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Digital Acceleration of Sustainability Transition: The Paradox of Push Impacts

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Abstract: Sustainability requires ongoing reform of resource production and consumption to reduce environmental harms. The main way that Information and Communication Technology (ICT) can address these resource impacts is through digital optimization. Spreng found that optimization of an industrial process either increases energy use or accelerates production or consumption. It was assumed that reducing energy use progresses sustainability, whilst accelerating production or consumption to meet market demand is consumerist and generally detrimental to sustainability. In this paper, we argue that there are two important cases in which accelerating economic processes actually has an essential role in enabling sustainability by ICT: (1) when the process drives the production and adoption of an environmentally beneficial product such as a solar panel, often referred to as "cleantech", or (2) when the process being increased 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: not just saving resources with efficiency, but also pushing the adoption of cleantech, and pushing the circulation of resources.

Keywords: ICT4S; sustainability by ICT; resource efficiency; optimization; cleantech; Circular Economy; renewable energy; sharing economy; LES Model; Spreng's Triangle; Smart Green Map; push impacts; substitution effects

1. Introduction

The rapid development of Information and Communication Technologies (ICTs) alongside looming environmental risks has spurred interest in using ICT for sustainability. The digital industry has launched systems that manage energy, water and other resources with potential benefits for the environment. For instance, smart thermostats such as Google Nest can heat homes more efficiently, whilst ride-sharing platforms such as BlaBlaCar can find passengers to fill empty car seats. Such systems have been termed "Sustainability by ICT" by the field of ICT for Sustainability (ICT4S) [1], and "smart green" [2] or "cleanweb" [3,4] within industry and entrepreneurship, amongst other designations. Smart green systems have achieved widespread adoption and large economic impact: Nest was bought for $3.2 bn, the Climate Corporation for $1.1 bn, Opower and Zipcar for $500 m.

Understanding the various mechanisms by which smart green systems work is valuable for research, investment and innovation. Consequently, the field of ICT4S has developed theory to explain how ICT can address sustainability challenges, most notably the Life-cycle/Enabling/Structural Impact (LES) Model by Hilty and Aebischer (Figure 1). Sustainability by ICT is described as micro-scale *enabling impacts* which may be successful in realizing macro-scale *structural impacts*. A lower level of the LES Model describes the life cycle impacts of ICTs themselves, but this *Sustainability in ICT* is not shown as it is out of the scope of this investigation of enabling impacts.

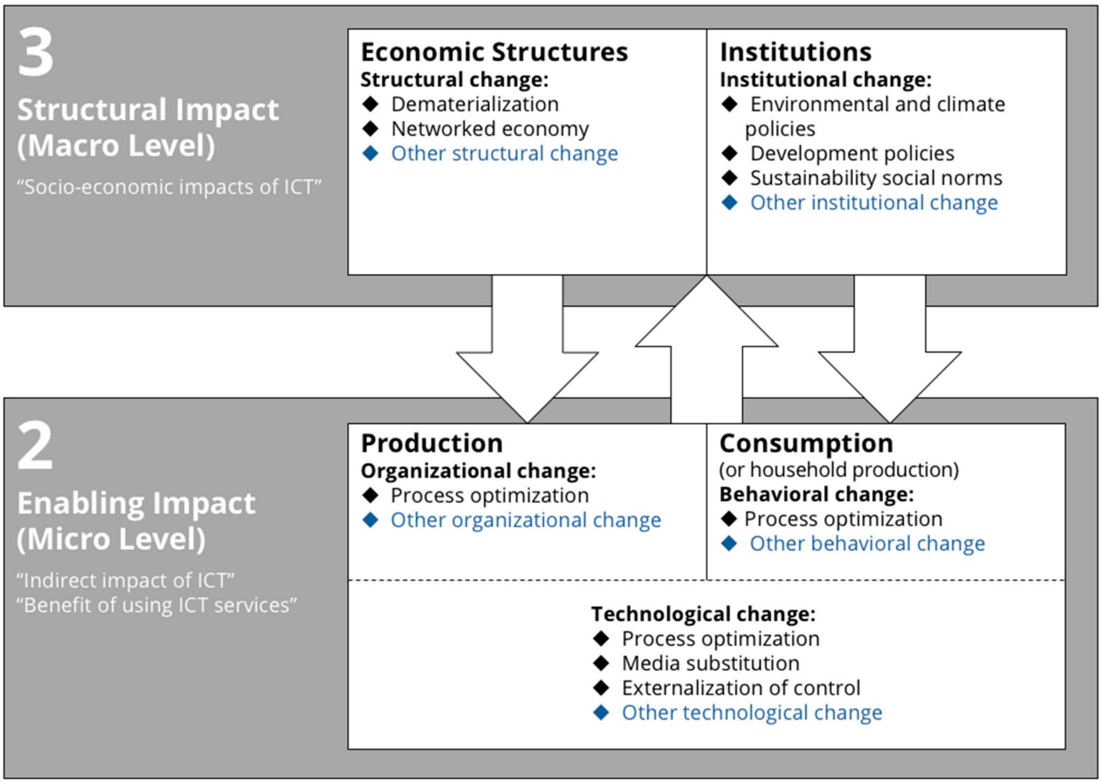

Figure 1. Theorizing Sustainability by ICT: the second and third levels of the LES Model, which stand for enabling impact and structural impact, respectively (Hilty and Aebischer [1]). For clarity, the first level is not shown as it describes Sustainability *in* ICT, the life-cycle impact of ICT devices, which is out of the scope this paper. (With thanks to L Hilty).

The LES Model theorizes that ICTs can save resources directly through enabling impacts of *process optimization*, *media substitution* or externalization of control [1]. In any process optimization, a production or consumption process is made more efficient by gathering and analyzing data on its resources in order to better control their use, e.g., a smart thermostat can reduce the fuel required to heat a home. We interpret externalization of control as a special form of process optimization that takes place at a distance. In media substitution, a digital medium substitutes for a more energy demanding process, e.g., a videoconference can substitute for air travel.

Whilst the LES Model provides a strong theoretical basis for ICT4S, it does face several limitations. In his ICT4S 2014 keynote, Hilty challenged the ICT4S community to better explain *technological substitution*—the transition to more sustainable technologies, products and practices—and the *micro-macro link* between the enabling impacts of ICT and their ultimate structural impact. Cleantech technologies (e.g., renewable energy) substitute for environmentally harmful legacy technologies (e.g., fossil fuels). Increasing the production and consumption of such cleantech has a major role in achieving technological substitution for sustainability. As it stands, the LES Model does not clearly describe this key mechanism for technological substitution. There is an assumption in the underlying theory (Spreng's Triangle [5]) that accelerating the production and consumption of products is a commercial objective intrinsically in conflict with the need for resource efficiencies for sustainability through e.g., process optimizations.

