Resource Scarcity and Socially Just Internet Access over Time and Space

Daniel Pargman
KTH Royal Institute of Technology
Stockholm, Sweden
pargman@kth.se

Björn Wallsten
Linköping University
Linköping, Sweden
bjorn.wallsten@liu.se

ABSTRACT

Computing within Limits is concerned with "the impact of present and future ecological, material, energetic, and societal limits on computing". This paper discusses limits to computing by adopting a resource perspective on the provisioning of infrastructure for computing with a particular focus on present and future availability of material resources such as minerals and energy. While making claims about resources in general, we use copper as a specific example of coping with finiteness. The first part of the paper summarizes known facts but it is also a set-up for the latter part of the paper where we problematize the concept of "innovation" and argue that the term needs to be both refined and broadened to also take scarcity and just access to resources into account. We suggest that in a resource-constrained world and in the area of computing, a suitable goal for innovation should be to guarantee (to the largest extent possible) internet access over space and time, e.g., to the largest number of people and for the longest duration of time.

CCS CONCEPTS

• Social and professional topics~Sustainability

KEYWORDS

Sustainability; Infrastructure; Maintenance; Copper; Innovation

1 RESOURCES, INFRASTRUCTURE, AND COMPUTING

The process of transferring materials from the Earth's crust to our built environments has accelerated dramatically since the Industrial Revolution. A speed-up since the post-World War II period has been called "the great acceleration" [24, 56] and it has been argued that the planet has now entered a new geological era, the Anthropocene [57]. The Anthropocene is characterized by humankind being the most prominent force of geological change, and our collective actions now have a global impact on the Earth's ecosystems. Driven by widespread industrial activity and rapid urbanization, the Anthropocene is in many ways intertwined with the construction of the technological backbone which cities in industrialized societies rely on, i.e., infrastructure. Infrastructure — planetary networks of nodes and flows of immense variety — is the operating system of global society, setting the rules that govern our everyday lives. The size and scope of our infrastructure — the technosphere and its "technomass" as Hornborg calls it [26] — has grown in continuous lockstep with an increased use of the energy required to extract resources necessary for its construction and upkeep.

Infrastructure in general as well as the latest addition to the infrastructural palimpsest — the Internet — is hidden away under streets, inside walls, or, in the case of Wi-Fi, pervading the air in homes, cafés, and public spaces [36]. The Internet relies on vast networks of cables, wires, electricity, and cooling to make communication through and between digital artifacts (routers, servers, laptops, smartphones etc.) possible [36]. Since its inception, computing has increased in scope and in importance by leaps and bounds [9, 22], and progress in computing has often been "explained" by referring to Moore's law, i.e., computational power (or more specifically, the number of transistors on an integrated circuit) doubles every 18-24 months [51]. Moore's law has been used to guide the semiconductor industry. The general public often perceives it as a rule-bound law, but there are signs that the exponential growth of the last few decades has, or is, slowing down. While some [61] have questioned the validity of Moore's law (e.g. is it really true that computational power has doubled repeatedly for decades?), it is beyond doubt that developments in the area have been explosive. With the advent of cloud computing [8], computing is rapidly taking on characteristics of other utilities such as electricity or running water — a flick of a switch opens a flow of computing power that comes from some unknown (and possibly distant) elsewhere.

Due to the everyday invisibility of radio waves, hidden-away routers, coaxial cables, network access points, and Internet exchange points, many people mistakenly believe that the Internet and digital technologies do not have an ecological footprint, or that its footprint is infinitesimal and negligible [10]. Eco-critical thinkers and media theorists have, however, explored the material underpinnings of ICT and, for example, highlighted the inextricable

LIMITS'17, June 22-24, 2017, Santa Barbara, CA, USA.

ACM 978-1-4503-4950-5/17/06…$15.00
http://dx.doi.org/10.1145/3080556.3084083

connections to e-waste proliferation [21], the specifics of labor in toxic residue processing [18], and how the benefits and costs of computing are unevenly distributed. Ecological World Systems Theory views technological development partly as a zero-sum game and focuses on the uneven global distribution of environmental degradation, where degradation tends to happen in those places that have benefitted least from technological developments, including progress in computing [25, 27, 33]. If we look to the future, it is thus easy to realize that computation in general and hypes around (for example) the Internet of Things, Big Data, augmented reality, and self-driving cars, are dependent on a vast material/physical infrastructure, and, that the task of upholding and extending our infrastructure for computing comes with high material and energetic requirements.

While Life-Cycle Assessment (LCA) is a well-known methodology to map energy flows and CO2 emissions over the life cycle of a product or service [23], studies of the total sums of different materials required to manufacture the world's product base are rarer. Quite unlike LCA, the typical material flow analysis (MFA) often takes some kind of material (such as metals) and their circulation within a large geographical area as its starting point, instead of starting with a particular object of inquiry (e.g., infrastructure, a business sector, cars or routers). Bottom-up MFAs rely on product sheet information and estimates of the prevalence of a product to calculate stocks from the ground up [63]. Based on such studies we now know that the accumulation of metals in urban locales can be more than a hundred times higher than in rural areas [65], making cities the heaviest things humankind has ever built.

