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ICT for Sustainability Beyond Efficiency: Pushing Cleantech and the Circular Economy

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***Abstract*— Sustainability necessitates reform of resource production and consumption to reduce environmental harms. The main way that ICT can address these resource impacts is through digital optimization. Spreng found that optimization of an industrial process either increases resource efficiency by reducing energy inputs ("save impacts") or reduces production and consumption times to increase resource outputs ("push impacts"). It was assumed that a difficult choice then exists between save impacts that progress sustainability and push impacts that meet market demand. Based on a new typology of enabling impacts, this paper argues that there are two important cases in which push impacts can be just as valuable for sustainability as save impacts: 1) when the process drives the production and adoption of an environmentally beneficial product i.e. "cleantech" e.g. a solar panel or 2) when the process is specific to the Circular Economy, such as recycling, maintenance/refurbishment, and sharing/reuse e.g. car-sharing, ride-sharing and tool-sharing in the Sharing Economy. The opportunities for ICT4S optimization are thus threefold: "saving" resources with efficiency, "pushing" the adoption of cleantech, and "pushing" the circulation of resources.**

***Index Terms*— ICT4S, Sustainability by ICT, Resource Efficiency, Optimization, Cleantech, Circular Economy, Renewable Energy, Sharing Economy, LES Model, Spreng's Triangle, Smart Green Map, Push Impacts.**

I. Introduction

The rapid development of Information and Communication Technologies (ICTs) alongside looming environmental risks has spurred interest in applying ICT to sustainability. The digital industry has launched systems that manage energy, water and other resources with potential benefits for the environment e.g. smart thermostats that heat homes efficiently, and ridesharing platforms that find passengers for empty car seats[1]. These systems have been termed “smart green”, “cleanweb” or “Sustainability by ICT” [1]–[3], and have achieved widespread adoption and large economic impact[2].

Understanding the various mechanisms by which smart green systems work is valuable for research, investment and innovation[3]. Consequently, the field of ICT for Sustainability (ICT4S) has developed theory to explain how ICT can address sustainability challenges. Most notably, the LES Model by Hilty and Aebischer (Fig. 1.) theorizes that ICTs can *save resources directly* through *process optimization* or *media substitution* [4]; in process optimization, a production or consumption process is made more efficient by gathering and analyzing data on its use of resources.

However, the LES Model theory faces several limitations. Firstly, it does not sufficiently explain the role of ICT in *technological substitution*, the transition to more sustainable technologies, products and practices sometimes termed *cleantech*[4]. Hilty himself challenged the community to better explain this in his ICT4S2014 keynote. The LES Model and its precursors assume that to progress sustainability *process optimizations* must create resource efficiencies, which intrinsically conflicts with the commercial need to *accelerate* the production and consumption of products. However, in the specific case where the product is cleantech, sustainability is actually progressed by *increasing* production and consumption to enable technological substitution.

Another limitation of existing ICT4S theory is that it does not incorporate the concept of *circularity*, which is important in sustainability theory and practice [5]. In his best paper at ICT4S2013, Blumendorf challenged the community to better integrate the idea of circularity [6]. The Circular Economy entails processes such as recycling, maintenance and sharing [7]. An important subdomain is therefore the Sharing Economy, such as tool-sharing, car-sharing and ride-sharing platforms [8]. Action research conducted early in the investigation found that many smart green systems in the Circular Economy, Sharing Economy and cleantech industries do not just work through efficiencies that save resources, as suggested by ICT4S theory.

The list of processes by which ICT can progress sustainability in the LES Model is not exhaustive. Can new processes be identified that expand the LES Model to better describe *circularity*, *sharing*, *cleantech* and the sustainability benefits of *accelerating* certain production and consumption? This question emerged from a doctoral investigation that is partly summarized in this paper[5] [17]. The investigation drew upon the ingenuity of entrepreneurs and researchers, whose smart green innovations are exploring the range of ways by which ICT can progress sustainability. A new classification was developed of these smart green systems, a typology called the Smart Green Map (SGM)[6] [9].

The dimensions of the SGM show that many smart green systems work in other ways than directly saving resources as assumed previously. The new concepts of *push impacts* and *circular processes of production and consumption* address the challenges posed by Hilty and Blumendorf to explain ICT’s

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[1] E.g. Nest https://nest.com/ and BlaBlaCar https://www.blablacar.com/
[2] E.g. Nest was bought for $3.2bn [38], Climate Corporation for $1.1bn, Opower and Zipcar for $500m.
[3] e.g. the case study of an investment framework created by a venture capital firm based on these results (the SGM) in Chapter 7 of the accompanying thesis [17].
[4] Technological substitution can be situated within the field of *sustainability transitions* along with concepts such as *socio-technical transitions to sustainability* [39], the *Third Industrial Revolution* [40], and policies of renewable energy adoption such as Germany’s *Energiewende*.
[5] References to particular chapters of the doctoral thesis are provided throughout [15].
[6] This supersedes an earlier version of the SGM presented at ICT4S2015 [41].

role in *technological substitution* and *circularity* for sustainability, connecting ICT4S with three important communities of praxis and research.

Section II details the theoretical context for readers unfamiliar with it. The mixed methods used to create the SGM typology are described in Section III. The dimensions of the SGM are described in the Results section, IV. The new concepts implicit in the SGM dimensions are then analyzed and modelled theoretically in Section V, identifying the two new digital optimizations for sustainability: *pushing cleantech* and *pushing circularity*.

II. Background

A. Digital Optimization, Spreng's Triangle and the LES Model

Hilty and Aebischer describe *Sustainability by ICT* as "the transformational power of [ICT] to develop more sustainable patterns of production and consumption" [4]. Their "LES" Model divides the environmental impacts of ICT into three levels, with the top two describing Sustainability by ICT (Fig. 1). The second level describes the *enabling impacts* of ICTs at the micro-level. Enabling impacts are simply any action enabled by the application of ICT. "In the context of sustainability, it is important to understand the effects of these actions on resource use. We therefore view all actions as *processes of production or consumption*" [4].

Three mechanisms of enabling impacts are identified by the LES Model, although others are possible: *process optimization*, *media substitution* and *externalisation of control*. All three mechanisms are modelled as *resource-use hierarchies*, trees of dependent processes that ultimately deliver the value required by the user or customer[7]. The primary mechanism, ***process optimization*,** is the use of information to control any process that has a purpose, in order to minimise its use of resources. Hilty has challenged the ICT4S community to investigate the role of ICT in technological substitution *at all levels of the resource-use tree*.