Another limitation of existing ICT4S theory of Sustainability by ICT is that it does not incorporate the concept of *circularity*, as Blumendorf challenged the community to do in his best paper at the first ICT4S conference [6]. Beyond ICT4S, much theory and practice of sustainability champions recycling, maintenance and sharing within a *Circular Economy*, and smart green systems have been developed to enable these processes [7]. In particular, the ICT-enabled tool-sharing, car-sharing and ride-sharing platforms of the *Sharing Economy* fall within the Circular Economy and must be situated within ICT4S as they often claim sustainability benefits [8].

Numerous smart green systems within the cleantech industry, the Circular Economy and the Sharing Economy do not progress sustainability with resource efficiencies, as described by the prevalent ICT4S theory. 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 paper formulates the concept of push impacts and links it with that of circular economic processes in order to address the challenges posed by Hilty and Blumendorf respectively, and better explain ICT's role in technological substitution and circularity for sustainability. This theory is developed from a classification of smart green startups and ICT4S research called the Smart Green Map [9].

Section 2 details the theoretical framework for readers unfamiliar with it: the LES Model, and its links to rebound effects and the mutual substitutability of time, energy and information described by Spreng's Triangle. It then describes the Circular Economy and links it with the LES Model. Section 3 describes the method that was used to originate these concepts, and uses them to classify a sample of smart green startups and ICT4S literature. Section 4 offers a definition of push impacts, the central conceptual contribution, distinguishing two major applications of them: cleantech products and circulation processes. Section 5 discusses push impacts, exploring their paradoxical properties and comparing them with existing ICT4S theory.

2. Background

Here we describe our theoretical framework, the LES Model, and its links to other theory. The following subsections describe the LES Model's theoretical foundations: the challenges to realizing macro-scale decoupling due to rebound effects, and the mutual substitutability of time, energy and information described by Spreng's Triangle. The concept of the Circular Economy is then introduced to more richly characterize the economic processes of production and consumption in the LES Model and to describe circulation and sharing.

2.1. The LES Model, Digital Optimization and Spreng's Triangle

Hilty and Aebischer describe *Sustainability by ICT* as "the transformational power of [ICT] to develop more sustainable patterns of production and consumption" [1]. Their LES Model divides the environmental impacts of ICT into three levels, with the top two describing Sustainability by ICT (Figure 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" [1].

Three mechanisms of enabling impacts are identified by the LES Model, although others are possible: process optimization, media substitution and externalization of control. All three mechanisms are modelled as resource-use hierarchies, causal trees of dependent processes that ultimately deliver the value required by the user or customer. Resource-use hierarchies are therefore similar to the commercial concept of value chains [10]. Hilty challenged the ICT4S community to investigate the role of ICT in technological substitution at all levels of the resource-use tree. 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.

Dematerialization is stated to be a necessary but insufficient condition for sustainable development. Dematerialization is a form of economic structural impact at the third level of the LES Model which describes ICT impacts that lead to persistent changes observable at the macro-level. Decoupling is increasing the ratio of human well-being to resource use, and dematerialization is the "special case of decoupling based on the substitution of immaterial resources for material resources . . . the aggregate result of many process optimizations and media substitutions, moderated by rebound effects" [1].

2.2. Rebound and Substitution Effects

Rebound effects are the "negative side effects of efficiency policies and strategies that end up taking back the environmental gains they had permitted" [11]. The expected gain "rebounds" due to systemic and behavioral responses in a complex economy. In particular, material or energy efficiency gains in the production of a good or service lead to cheaper production of that product or service, other factors remaining equal. Classical economics implies that a price decrease generally leads to more demand for that good. The increased demand, in turn, yields an increased consumption of the resource that had been used more efficiently per unit of product, thus reducing the initial gain in efficiency and thus causing rebound [12]. This can vastly increase the consumption of the good or service, an effect known as *Jevons' paradox* [13].

To the extent to which the more efficiently produced good can be substituted for others, it will partly replace them, as it now became relatively cheaper compared to the previous equilibrium. This *substitution effect* can lead to increased overall consumption of the two goods, a further type of rebound effect [14].

2.3. Spreng: The Mutual Substitutability of Time, Energy and Information

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. "Increasing efficiency ... can be regarded as substituting immaterial resources (information) for other resources" [1]. Spreng's theory is based on case studies of the optimization of industrial production processes [5]. 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 (Figure 2), the geometry of which 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 is assumed to favor the acceleration of production i.e., the reduction of output time.

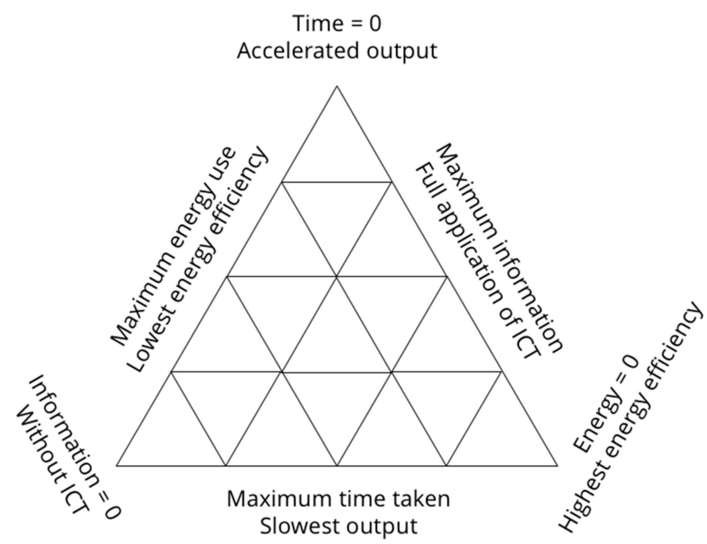

Figure 2. Spreng's Triangle representing mutual substitutability of time, energy and information within an economic process.

2.4. The Circular Economy and the Sharing Economy

This subsection introduces the Circular Economy to more richly characterize the economic processes of production and consumption in the LES Model. 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" [15]. The Circular Economy vision comprises closed-loop cycles for materials, consisting of reuse and recycling, reducing and ultimately eliminating the extraction of finite resources. The Ellen MacArthur foundation has promoted the Circular Economy concept in Europe amongst policymakers, industry, and the public, arguing that circularity would offer both major environmental and economic benefits [7].

The Circular Economy also includes processes of sharing and thus the Sharing Economy, such as tool-sharing, car-sharing or ride-sharing platforms. 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, sometimes referred to as *collaborative consumption*, has become a major theme within the digital sector, and includes many of the smart green systems as they have the potential to reduce resource use. Pascual envisions the cleanweb (i.e., smart green) industry at the intersection of the Sharing Economy, Cleantech and the Internet of Things [16].