The average ICT device contains significant amounts of aluminum, copper, and iron, as well as the geochemically scarce metals gold, silver, and palladium [66]. Looking specifically at circuit boards, the number of materials that goes into their assembly has increased from a mere four in the 1980's to more than 45 twenty years later (McManus, quoted in [31]). In their paper on the material dependence of ICT, Raghavan and Hasan [45] enumerate a long list of more or less exotic materials, pointing out how these materials often come from geopolitically unstable areas and how this constitutes a threat to the stable provisioning of Internet services. While there are detailed studies of mineral use, energy use, and GHG emissions of manufacturing various gadgets (for example, a specific smartphone, see [16]), the research community has thus far not been able to come up with a good estimate of the total weight of the Internet.

2 COPING WITH FINITENESS

Switching the focus from demand to supply, we here discuss one limited quantity that ICT developments will need to handle during the remainder of the 21st century. While our arguments are applicable to resources in general, we have singled out copper in particular as an example. Copper is the third most–used metal in the world, it is a malleable and ductile metal, and, as an excellent conductor of electricity, it transmits nearly all the world's power [32]. Consequently, copper is indispensable for the Internet's functionality.

The world's best and highest-concentration ores have already been depleted for many minerals and the predominant mineral resource extraction strategy of the 20th century assumed that technological developments would safeguard our continued ability to economically extract minerals from bedrock with ever-decreasing ore grades [40]. This strategy would, in theory, guarantee a mineral resource base that is forever sufficient in comparison to future global demand. The success of this paradigm has depended on a great historical exception, namely the continued availability of cheap and abundant energy supplies in the form of fossil fuels. The importance of inexpensive and plentiful energy is something that tends to be forgotten in the default worldview of most mining economists and prospectors. The fact that the age of fossil energy by necessity is transitory [60] should instead be ever present when we think about and plan for the future. As historian Rolf Sieferle has pointed out, the finiteness and exhaustibility of fossil fuels set distinct limits, effectively making a society built upon a fossil energy regime a transitional society as "*no stationary state is possible based on fossil energy; when this system has reached its limits, a new contraction must set in"* [53, p.197].

If energy requirements are added to the extraction equation, the longer–term prospects for mineral extraction become gloomy [54]. The combination of decreased ore grades and the fact that fossil energies inevitably will become more expensive and/or scarce means that the production of minerals will decline. Taking copper as an example, the value of low–grade ores currently mined will in a not too distant future no longer economically justify the expenditure of energy needed to extract and refine them [2, p. 158]. We will, in other words, run out of the energy and money needed to produce copper long before the planet "runs out of copper" [59]. The best material substitute for copper is aluminum. Aluminum is also the better environmental choice [41], though it has significant disadvantages and substitution tends to be a costly and time-consuming process due to path dependencies and various technical difficulties [39]. Scarcity and energy requirements aside, large-scale mining processes also have enormous environmental consequences and are oftentimes accompanied by major social disruptions [3]. This constellation of factors undermines mining companies' future possibilities to acquire their (already contested) social license to mine [42].

We have thus noted that there are several reasons to dismiss the future success of the traditional extraction strategy (i.e., "the extractivist paradigm"). In terms of copper, 550 Mt of copper has been extracted globally between 1930 and 2011. 530 Mt is estimated to remain for future exploitation. The term "reserves" denotes quantities that are economically justifiable to extract, and reserves, therefore, increase when energy prices decrease or when mining technologies improve, but that reserves will decrease if (or when) energy prices rise. To summarize, more than half of all copper that will ever be produced has already been extracted [55] and is either in use or can be found in abandoned infrastructure, in landfills, or in scrapyards. Copper production has been predicted to peak before 2020 [67], and while the size of remaining copper deposits does not indicate immediate supply risks in a short–term perspective [1], the possibility of scarcity of future supplies creates room for discussion about the unequal distribution of the global copper stock. In 2000, the per capita in–use stock of copper varied from 30–40 kg per person in countries in the Global South to 140 to 300 kg per person in the Global North [19]. Sweden has been estimated to have 189 kg of in–use copper per person [48]. Based on an estimated future global population of ten billion, Exner et. al. [17] arrive at an approximate average of 100 kg per person if all of the planetary copper stock were to be extracted and then distributed equally.

3 WHY SUSTAINABLE COMPUTING AS WE KNOW IT IS UNSUSTAINABLE

What are the implications of resource scarcity in relation to limits within computing and to ICT for Sustainability (ICT4S)? What needs for actions can be envisioned? While all processes that use non-renewable inputs (energy, material resources) are by definition unsustainable, it is possible to posit different degrees of unsustainability. The infrastructure for computing (as an example of industrial production in general) builds on linear flows starting with resources becoming products that are later turned into waste. Growth of linear industrial production processes is, of course, unsustainable, but exponential growth is yet more unsustainable. The absence of growth, i.e., a steady-state economy [11] is less unsustainable, but the steady state might be situated either at a higher (Western, affluent and more unsustainable) level or a lower (sustainable or less unsustainable) level. Any model of growth (including the absence of growth) will, however, be unsustainable if the production of goods builds on a linear flow of non-renewable resources (see Figure 1).

