tackle this infernal complexity? Maxwell et al. [34] recommend a mixture of policy instruments to tackle the rebound effect including technical and behavioural interventions and fiscal measures such as taxation that limit resource availability, as well as information sharing. Moreover, regulatory constraints on resource use also improve the profitability of resource-use interventions. Such regulatory changes require political support, which, in turn, rely on public opinion about the reality and importance of sustainability challenges.

So, resource-use focused technological approaches are unlikely to advance sustainability on their own because of rebound effects. If sustainability progress is to be made, it is necessary to both improve *resource-use* and support *broad sustainability* objectives such as education, behaviour change, innovation and political change. This implies that *ICT and web for sustainability* research should integrate the social sciences and even humanities, via interdisciplinary approaches, such as web science. The implication for the cleanweb sector (as discussed in the previous section) is the importance of developing *sustainability insight* and *sustainability network* systems, and not overlook them in favour of *resource insight* systems and *resource networks.* Innovative broad sustainability systems such as *Climate Colab* (which develops and prioritises public policy) are not peripheral to ICT and web for sustainability, but are vital to addressing rebound effects enabling high profile resource-based approaches (such as heating optimization system *Nest)* to fulfil their promise of significant sustainability outcomes.

XI. Conclusion

There are contrasting ways to understand the Web: as global technical infrastructure, the largest ever information construct, and as social new media. The Web is enabled by ICT but it is not identical to it; hence new interdisciplinary research approaches have arisen, such as web science, that go beyond computer science to compliment insights from engineering with those of social science and other areas. Existing communities of ICT for sustainability tend to focus on engineering and the individual user. In order to understand how the Web can advance environmental sustainability, novel approaches are required that also acknowledge *social communication*, its *content,* and especially its *massive scale and diversity.*

There is evidence of a rapid development of commercial activity and government interest in using the Web for sustainability, with communities developing internationally under the term *cleanweb.* In order to understand these developments, a set of relevant companies was identified by keyword searches of the CrunchBase database of technologies companies. Relevant systems were also identified from cleanweb communities. A brief quantitative analysis of CrunchBase generated an estimate of at least 2000 web for sustainability companies worldwide.

Through a grounded-theory-based [17] qualitative analysis of the descriptions of over 400 systems, this research has found that, in order to understand how the Web can be applied to advancing environmental sustainability it is necessary to consider both the web *means* and the environmental *ends*. On the one hand, the two ways in which the vast *scale* of the Web can be brought to bear to create either more valuable insight or relationships. On the other hand, the range in complexity of sustainability outcomes: from a narrow focus on resource-use to the broad physical and social complexity of sustainability. These two dimensions demarcate four contrasting domains of web for sustainability: *resource insight*, *resource networks*, *sustainability insight*, and *sustainability networks*. Current areas of activity within each are identified, and examples systems given. Just as successful teams are often said to require a mixture of personality types, all these domains have a significant role to play in web for sustainability. Defining them may support their development within and beyond practitioners.

Because of sheer complexity, it is probably not possible to determine whether the rise of Web *per se* will advance or hinder sustainability. Either way, it is beyond the scope of this investigation. Like any technology, the Web can be applied with different intentions and complex outcomes. However, the development of the Web offers new tools that can advance or impede environmental sustainability, whether for resource use or broad sustainability.

The Web's affordance to successful projects of rapid growth to global scales, at limited cost, is key. For businesses, this can make them more attractive to investment than the non-digital *cleantech*, such as renewable energy, with high start-up costs. Successful resource-use focussed web systems (such as ride-sharing) generate their own robust source of revenue to support rapid expansion by decreasing waste or increasing productivity. They are therefore prevalent in both commercial and academic web for sustainability. However, the ultimate sustainability impact of resource-use approaches is limited by rebound and related effects, due to the deep complexity of the technological, economic, social and natural systems being altered. This has to be tackled on all relevant fronts, and particularly the social and political challenges of sustainability. This poses difficult normative questions of less relevance to engineering and commercial actors. However, whether their work is ultimately to have a positive impact on sustainability depends on regulatory changes and political progress, in particular to limit the overall extraction and consumption of unsustainable resources. In addition, this will increase the commercial viability and competitiveness of these sectors with respect to traditional industry. Whilst *green ICT*, *cleanweb*, and indeed *cleantech* have primarily focussed on resource-use, the new interdisciplinary approaches, such as *web science,* are well placed to contribute as they straddle engineering, social sciences and humanities.

So, there is a need for *ICT for sustainability* to avoid focussing too narrowly on resource use. The normative questions of broader sustainability are unavoidable. The web is as relevant to this activity as to more positivist resource-use efforts, because it is not just a technical infrastructure but social new media, the site of "struggles of social beliefs and meanings" about sustainability [22]. The affordance of rapid growth to global scales at limited cost enables even non-profit donation supported systems such as 350.org to have a swift global impact. However, "modernist" attempts to "engineer" sustainable behaviour, political change or values with web technologies raise weighty ethical and practical issues beyond the scope of this paper. Whatever they do, web for sustainability practitioners have a responsibility to scrutinise the varied environmental, social and political implications, positive or negative, of any intervention, such as to privacy and autonomy [30], [37].

This research explores the nature of web for environmental sustainability through qualitative analysis of data describing systems and companies. These have been called cleanweb companies, and the definition of cleanweb is discussed and an estimate found of the number of firms (at least 2000). Two major dimensions of web for sustainability are identified: the web means (more valuable insight or relationships) and the complexity of the environmental ends (narrow resource-use or broad sustainability). These demarcate a matrix of four domains of web for sustainability systems (resource insight, sustainability insight, resource networks and sustainability networks). Each domain has a distinct and valuable role, and the complexity of environmental sustainability, and particularly rebound effects, create both congruities and interdependencies between them. Areas of current activity within each domain are identified, along with example systems. The matrix highlights the importance of innovation in *broad sustainability* web systems, not just in *resource-use* systems. It spans from engineering to the humanities, illustrating the need for interdisciplinary research approaches such as web science, in order to realise the transformative sustainability opportunities presented by the scale of the Web.

XII. References

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