Rethinking Sustainability in Computing: From Buzzword to Non-negotiable Limits

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ABSTRACT

Recent years have seen a flurry of work on sustainable computing and sustainable HCI, but it is unclear whether this body of work adheres to a meaningful definition of sustainability. In this paper, we review four interlocking frameworks that together provide a rigorous foundation for what constitutes sustainability. Each consecutive framework both builds upon and can loosely be seen as a refinement of the previous framework. More specifically, we leverage prominent ecological thinking from outside of computer science to inform what sustainability means in the context of computing. To this end, we re-evaluate some recent results from the field of sustainable HCI and offer thoughts on further research in the field.

Author Keywords

Sustainability; sustainable development; sustainable HCI; ecological sustainability, environmental sustainability; critical reflection; collapse informatics; limits to growth; steady-state economy; ecological footprint.

ACM Classification Keywords

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

INTRODUCTION

Sustainability is important. Indeed, the challenge of shifting individual, societal, and global behavior to halt climate change is said to be of crucial importance in the history of humankind according to world leaders as well as the Intergovernmental Panel of Climate Change [29, 30, 31]. In addition to this challenge, the world remains dependent on dwindling finite resources that have given rise to our advanced industrial civilization, including the advancements we have seen in computing over the last several decades [57].

Sustainability has lately become an important theme within every sub-discipline of computer science. The growing importance of sustainability can also be noted in Human-Computer Interaction (HCI) and related areas (e.g. Ubicomp, DIS, CSCW, Persuasive), with the boom in work on "sustainable HCI" following Blevis's widely cited 2007 paper "Sustainable interaction design" [4]. Sustainable HCI has since been the topic of numerous papers [11, 17, 22, 33]. Similarly, outside of HCI, the number of general or specialized "green computing" conferences has mushroomed. These are descriptive statements, but we also believe there is a normative corollary: at this point in time, the topic of sustainability *should* be central to HCI (both research and practice), computing in general, and most other applied academic disciplines.

Despite this growth of interest and work, there is little discussion about what actually constitutes sustainability (i.e. what we are aiming for). Sustainable HCI is furthermore for the most part ignore seminal papers, books, and discussion about sustainability from the past several decades [18, 20, 35]. Thus despite the need for a greater emphasis on sustainability in both computing in general and in HCI, we find that work with a sustainability mindset is rare, and that even when present, the meaning of "sustainability" is questionable. Worse still is that even papers that discuss "What are, or should be, the boundaries of sustainable HCI" [17], or that correctly observe that *others'* approach to sustainable HCI is misguided and "based on a limited framing of sustainability, human behavior, and their interrelationship" [11] themselves leave the concept of sustainability undefined. As a result, definitions of sustainability in the sustainable HCI literature have become so broad as to become meaningless.

In this paper, we aim to evaluate past approaches to the subject and incorporate sustainability thinking from outside of sustainable HCI. Our main contribution is to lay a foundation for Sustainable HCI and by providing a more rigorous definition of sustainability for Sustainable HCI, for HCI, and for computing in general. The four frameworks we present are Meadows et. al's. Limits to Growth [37, 36], Daly's Steady-state economics [14, 15], Wackernagel and Rees' Ecological Footprint [60] and Heinberg's five axioms of sustainability [24]. We believe that Heinberg's five axioms of sustainability—descending from and building on the previ-

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ous three frameworks—constitutes a reasonable definition of sustainability. Furthermore, we sketch some of the implications of such a definition for Sustainable HCI and Green Computing, but leave a full analysis of the implications to future work. What is proposed here is, unfortunately, a grim, slow foundation for Sustainable HCI.

The structure of the paper is as follows: we begin by discussing popular ways of framing sustainability within, but primarily outside of HCI. We then present four interlocking frameworks that we believe provide a rigorous foundation for what constitutes sustainability; each consecutive framework both builds upon and can loosely be seen as a gradual specification and operationalization of the previous framework. We then describe a few of the consequences of applying these frameworks. We end the paper by proposing avenues for further research in hitherto underdeveloped areas that we believe sustainable HCI should explore.