Alternatives to linear processes are found in ideas about the Circular Economy [34] and related concepts such as cradle to cradle design [38] or biomimicry [4]. These schools of thought aim at keeping products, components, and materials at their highest utility and value at all times (see figure 2). On top of designing things to last, this means we should prolong the lifespan of products by primarily *repairing* (or sharing) them and otherwise (in order of decreasing desirability) through *reuse* (redistribution) or *refurbishing* (remanufacturing). The last remaining option — with the exception of disposal — is to *recycle* materials [34]. The end goal of a circular economy is to produce products that do not become useless waste, but that can instead decompose and become nutrients for the soil or that can supply new industrial cycles with high-quality raw materials. The main challenge becomes to husband resources in such a way that the benefits of modern (digital) technologies can be extended to the largest number of people as far as possible into the future.

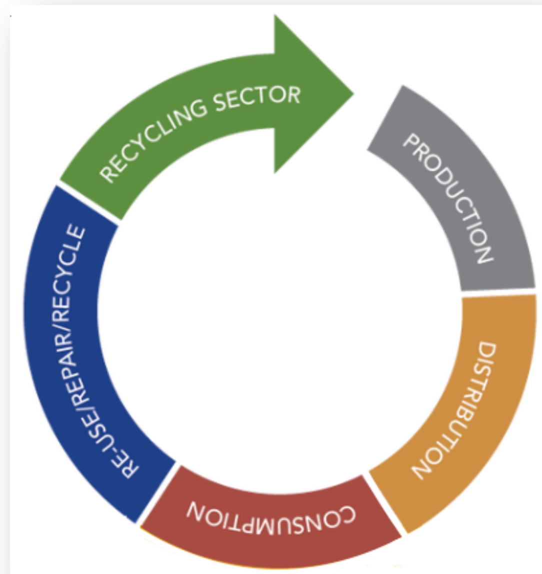

Figure 2: A circular flow of non-renewable resources.

Computing can in its current form not easily be adapted to circular economy concepts. Various attempts to prolong the lifespan of digital products are summarized by [49], e.g. “pleasure engineering”, “heirloom status”, “ensoulment”, “slow design”, “new luxury” etc., but the current trajectory in computing is to always invent and produce more advanced and complex products.

A more circular economy-compliant model would instead insist on figuring out clever ways to deliver the same (or similar) functionality but at a lower cost in terms of resources, emissions, complexity, expenditures etc. Recent work that points in that

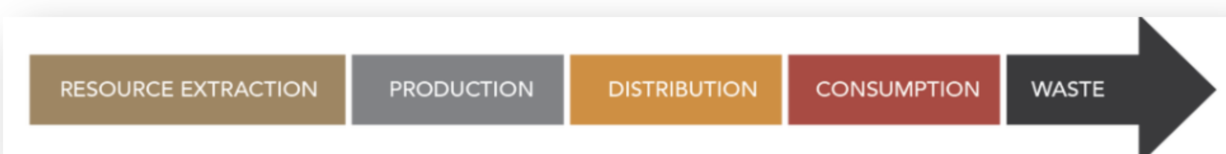

Figure 1: A linear flow of non-renewable resources.

direction suggests we should "refactor" systems [46] and "disintermediate" services [47]. While using software engineering (code) as a template to talk about larger (computing) systems, the idea of refactoring could be applied also to other products, systems, and services:

"*The resulting system* [...] *will not only be more robust and easier to improve and maintain, but will result in lower costs* [...]. *Some refactoring requires the elision of previously desired functionality in a deliberate simplification that may result in fewer features but a more streamlined system*" [46].

4 TECHNOLOGY AND RESOURCE LIMITS

The challenges we face are in one sense impossible to solve. Exploiting non-renewable resources is a story that can only have one end as every mine will invariably yield diminishing returns in terms inputs (energy and ore grades) and outputs (copper, iron, silver etc.). Greer's [20] distinction between problems and predicaments is useful for framing any advice given in the current situation. While a problem can be solved once and for all, a predicament can only be handled in better or worse ways (or, in bad and worse ways). Resource depletion can not be "solved" but has to be "handled".

Our best advice is that we should regard society's material build–up as a resource base that can be recycled/exploited. Apart from the stuff that we have exiled beyond the planetary boundaries and into space, nothing we have ever dug up from the Earth's crust has disappeared, it has just been rearranged. Some of it is disseminated and much harder to get at, but much is stocked in different societal "storage facilities" that might eventually be mined. An added benefit is that this can be done in ways that are significantly less environmentally detrimental than extracting additional resources from the Earth's crust.