The third level describes ICT impacts that lead to persistent changes observable at the macro-level, the ultimate *structural impact*. "[Dematerialization is the] special case of decoupling based on the substitution of immaterial resources for material resources. In broad terms, dematerialization is the aggregate result of many process optimizations and media substitutions, moderated by rebound effects" [4]. Dematerialization is stated to be a necessary but insufficient condition for sustainable development.

In the LES Model, all enabling impacts of ICT are viewed as special types of ICT-enabled resource substitution, based on Spreng's theory of the mutual substitutability of time, energy and information. Spreng's theory is based on case studies of the optimization of industrial production processes [10]. The inputs required to produce a good or service are characterized by the three quantities energy, time and information. The way in which the process is performed is represented as a point in the triangle Fig. 2. whose geometry thus implies mutual substitutability. Application of ICT (i.e. information) to a process allows either time or energy to be saved. However, the profit imperative favours the acceleration of production i.e. the reduction of time: "Both, IT's potential to do things with less energy input, thus generally more sustainably, and IT's potential to do things faster, i.e. less sustainably, are enormous. Unfortunately, so far, the latter potential has been extensively tapped while the former remains but potential." [11].

[7] Resource-use hierarchies are therefore similar to value chains [34].

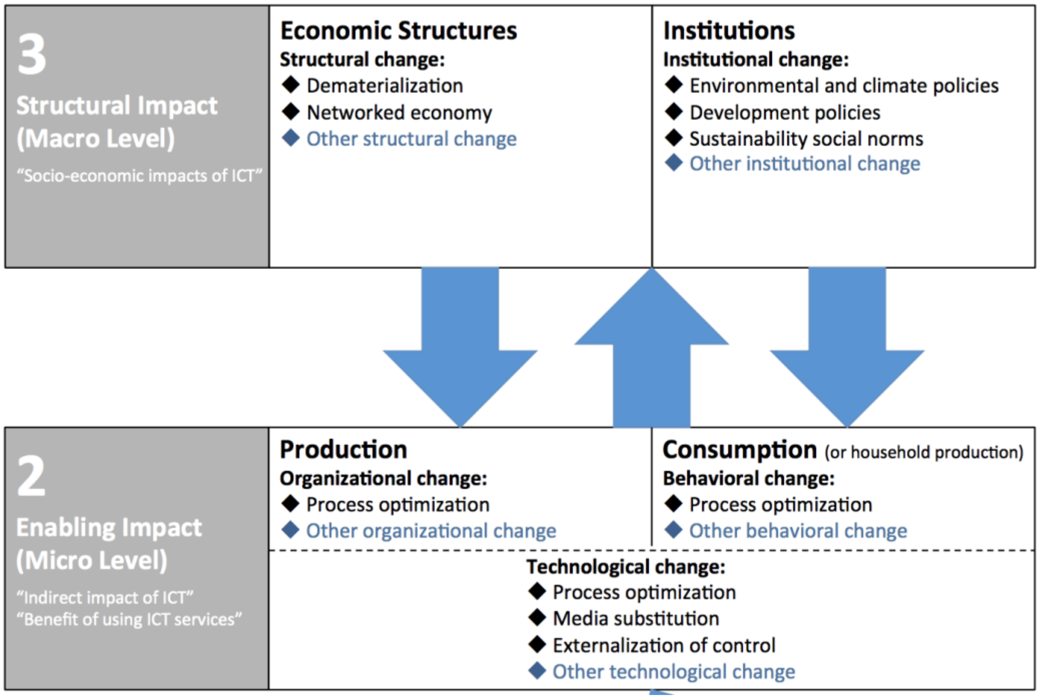

Fig. 1. Theorizing Sustainability by ICT: the second and third levels of the LES Model, which stands for Life-cycle Impact (not shown), Enabling Impact and Structural Impact. (Hilty & Aebischer [4]).

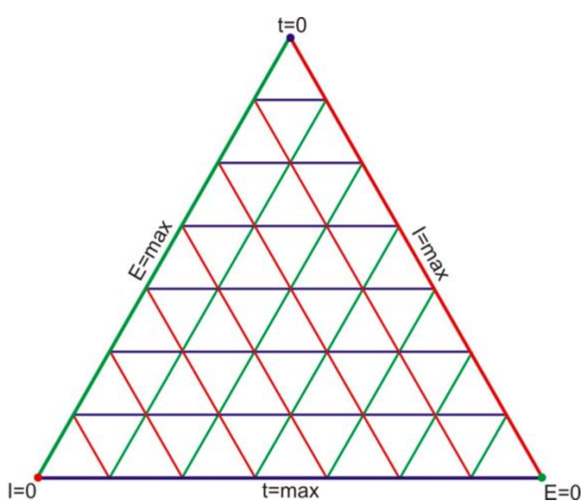

Fig. 2. Spreng's Triangle representing the mutual substitutability of time, energy and information.[8]

[8] Image credit: http://backreaction.blogspot.co.uk/2011/11/sprengs-triangle.html

B. Three Emerging Industries of Direct Relevance to ICT4S

This section describes three industries creating important digital products that can make resource-use more sustainable, encountered in the course of the initial action research.

The Cleantech Industry— The term "cleantech" is widely used for the innovation of more sustainable products and technologies such as renewable energy [12]. The cleantech industry, like many others, is rapidly digitalizing and thus entering the purview of ICT4S. Indeed, "Cleantech" is the basis of the term "cleanweb" for these smart green systems. Products that use resources more sustainably existed long before the term "cleantech" was coined, and the term is used here to mean any and all such products. Theories of *technological substitution* and *sustainability transition* must involve a transition towards cleantech.

The Sharing Economy— Botsman defines the Sharing Economy as "an economic system based on sharing underused assets or services, for free or for a fee, directly from individuals" [8]. The Sharing Economy, and the similar concept of collaborative consumption, has become a major theme within the digital sector, and includes many of the startups encountered, such as tool-sharing, car-sharing or ride-sharing[9]. All have the potential to reduce resource use. Pascual states that the Sharing Economy as a major contributor to the cleanweb industry, along with Cleantech and the Internet of Things [13].