The LES Model organizes enabling impacts by whether they act upon processes of production or consumption. To this we add processes of circulation, as proposed by the Smart Green Map classification of enabling impacts [9]. Including circulation addresses Blumendorf's call to place circularity within ICT for sustainability [6] and allows ICT4S theory to better integrate concepts such as recycling, reuse, maintenance, and sharing. Figure 3 shows how traditional Linear Economy drives environmentally harmful extraction and disposal of resources (red arrow). By undertaking circulation processes of the Circular Economy (blue arrow), we link consumption with renewed production and mitigate wasteful destruction of value and the pollution it generates.

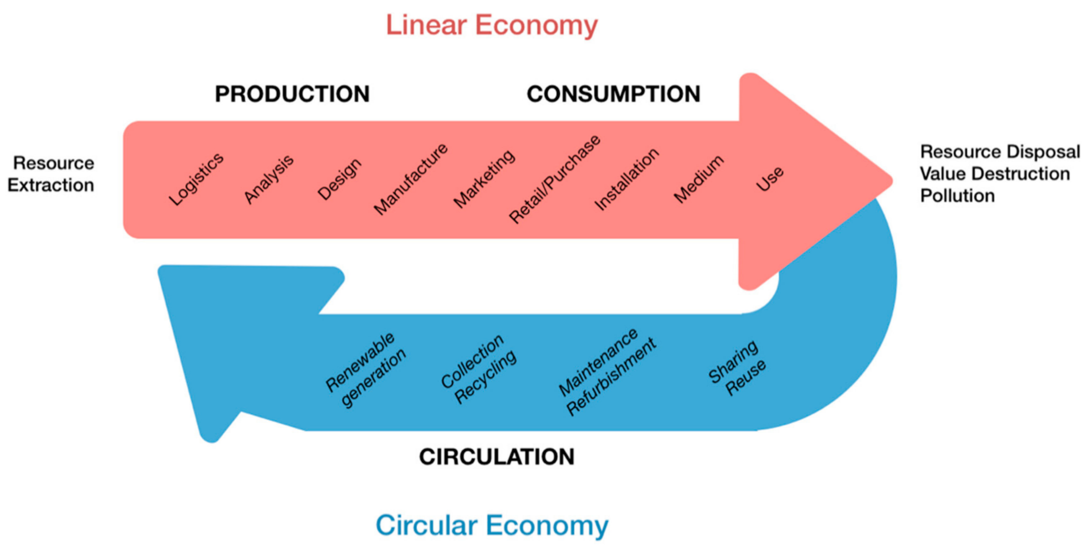

Figure 3. Economic processes of production, consumption and circulation. The circulation of resources in the blue processes of the Circular Economy reduces the extraction and disposal of resources in the traditional Linear Economy that is environmentally harmful. This list is indicative and not exhaustive.

Figure 3 shows a draft list of these processes of production, consumption and circulation, based on the Smart Green Map [9], the Ellen MacArthur model of the Circular Economy [7], and a precursor to the LES model called the "Linked Life Cycle Model" which described ICT's optimization of design, production, use, and end of life, as well as substituting for and inducing demand [17]. The list of processes in Figure 3 is not exhaustive, and different products undergo different sets of processes linked together into complicated resource-use hierarchies.

3. Method

A qualitative classification was developed [9] to map out the space of possible enabling impacts employed in the smart green systems created by entrepreneurs and researched by ICT4S. A list of search terms relevant to ICT4S enabling impacts was developed by word frequency analysis of literature from the domains of ICT, sustainability, ICT4S, and cleantech. Using these search terms in the CrunchBase online database of digital startup companies, 500 of the most relevant companies were identified. Descriptions of these smart green companies were analyzed with some principles from grounded theory [18]. Significant characteristics of the companies were coded, and the codes were then sorted and resorted to identify higher-level concepts and categories. Potential mechanistic models to explain the observed variation were explored by diagramming, employing Hilty and Aebischer's theory of resource-use hierarchies [1].

Whilst sorting and resorting the initial concepts and reviewing the company description data, it was noted that some systems enable the adoption of a form of sustainable product i.e., "cleantech" e.g., renewable energy. This concept was influenced by "catalyzing cleantech", a category of smart green startups in a study by Pure Energy Partners (provided in private correspondence). Most other systems were controlling machines or influencing users' behavior to be more resource efficient. This dichotomy became a dimension with two categories, ultimately termed "save impacts" and "push impacts".

To test out and develop these new categories, they were used to classify a fresh sample of ICT4S research and smart green startups, thus offering a quantitative comparison of their relative distribution. To maximize comparability between industry and academia, a similar geographical and temporal focus was used: the leading conferences in Europe between mid-2014 and mid-2016. A total of 57 research papers and 59 startup companies could be classified, as shown in Table 1. Reasons that a paper or company could not be classified included: if they only addressed the life-cycle impact of ICT (i.e., Sustainability in ICT); if they described purely non-digital cleantech such a photovoltaic cell, or if they worked primarily by institutional change rather than by contributing to resource decoupling. A minority of the papers or companies could be classified into both categories for a variety of reasons e.g., a particular company creating multiple systems, a paper describing multiple systems, one system having multiple functionalities, or one functionality having multiple enabling impacts.

Table 1. Number of research papers and companies that were successfully classified by source event or publication. Items that could not be classified are shown in the third column. Acronyms are defined above in Section 3. * The CHI conference, SHCI workshop and ICT Innovations for Sustainability samples were pre-filtered so the figures for unclassified papers are not complete.

	Classified Companies or Research Papers	Unclassified Companies or Research Papers
CHI 2015 conference	8	11 *
ICT4S conference 2014	19	30
ICT4S conference 2015	20	22
ICT Innovations for Sustainability	8	2 *
Sustainable HCI Workshop	2	1 *
Total research papers	**57**	**66 ***
Ecosummit 2015 London	25	15
Ecosummit 2016 Berlin	34	26
Total startups	**59**	**41**
Total papers and startups	**116**	**107 ***

To sample ICT4S research, all the proceedings of the ICT4S conferences 2014 in Stockholm and 2015 in Copenhagen were analysed. The most relevant papers from across the field of ICT4S within the major volume "ICT Innovations for Sustainability" were also classified [19] (Seven of the chapters of "ICT Innovations for Sustainability" focus on enabling impacts, forming most of section IV "Saving Energy And Materials Through ICT–Enabled Solutions"). As "Sustainable Human-Computer Interaction" (SHCI) is a closely related area to ICT4S, the proceedings of CHI 2016, the Conference on Human Factors in Computing Systems and a co-located SHCI workshop were also investigated

("Design patterns, principles, and strategies for Sustainable HCI"). The Proceedings of the 2016 CHI were downloaded, a total of 545 papers. A search term was devised to identify those papers of potential relevance to sustainable resource use: "*sustainab* ("Sustainab" and "efficien" allows for different word endings like "sustainability" and "sustainable") *(energy OR food OR water OR efficien OR agricultur OR waste OR materials OR carbon OR grid OR transport OR renewable OR power)*". 80 papers were identified with the search terms. To these were added 8 papers from the co-located SHCI workshop. Many papers were excluded from the study as they did not mention sustainability in the body of the paper, or only in a non-environmental sense. Ultimately, 22 papers were identified of likely relevance, and from these, only 10 identified a specific type of system the enabling impact of which could be classified. Numerous SHCI papers were excluded from this study as they took a high-level strategic perspective on the nature of the field and its challenges, or how to support it, or discussed the design process of ICT4S systems rather than focussing on a type of smart green system.