The possibility of regarding cities as a resource base was elaborated upon by the urban theorist Jacobs [30] almost 50 years ago. She observed that cities generate a materials surplus due to continuous inflows of goods and materials and, that these, in theory, could be recycled. Unlike a mountain's mineral veins that will eventually be exhausted, she optimistically suggested that the urban overflows could "*be retrieved over and over again*" [30, p.111].

Transferring these arguments to the infrastructure sector, Swedish 'urban mining' research has shown that disconnected parts of larger systems that still remain underneath city streets, so-called "urks"[1] [64], might contain as much as 25 kilos of copper per Swede. If we additionally add those parts of the system that are expected to be cut-off (e.g., that have reached their expected lifespan or that need to be replaced for other reasons), we instead arrive at quantities which are of the same order of magnitude per person (approx. 50 kg) as the amount of per capita in-use stock of copper in the Global South [19]. Disconnected stocks of infrastructures are thus not only an example of industrialized societies' persistently wasteful use of mineral resources, they are also problematic from a global justice perspective, implying that preventive measures should be taken towards further "urk accumulation". An inward turn towards the built environment is imperative in order to extend our current use of resources in time and space.

It should be noted that only 4% of the Internet is estimated to specifically consist of copper. Among the remaining 96% of Internet materials there are those that face similar obstacles in relation to various limitations (e.g. rare earth minerals which are even harder to find in sufficiently concentrated ore grades), and others that do not (e.g. aluminum which is widely available given the generous availability of bauxite ore). We might compare different aspects of their respective criticalities and for example weigh in their scrap value (for recycling reasons), environmental burdens of further extraction (for social acceptance reasons), geopolitical concerns (for supply side reasons) as well as other factors. Due to the heterogeneous material basis of ICT, concern about scarcity is a complex matter, but the implications of looking specifically at copper are relevant as an entry point for further discussions.

Assuming we go after the low-hanging fruit first, we will at some point (or continuously) have to make hard choices between different kinds of services and infrastructures. It will come to choosing between different ways of using limited resources, e.g., what infrastructure to maintain and what to let go of, both within and between different sectors. We expect non-continuation of infrastructure and services to initially be a slow and painful process of "deferred maintenance" rather than the result of actual decisions about what to let go of. Assuming emergent tensions do not lead to a collapse of various parts, or of the larger system, there might be conflicts between, for example, spending resources (such as oil) in the food sector, in the health sector, or on transportation, petrochemicals, or ICT. It would be illuminating to study how countries that have fallen upon hard times (e.g., Greece) have chosen to prioritize spending. This is, however, an endeavor that should be undertaken with care since current outcomes presumably are the fallout of *not* carefully considering what decisions to make and how to prioritize.

5 SUSTAINABILITY AND ENVIRONMENTAL JUSTICE

The academic area of environmental justice [7, 37] has often been concerned with the question of where waste — toxic and otherwise — "ends up". It should come as no surprise that the undesirable detritus of industrial society often ends up near places where poor

[1] "Urk" is an abbreviation of "urkopplad" [disconnected], i.e., the term printed on maps of the urban underground infrastructure.

people live, and this is true both within as well as between countries.

A related question that has drawn less attention is where resources come from and where, in the form of infrastructure, they end up. Most of the copper, as well as other valuable materials, have ended up in the Global North, but how exactly did that happen? Was it the case that the most promising sites for extracting valuable materials happened to exist in the Global North? Not exactly. The answer is rather that global trade, according to the theory of unequal exchange [15, 62], can be regarded as rigged. While the value of poor countries' exports of raw materials on paper, for the most part, is near equal to the value of imported finished goods, the aggregate flow of raw materials is decidedly unidirectional, as has been shown through environmentally-extended, multi-regional input–output (EEMRIO) analyses [13]. Such material flows have, over time, led to the build-up of societal stocks of copper and other valuable materials in affluent countries rather than in the countries where these materials were mined. Since cradle to cradle design is, for the most part, focused on product design (e.g., how can we design a carpet that is biodegradable?), it does not extend to, or particularly fit, arguments having to do with justice or unequal exchange. We do, however, believe that cradle to cradle principles could be extended to encompass issues *surrounding* the product design process, e.g., where do resources come from and where do they end up?

Let us assume that global social sustainability and environmental justice are just as important as ecological sustainability. Would this assumption not imply that we should then strive for a more even distribution of resources across the globe? If all the copper that has ever been extracted amounts to 100 kilos per person on Earth, should we not then strive to distribute those and other resources more equally on a global basis? If so, countries that long ago exceeded their fair share of copper per capita should decrease their in–use copper stock and contribute towards an equal distribution of copper for all. If Sweden wants to contribute to the goal of equal access to copper for all, this would mean a significant degrowth of the country's in–use copper stocks and "urk mining" could contribute to realizing such ambitions.