The Circular Economy— is "an alternative to a traditional linear (make, use, dispose) [economy] in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life" [7]. There is a strong link between circularity and sustainability. Blumendorf argued for circularity in ICT4S at the first ICT4S conference, being awarded best paper [6]. The model of the Circular Economy in Fig. 3. also includes processes of sharing and thus the Sharing Economy.

III. Methods

Mixed methods are useful for analyzing the complex sociotechnical phenomena of the Web [14]. The investigation was primarily qualitative and inductive, but included the deductive and quantitative, as detailed in the doctoral thesis [15]. It began with action research that engaged with relevant communities, learning of their possible research requirements [16].

Based on the action research findings and identified limitations with existing conceptualizations of ICT4S, qualitative classification development was undertaken [9], to map out the space of possible enabling impacts revealed by cleanweb entrepreneurship and ICT4S scholarship. Certain principles from grounded theory [17] were employed.

500 descriptions of cleanweb companies were analyzed, primarily from the CrunchBase online database. A list of search terms was developed to identify the most relevant companies. Significant characteristics of the companies were coded, and the codes were then sorted and resorted to identify higher-level concepts and categories. Diagramming developed conceptual and mechanistic models to explain the observed variation.

Whilst sorting and resorting the initial concepts and reviewing the company description data, it was noted that some systems involve a form of sustainable product i.e. "cleantech" e.g. renewable energy. Most of the other systems controlled machines or influenced users' behaviour to be more resource

[9] E.g. Ride-sharing platform BlaBlaCar https://www.blablacar.com/

efficient. This dichotomy became a dimension of the SGM with two categories: "save" and "push" impacts.

This resulted in the first version of the "Smart Green Map" (SGM) [9], a typology that maps out the range of possibilities for ICTS to make resource use more sustainable (DI).

The effectiveness and utility of this first version of the SGM was assessed by using it to classify a fresh sample of ICT4S research and smart green startups, as a quantitative comparison of their relative distribution. The samples were from the ICT4S conference and the analogous Ecosummit conference of smart green startups [18].

A more granular level of classification was also identified, termed the "submarkets". Regularities in the submarkets were related to processes of production and consumption such as design, manufacture, usage and maintenance. This linked the SGM to the LES Model, and also to models of the Circular Economy. This enabled a theoretical synthesis that generated the latest version of the SGM, which organizes DI along five dimensions, described in the results.

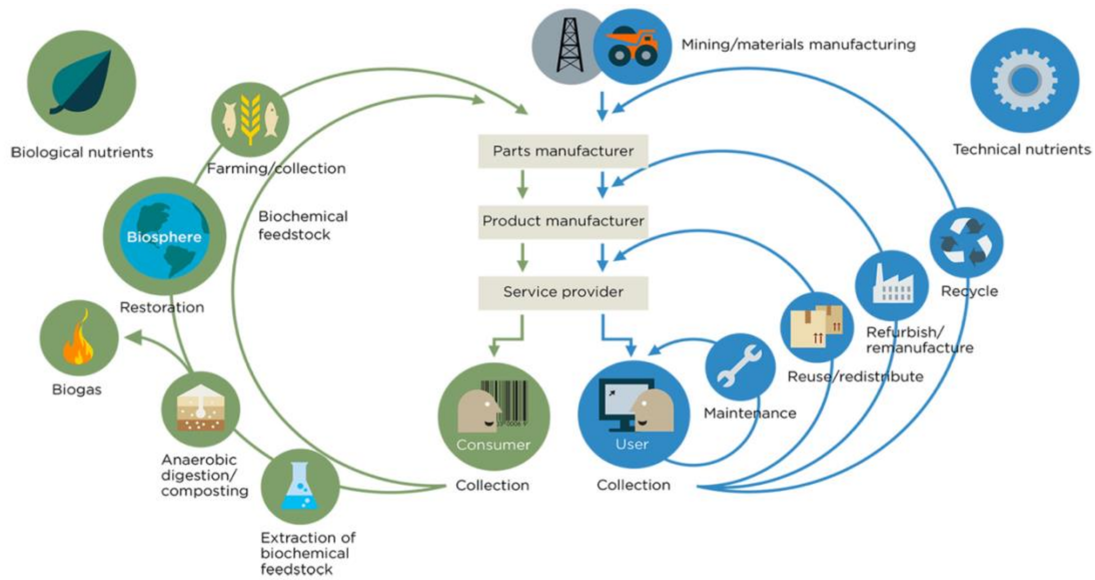

Fig. 3. A Model of the Circular Economy. ©Ellen MacArthur Foundation[10].

IV. Results: the Smart Green Map (SGM)

A. SGM Scope: Decoupling Impacts (DI)

The scope of the SGM is enabling impacts that make resource-use more sustainable i.e. enabling actions that contribute to resource decoupling at the macro-scale by creating, enabling and encouraging sustainable patterns of production and consumption. This set of enabling impacts are here termed "decoupling impacts" (DI). In the LES Model, they may be all the enabling impacts that contribute to Economic/Structural Change moderated by rebound effects, including process optimizations, media substitutions, externalizations of control and ultimately dematerialization.

[10] Ellen MacArthur Foundation http://www.ellenmacarthurfoundation.org

The scope of this paper, and of the SGM, is the possibility space of all DI, the core of Sustainability by ICT, and the subject of most ICT4S research and commercial innovation[11]. However, this scope excludes the following topics that sit within ICT4S in a broader sense:

Sustainability in ICT— the first level of the LES Model that considers the life-cycle-impact of the production, use and disposal of ICTs themselves.

Institutional change— that shapes "law, policies, social norms, and anything that can be regarded as the 'rules of the game.'" [4] Presumably this includes important areas such as *adaptation to environmental change* e.g. monitoring and responding to air pollution, and also biodiversity conservation as pursued by *conservation technology*[12] innovation. Neither does this cover the "social pillar" of sustainability beyond the environment.

Sector-wide impacts— the effects of the ICT sector as a whole, which is the concern of much of the literature. This paper is about the enabling impacts arising from specific applications. For simplicity, this paper focuses on enabling impacts rather than the digital systems themselves, the nature of which is theorized in the thesis[13].

Quantification of structural impacts— the paper will only briefly touch on the calculation of structural impacts at the third level of the LES Model, moderated by rebound effects.

ICT4S design, support and strategy— the process by which such systems are designed[14], or the nature of ICT4S practice, research and education.