For a comparable sample of commercial smart green systems, the startups were analysed from Ecosummit, "Europe's leading smart green innovation and impact conference for startups, investors and corporates" [20]. Unlike other cleantech industry events at the time, Ecosummit has an explicitly digital agenda. Whilst some startups pitch purely physical cleantech such as photovoltaic cells, the majority are developing software as part of their product. Ecosummit has run every year in Berlin since 2010, in London since 2013, and now also takes place in Amsterdam, Stockholm and Paris. Startups compete for the Ecosummit award incentivizing participation. Most startups at Ecosummit are just a few years old but mature enough to need investment. All the companies from the Berlin 2015 and London 2016 Ecosummits were analysed.

4. Push Impacts: Fostering Cleantech and the Circular Economy

This section introduces the concept of *push impacts* in contrast to the established mechanisms of *process optimization for efficiency* and *media substitution*, which are collectively termed *save impacts*. The first subsection defines push impacts using the resource-use hierarchy theory. The second subsection distinguishes two major applications of push impacts: cleantech products and circulation processes. The final subsection presents how the sample of smart green systems from startup companies and ICT4S research were distributed between save and push impacts and gives examples of such systems.

4.1. Defining Push Impacts

This subsection proposes a theoretical definition of the new concept of push impacts. Push impacts are modelled with the theory of resource-use hierarchies and ICT-enabled substitutions upon which with the LES Model is based [1,21]. Push impacts thus contrast with those mechanisms that are well understood already, here termed save impacts. These models develop the conceptual basis for sustainability by ICT.

Firstly, we present a simple model of any product as a resource use hierarchy (Figure 4). By definition, a product is produced by production processes listed in Figure 3 such as design, manufacture, logistics and indeed marketing. The product is then consumed by consumption processes, e.g., being presented on a medium or being used. Here we also consider the potential for processes of circulation such as maintenance, sharing and recycling which link consumption with renewed production (blue arrow in Figure 3). Any product therefore depends upon a life cycle of economic processes of production, consumption, and potentially circulation. Each economic process 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.

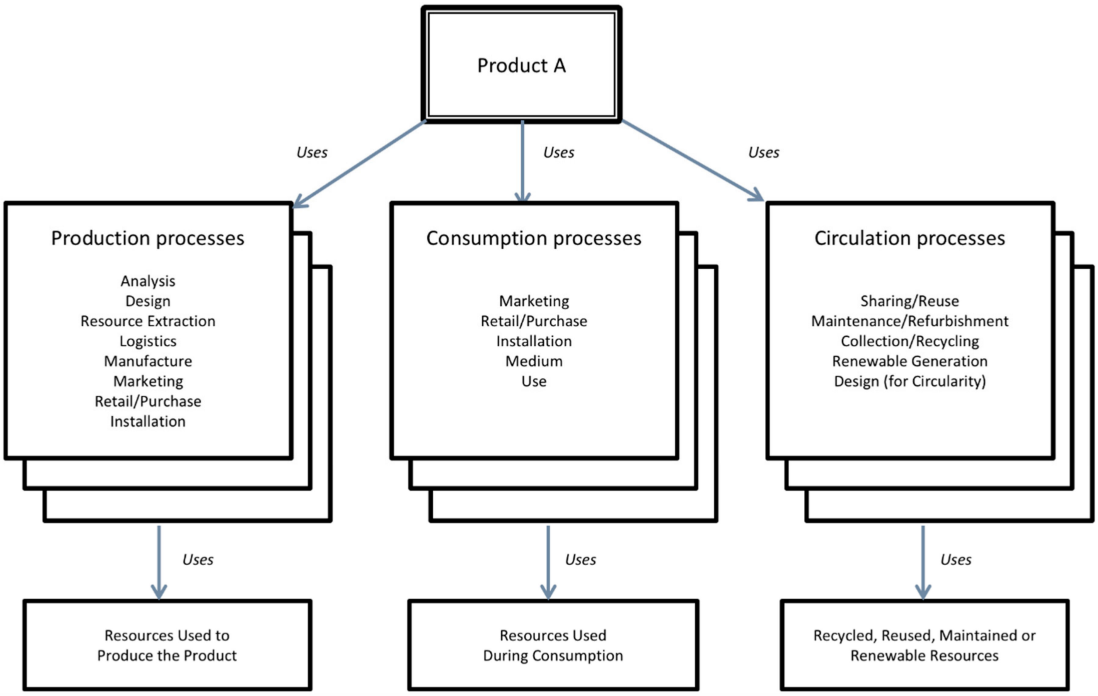

Figure 4. Generic model of any product, developed using Hilty and Aebischer's resource-use hierarchy diagrams [1,21]. The diagram models a functioning product as dependent on hierarchies of economic processes of production, consumption and potentially circulation (Figure 3), which in turn depend on precursor resources.

Secondly, we address those enabling impacts that are already well known within ICT4S, which we shall here term save impacts as they save resources directly. We use the generic model of any product in Figure 4 to model save impacts in Figure 5. The LES Model identifies two mechanisms by which ICTs can save resources directly, which are termed here save impacts:

Process optimization for efficiency—using ICTs to gather and analyze data on resource use within production, consumption and circulation of a product (Product A) to better control and thus reduce the input of environmentally harmful resources. For example, London startup Winnow Solutions monitors waste in commercial kitchens in order to use food more efficiently. Following Spreng [5], the LES Model describes this as a partial substitution of a material resource with an immaterial one (information). We have interpreted externalization of control as a special form of process optimization for efficiency that takes place at a distance.

Media substitution—in media substitution, a digital medium substitutes for a production or consumption process of a product (Product A). The digital medium could substitute for a non-digital medium, such as e-books replacing paper ones to enable reading, or for another digital medium, such as music downloads replacing CDs. Moreover, it could substitute for any process of production or consumption, such as substituting air travel with a teleconference to allow professional communications.

Thirdly and most notably, we propose a theoretical definition of the new concept of push impacts. Push impacts function by process optimization, like many save impacts do, optimizing resource use in the production, consumption and circulation processes that underlie a product. Like save impacts, push impacts are also beneficial to sustainability, i.e., they enable a micro-scale contribution to decoupling of resource use at the structural macro-level of the LES Model (Figure 1). However, whilst save impacts minimise the use of environmentally harmful resources directly consumed by these processes, push impacts work by accelerating the output of certain processes which are ultimately beneficial for sustainability.