Beyond distribution of resources *between* countries, we would also like to point out a number of questions having to do with the distribution of resources *within* countries. For copper, how would we distribute our fair share (100 kilos of copper per person) between our various cupriferous needs such as transportation, electricity, and construction? How large a part should be allocated to providing an ICT infrastructure in comparison to other cupriferous needs, and how far would a proposed future resource-sleek ICT infrastructure meet our ICT-related needs and wants?

While infrastructure is often seen as apolitical and as an issue best left to "experts", it is nothing *but* ideological, as has been shown a great number of times in research on large technical systems (LTS) [29, 58]. Exactly what a future resource-sleek Internet would look like is thus a deeply *political* question pertaining to for whom and for what purposes such an Internet would be built. Blomkvist [5] describes a fascinating case of how the early Swedish car lobby argued for better roads and for the modernisation of road maintenance 100 years ago. Who could object to better roads? As it turns out, the most important affordance for the few automobiles that existed at that time was a hard and smooth road surface, but in wintertime, at least some snow (for traction) was preferred by the numerous farmers and their horse-drawn sleds. This example shows how a seemingly "technical" question can harbor multilayered ideological dimensions, and, just as Blomqvist asks "who are the roads for?", so might we ask for whom and for what we will use the Internet of the future. While most innovations currently aim at developing more advanced products and services for the top one billion, we could instead request innovations that guarantee (low-bandwidth) access and services for the largest number of persons.

6 INNOVATION AS ANTI-SUSTAINABLE BEHAVIOR

We argue that we need to both *refine* and *broaden* our conception of the term "innovation". Current use construes it as something that is purely beneficial. A more refined view acknowledges both positive *and* negative aspects of innovation in terms of ecological sustainability and resource use, not the least since the negative consequences of scientific and technological development are seldom perceived as related to their causes and tend to occur in "*unanticipated forms and in distant locations, and sometimes after significant time intervals.* […] *This character of technology creates a serious intellectual challenge for technological optimists, who exclusively focus on the positive aspects of technology while ignoring the, often enormous, negatives*" [28, p.7].

While we usually think of infrastructure as long-lasting, the pace of innovation within computing is lightning fast. Yesterday's infrastructure is bound for the scrapyard tomorrow. Since an increasing pace of innovation, production, and consumption of goods has negative effects for sustainability and leads to resource depletion, it is easy to problematize innovation. A fast pace of innovation can even be framed as a deeply destructive activity since it eradicates values while quickly using up material resources.

In mobile telephony, we have seen 2G systems being replaced by 3G systems (≈2001), 3G systems being replaced by 4G systems (≈2012) and 4G systems being slated to be replaced by 5G systems a few years from now. We hypothesize that each new generation costs more, uses more resources (not the least due to the increased complexity of each new generation), and delivers decreasing marginal returns in terms of functionality. Innovation surely creates new values such as useful and nifty functionalities, but each generation also represents a massive destruction of already-invested capital, much in line with Schumpeter's notion of "creative destruction" [52]. Similarly, at the very moment that a new smartphone or a new gaming console is launched, both the price and the perceived value of all previous phones and gaming consoles decreases despite the fact that they perform the very same functions they did last week, last month, and a year ago.

Not only do we need to *refine* our conception of innovation (to include also negative effects of innovation), but we also need to *widen* our conception of the term "innovation" to discuss who benefits and who is disadvantaged by new technologies. Put simply, new technologies tend to favor some groups while harming other groups, thereby creating winners and losers [6, 42]. While this perspective is for the most part absent within computing, there are a few exceptions, and, for example Ekbia and Nardi [14] recently wrote that "*System designs often benefit, de facto, the members of privileged socioeconomic classes. The fact that class is not explicitly incorporated into the design process does not eliminate this reality; it just hides it.*"

A widened conception of innovation would thus acknowledge that while innovations can be useful, benefits will tend to accrue to some (winners) rather than others (losers), just as any potential problems will tend to accrue to some (losers) rather than others (winners). In fact, "*almost nothing happens to the losers that they need, which is why they are losers*" [43]. Ekbia and Nardi [14] comment that most apps "*are built to help people find good restaurants but not good jobs*" and to "*organize flash mobs but not labor and trade unions*".

We have here discussed the distribution of benefits and disadvantages *within* societies, but it is also possible to tie this discussion to an environmental justice perspective. While benefits of computing technologies primarily fall on those living in the affluent Global North, disadvantages, problems, and costs (e.g., depleted resources, degraded environments) tend to fall on those living the Global South. It is possible to say that while we get the resources, the infrastructure, and the devices, they get the e-waste.

A group that straddles both perspectives raised here, i.e., the *resource* perspective and the *justice* perspective, is our unborn grandchildren/descendants. What resources do we leave for them and how are these resources distributed in space, e.g., within and between countries?