B. Save and Push Impacts

The action research first identified a set of smart green companies that were "catalyzing cleantech" i.e. their systems help design, manufacture, maintain and sell environmentally beneficial technologies. For instance, certain websites encourage homeowners to install solar panels, by helping them plan and budget for the project[15]. This category had been identified by Pure Energy Partners[16] specialist analysts of the cleanweb industry. This eventually lead to the identification of a two-category dimension of the SGM, termed *decoupling directness* in the thesis[17].

Save impacts— when saving resources, DI contribute to resource efficiencies more directly by monitoring and optimizing resource use, or by media substitution. Examples of such save impacts are smart thermostats and ridesharing apps. Save impacts appear to have dominated ICT4S research.

Push impacts— in contrast, when "pushing" cleantech, DI enhance the adoption, construction and operation of more sustainable products. Examples include manufacturing robots and crowdfunding platforms for solar panels. Whilst push impacts have been less researched in ICT4S than save impacts, there have been publications on pushing renewable energy through the smart grid [19], household retrofitting [20], [21], bicycles [22] and organic food [23].

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[11] Chapter 8 of doctoral thesis for statistics [15].
[12] E.g. https://www.zsl.org/conservation-initiatives/conservation-technology
[13] Chapter 5 of doctoral thesis [15].
[14] As often researched in Sustainable Human Computer Interaction (SHCI).
[15] E.g. Sungevity http://www.sungevity.com
[16] Pure Energy Partners http://pureenergypartners.com. "Cleantech catalyst" concept shared in personal correspondence.
[17] Chapter 6 of the doctoral thesis [15].

C. Distribution of Smart Green Entrepreneurship & Research

The enabling impacts of a fresh sample of ICT4S research and smart green startups were classified with the SGM, to test its effectiveness and utility, and as a quantitative comparison of their relative distribution (Chapter 8). The results indicate that push impacts constitute around half of the cleanweb startups analyzed, and thus comprise considerable economic value and potential sustainability benefit. Push impacts were a lot more prevalent amongst smart green startups than ICT4S research papers. The ratio of Save to Push for the research papers was around 80:20, whilst for the startups it was 50:50.

Whether through save or push, digital optimization was found to make up the large majority of all the DI encountered, with only a small proportion of the sample functioning through the other mechanism, media substitution (5 of 62 research papers and 1 of 68 startups).

D. Circular Processes of Consumption and Production

DI were found to work via economic processes of production and consumption identified by the Circular Economy model, forming a dimension of the SGM. This connects ICT4S theory with leading concepts of sustainability as circularity by recycling, reuse, maintenance, and to sharing of resources through collaborative consumption.

A list of processes was required to map out the possibility space along the production/consumption dimension identified by the LES Model, and which emerged from classification development. Processes of production and consumption could be grouped or divided in different ways, and different products undergo different sets of processes. A moderately exhaustive and granular list of such processes would suffice to form a supplementary dimension of the SGM. But where could such a list be found?

One list was given by a precursor to the LES model called the “Linked Life Cycle Model” which describes ICTs as optimizing design, production, use and end of life, as well as substituting for and inducing demand [24]. A more granular list was found in models of the Circular Economy such as Fig. 3. These were integrated with the identified submarkets to form Fig. 4. simplifying the nested loops of the Circular Economy into a list of processes of production and consumption. This is an indicative rather than an exhaustive list, and products may not undergo every process.

Using Circular Economy processes in the SGM has the dual benefits of including both circularity and sharing, also integrating the Sharing Economy, another major community of Sustainability by ICT practice that was engaged with during the action research.

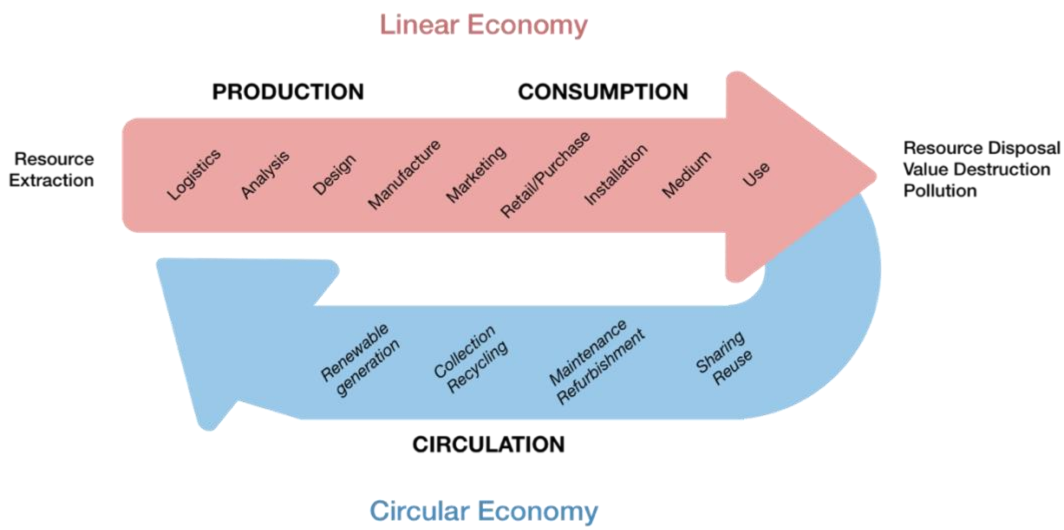

Fig. 4. Processes of production and consumption in the Circular Economy, one dimension of the SGM. The circulation of resources in the blue processes reduces extraction and disposal that is environmentally harmful. This list is indicative and not exhaustive. ICT can progress sustainability by optimizing all processes and by media substitution of the *medium* process.

E. Resource type

Another dimension of the SGM of self-evident utility is the type of resource decoupled by the DI e.g. heat energy, electrical energy, water, materials or space. It is this resource-type dimension that is the basis of most classifications of industrial activity, including notable examples from the cleantech industry and the Sharing Economy[18].

F. The Enablers: Social Variation in Enabling Impacts

Enabling effects were found to combine people and digital technology in four contrasting ways: “Automation”; “Augmentation”; “Coordination” and “Autination”. These were termed the “Enablers” and defined by a matrix of two SGM dimensions: “level of automation” and “level of social interaction”. For brevity, the Enablers are not addressed in this paper, but they form an important component of the SGM typology that is fully described in the thesis[19].