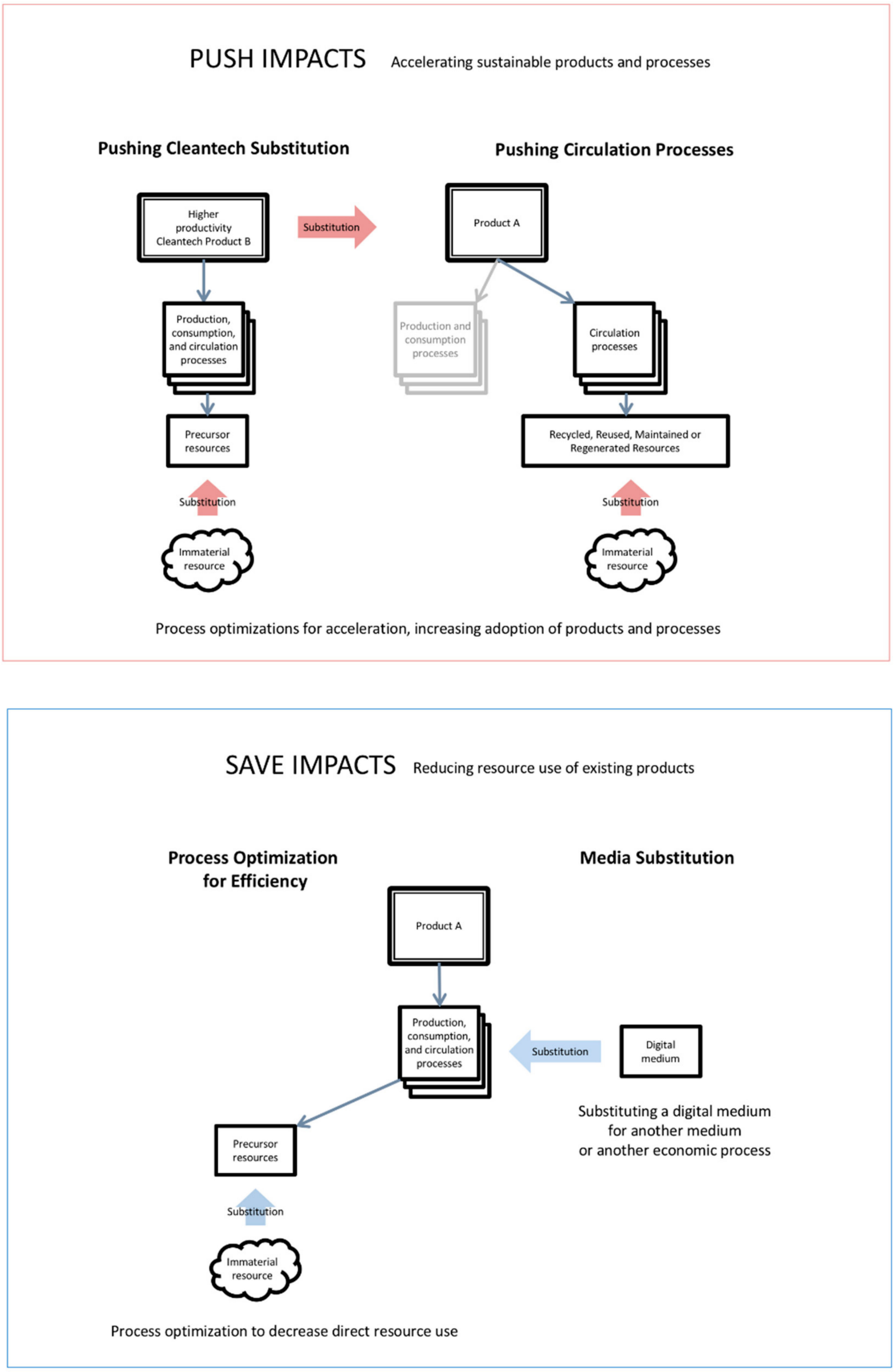

Figure 5. Save and push impacts modelled with Hilty and Aebischer's resource-use hierarchy diagrams [1,21]. Save impacts decrease environmental impact by optimizing resource use in the production, consumption and circulation processes of a Product A, or substituting them with a digital medium. In contrast, push impacts accelerate production, consumption and circulation processes to either maximize the adoption of a cleantech Product B that substitutes for a legacy Product A, or to increase the circulation of wasted resources to provide Product A.

4.2. Two Applications of Push Impacts: Cleantech and Circulation

Two mechanisms were identified by which ICT-enabled acceleration of economic processes can contribute to sustainability. These two mechanisms are thus two forms of push impact i.e., ICT-enabled accelerations for sustainability:

Pushing the production and adoption of cleantech—the term "cleantech" is widely used for the industry that innovates products and technologies that are more sustainable such as renewable energy [22], and the term is used broadly here for any and all such products. Technological substitution and sustainability transition can thus be considered a transition towards cleantech. Like all industries, the cleantech industry is rapidly digitalizing and thus entering the purview of ICT4S. As Pure Energy Partners noted, many smart green systems progress sustainability by *catalyzing cleantech*, i.e., they commercially optimize the production, consumption and circulation processes to increase output, decrease price and ultimately increase adoption of more environmentally beneficial technologies. In Figure 5, the push impacts are shown increasing the productivity of a production, consumption or circulation process to substitute a cleantech product (Product B) for a more environmentally harmful legacy product (Product A).

Pushing the circulation of all resources—certain economic processes can themselves be environmentally beneficial, notably those of the Circular Economy such as recycling, maintenance/refurbishment, and sharing/reuse. Each of these circulation processes can be digitally optimized to become more competitive with wasteful and polluting value destruction. There is a potential sustainability benefit to employing ICTs to optimize the circulation of most products, as represented in Figure 5.

4.3. Prevalence of Pushing Cleantech in Smart Green Entrepreneurship and ICT4S Research

The distribution of research papers and startup companies between save impacts and pushing cleantech that was found is shown in Table 2. Push impacts were a lot more prevalent amongst smart green startups than among ICT4S research papers. The startups were split equally between save impacts and pushing cleantech. In contrast, the research papers were dominated by save impacts with only a fifth describing push impacts. The research into pushing cleantech included renewable energy through the smart grid [23] and household retrofitting of insulation [24,25].

Table 2. Proportion of smart green systems found to work via save impacts, pushing of cleantech or both, described by research papers or created by startup companies.

	Number of Papers or Companies (% of Total Paper or Company Classifications)		
	Save Impacts	**Pushing Cleantech**	**Save Impacts and Pushing Cleantech**
Research papers	46 (81%)	9 (16%)	2 (4%)
Startups	28 (47%)	27 (46%)	4 (7%)

Startups were found that push a great diversity of cleantech, from transportation to thermal insulation. Loco2 broker ticket sales for international travel on European railways to challenge the dominance of more polluting air travel. Ubitricity offer a digital network of charging points accessible via an app to support the substitution of liquid fuel cars with electric vehicles. Ofo offer a network of location-sensing dockless bicycles that may substitute for car travel. In contrast, Q-Bot use small autonomous robots to apply home insulation to inaccessible floor cavities, ultimately but indirectly reducing the demand for heating fuel.