SUSTAINABILITY IN HCI

There are many different conceptions of what the term sustainability means and how it should be defined. Unfortunately, we believe many of these conceptions are in fact *misconceptions*. Sustainability is not equivalent to "decoupling" [51] or "dematerialization" [13, 44]—which describe processes—nor is sustainability an ongoing (prospectively negotiable) process. Neither is it a relative measure (e.g. "[referring] to practices that are reputed to be [somewhat] more environmentally sound than others" [24]) or "an emergent property of a conversation about desired futures" [47]. These conceptions of sustainability focus on potential consequences of normatively-desirable behaviors or characteristics, without ever addressing what sustainability itself is.

In this paper, we instead adhere to a concrete definition: *sustainability is an absolute measure and an end-state in which the Ecological Footprint [60] of humanity is below the regenerative biocapacity of planet Earth.* Next we review previous definitions and consider their strengths and weaknesses.

Previous Definitions

The most widely cited definition of sustainability is that of the United Nations Commission on Environment and Development 1987 report "Our Common Future" [10]. The report (also referred to as the Brundtland report) states that "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Joseph Tainter [53] has astutely commented that "[w]hile this definition will no doubt continue to be widely cited, it has limited operational usefulness. Befitting a political leader, the definition is too general to guide behavior". It should be noted that the terms "sustainability" and "sustainable development" often are conflated and used interchangeably, but the two terms actually have very different origins and are not particularly compatible [47]. The term "sustainable development", as referenced in the Brundtland report [10], is the result of a compromise between environment-first and economic development/social justice-first proponents. This uneasy compromise opens the term up for serious critique and Robinson [47] points out in great detail the various problems and weaknesses of the term "sustainable development" due to its vagueness, its implicit inducement to hypocrisy, and its fostering of delusions:

Vagueness. The term "sustainable development" means different things to different people and organizations. Different concepts tend to reflect a variety of agendas and beliefs and conflicts over the exact meaning of the term have been rife during the more than 25 years since it came into use.

Hypocrisy. The vagueness of the term opens up ample opportunities for "greenwashing', e.g. for appropriating green language to market or justify unsustainable practices and activities. Many if not most activities that really aren't, can seem deceptively green through the application of a thin green patina. A case in point are the marginal CO2 savings of airplanes' "green approaches" to airports as well as projects such as "EcoFly", "Project Green Flights", etc.[1]

Delusions. Biophysical as well as "social limits to growth" [28] are impossible to reconcile with increasing global industrial output by a factor of 5 or 10 (as was proposed in the Brundtland report).[2] The term "sustainable development" also signals a single-minded anthropocentric (humans-only or humans-first) focus.

Here we thus distance ourselves from the flexible-but-vague Brundtland definition as well as the "three pillars of sustainability" model [21] that emphasizes the balance or "trade-off" between ecological, social, economic sustainability that we don't believe go far enough. Despite this, it must (unfortunately) be acknowledged that it is not unusual for sustainable HCI papers to be built on an even flimsier foundation of what "sustainability" might entail. The concept of sustainability is oftentimes not so much defined and applied as it is invoked as a shibboleth to get a "free pass" as it is often assumed that decreasing the energy consumption of gadget X or habit Y by a certain fraction automatically represents sustainability. Or, alternatively, it is invoked to mean that any change for the better—no matter how small—constitutes a first step that will naturally lead to a sustainable society.

Such approaches for the most part assume that sustainability in computing is primarily a problem of optimizing, visualizing, or perfecting some isolated discrete gadget or (feedback) process, or that it is a relatively straightforward matter of persuading individuals to change their behaviours by "increasing awareness" (as criticised by [11] and others) on the level of the individual citizen and her behaviour (as criticised by [19] and others). Despite our sympathy for the approaches

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[1] Meanwhile, air traffic at the same time is expected to rise by an estimated 5% on an annual basis.

[2] The belief in "sustainable development" and continuous economic growth might furthermore distract us from real problems such as challenges relating to power, exploitation, and unequal distribution of wealth.

in question, perhaps there is—at least from a theoretical point of view—more to sustainability than choosing "simple living" [23] or adopting a "bright green lifestyle" [65]? Our critique shadows that of [33] (building on [32]), which states:

> "Sustainable HCI is premised in a set of modernist assumptions which prescribe a limited solution space and a particular strategy for garnering buy-in and enthusiasm. These assumptions are that people are rational, and determine the most beneficial actions to take with respect to their own self-interests. [...] These solutions can at best have an only minor impact towards any measurable sustainability goals, such as carbon emissions reductions; worse, they may reinforce a worldview and a set of values that is incompatible with sustainability and lead to a net negative impact for sustainability."