V. Discussion

The LES Model does not distinguish push impacts. Nor are they clearly distinguished by other strategic conceptualizations of ICT4S, which focus heavily on save impacts (Chapter 9). Whilst three studies had a category that was a form of push impact: the WWF, Smarter 2020 and E-topia studies [25]–[27], the only category fully equivalent to push impacts was “Catalyzing Cleantech” in Pure Energy Partners “Cleanweb themes”.

[18] Chapter 3 of doctoral thesis [15].
[19] Chapter 5 and 7-10 of doctoral thesis [15].

As they stimulate the consumption of another resource, push impacts act like an environmentally beneficial form of "induction" in the Three-Levels category, a precursor of the LES Model. They do not fit in the "substitution" category of the Three-Level model, as it appears to be limited to media substitution, which works differently.

A. Resource-Use Hierachy Model of Push Impacts

The LES Model enabling impacts are based on a theory of resource-use hierarchies and ICT-enabled substitutions. To develop the conceptual basis for the observed variation in DI, and better explain how some DI *push cleantech*, this section uses the resource-use hierarchy theory to model push impacts, in contrast to the save impacts already described by Hilty & Aebischer.

By definition, a product is produced by production processes, and consumed by consumption processes. Therefore, any product depends upon a life cycle of production and consumption processes. Each of the production and consumption processes is itself a resource-use hierarchy, a tree of interdependent resources that includes the material resources - such as raw materials, parts and energy – and the immaterial resources – such as designs and calculations – that are required to create the product. A simple model of any product based on the theory of resource-use hierarchies can therefore be described with Fig. 5. The production and consumption processes are generally amongst those identified in Fig. 4.

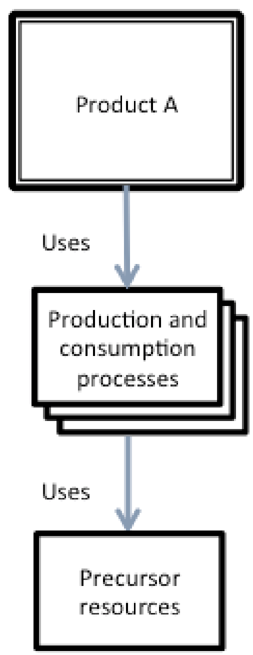

Fig. 5. Generic model of any product, developed using Hilty & Aebischer's resource-use hierarchy diagrams [4], [28]. The diagram models a functioning product as dependent on a hierarchy of production and consumption processes (Fig. 4), which in turn depend on precursor resources.

The submarkets identified by the classification development process suggested that save impacts function through both process optimization and media substitution, whilst push impacts function by process optimization alone. Hilty & Aebischer use the resource-hierarchy model to define these three processes as forms of ICT-enabled substitution. Based on this definition, the generic model of any product in Fig. 5. and the empirically-derived submarkets, Fig. 6. models the save/push dichotomy.

Save impacts decrease environmental impact through ICT-enabled optimization of resource use in the production and consumption processes of a Product A, or by substituting its medium for ICT hardware. On the other hand, push impacts enable the substitution of Product A with another more sustainable Product B by optimizing the production and consumption processes to maximize product adoption.

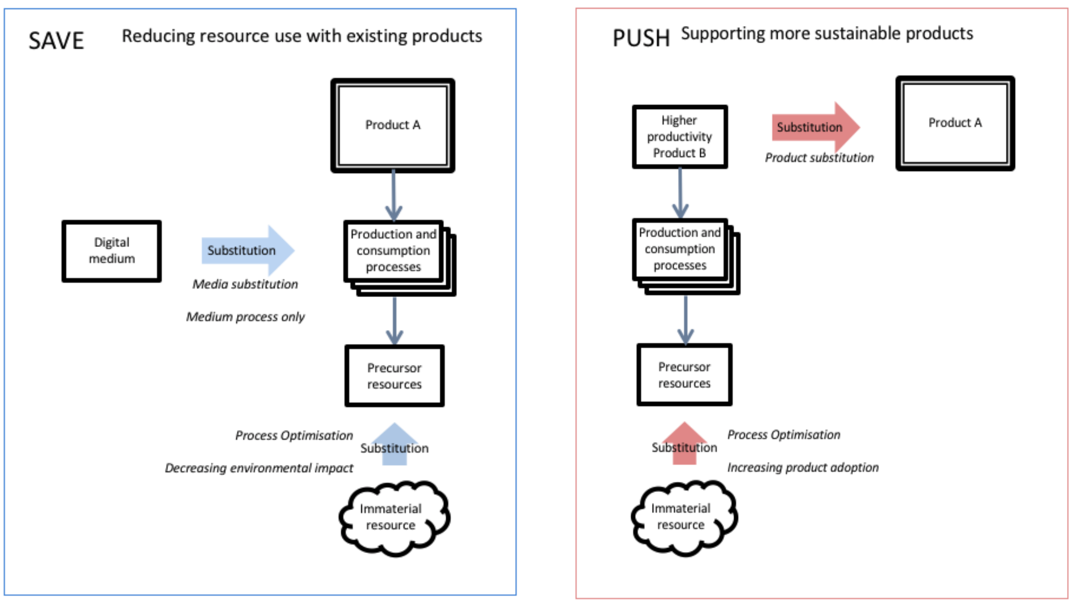

Fig. 6. Save and push impacts modelled with Hilty & Aebischer's resource-use hierarchy diagrams [4], [28]. Save impacts decrease environmental impact by optimising resource use in the production and consumption processes of a Product A, or substituting its medium for a digital one. On the other hand, push impacts enable the substitution of Product A with another more sustainable Product B by optimising the production and consumption processes to maximize growth.

B. The Paradox of Push Impacts

When ICT applies more information/knowledge to an economic process, Spreng's Triangle implies that there is a choice between doing things with less energy and doing thing faster. Generalizing from energy to all precursor resources of a production or consumption process, the choice presented by Spreng's Triangle is that between push and save. Save impacts use ICT to increase resource efficiency, such as energy. Push impacts use ICT to reduce production or consumption time rather than resource usage, and thus increase production rates or qualities for "greater convenience on the consumer side" [10].