Many push impacts were applied to the production and consumption of renewable energy in order to substitute for fossil fuels. Enian finds investors for large solar or wind projects. HelioScope offers design software for large solar installations, whilst Sungevity markets and maintains domestic solar with an online design tool for homeowners and an app to monitor panel performance. Aerial Power use automated drones to clean dust from solar panels, whilst Cyber Hawk use them to inspect and thus maintain wind turbines.

As renewable energy generation is a circulation process (Figure 3), pushing renewable energy can enable cleantech and circularity simultaneously. Moreover, save and push impacts can operate at the same time as reflected in the final column of Table 2. Many smart green systems can thus save resources, push cleantech, and push resource circulation, and sometimes in multiple ways. These are not mutually exclusive categories and each impact represents a distinct sustainability benefit that may be quantified separately.

The smart grid is a concept that both saves energy (e.g., through demand response) whilst pushing the transition to distributed generation. The smart grid has been the subject of considerable ICT4S research [23,26,27], and popular interest [28]. Similarly, the smart battery for the home sold by German startup Sonnen is algorithmically optimized to save electricity, which then makes the adoption of domestic solar panels more feasible. Furthermore, British company Onzo offers disaggregation of smart meter data to help homeowners save energy by identifying wasteful habits and wasteful appliances. They can then offer more efficient appliances or distributed energy technologies relevant to that particular home.

Circular economy systems often also save resources. BlaBlaCar, a French Sharing Economy startup that pitched at Ecosummit London 2015, offers a network for dynamic sharing of one-time rides with other members of the public at very short notice. BlaBlaCar leverages several ICTs (smartphone, GPS navigation and social networking) with both save and push impacts: filling empty passenger seats through the sharing/reuse circulation process to substitute journeys on other modes of transport; coordinating passengers and drivers efficiently to save fuel; and even driving its own adoption to substitute for car ownership itself.

5. Discussion

The first subsection of this discussion section argues that the concept of push impacts identifies two major new forms of digital optimization for research within ICT4S. The next subsection discusses the paradoxically consumerist nature of push impacts, and the following subsection situates push impacts within existing strategic conceptualizations of ICT4S. The final subsection then explores the properties of push impacts in comparison to save impacts, and the micro-macro link between push impacts and resource decoupling, and between cleantech innovation and the displacing of established technologies.

5.1. The Three Digital Optimizations for Sustainability

It is now possible to examine Sustainability by ICT overall and identify three major opportunities for ICT4S optimization (Figure 6): not just saving resources with efficiency, but also pushing the adoption of cleantech, and pushing the circulation of resources. All the smart green systems identified were found to operate by either save or push impacts for one or more of the processes of production, consumption or circulation, listed in Figure 3. By smart green systems we mean those that could claim to contribute to resource decoupling at the structural macro-scale, not those that contribute to institutional change to law, politics or social structures (Figure 1). Metaphorically, the economy can be imagined as a wheel, with save effects being a brake on the resource-use of the established economy, pushing cleantech an accelerator for the new economy, and pushing circulation as an axle to make all the resources circulate.

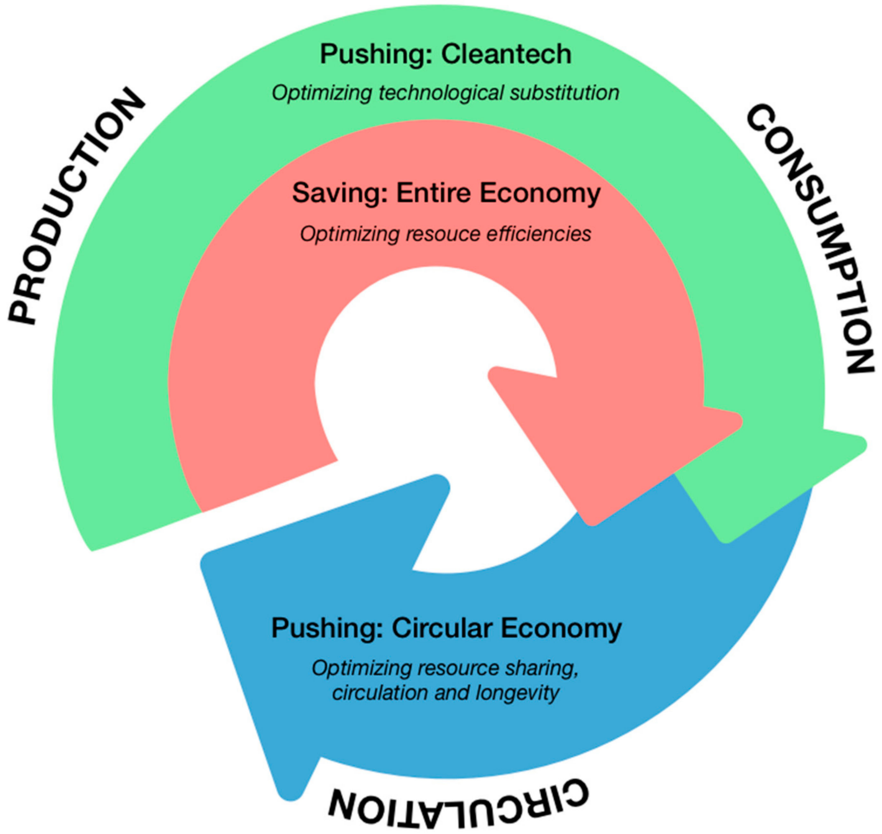

Figure 6. The three digital optimizations for sustainability. These three mechanisms describe how the great majority of smart green systems encountered enable sustainability by ICT. The specific processes of production, consumption and circulation are detailed in Figure 3.

5.2. The Paradox of Push Impacts

Spreng's Triangle (Figure 2) encapsulates the finding that energy, information and time can be mutually substituted. We might generalize this from just energy to all environmentally impactful precursor resources of an economic process other than time, such as the consumption of water or materials. When ICT applies information/knowledge to an economic process, there was found to be a choice between doing it with less resources (the right corner of Spreng's Triangle) or doing it faster (the top corner of the Triangle). The former can therefore be equated to a save impact, applying ICT in order to use less resources in the economic process itself.

There may be an assumption by Spreng that these save impacts are the overarching mechanism by which ICT enables sustainability. In contrast, accelerating output in the top corner of the triangle is assumed to be environmentally harmful. Moreover, accelerating output is commercially beneficial, leading it to win out over resource-saving in a competitive market. "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" [29].

These assumptions are questioned by distinguishing push impacts, which increase output rates or qualities for "greater convenience on the consumer side" [5], and thus sit in the top corner of the Triangle. There appears to be a *paradox of push impacts*: how can they benefit sustainability when they increase production and consumption, with an inevitable increase in resource use by that process?