Many sustainable HCI approaches are thus deeply and problematically "presentist" (i.e. ahistorical), and narrowly based on minimal changes to the current state of affairs, as well as mired in the belief that "every little bit" makes a difference. David MacKay, chief scientific adviser to the UK Department of Energy and Climate Change, criticizes the "small changes can make a big difference" approach to energy savings. His conclusion is instead that "if everyone does a little, well achieve only a little" [34]. MacKay's suggestion is instead to start with "the big picture" and, with an open mind, work our way forward from it by counting on and exploring what the implications are. This is the approach we have adopted in this paper.

DEFINING SUSTAINABILITY

Widespread public awareness of the unsustainable nature of modern industrial civilization has existed for several decades. In the 1970s, eminent ecologists described the physical constraints placed upon industrial civilization by the ecosystem [1, 12, 63]. In this section, we review this ecological thinking and discuss four frameworks for understanding sustainability. First we provide an overview of the insights from these and other prior treatises, and then describe the four models in greater detail.

Overview

A key insight from modern work on ecology is the rediscovery of the fact that human life and the human economy are subsets of a global ecosystem: humans extract resources (matter and energy) from nature and return wastes back to nature. These two flows—input and output—are crucial, as they help us understand what it means for humanity to be sustainable. To say that something is sustainable is to say that it can persist for a long time, if not indefinitely. For the human economy to be sustainable, therefore, it must recognize two limits: 1) limits on the input rate (limits on resource extraction), and 2) limits on the output rate (limits on pollution). Due to their finiteness, the use of non-renewable resources is not sustainable. However, it is equally unsustainable to use renewable resources faster than their natural rate of replenishment. The same holds for pollution: producing non-assimilable wastes (i.e., wastes that do not naturally decompose on human timescales) is unsustainable, as is producing assimilable wastes (e.g., CO_2) faster than natural systems can absorb them.

Limits to Growth

With this understanding in mind, Meadows et al. [37] explored a variety of scenarios for the global economy in their classical modeling study *Limits to Growth*. Their aim was to examine how ecosystem limits placed limits on the global human economy. They found that if policies were to remain roughly the same ("business as usual"), the world economy would face a crisis and would decline in the early 21st century due to non-renewable resource depletion. If, on the other hand, more non-renewable resources were somehow found (for example new oil deposits), then the economic decline would be postponed only by a few decades and would be swifter when it arrived, manifesting as a pollution crisis. That is, the policies in place then—which are for the most part the policies still in place today—have boxed in the global industrial system: with "business as usual" we get to choose between Scylla and Charybdis, between a resource crisis and a pollution crisis. These relatively abstract terms are often thought of in terms of their more concrete instantiations, such as peak oil for the former (resource crisis) and climate change for the latter (pollution crisis). In addition, a key aspect of their modeling work was the inclusion of feedback loops and delays—the former can cause processes to amplify or decay and the latter are inherent in large systems and necessitate significant advance planning to shift course.

Many people erroneously believe that the Limits to Growth work made predictions for the future and that the model was a failure. Nothing could be further from the truth and recent re-evaluations of the model, especially of the business as usual scenario (the so-called "standard run"), have found that it has been remarkably accurate so far [59]. Meadows et. al. [36], in their 30-year update, concluded that it would have been possible to arrive at a sustainable state had major policy changes been implemented in the 1970s or 1980s. Unfortunately, those changes were not made and the global human footprint has since proceeded well into overshoot [12, 60]. Due to inherent inertia and delays in natural systems (e.g., the multi-decade delay between CO_2 emissions and climate change impacts) it is now no longer possible to avoid a decline. The challenge now is instead to ensure that the decline is a controlled descent that brings us to an attractive equilibrium.