There appears to be a reasonable assumption in Spreng's Triangle and the LES Model, that the potential sustainability benefit of process optimization is reducing resource use by the process itself i.e. increasing resource efficiency with save impacts. However, push impacts do the opposite, increasing production and consumption rates. There appear to be a *Paradox of Push Impacts*: how can they actually benefit sustainability by increasing production and consumption, with an inevitable increase in resource use by that process? This is an important question as fully half of smart green startups may work through push impacts. Indeed, push impacts incentivize entrepreneurship by aligning commercial priorities of production and adoption with sustainability goals.

The paradox can be resolved by noting that not all products and processes are equal. To achieve technological transition that addresses Hilty's challenge, certain products and processes need to flourish. Based on the dimensions of the SGM, this paper identifies *cleantech* with such products, and *circularity* with such processes. There are discussed in the following sections.

Their paradoxical nature makes push impacts particularly open to critiques of consumerism from ICT4S such as by Knowles (2014) and Brynjarsdottir et al. (2012). Similarly Gossart warns of green consumerism in the context of rebound effects which can make "individuals feel that they belong to a community of people who care about the environment, and that they are esteemed by other people because they adopt responsible consumption patterns" [29]. As well as accelerating production and consumption, push impacts are applied to processes of design and entrepreneurship to accelerate the development of better cleantech[20]. This is then subject to critiques of innovation itself from environmental economists such as Jackson [30].

This intrinsic consumerism may have reduced research interest into push impacts within ICT4S, which has been limited in comparison to entrepreneurial activity. Moreover, as they function similarly to other commercial ICT systems in supporting the growth of a product rather than saving resources directly, the research problems push impacts generate may be less specific to ICT4S.

C. The Three Digital Optimizations for Sustainability

All DI operate by saving resource inputs or increasing production rates for one or more of the processes of production and consumption of the Circular Economy. Fig. 7. shows how these two dimensions of DI identify three opportunities for smart green optimization.

Saving resources in all processes— every process of production and consumption that make up the *Established Economy* can have its resource use digitally optimized with save impacts i.e. ICT-controlled resource efficiency.

Pushing cleantech products— environmentally-beneficial technologies that make must up the "*New Economy"* e.g. renewable energy, have processes of production and consumption that can be digitally-optimized commercially with push impacts to increase output and decrease price, leading to increased adoption.

[20] E.g. Design software that incorporate sustainability metrics e.g. AutoDesk https://www.autodesk.co.uk/

Pushing circular processes— environmentally-beneficial processes specific to the *Circular Economy* such as recycling, maintenance/refurbishment, and sharing/reuse can be digitally-optimized to become more competitive with wasteful and polluting value destruction for all products.

If the Circular Economy processes are imagined as a wheel, then these can be thought of metaphorically as a brake on the resource-use of the established economy, an accelerator for the new economy, and an axle to make all resources circulate.

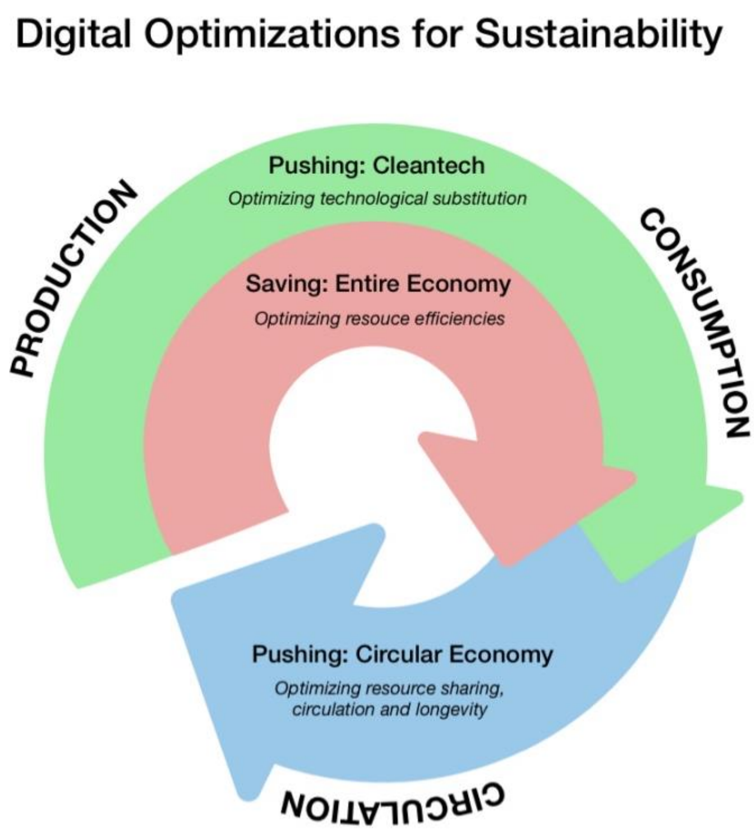

Fig. 7. The Three Digital Optimizations for Sustainability. All smart green systems encountered functioned by one or more of these mechanisms.

D. *Properties of Push and Save Impacts*

This section summarizes some likely properties of push impacts and the push/save dimension of the SGM, as summarized in Table I.

Measuring save and push impacts— push impacts are ICT enabling some other form of cleantech, whilst save impacts are a form of cleantech themselves. Save impacts can be measured by how much resource they save directly, whilst push impacts by how much of a more sustainable product they support. From this it may also be possible to calculate how much resource push impacts ultimately save.

Possible exhaustiveness of save/push— digital optimization formed the large majority of all identified DI. The model of save and push impacts based on resource-use hierarchies in Fig. 6. implies that that they form an *exhaustive* two-category typology of all digital optimization. By including media substitution within save impacts, all examples of DI encountered empirically could be classified as save impacts, push impacts or occasionally both. This suggests that save/push may be exhaustive for all DI i.e. for all digital enabling of sustainable resource use.

Lack of mutual exclusivity of save/push— save/push is not a mutually exclusive classification, as enabling impacts that save resources can simultaneously push a sustainable product. This lack of mutual exclusivity is actually not a disadvantage to the classification, as it identifies two different sustainability claims, which must be calculated differently and can be targeted simultaneously.

Push impacts work similarly to rebound effects— whilst rebound effects may be environmentally harmful by definition, they appear to function in a similar way to push impacts. For instance, "Direct rebound effects appear when technological change enables an improvement in the efficiency with which some output can be produced from a resource, whose demand then increases as prices go down [therefore] more of the same resource is consumed" [29].