The paradox can be resolved by noting that not all products and processes are equal. To achieve technological substitution that addresses Hilty's challenge, certain products and processes need to flourish. This paper identifies cleantech with such products, and circularity with such processes. Push impacts can accelerate the production and consumption of cleantech or accelerate the circulation of any resource, to contribute to macro-scale decoupling and technological substitution. These push impacts do not reduce the use of harmful resources in those processes—although the same system may simultaneously have save impacts which do.

Table 2 showed that around half of the smart green startups in the sample were pushing cleantech to be sustainable. Therefore, these push impacts may be just as important as save impacts as a mechanism of Sustainability by ICT. Indeed, push impacts incentivize cleantech entrepreneurship by aligning commercial priorities of production and sales with sustainability goals. As Spreng noted, the acceleration of output will generally dominate in a competitive marketplace.

Their paradoxical nature makes push impacts particularly open to critiques of consumerism within ICT4S such as by Knowles [30] and Brynjarsdottir et al. [31]. 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" [11].

In addition to accelerating production and consumption, push impacts are applied to processes of design and entrepreneurship to accelerate the development of better cleantech. This is then open to critiques of the sustainability of innovation itself from environmental economists such as Jackson [32].

5.3. Push Impacts in ICT4S Theory

Mirroring the limited academic consideration, the LES and other models do not distinguish push impacts. The LES identifies process optimizations in production and consumption at the micro-level, but these could be either push or save which work differently. Dematerialization is described as an ultimate macro-level goal, but there are different ways to achieve it.

The LES Model also identifies media substitutions, which are here placed within save impacts as they create resource efficiencies directly. Like push impacts, media substitutions are a form of substitution; however, unlike push impacts they substitute with a digital medium. By contrast, push impacts typically lead to a physical substitution, in which cleantech replaces less resource efficient technologies. For instance, a website that sells domestic solar panels is a push impact operating on the "Marketing" economic process (Figure 3) and is clearly not a media substitution.

As far as we know, Pure Energy Partners' analysis is the only strategic conceptualization with a category fully equivalent to push impacts. Three other strategic conceptualizations of ICT4S have a category that is relevant to push impacts but not equivalent: the WWF [33], Smarter 2020 [34] and E-topia [35] studies.

Neither can push impacts be placed satisfactorily on the Three-Levels Model, a precursor of the LES Model that is well known within ICT4S [1]. As they stimulate the consumption of another resource, push impacts act like an environmentally beneficial form of "induction"; however, induction is defined to be "ICT as part of the problem" rather than the solution. They would better fit in the "substitution" category of the Three-Level model, but this appears to be limited to media substitution which works differently, as noted above.

One concept for further analysis is ICT's role in *intensification* of resource use for sustainability, as described by Höjer et al. [36], such as running more trains on the same track thanks to ICT. This is a form of save impact, a process optimization for efficiency and yet like a push impact it also works by accelerating outputs in order to reduce resource use per unit output.

5.4. Push Impacts, Rebound and Technological Transition

This subsection discusses the likely properties of push impacts in comparison to save impacts and rebound effects. Table 3 contrasts some of the properties of push and save impacts.

Table 3. Comparing save and push impacts.

Save Impacts	Push Impacts
Digital system *as* cleantech	Digital system *catalyzing* cleantech or circulation
Use a *product better* or substitute a process with a digital medium	Use a *better product or process*
Discouraging the consumption of environmentally *harmful* resources	*Encouraging* the consumption of environmentally *beneficial or wasted* resources
Using digital systems per se to control resource use and thus decouple more *directly*	Using digital systems to decouple more *indirectly* by accelerating the adoption, construction and operation of more sustainable products and processes
Success metric: resource saved *directly*	Success metric: amount of cleantech adopted or resources not wasted. Resources saved *indirectly*
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 does similarly take place by process optimization
Spreng's Triangle: reducing energy use and increasing resource efficiency.	Spreng's Triangle: reducing production or consumption time
Similar proportion have been found in samples of ICT4S research and smart green entrepreneurship	Much more prominent in the sample of smart green entrepreneurship than ICT4S research

Push impacts are micro-scale enabling impacts that contribute to technological transition and thus resource decoupling at the macro-scale. As push impacts can be modelled with substitutions to resource-use hierarchies (Figure 5) they are enabling impacts that operate at the micro-scale, just as save impacts are. As push impacts function at the micro-scale, they can be created by individuals and teams, i.e., smart green entrepreneurs. To achieve macro-scale decoupling these systems must not just aggregate their micro-scale impacts, but must scale themselves and the products they push to displace existing socio-technological regimes as described in the theory of Technological Transitions [37]. The enabling impacts and structural change categories of the LES Model are defined in very broad terms, but as Hilty noted in his ICT4S 2014 keynote, we must better explain the role of ICT in technological substitution and better characterize the micro-macro link. The concept of push impacts is a step towards a more complete and concrete description of the role of micro-scale enabling impacts of ICT in driving macro-scale Technological Transition.

Many push impacts work like a form of rebound—The more efficiently a product can be produced, the more it will tend to substitute for less efficient and thus more expensive economic processes. This causes a common form of rebound effect called a "substitution effect" (Section 2.2), but many push impacts also work this way, increasing such efficiencies to substitute for a less sustainable product.

But the benefits of push impacts may also be limited by their own rebound effects—Any benefit arising from push impacts at the micro-level may have limited impact at the macro-level; push impacts may be moderated by their own rebound effects.

Push impacts can be behavioral or automatic—Just as persuasive technology can be used in save impacts to influence people to behave more resource efficiently, it can be employed in push impacts to, e.g., influence consumers to buy more cleantech with digital marketing, or indeed to influence workers to install solar panels more effectively. In the LES Model these persuasive techniques are considered a form of process optimization, and that is equally the case for push impacts. The distinction between automation and social/persuasive technology in smart green systems has been classified by Townsend into four *enablers* [9]. That distinction is orthogonal to the distinction between save and push, and to the distinction between consumption and production, something that may be less clear in the LES Model. For instance, using robots to manufacture solar panels more cheaply is a push impact that is neither behavioral nor applied to consumption.

Measuring push impacts—As save impacts directly generate resource savings, the smart green systems that create them are a form of cleantech themselves, e.g., a smart thermostat system is a form of digital cleantech. In contrast, push impacts function indirectly, by enabling some other form of cleantech, e.g., a sales website for domestic solar panels. Save impacts can be measured by how much resource they save directly, whilst push impacts by how much of a more sustainable product is adopted. It may then be possible to estimate how much resources are saved indirectly by the push impacts. As the comparison baseline, however, is inherently hypothetical (i.e., how the world would have evolved without the pushed cleantech), any such estimate is subject to ontological uncertainty [38]. Further research is required to measure push impacts, as described below.

