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Innovation for Sustainability in Information and Communication Technologies (ICT)

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October 26, 2010

I. Introduction

With increasing concern regarding global climate change and volatility of energy markets, computing has begun to embrace the notion of green information and communication technologies (ICT), in which the environmental impact is taken as a consideration in the design of new technologies and systems. A broad concept, "Green ICT," of course, has varied meanings. Some consider recycling of components with minimal use of corrosive solvents as a green avenue. Another might be the U.S. government's Energy Star program, which produces benchmark criteria on energy consumption for consumer products, including personal computers. Qualifying products are rewarded with official certification for meeting or exceeding efficiency guidelines. It is on this second thrust regarding energy efficiency that we argue for a change of thinking to acknowledge economic and technological factors broader than performance alone.

While the march to greater concern and awareness on global climate change has stretched over several decades, when oil and gas prices rose into previously unforeseen high territory during the summer of 2008, the desire for ICT designed to consume less electricity became a significant concern in the world of computing. This marked a change. Although researchers and engineers in computing have been concerned about the environment, emphasis has always been placed on innovation meant to sustain Moore's Law, without explicitly addressing the question of sustainability and impact on the environment. In this paper, we propose a novel measure, the sustainable innovation quotient, or SIQ, that we believe provides a unified approach to thinking about innovation and growth, while being cognizant of the potential environmental impact. For the purposes of this paper, the acronym ICT, a commonly used term that includes computing of a variety of sorts, is an umbrella that includes all technologies for the manipulation and communication of information.

A. Framing the Carbon Problem

There was a time in the 1980s during which some people were quoted as saying that trees caused more pollution than automobiles. By this, they might have meant that emissions of carbon dioxide (CO_2) by trees and other flora were significant. But plants and bodies of water also break down CO_2 in a relatively balanced cyclical activity. By contrast, human-produced CO_2 (along with other greenhouse gases which many believe to have an effect on the climate), from the production of concrete, running of internal combustion engines or generation of electricity from fossil fuels for example, are not naturally removed and therefore add to the global atmospheric stores of the gas [1]. Thus, human generated carbon emissions are out of balance with nature.

This carbon imbalance is precisely the reason for diplomats and activists to engage in international dialogue on global carbon emissions. We know, of course, that these discussions bog down largely in the political details and the ramifications to individual nation states. A frequently asked question is: The world's most developed economies all burned fossil fuels in their economic rise and, therefore, why shouldn't the less developed states do the same now? As C.K. Prahalad argued [2], there is considerable room at the bottom of the pyramid that is the global economy; however this growth will also come at some sort of a carbon cost. As a result, a concern frequently voiced is that limiting carbon emissions will attenuate economic growth in most-developed and developing countries alike. Holtz-Eakin et al. [14], note that while one might see a reduced propensity to emit carbon in most developed countries, emissions have been—and will likely remain—closely linked to population and economic growth in the developing world.

B. How IT Translates to Economic Activity

Divergence of opinion regarding ICT's role in economic growth should not come as a surprise. In the wake of the largest economic crisis since the Great Depression, determining what models better fit complex economic realities continues to engender considerable debate. A central concern in the debate revolves around the ability to quantitatively predict economic growth. Of the many elements of this debate, the measurement of growth over time—which is a modeling activity that measures capital (K) and labor (L) as inputs in the creation of an output measured as total factor productivity (TFP)—is germane to this study. When economists aggregate output at the national level, the gross domestic product (GDP) is often used as a useful measure. Specifically, economic forecasting is typically aimed at determining the TFP, which is then factored into determining the growth of the GDP.

Turning to the ICT sector, economist Dale Jorgenson argued that declining prices of ICT, coupled with its widespread adoption across the span of the U.S. economy, produced significant productivity growth [12]. After the dot-com collapse in 2000-2001, many found it easy to mark ICT’s role in economic activity as hyperbolic—however, research after the crash indicates that ICT can indeed contribute to strong growth [11].

II. The SIQ, Motivation, and Some Background

Among the factors at play in a model for ICT’s relationship to productivity, we see the volume of deployment of ICT as favorable. However, in this paper, we also argue for consideration of measures that bridge the growth of ICT to their energy efficiencies—this relationship between productivity and energy efficiency in the context of ICT, we believe, is novel and increasingly important. To help establish this relationship on a quantitative basis, we propose a sustainability innovation quotient (SIQ), which is determined through the measured energy consumption, the concomitant carbon emissions attributable to that consumption, and economic output measured through GDP.

Intuitively, our approach can be argued as follows: Since devices and utilities in the ICT sector use electricity—which in turn can be linked to carbon emissions when fossil fuels are used for generation—productivity and, hence, growth entails an associated carbon cost. Now, if an oracle were to approach us and inform us that there is a limit on how much carbon we can expend and we choose to accept this advice, then we use the oracle as a way of introducing a constraint without imputing any personal bias, whether or not we believe such a limit exists. Then, this places an immediate constraint on the amount of computing activity and, hence, on the amount of computing units sold. The next link in developing the concept of SIQ will be to relate the number of units sold, which determines the contribution of the ICT sector to GDP. Accepting the oracle’s limit, we will create a ceiling to the amount of GDP contributions that can be achieved through the ICT (or any other) sector.