But push impacts may have rebound effects— any benefit arising from push impacts at the micro-level may have limited impact at the macro-level; push impacts are likely to be moderated by their own rebound effects. LCA and systems dynamics models have been developed to quantify the structural impacts of save impacts [31], [32], and these might be adapted to quantify push impacts and investigate their rebound effects. Research on improvements to general economic productivity due to ICT [33] might form a basis for analyzing the application of ICT productivity to cleantech, moderated by rebound effects[21]. This might better characterize the micro-macro link between the Enabling and Structural Levels of the LES Model, another of Hilty's challenges at ICT4S2014.

Multi-stage push impacts— push impacts can be mediated by more than one stage between the digital technology and the ultimate resource decoupling. For instance, JPM Silicon[22] use digital technology to improve the production of silicon, which can then create solar panels, which can then decouple. This chain of effects may be similar to indirect rebound effects [29], the resource-use hierarchy, and the commercial concept of value chains [34].

Save-Push systems— as save and push impacts are not mutually exclusive, a single DI can both save harmful resources and push beneficial ones. Such DI are here termed "save-push". For example, Sonnen[23] use algorithms to optimize the efficient function of a smart battery in the home. This has save impacts by optimizing battery function to save energy, but it also has push impacts by enabling the adoption of both the battery itself and domestic solar energy. The smart grid is perhaps the most prominent example of a save-push system, and has been subject to considerable ICT4S research [19], [35], [36], and promotion as the "Energy Internet", bringing together Internet technologies, renewable energy, and energy storage [37].

Example— Stratajet[24] is a company that allows private jet owners to rent out their underused private jets to others. The question of whether Stratajet is sustainable was a point of debate with practitioners

[21] Chapter 9 of the doctoral thesis [15].
[22] JPM Silicon http://www.jpmsilicon.de.
[23] Sonnen https://www.sonnen-batterie.com.
[24] Stratajet https://www.stratajet.com.

during the action research. As a Sharing Economy platform Stratajet may "save" resources by allowing fewer jets to be used more intensively. However, it may also push private jet travel to the exclusion of less energy intensive modes of travel. Both save and push impacts must be analysed at the systemic macro-level to assess the sustainability or otherwise of Stratajet, and the push impact may well be an environmentally harmful rebound effect[25].

TABLE I. COMPARING SAVE AND PUSH IMPACTS

Save Impacts	**Push Impacts**
Using digital systems per se to control resource use and thus *decouple more directly*	Using digital systems to *decouple indirectly* by enhancing the adoption, construction and operation of more sustainable products
Digital system *as cleantech*	Digital system *catalyzing cleantech*
Success metric: *resource saved* directly	Success metric: *amount of cleantech* adopted Or indirect resource gained / saved
Use a *product better*	Use a *better product*
Well described by the LES Model enabling impacts of *process optimization*, as well as *media substitution, and perhaps externalization of control*	Not distinguished by the LES Model enabling impacts but do similarly take place by *process optimization*.
Discouraging the consumption of environmentally *harmful* resources	*Encouraging* the consumption of environmentally *beneficial* resources
Spreng's Triangle: reducing *energy use* and increasing *resource efficiency*.	Spreng's Triangle: reducing *production or consumption time*.
Similar proportion in samples of ICT4S research and cleanweb entrepreneurship	Much more prominent in the sample of cleanweb entrepreneurship than ICT4S research

E. Conclusions

This paper has argued that push impacts and circularity are major features of ICT4S praxis which can be integrated into strategic conceptualizations of the field. The theory and praxis of ICT4S has tended to focus on save impacts that address sustainability by generating resource efficiencies. However, it was found that there are also push impacts that can benefit sustainability by increasing the productivity of cleantech products or circular processes. The distinction between save and push impacts aligns with the choice in Spreng's Triangle between reducing energy inputs or reducing output time. The distinction was modelled with the resource-use heirachies of the LES Model. The save/push classification is not mutually exclusive, but appears exhaustive for all enabling impacts that make resource-use more sustainable (DI). Push impacts may make up half of cleanweb entrepreneurship, and thus comprise considerable economic value and positive sustainability impact. Nevertheless, ICT4S research into them has been limited. Push

[25] Interesting examples might also include optimizing lithium mining operations for electric vehicle batteries and optimizing solar energy on an oil rig.

impacts are paradoxically consumerist and yet sustainable. Their paradoxical nature makes them open to critiques of consumerism, but their alignment of commercial priorities with sustainability incentivizes entrepreneurship, production and adoption which is vital for sustainability transition.

Circular proceses of consumption and production bring the key concept of circularity into ICT4S (e.g. the Natural Step Framework [5]), thus addressing Blumendorf's call for circularity at ICT4S2013 [6] and linking with the Circular Economy community. The Circular Economy also includes the Sharing Economy concept, situating applications such as tool-sharing, car-sharing and ride-sharing within ICT4S.

The role of ICT in technological substitution is found to be the application of push and save impacts to optimize circular processes of production and consumption in the resource-use hierachy. This addresses Hilty's first major challenge posed at ICT4S2014. With the exception of media substitution, this covers all mechanisms of ICT-enabled decoupling encountered. As shown in Fig. 7. the three opportunities for ICT4S optimization are: "saving" resources with efficiency, "pushing" the adoption of cleantech, and "pushing" the circulation of resources.

VI. References

[1] S. Paul and N. Allen, "Inventing the Cleanweb," *MIT Technology Review*, 2012.

[2] S. Masero and J. H. Townsend, "Cleanweb UK: How British Companies are using the Web for Economic Growth & Environmental Impact," Nesta, London, 2014.

[3] Carlota Perez, "'Smart green' technology is the path to follow," *Financial Times*, 2016.

[4] L. Hilty and B. Aebischer, "ICT for Sustainability: An Emerging Research Field," *ICT Innov. Sustain. Adv. Intell. Syst. Comput. 310*, no. August, pp. 3–36, 2014.

[5] J. Robért, K., Daly, H., Hawken, P., Holmberg, "A Compass for Sustainability," *Int. J. Sustain. Dev. World Ecol.*, vol. 4, no. 2, pp. 79–92, 1997.

[6] M. Blumendorf, "Building Sustainable Smart Homes," in *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability ETH*, 2013.

[7] P. Mitchell and K. James, "Economic Growth Potential of more Circular Economies," WRAP, Banbury, UK, 2015.