Steady-state Economics

One of the foundations of modern thinking about sustainability is the work on steady-state economics by Herman Daly [14] in the field of ecological economics. While *environmental* economists had taken the necessary (but inadequate) step of acknowledging "externalities" that impact the environment in general, Daly and other *ecological* economists instead situated the human economy within the finite, global ecosystem. Where Meadows et. al. analysed and extrapolated (then-current) trends (with the help of computer modeling) and came to the conclusion that they were unsustainable, Daly further specified necessary conditions for what constitutes sustainability.

Daly identified what was obvious in retrospect—the hard reality that it is impossible for the economy (and for resource throughput) of a society to continue to grow forever: "For steady-state economics, the preanalytic vision is that the economy is an open subsystem of a finite and nongrowing ecosystem (the environment). The economy lives by importing low-entropy matter-energy (raw materials) and exporting high-entropy matter-energy (waste). Any subsystem of a finite nongrowing system must itself at some point also become nongrowing" [15]. Kenneth Boulding [9] concisely captures the same predicament in one short sentence: "Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist".

Daly's contribution to the line of reasoning we explicate in this paper was the realization that it is the "stocks", or what is sometimes called "natural capital", that need to be kept constant to achieve sustainability. One way to think of this is as a bank account where the savings in the bank account represent the renewable natural resources that exist (everything from groundwater reserves to fish in the sea). The goal in a steady-state economy is to maximize the long-term benefits rendered to society by both the economic system and the natural ecosystem in which it is embedded. With that goal in mind, the economy's rate of consumption (replacement of stocks) must be limited by both what the ecosystem can provide as constant income (e.g., solar energy) and by what it can accept as waste, so as to not draw down stocks (the bank account) below some given level.

Ecological Footprint

Meadows et. al. and Daly specified necessary conditions for what constitutes sustainability, but it can be hard to go from insight to action based on these ideas about "stocks" and "limits". While it might be possible to determine processes and practices that are unsustainable, it is harder to determine what exactly is sustainable and how to attain such a state. We mentioned earlier that we assume sustainability to be an absolute measure and an end-state in which the Ecological Footprint [60] of humanity indefinitely stays below the regenerative biocapacity of planet Earth. Wackernagel and his collaborators have spent the last 20 years measuring and counting just that [8, 61]: "The Ecological Footprint is a measure of the demand human activity puts on the biosphere. More precisely, it measures the amount of biologically productive land and water area required to produce all the resources an individual, population, or activity consumes, and to absorb the waste they generate, given prevailing technology and resource management practices" [54].

The Ecological Footprint (demand) of humankind is a product of 1) population, 2) consumption per person and 3) resource and waste intensity. This measure should ideally be matched by the global biocapacity which is the product of 1) area and 2) bioproductivity. The ecological footprint is measured in "global hectares", a unit that refers to the average productive capacity (bioproductivity) of land and sea areas on Earth in a given year (the productive capacity can increase or decrease over time). Since croplands and fishing grounds have a higher bioproductive capacity than deserts and glaciers, ten hectares of cropland provides more productive capacity (and more global hectares) than ten hectares of desert. The 2007 global biocapacity was 1.8 global hectares per person, but the Ecological Footprint was higher—2.7 global hectares per person. That is, humanity consumed ecological services at a rate that was 50% higher than the rate of renewal of these resources [54]. We are today thus living beyond our means and this is clearly an unsustainable situation.

It might seem counterintuitive that humanity ever could consume more biocapacity than what the planet can provide. This reveals a fundamental and often overlooked aspect of ecosystem dynamics that Meadows et. al. emphasized: that there exist fundamental delays in all ecosystems between action and reaction, and that it thus can take time for impacts to be seen (e.g. the impact of climate change). Similarly, Daly emphasized that it is possible to draw down the bank account of natural resources for an extended period of time before actually running out. Thus it is possible to overexploit the ecosystem for short-term benefits, while simultaneously degrading the long-term biocapacity through overfishing, overgrazing, deforestation, desertification, etc. Humanity's Ecological Footprint is furthermore increasing due to population growth and increased affluence (which leads to greater consumption) and many trends currently thus point in the wrong direction.

The Ecological Footprint is unevenly distributed and the lifestyle of the average American required 8.0 global hectares per person in 2007 [54]. This means that if everyone on Earth adopted the lifestyle of the average American, we would need the bioproductive capacity of four and a half planets. While the Ecological Footprint is powerful in that it defines the end-state/goal and allows for measurements of both the capacity and the demand of a geographic area (typically a country), it does not give clear instructions for how to decrease the Ecological Footprint so that it stays below biocapacity. We therefore turn to our fourth and final framework, Heinberg's [24] Five axioms of sustainability.