We want to emphasize that we do not condemn innovation per se, but we do condemn an uncritical perspective on innovation as well as certain *types* of innovations. *Profitable* but *marginal* innovations (e.g. 5G vs 4G mobile systems) that are *resource-demanding* and that *only benefit the few* rather than the many should not be framed as a positive force in society, but rather as a destructive and perhaps even subversive force (from a social and an ecological sustainability point of view). Discussing the steady-state economy, Herman Daly [12] has gone to great lengths to differentiate between qualitative *development* as opposed to quantitative *growth*. He and other ecological economists advocate "*development without growth — qualitative improvement without quantitative increase in resource throughput*" [12]. Just has Daly has coined the term "uneconomic growth", i.e., economic growth that creates a decline in the quality of life, we need to differentiate between innovations that for the most part are "good", and those that for the most part are "bad", i.e. to differentiate between "beneficial innovations" and "destructive innovations".

While space does not allow us to discuss these issues here, we have been inspired by a recent article by Preist et. al. [44]. They end their paper with seven questions that can also be seen as challenges for designers, and their first question is:

"*If this service were to be used by all the world's population, what would the overall environmental impact of the infrastructure be? Can we imagine a future scenario where this would lie within limits imposed by planetary boundaries?*"

The corollary of this question is that if a service (or a product) cannot feasibly be scaled up so that it can be used by and benefit *everyone*, then scarce resources (and time, effort, production capacity, capital, etc.) should perhaps not be spent on developing that particular service. Other proposed question for prospective designers [44] ask about the societal value of a proposed service and whether the service could be justified in "*scenarios of restricted infrastructure*" (question 4) and "*Is the service in tune with your values, as a designer? Can you say with heart that the benefit it brings humanity is worth the environmental costs of the supporting infrastructure?*" (question 7). It would be interesting to examine whether it is possible to develop criteria to discern whether particular innovations are sustainable or not from a broader perspective, taking radically different factors beyond novelty, marginal improvement, and profitability into account.

A final line of criticism is that *innovation* is magnificently overvalued in relation to *maintenance*. Critical voices argue that what happens *after* innovation, i.e., all the things that make innovations sustain and fulfill important societal functions for extended periods of time are far more important and hugely undervalued [50]. A future in which resources are less accessible and more expensive requires a turn to maintenance (and repair) since the upkeep of systems by necessity will require a larger proportion of investments and work hours than innovation and upgrades. This implies we should put more effort and more resources into *sustaining* rather than *extending*.

7 CONCLUSIONS

We have shown that the infrastructure for computing is dependent on limited non-renewable material resources and how the costs for extraction can be expected to rise during the coming decades due to limits on mining the Earth's crust. The current path of innovating and deploying progressively more advanced systems for computing is hardly sustainable in the medium to long run. Bearing this in mind, it would be prudent to husband resources and to shift from an emphasis on innovation to a focus on maintenance. The goal should be to reject "the cornucopian paradigm" [44] and aim for developing a suitable infrastructure and a "sufficient" level of service so as to guarantee the largest functionality for the lowest cost and the greatest number of people for the longest possible duration both within and between countries. This is what we mean when we refer to socially just internet access over time (extending the benefits of digital technologies as far as possible into the future) and space (extending the benefits of digital technologies to the largest number of people possible). To that end, it seems prudent to restrict innovations that use up scarce resources, and especially so if they deliver only marginal improvements that benefit only the few. We have refrained from suggesting exactly how this could be done, but any concrete policy suggestion for how to alter incentives for innovation is bound to be provocative-bordering-on-incendiary. Yet these are essential conversations we must have.

8 ACKNOWLEDGEMENTS

We would like to express our gratitude to the reviewers, whose comments encouraged us to extend our arguments and make them more forceful. We would also like to thank Bonnie Nardi for numerious useful comments and suggestions.