[8] R. Botsman, "Defining The Sharing Economy: What Is Collaborative Consumption--And What Isn't?," *fastcoexist.com*, 2015.

[9] K. D. K. Bailey, *Typologies and taxonomies: an introduction to classification techniques*, vol. 102. New York, USA: Sage, 1994.

[10] D. Spreng, "Interactions between Energy, Information and Growth," in *First International Conference on Information and Communication Technologies for Sustainability*, 2013, p. 6.

[11] D. Spreng, "Does IT have boundless influence on energy consumption," in *EnviroInfo 2001: Sustainability in the Information Society*, 2001.

[12] Cleantech Group, "Global Cleantech 100," Cleantech Group, 2016.

[13] O. Pascual, "Cleanweb: How ICT Creates Environmental, User, and Market Value," 2014.

[14] R. Tinati, S. Halford, L. Carr, and C. Pope, "Mixing methods and theory to explore web activity," in *Third Annual Web Science Conference (WebSci2012)*, 2012.

[15] J. H. Townsend, "Digital Systems for Sustainability: a Classification of ICT4S and Smart Green Startups Distinguishing Automation, Social Computing and Cleantech Push," University of Southampton, 2017.

[16] P. Reason and H. Bradbury, "Handbook of Action Research Participative Inquiry and Practice," *Eur. J. Inf. Syst.*, vol. 10, no. 3, pp. 176–177, 2001.

[17] B. Glaser and A. Strauss, *The discovery of grounded theory: Strategies for qualitative*

research. New Jersey: Transaction Publishers, 1999.
[18] J. M. Hess and T. Butter, “Ecosummit - Smart Green Business Network and Conference,” 2016. [Online]. Available: http://ecosummit.net/. [Accessed: 18-Sep-2014].
[19] M. Sonnenschein, C. Hinrichs, A. Niesse, and U. Vogel, “Supporting Renewable Power Supply Through Distributed Coordination of Energy Resources,” in *ICT Innovations for Sustainability*, vol. 310, B. Hilty, LM and Aebischer, Ed. Switzerland: Springer International Publishing AG, 2015, pp. 387–404.
[20] E. Massung, D. Schien, and C. Preist, “Beyond Behavior Change: Household Retrofitting and ICT,” in *2nd International Conference on ICT for Sustainability 2014*, 2014, no. Ict4s, pp. 132–139.
[21] C. Weeks, C. Delalonde, and C. Preist, “Investigation into the slow adoption of retrofitting: what are the barriers and drivers to retrofitting, and how can ICT help?,” in *Proceedings of Enviroinfo and ICT for Sustainability 2015*, 2015, vol. 22, pp. 325–334.
[22] S. Claes, K. Slegers, and A. Vande Moere, “The Bicycle Barometer: Design and Evaluation of Cyclist-Specific Interaction for a Public Display,” in *34th Conference on Human Factors in Computing Systems, CHI2016*, 2015, pp. 5824–5835.
[23] U. Bohne, J. L. Zapico, and C. Katzeff, “The EcoPanel: designing for reflection on greener grocery shopping practices,” in *Proceedings of Enviroinfo and ICT for Sustainability 2015*, 2015, vol. 22, pp. 221–228.
[24] L. Hilty, *Information Technology and Sustainability: Essays on the Relationship between Information Technology and Sustainable Development*. Books on Demand, 2008.
[25] Global eSustainability Initiative (GeSI) and Boston Consulting Group, “GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future,” 2012.
[26] D. Pamlin and S. Pahlman, “Outline for the first global IT strategy for CO2 reductions,” World Wildlife Fund Sweden, 2008.
[27] W. J. Mitchell, *E-topia: “Urban Life, Jim-But Not As We Know It.”* Cambridge, MA: MIT Press, 1999.
[28] UNEP, *Decoupling natural resource use and environmental impacts from economic growth*. United Nations Environmental Program, 2011.
[29] C. Gossart, “Rebound Effects and ICT: A Review of the Literature,” in *ICT Innovations for Sustainability*, vol. 310, B. Hilty, LM and Aebischer, Ed. Switzerland: Springer International Publishing AG, 2015, pp. 435–448.
[30] T. Jackson, *Prosperity without growth: Economics for a finite planet*. Routledge, 2012.
[31] M. Achachlouei and L. Hilty, “Modeling the Effects of ICT on Environmental Sustainability: Revisiting a System Dynamics Model Developed for the European Commission,” in *ICT Innovations for Sustainability*, vol. 310, B. Hilty, LM and Aebischer, Ed. Switzerland: Springer International Publishing AG, 2015, pp. 449–474.
[32] M. A. Achachlouei, “Exploring the Effects of ICT on Environmental Sustainability: From Life Cycle Assessment to Complex Systems Modeling,” Doctoral thesis. KTH, Stockholm, 2015.
[33] M. O’Mahony and M. P. M. Timmer, “Output, input and productivity measures at the industry level: The EU KLEMS database,” *Econ. J.*, vol. 119, no. 538, pp. 374–403, 2009.
[34] Simon Wardley, “An introduction to Wardley ‘Value Chain’ Mapping,” *IT Strategy - CIO*, CIO UK, 2015.
[35] C. Katzeff and J. Wangel, “Social Practices, Households, and Design in the Smart Grid,” in *ICT Innovations for Sustainability*, vol. 310, B. Hilty, LM and Aebischer, Ed. Switzerland: Springer International Publishing AG, 2015, pp. 351–365.
[36] M. Uslar and J. Masurkewitz, “A Survey on Application of Maturity Models for Smart Grid: Review of the State-of-the-Art,” 2015.
[37] J. Rifkin, *The zero marginal cost society: The internet of things, the collaborative commons,*

and the eclipse of capitalism. St. Martin's Press, 2014.
[38] BBC News, "BBC News - Google to buy Nest Labs for $3.2bn," 2013.
[39] F. W. Geels, "Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective," *Res. Policy*, vol. 39, no. 4, pp. 495–510, May 2010.
[40] J. Rifkin, *The third industrial revolution: how lateral power is transforming energy, the economy, and the world*. Palgrave Macmillan, 2011.
[41] J. H. Townsend, "Digital Taxonomy for Sustainability," in *Proceedings of Enviroinfo and ICT for Sustainability 2015*, 2015.