Five Axioms of Sustainability

Richard Heinberg's five axioms come from his 2010 text *What is sustainability?* [24]. To Heinberg, "The essence of the term sustainable is 'that which can be maintained over time.' By implication, this means that any society that is unsustainable cannot be maintained for long and will cease to function at some point." While the time dimension might cause some uncertainty (how long is "over time"?), Heinberg suggests it is reasonable to put this in relation to the duration of prior civilizations. Such civilizations have endured from hundreds of years to thousands of years and a "sustainable society, then, would be able to maintain itself for many centuries at least." One example is the ancient Egyptian civilization that coalesced around 3150 BC and came to an end not because of environmental degradation, but as an effect of military conquest when it became a Roman province (and a granary for Rome) in 30 BC.

Heinberg suggests a minimal set of five axioms that together define sustainability:

1. Any society that continues to use critical resources unsustainably will collapse.
2. Population growth and/or growth in the rates of consumption of resources cannot be sustained.
3. To be sustainable, the use of renewable resources must proceed at a rate that is less than or equal to the rate of natural replenishment.
4. To be sustainable, the use of nonrenewable resources must proceed at a rate that is declining, and the rate of decline must be greater than or equal to the rate of depletion.
5. Sustainability requires that substances introduced into the environment from human activities be minimized and rendered harmless to biosphere functions.

There are a few additions to these axioms. For the first axiom, an exception is given ("A society can avoid collapse by finding replacement resources") as well as a limit to that exception ("In a finite world, the number of possible replacements is also finite"). Heinberg furthermore explains that a society that uses resources sustainably is not immune to collapse—it can collapse for other reasons such as an overwhelming natural disaster or a conquest by hostile civilizations. Still, Heinberg's first axiom "focuses on resource consumption because that is a decisive, quantifiable, and, in principle, controllable determinant of a society's long-term survival." Heinberg also develops the argument about nonrenewable resources (axiom 4) as follows: "No continuous rate of use of any nonrenewable resource is sustainable. However, if the rate of use is declining at a rate greater than or equal to the rate of depletion, this can be said to be a sustainable situation because societys dependence on the resources will be reduced to insignificance before the resource is exhausted."

Below we sketch some of the implications of these four frameworks for HCI and Sustainable HCI and for (green) computing in general. While this paper represents a foundation for discussing sustainability in computing, a treatment of the *implications* and *applications* of this framework is currently being prepared and will be published in a companion paper.

RE-EVALUATION OF PRIOR WORK

Sustainability is relatively easy to define at the macro level—as shown above—but it is often difficult to identify exactly whether a specific project does or does not contribute to the macro vision. A key challenge is identifying intentional and inadvertent "greenwashing" where something is described as "green" or "sustainable" but is in reality not.

Beyond this paper, our goal is to help develop approaches and metrics for building sustainable systems; however, this is an involved subject and is beyond the scope of this paper. In this section we focus on more modest goal: to understand where recent work in Sustainable HCI and Green Computing has missed the mark, and to extract lessons from this re-evaluation.

Smart Homes

Smart home systems have been a popular research area in Sustainable HCI and Green Computing. A common model is a smart home system that involves a number of sensors and devices scattered throughout the home, and a display that indicates the home's energy consumption. If such a system, which aims at decreasing energy use by increasing awareness and by eliminating inefficiencies like heating or lighting a home where there are currently no inhabitants, is considered only from the usual perspective of electrical energy consumption, then it is likely to be beneficial. However, the devices themselves have embodied energy costs that are ignored in most work in Sustainable HCI and Green Computing: the energy that goes into designing, manufacturing, distributing, installing, servicing and, eventually, disposing of the devices [25]. Although seldom specified, there is also some time span after which the devices must be replaced (perhaps as short as a few years). We should thus also consider the embodied energy of the larger smart home system and if it is greater than or equal to the savings the system was supposed to produce, then it is most certainly not beneficial; if the benefit is found to be slim, then the materials impact of the devices must be considered, as natural resources for manufacturing are limited and e-waste is a growing source of pollution worldwide. It is natural for HCI researchers to concentrate on building (hopefully power-stingy) software and systems. Still, one of the leading researchers in the area of ICT and sustainability states that "As a rule of thumb, the length of the useful life of most ICT devices is more important than their power consumption during use" [27]. This may sound self-evident, but there is no lack of studies that conveniently forgets to mention or to take the embodied energy of systems and devices into account. It is certainly easier to measure energy flows when the system in question is in use rather than to try to take stock of and measure embodied energy—for example through Life-Cycle Analysis (LCA) [25].