REFERENCES

[1] Alonso, E., Gregory, J., Field, F., and Kirchain, R. (2007). Material availability and the supply chain: risks, effects, and responses. *Environmental Science & Technology* 41(19) 6649–6656.
[2] Ayres, R. U. (1997). Metals recycling: economic and environmental implications. *Resources, Conservation & Recycling*, 21(3) 145–173.
[3] Bardi, U. (2014). Extracted: How the quest for mineral wealth is plundering the planet. Chelsea Green Publishing
[4] Benyus, J. M. (1997). *Biomimicry*: *Innovation inspired by nature*. New York: William Morrow.
[5] Blomkvist, P. (1998). Ny teknik som politisk strategi [New technology as political strategy]. In P. Blomkvist & A. Kaijser (Eds.), *Den konstruerade världen: Tekniska system i historiskt perspektiv* [The constructed world: Technical systems in a historical perspective]. Stockholm: Brutus Östlings Bokförlag Symposion
[6] Brynjolfsson, E., & McAfee, A. (2011). Race against the machine: How the digital revolution is accelerating innovation, driving productivity, and irreversibly transforming employment and the economy. Digital Frontier Press.
[7] Bullard, R. (2000). Environmental justice in the 21st century. *People of color environmental groups. Directory*, 1-21.
[8] Carr, N. G. (2008). The big switch: Rewiring the world, from Edison to Google. WW Norton & Company.
[9] Ceruzzi, P. E. (2003). *A history of modern computing*. MIT press.
[10] Cubitt, S. (2016). Finite Media: Environmental Implications of Digital Technologies. Duke University Press.
[11] Daly, H. (1977). *Steady state economy*. San Francisco.
[12] Daly, H. (2005). Economics in a full world. *Scientific American*, *293*(3), 100-107.
[13] Dorninger, C., & Hornborg, A. (2015). Can EEMRIO analyses establish the occurrence of ecologically unequal exchange?. *Ecological Economics*, *119*, 414-418.
[14] Ekbia, H., & Nardi, B. (2015). The political economy of computing: The elephant in the HCI room. *interactions*, *22*(6), 46-49.
[15] Emmanuel, A., Bettelheim, C., & Pearce, B. (1972). *Unequal exchange: A study of the imperialism of trade*. New York: Monthly Review Press.
[16] Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., & Nilsson, E. (2016). Life Cycle Assessment of a Smartphone. In *4th International Conference ICT for Sustainability* (ICT4S). Atlantis Press.
[17] Exner, A., Lauk, C., and Zittel, W. (2015) Sold futures? The global availability of metals and economic growth at the peripheries: Distribution and regulation in a degrowth perspective. *Antipode* 47(2) 342–359.
[18] Feilhauer, M. and Zehle, S. (Eds.) (2009) *Ethics of Waste in the Information Society.* Special issue of International Review of Information Ethics, 11.
[19] Gerst, M.D., and Graedel, T.E. (2008) In-use stocks of metals: status and implications. *Environmental Science & Technology,* 42(19), 7038–7045.
[20] Greer, J. M. (2008). The long descent: A user's guide to the end of the industrial age. New Society Publishers.
[21] Grossman, E. (2007). High tech trash: Digital devices, hidden toxics, and human health. Island Press.
[22] Grudin, J. (1990). The computer reaches out: the historical continuity of interface design. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp.261-268). ACM.
[23] Guinée, J. B. (ed.) (2002) *Handbook of Life Cycle Assessment: Operational Guide to the ISO standards.* Dordrecht, Kluwer.
[24] Hibbard, K. A., Crutzen, P. J., Lambin, E. F. et. al. (2006). Decadal-scale interactions of humans and the environment. In *Sustainability or Collapse? An Integrated History and Future of People on Earth*. MIT Press.
[25] Hornborg, A. (1998). Towards an ecological theory of unequal exchange: articulating world system theory and ecological economics. *Ecological economics*, *25*(1), 127-136.
[26] Hornborg, A. (2001). *The power of the machine: Global inequalities of economy, technology, and environment*. Rowman Altamira.
[27] Hornborg, A. (2009). Zero-sum world challenges in conceptualizing environmental load displacement and ecologically unequal exchange in the world-system. *International Journal of Comparative Sociology*, *50*(3-4), 237-262.
[28] Huesemann, M., & Huesemann, J. (2011). *Techno-fix: why technology won't save us or the environment*. New Society Publishers.
[29] Hughes, T. P. (1983). *Networks of power: electrification in Western society, 1880-1930*. Johns Hopkins University Press.
[30] Jacobs, J. (1969). *The economy of cities*. Vintage Books.
[31] Johnson, J., Harper, E.M., Lifset, R., and Graedel, T.E.,(2007) Dining at the periodic table: metals concentrations as they relate to recycling. *Environmental Science & Technology* 41(5), 1759–1765
[32] LeCain, T. J. (2009). *Mass destruction: the men and giant mines that wired America and scarred the planet*. Rutgers University Press.
[33] Lennerfors, T. T., Fors, P., & van Rooijen, J. (2015). ICT and environmental sustainability in a changing society: The view of ecological World Systems Theory. *Information Technology & People*, *28*(4), 758-774.
[34] MacArthur, E. (2012). *Towards the Circular Economy: An economic and business rationale for an accelerated transition*. Ellen MacArthur Foundation.
[35] MacKay, D. J. (2009). *Sustainable Energy: Without the hot air*. UIT Cambridge, England.
[36] Mackenzie, A. (2010). *Wirelessness: Radical empiricism in network cultures*. MIT Press.
[37] Martinez-Alier, J. (2003). *The Environmentalism of the poor: a study of ecological conflicts and valuation*. Edward Elgar Publishing.
[38] McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. North Point Press.
[39] Messner, F. (2002) Material substitution and path dependence: empirical evidence on the substitution of copper for aluminum. *Ecological Economics* 42(1), 259-271
[40] Mudd, G.M. (2007) Global trends in gold mining: Towards quantifying environmental and resource sustainability. *Resources Policy* 32(1), 42-56.
[41] Nusselder, S. and Bergsma, G. (2016). *Environmental impact of metal use in electricity cables.* CE_Delft_2.H95_Environmental impact copper or aluminium cables Accessed: March 9, 2017.
[42] Owen, J.R. & Kemp, D. (2013). Social licence and mining: A critical perspective. *Resources Policy*, 38(1), 29–35.
[43] Postman, N. (1992). *Technopoly: The surrender of culture to technology*. New York: Knopf.
[44] Preist, C., Schien, D., & Blevis, E. (2016). Understanding and Mitigating the Effects of Device and Cloud Service Design Decisions on the Environmental Footprint of Digital Infrastructure. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 1324-1337). ACM.
[45] Raghavan, B. & Hasan, S. (2016). Macroscopically Sustainable Networking: On Internet Quines. In *Proceedings of the Second Workshop on Computing within Limits*. ACM.
[46] Raghavan, B., & Pargman, D. (2016). Refactoring society: systems complexity in an age of limits. In *Proceedings of the Second Workshop on Computing within Limits*. ACM.
[47] Raghavan, B., & Pargman, D. (2017). Means and Ends in Human-Computer Interaction: Sustainability through Disintermediation. In *Proceedings of the CHI 2017 Conference*. ACM.
[48] Rauch, J. (2009). Global mapping of Al, Cu, Fe, and Zn in–use stocks and in–ground resources. *Proceedings of the National Academy of Sciences*, 106 (45) 18920–18925.
[49] Remy, C., & Huang, E. M. (2015). Addressing the obsolescence of end-user devices: Approaches from the field of sustainable HCI. In *ICT Innovations for Sustainability* (pp. 257-267). Springer International Publishing.
[50] Russell, A., and Vinsel, L. (2016). Hail the Maintainers. *Aeon*. Available online at: https://aeon.co/essays/innovation-is-overvalued-maintenance-often-matters-more Accessed: 2017-03-17
[51] Schaller, R. R. (1997). Moore's law: past, present and future. *IEEE Spectrum*, 34(6) 52-59.
[52] Schumpeter, J. A. (1942). *Capitalism, socialism and democracy*. New York: Harper & Brothers.
[53] Sieferle, R. P. (2001). *The subterranean forest: energy systems and the industrial revolution*. White Horse Press.
[54] Sorrell, S., Miller, R., Bentley, R., & Speirs, J. (2010). Oil futures: A comparison of global supply forecasts. *Energy Policy*, *38*(9), 4990-5003.
[55] Spatari, S., Bertram, M., Gordon, B., Henderson, K., and Graedel, T.E. (2005). Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics*, 54(1) 37–51.
[56] Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: the great acceleration. *The Anthropocene*