Possible exhaustiveness of save/push—All the smart green systems identified, i.e., all those that could claim to contribute to macro-scale resource decoupling, were found to operate by either save or push impacts for one or more of the processes of production, consumption or circulation, listed in Figure 3. It is therefore possible that save/push may be an exhaustive classification of all such smart green systems.

Multi-stage push impacts—As resource-use hierarchies have many levels, push impacts can be mediated by more than one stage between the digital technology and the macro-scale resource decoupling. For instance, German startup JPM Silicon uses digital technology to improve the production of silicon, which can then create solar panels, which can then contribute to decoupling.

5.5. Push Impact Policy, Investment and Innovation

The expansion of push impacts in the economy is equivalent to the digitalization of cleantech and the Circular Economy for different resources and thus different sectors, notably energy services, energy generation and transmission, water, cities, transport, agriculture, waste management and finance [4]. This digitalization applies the latest capabilities of ICTs, such as social media and compelling user experiences (UX), and the latest technologies such as artificial intelligence and blockchain. The innovative digitalization of cleantech and the Circular Economy can occur either within existing corporations or through smart green entrepreneurship. The following policy opportunities are based on those proposed by Masero and Townsend to support the UK smart green economy [4]. Further research is required into these policy levers to encourage the growth of push impacts.

Smart green entrepreneurship—Policy opportunities include: funding early stage research and development with grants; financing smart green acceleration and incubation programs such as London's Sustainable Accelerator, Amsterdam's Rockstart or San Francisco's GreenStart; supporting attendance at pitching events such as Ecosummit to broker relations with investors for growth capital; and organizing trade missions to support entry to foreign markets with diverse regulatory regimes, such as the UK Clean and Cool programme.

Reform of resource industries—Like all industries, the cleantech industry is digitalizing. Similarly, many companies in resource industries such as utilities are digitalizing whilst also introducing cleaner technologies. Supporting the recruitment of digital skills and education of staff in digitalization can facilitate these processes.

Partnerships—A major opportunity is brokering partnerships between innovative smart green startups and established companies with deep knowledge of resource industries. For instance, a supplier of renewable energy, Good Energy, partnered with startup Open Utility to offer domestic consumers a digital marketplace for their power with greater transparency. Entrepreneurs can learn about the problems resource industries face through mentoring programs, by attending industry events, or mounting hack events and product workshops. Corporations can develop open innovation programs to buy from smart green startups, or create corporate venturing arms to invest in them, such as Innogy Venture Capital or Centrica Innovations. Effective regulation may encourage this corporate support.

Open standards—Finally, the development of open digital standards for the many economic processes enabling cleantech adoption and resource circulation, can be a systemic means to support digital integration within resource industries whilst reducing barriers to entry to startups.

5.6. Push Impact Research Opportunities

Push impacts are paradoxically consumerist and yet sustainable. Their alignment of commercial priorities with sustainability incentivizes entrepreneurship, production and adoption, which could play key roles in technological transition towards sustainability. This paradoxical consumerism might have reduced the interest of ICT4S researchers in push impacts, as such research has been limited in comparison to the level of push impact entrepreneurship.

Research is needed into a number of areas: studies into the many forms of push impacts for different economic processes and in the context of different industries; studies into the quantification of push impacts; and conceptual analyses to better place push impacts within the context of technological transitions and rebound effects.

Identifying forms of push impacts across resource industries—Even though ICT4S research into push systems is limited, it does encompass a variety of applications, particularly renewable energy through the smart grid [23] and household retrofitting [24,25]. Nevertheless, as the examples in this article show, the breadth of pushed cleantech and circularity is much wider, and still underexplored by the ICT4S research community. As with save impacts, a range of studies is needed to investigate the diversity of commercial innovations that are taking place.

Quantifying push impacts—Research is further required to measure push impacts. Life-cycle assessment (LCA) and systems dynamics models have been developed to quantify save impacts at the macro-scale structural level [39], and these might be adapted to quantify push impacts and investigate their rebound effects. A basis for analyzing the acceleration of cleantech with ICTs moderated by rebound effects may be research into the improvements to general economic productivity due to ICT [40]. This will better characterize the *micro-macro link* between the Enabling and Structural Levels of the LES Model, as called for by Hilty.

Push impacts, Technological Transitions and rebound effects—Finally, push impacts offer a mechanism by which ICT4S theory such as the LES Model can be integrated with the theory of *Technological Transitions*, which describes how technological innovations occur and are incorporated into society [37]. How can digital systems be created to generate specific push impacts at each stage of the innovation process, so innovators of novel cleantech can better experiment in technological niches, scale, disrupt and replace existing sociotechnical regimes? Digital entrepreneurship has created its own empirical methodologies for how to do this as effectively as possible—notably Lean Startup [41] and growth hacking [42]. How are digital technologies being applied within these methods, and are there considerations specific to the enabling of cleantech? In addition, how are the macro-scale landscape changes caused by the digital "revolution" creating opportunities for cleantech by disrupting existing sociotechnical regimes? Should the third level of the LES Model also list "Digital disruption and destabilization of legacy sociotechnical regimes" under Economic Structures?

Last but not least, a better understanding of the relation between rebound and push effects is needed. Rebound effects are assumed to be harmful to sustainability as they foster more use of resources. However, push impacts can work like a beneficial form of rebound by pushing the substitution of legacy technology and processes with cleantech or circularity.

6. Conclusions

This paper has argued that pushing cleantech and circularity are important ways by which ICT can progress sustainability. As these push impacts feature heavily in ICT4S praxis they should be integrated into strategic conceptualizations of the field. So far, however, the theory of ICT4S has tended to focus on save impacts that address sustainability by generating resource efficiencies more directly. By contrast, the class of push impacts identified here can benefit sustainability by accelerating the adoption of cleantech products and circular processes, and thus yielding resource savings more indirectly. The existence of push impacts shows that accelerating certain outputs can be beneficial for sustainability and not simply environmentally harmful, as implied by Spreng's Triangle. The save/push classification is not mutually exclusive, so push impacts identify additional mechanisms by which the same digital system can progress sustainability. However, push impacts may be exhaustive for all enabling impacts that contribute to macro-scale decoupling of resource use. Half of the smart green entrepreneurship encountered pushed cleantech, and push impacts therefore comprise considerable economic value and potential sustainability benefit.

Pushing circular economic processes addresses Blumendorf's call to bring circularity into ICT4S, including sustainability theory such as the Natural Step Framework [6], and linking with the Circular Economy community [43]. The Circular Economy also includes the Sharing Economy, situating digital platforms for tool-sharing, car-sharing and ride-sharing within ICT4S. Push impacts help address Hilty's challenge to better explain the role of ICT in technological substitution, the transition to more sustainable technologies, products and practices. ICT's primary role is the application of push and save impacts to optimize economic processes of production, consumption and circulation throughout the resource-use hierarchies that underlie all products. The three opportunities for ICT4S optimization are thus not just saving resources with efficiency or media substitution, but also pushing the adoption of cleantech, and pushing the circulation of resources.

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