Svane [52] studied Stockholm's Hammarby Sjöstad, "one of the world's highest profile examples of Sustainable City Development". Planning started in the early 1990's and construction began in 2000. Svane was specifically interested in the area's (government-subsidised) environmental profile and environmental goals—some of them having been targeted towards ICT, "smart homes" and "smart infrastructure"—in order to understand whether their goals had been attained. Looking specifically at smart infrastructure which "makes it easy for users and managers to keep energy use and its impacts low, without compromising utility or comfort", he found that elements of smart infrastructure was found in 8 houses, or, around 5% of the flats that had been built. Unfortunately, "In one case the interactive ICT for management was just prepared for, in another it was accidentally [permanently] disconnected. [...] Some of the designed smartness was never installed, a few elements were defective or have become outdated. Board members and managers in three of the studied housing cooperatives are uncertain if part of their smart infrastructure is functioning as intended" [52]. Svane points at the need for maintenance, development and education (of building managers) if smart infrastructure is to stay smart (and if it is to be utilised in the first place). Smart home technologies with short life spans were furthermore "integrated into the buildings' walls that have a very much longer service life, without due consideration on how to dismantle the former." If a building is to stand for at least 100 years, how many times should the ICT infrastructure (built into the very walls) be replaced and what are the implications from a sustainability point of view?

It is in the end hard to deem this high-profile project a success. One measure of energy use was defined in absolute terms; the total need for supplied energy should not exceed 60 kWh/m^2 per year but only one single (passive) house manages to reach that goal. Previous research shows that the energy efficiency of buildings in Hammarby Sjöstad are comparable to other buildings from the same period of time. Furthermore, "If energy use for heating and hot water is measured in terms of kWh per person and year", this newly-built area is, despite its environmental profile, no better than the neighboring Södermalm—predominantly comprised of buildings from the early 20th century but also with buildings from the 17th century and on. While houses that were build 100 years or more ago are less energy efficient than modern buildings, each resident of Hammarby Sjöstad on the other hand utilizes ca. 30% more of heated area than the average Södermalm resident" [52].

While this conclusion seemingly falls outside the area of ICT and computing, it points at the problems of drawing tight boundaries around the systems studied.

Tight Boundaries

The most broad and common source of unsustainability in sustainable HCI is a lack of holistic thinking. Sustainability requires an understanding of a system's inputs and outputs, and its systemic effects, rather than selectively ignoring those factors most harmful to measuring the gains (using the selected, and perhaps biased, metric of choice). Yet, it is too often the case that computing systems that purport to be "green" or "sustainable" selectively draw a tight boundary around the implemented system in question and then proceed to ignore important but "problematic" input and/or output flows.

While it is always commendable to reduce the energy consumption of a selected gadget or process by 10%, or to shift demand to better match the natural cycles of renewable energy generation (for example by using household machinery when the sun shines or when the wind blows), other factors and trends of equal or larger importance might weigh heavier such as "second order" [6] or "rebound effects" [26, 39]. One such example is the previously-mentioned gains in energy-efficiency being squandered by building larger apartments. Another is the efficiency gains of more energy-efficient internal combustion engines being squandered by building larger, heavier cars (with more elaborate electronics and in-car entertainment systems). In general, "Environmental impacts that arise when technologies co-evolve with everyday practices are not easily predictable. This seems to be one reason why the existing literature [...] contains relatively few or vague recommendations to policy-makers and other stakeholders" [6]. The fact that these are difficult problems and that few recommendations exist is however not a good enough reason to not take these factors into account when we design and deploy ICT systems. In a paper that reviews and discusses second order/rebound effects [7], no less than 11 different such effects were identified beyond two first order effects ("direct effects" and "substitution effects"), for example time, space, direct economic, indirect economic, economy-wide and transformational rebound effects, induction and rematerialisation effects, and changed practices.