Review, *2*(1), 81-98.

[57] Steffen, W., Crutzen, P.J., and McNeill, J.R., (2007). The Anthropocene: Are humans now overwhelming the great forces of Nature?. *Ambio: A Journal of the Human Environment*, 36(8) 614–621.

[58] Summerton, J. (Ed.). (1994). *Changing large technical systems*. Westview Press.

[59] Sverdrup, H.U., Ragnarsdottir, K.V., and Koca, D. (2017) An assessment of metal supply sustainability as an input to policy: Security of supply extraction rates, stocks–in–use, recycling and risk of scarcity. *Journal of Cleaner Production*, 140(1) 359-372.

[60] Tertzakian, P. (2007). *A thousand barrels a second: The coming oil break point and the challenges facing an energy dependent world*. McGraw-Hill.

[61] Tuomi, I. (2002). The lives and death of Moore's Law. *First Monday*, *7*(11).

[62] Wallerstein, I. (1974). *The modern world-system I: Capitalist agriculture and the origins of the European world-economy in the sixteenth century*. New York: Academic Press.

[63] Wallsten, B., Carlsson, A., Frändegård, P., Krook, J., and Svanström, S. (2013). To prospect an urban mine–assessing the metal recovery potential of infrastructure “cold spots” in Norrköping, Sweden, *Journal of Cleaner Production*, 55, 103–111.

[64] Wallsten, B. (2015) *The Urk World – Hibernating Infrastructures and the Quest for Urban Mining.* Linköping: Linköping University Electronic Press. PhD Thesis.

[65] Van Beers, D., and Graedel, T.E. (2007). Spatial characterisation of multi-level in-use copper and zinc stocks in Australia. *Journal of Cleaner Production*, 15(8) 849–861.

[66] Wäger, P. A., Hischier, R., & Widmer, R. (2015) The material basis of ICT, in Hilty, L. and Aebischer, B. (eds.) *ICT Innovations for Sustainability*. (Springer International Publishing) 209-221.

[67] Zittel, W. (2012). *Feasible futures for the common good; Energy transition paths in a period of increasing resource scarcities*. Progress Report, 1: Assessment of Fossil Fuels Availability [Task 2a] and of Key Metals Availability [Task 2b] (Sustainable Europe Research Institute, Vienna). Available online at: http://www.umweltbuero.at/feasiblefutures/wp-content/uploads/Progress%20Report%201_Feasible%20Futures_Zittel_final_14032012_WZ.pdf Accessed: March 9, 2017