Non-constructive Approaches

The pre-analytic vision of computing and HCI *cannot* be that a system always has to be built (despite the fact that that is what we as a community do) [17]. If sustainability is an overarching societal goal and ICT is to be a means to reach that goal, we must also be able to stop, take stock of the situation, and come to the conclusion that at some times and in some places, the implication can be to not design technology [2]. Baumer and Silberman [2] suggest "three specific questions to help articulate when, how, and why a technological intervention might be inappropriate" of which the first is "Could the technology be replaced by an equally viable low-tech or non-technological approach to the situation?" In the smart home example above, alternatives could for example be to build ("high-tech") advanced passive houses or ("low-tech") clay or cob houses [5]. An energy-saving solution that would always be appropriate is to make do with less, i.e. to build smaller houses and apartments. We argue that by widening the system boundaries and by adopting a more holistic perspective, radically different solutions might become conceivable or even apparent. This also implies that while there will always remain problems for computer researchers and professionals to solve, not all problems are necessarily best solved by the application of ICT/computing power or "high-tech" solutions, as evidenced by the title of the paper "Mate, we don't need a chip to tell us the soil's dry" [38].

For example, there has been significant recent interest in the community in "persuasive" approaches to sustainability, in which users are made aware of something via a new interface or device in the hope that this will persuade to change their behavior. Brynjarsdóttir et. al. [11] recently examined 86 papers from CHI 2009-2011 with the terms "environmental" and "sustainability". Of these, almost half (38) also included the term "persuasive". Many papers in the literature are about "eco-feedback" systems. The hope is that people will change their behavior as soon as the new system provides them with relevant information—for example by helping them visualise the electricity consumption in their home. Such persuasive systems are not unsustainable in and of themselves, but can be so due to a) often choosing the wrong goals (i.e., decrease the energy use by marginal percentages), and b) the systems themselves often require building new devices or interfaces, which has an impact that may not be outweighed by the benefits.

Persuasive systems have lately become an overwhelmingly common goal in (sustainable) HCI. The emphasis is most often on the systems themselves, often without an evaluation that sufficiently determines the impact of the system. Specifically, little evidence for long-term behavioral change is offered "in any of the papers we reviewed" [11][3]. Worse still are papers that only aim at increasing "awareness" (i.e., have no particular measurable goals—how do you evaluate the success of such a project?). Such systems have clear means but unclear ends—it is simply *assumed* that building a new system is better than not building it—are unlikely to be sustainable.

ECOLOGICAL VERSUS SOCIAL SUSTAINABILITY

We have thus far exclusively discussed ecological sustainability and the astute reader might wonder about the absence of social sustainability. Are issues such as social and environmental justice, equity and equality, human and labor rights unimportant to us? They are not unimportant, but they are on the other hand not essential to how we define sustainability here. A sustainable society is a society that could persist for a long time, if not indefinitely, and a society that would be able to maintain itself at least for many centuries. We mentioned that the ancient Egyptian civilization thrived for more than 3000 years before Egypt was conquered by Rome. The ancient Egyptian civilization was thus sustainable, but it was also a very unequal society: "During the age of the Pharaohs and the pyramid projects, ancient Egypt had a population of 3 million. About 95% of society was involved in agriculture. The surplus energy of about 5% was utilized for the Pharaohs and the great pyramids" [43]. We share Heinberg's perspective [24] of assuming that non-ecological factors are important but secondary: "The purpose of the axioms set forth here is not to describe conditions that would lead to a good or just society, merely to a society able to be maintained over time. It is not clear that perfect economic equality or a perfectly egalitarian system of decision-making is necessary to avert societal collapse."

If we on the other hand would manage to attain an ecologically sustainable society, what would we use our energies on but to work towards social sustainability? Daly [15] sketches a picture of what challenges a sustainable society could occupy itself with: "What is it precisely that is not growing, or held in a steady state? Two basic physical magnitudes are to be held constant: the population of human bodies and the population of artifacts (stock of physical wealth) [...] Of equal importance is what is not held constant. The culture, genetic inheritance, knowledge, goodness, ethical codes, and so forth embodied in human beings are not held constant. Likewise, the embodied technology, the design, and the product mix of the aggregate total stock of artifacts are not held constant. Nor is the current distribution of artifacts among the population taken as constant. Not only is quality free to evolve, but its development is positively encouraged in certain directions. If we use "growth" to mean quantitative change, and "development" to refer to qualitative change, then we may say that a steady-state economy develops but does not grow, just as the planet Earth, of which the human economy is a subsystem, develops but does not grow" [15].

A steady-state society could thus be a society that incorporates a lean use of resources and where quality, stability, functionality and durability is held in higher regard [4, 49] compared to an unsustainable growth- and resource throughput-oriented planned obsolescence-society, seee [40, 41, 3, 66] and others. Although this paper focuses on the macro level, at the micro level of individual behavior Walker [62] comments on how it seems that "our gadgets can't wear out fast enough", and that it's nowadays not unusual for affluent consumers to have a "gadget death wish", a wish for gadgets to wear out or break down as soon as a new generation of hardware/gadgets is released. This observation (durable quality vs. planned obsolescence) does not need to be limited to physical artifacts but could equally well be applied to computer hardware and software. We would do well to remind ourselves that: "For the greater part of human history, labor has been more significant than tools, the intelligent efforts of the producer more decisive than his simple equipment. The entire history of labor until very recently has been a history of skilled labor" [48].[4]

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[3] Indeed, it is quite possible that the systems are quickly abandoned by the researchers as well as by the users.

[4] This is not to romanticise pre-industrial societies, but to note Sahlins's reminder that there are two courses to affluence: the Zen

CONCLUSION

Our main observation is that sustainability is not inherently hard to define at the macro level—quite the opposite. Sustainability is a state in which the Ecological Footprint [60] of humanity stays below the regenerative biocapacity of the planet. The problem is rather that the frameworks and definitions we have presented in this paper inevitably have unpalatable consequences in terms of requiring major changes on individual, collective, institutional (including academic, research, and corporate), societal, and international levels. Nevertheless, the frameworks and definitions we have presented are grounded in ecological reality, which we believe must be the starting point of any real effort in sustainability research.

Due to limitations in space, we have here concentrated on laying the foundation for further work in sustainable HCI by defining what constitutes sustainability *at the macro level*. We know this limits the scope of the paper and that it makes it more directed at people who are already active within sustainable HCI and who can ”fill the gaps” between theory and practice on their own. We are aware of the fact that the paper might be less useful for system-builders and people in search of concrete advice on ”how to do sustainable HCI right”. A fuller range of concrete examples of implications and applications of the foundation presented here will be explicated in a companion paper that is under preparation.

While remaking today’s unsustainable societies and shifting today’s unsustainable trajectories represents a daunting task as well as a break with centuries-long processes and entrenched mindsets, we still believe we have no other option than to face those monumental challenges. Part of the task is to find ways to reformulate today’s problems first into challenges and then into possibilities. We believe that HCI and computing will remain very important for a long time and that there are numerous challenges that our community could and should work on [64, 46, 45, 58, 56, 55, 42, 50, 67], but, that these challenges are oftentimes radically different from the current thrust of research and development.

Still, we believe that HCI is well positioned or perhaps even in a unique position to make a difference since “HCI researchers and technologists [not only] have the ability to shine a light on society’s problems, [but also to] provide platforms that enable individuals and groups to act on today’s problems” [16]. Before we can do that, we however first have to acknowledge that sustainability in the early 21st century means adapting to a reality of limits, of trade-offs, and of hard choices. This makes sustainability a revolutionary project and at this point we beg to differ from the mainstream sustainable HCI evolutionary agenda. The task facing us as a community at this juncture should not be to tiptoe towards sustainability, but rather to immerse ourselves in “the study, design, and development of sociotechnical systems in the abundant present for use in a future of scarcity” [58].

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road to affluence through desiring little and easily satisfying the resulting needs, or to assume that our “wants are great, not to say infinite, whereas [our] means are limited, although improvable” [48]. Although our means are improvable, our wants always seem to be just out of reach, forcing us to run faster and faster just to remain in the same place.

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