Take a hypothetical value for the total carbon emissions by the ICT sector in the United States for a single year. Let us suppose it stands at about 70 megatonnes (Mt) with a corresponding

GDP contribution of $460 billion. The oracle then places a hypothetical limit of 40 Mt on the ICT sector. Again, for ease of understanding, let us hypothetically assume that the GDP contribution is uniform in that each Mt of carbon contributes $6.57 billion to GDP. Then, following our oracle's guidance, the ICT equipment generating the additional 30 Mt of carbon emissions cannot be contributed to the GDP, thereby removing $197 billion dollars from consideration.

A simple way of quantifying the SIQ for any sector (ICT in our case), usually at an annual boundary, is as follows and expressed in (dollars/kg of CO_2):

$$SIQ = \frac{\text{Change of GDP of a sector}}{\text{Change in carbon emissions of that sector}}$$ **Equation 1**

In order to determine the SIQ, we need reliable ways of quantifying the change in GDP, and also the concomitant change to the amount of carbon emitted—this is the carbon cost incurred to realizing this change. Of these two factors, measurement of the GDP and its change has been a mature activity, generally based upon well-accepted models. However, we found that reliable estimates of the carbon emissions of ICT sector were not readily available.

As a result, we began our study by trying to determine the proportion of the global carbon emissions contributed by ICT. One component determining this amount of carbon emitted, we realized, could be based on the electricity consumed by the ICT sector—since generation of electricity can be related to carbon emissions quite naturally. We used this component since the total carbon emissions that include other sources beyond the consumption of electric energy—the so-called embodied carbon emitted during the manufacturing and transportation of ICT products can only be larger than our estimate. Therefore, using the electricity-induced carbon emissions will give us a lower bound.

Prior to our study, the Climate Group, a London think tank, published its Smart 2020 report [5] regarding projected emissions of ICT at the end of the second decade of the twenty-first century. The authors argued that approximately 2 percent of all global carbon emissions may be attributed to the ICT sector. While possessing impressive figures, one researcher in particular, Koomey

[13], provided ample warning on the hyperbolic nature of assertions regarding the quantity of electricity consumed by ICT. Other than Koomey's report, which was robust and based on a comprehensive model that was explained explicitly, we found divergent views elsewhere. For example, when using a cell phone, did the electricity consumption of the network activity supporting its use equal that of using a home appliance? Was one policy pundit right to assert that "about one pound of coal [is required] to create, package, store, and move two megabytes of data?" Outside of the domain of data centers [18], in our opinion, anecdote dominated the discourse. So, our first step was to attempt to model and estimate the carbon footprint that could be reasonably attributed to ICT, including, but not limited to, data centers.

III. Measuring ICT's Carbon Footprint

Given the divergence in estimates in reports both scholarly and popular on the energy element of ICT and after contacting major vendors and market research firms, we concluded that it would be wise to make our own attempt to quantify the energy consumption of the ICT sector, and through this, determine the amount of carbon emitted. The ability to state all the assumptions and computational steps explicitly was an overarching concern that we strived to maintain throughout this exercise. In this way, a reader can either agree or disagree with our assumptions, and thus choose to accept our conclusions with all of the information being readily available. In so doing, we built on the work of others that we believed well grounded [6, 17, 18]. Subsequently, we will use these estimates in the context of the SIQ measure to relate the national economic growth (measured through GDP) to the cost of carbon involved, and thus to the concept of improving efficiencies as a way of enabling a higher ceiling for ICT's contribution to the GDP in the future.

Some previous studies have aimed to identify the energy consumption and/or carbon footprint of specific IT sectors such as PCs [9] or data centers [18], often confined to a particular region such as Europe [3] or the United States [6]. Very few [5] attempt to measure the global ICT energy consumption and resulting carbon footprint—this was our challenge. While ambitious in scope, we found the Smart 2020 report [5] to be based on assumptions about the future that we could not explicitly identify. For example, to compute the amount of carbon, the authors of this report use a single carbon conversion number for all of the years. We could not find a good justification for this assumption that affects the eventual analysis significantly, by assuming that electricity production could be reduced to a single conversion metric. Also, a simple and explicit model that allows us to take information from the past and project into the future was lacking, especially regarding the trend of ICT adoption when divided into sub-sectors.

A. Methodology

A General Framework for Projections: A central element in any predictive estimate is its ability to project future values accurately based on historical trends. We present a mathematical framework, which specifies the basis of our estimations or projections explicitly. Specifically, whenever we use the term “projection,” we adopt the following approach: estimating the value of a particular variable at a future time or instance (for example, the number of PCs in use in the year 2020) and the measured historical data to the current time. Regression analysis is then used to determine a function (curve) that fits or best approximates the historical data. The quality of the approximation is quantified through some metric, typically the mean square error. However, as is the case with any regression analysis, one significant pitfall is that all future estimates have a degree of uncertainty, since they are assumed to be some reasonable linear, quadratic, or other well-known growth function, of the past. We found that all of these attempts to extrapolate, sometimes referred to as business-as-usual trends, are vulnerable to unpredictable extremes such as the economic downturn of 2008–2009, the dot-com bubble burst, and so on. We wish to acknowledge this potential for being vulnerable to such unpredictable events in our business-as-usual predictions.

Illustrating our Methodology for Energy Consumption of the ICT Sector: Let us use the personal computer or PC as a driving example to explain our methodology, which consists of two elements. The first element consists of estimating the number of devices in use for a particular year, called the established base (EB), while the second encompasses an estimate of annual energy consumption (AEC) of each PC. Operating under this assumption, the global annual energy consumption (GAEC) of the PC sector for a particular year may be expressed as:

$$GAEC_{PC} = EB_{PC} \times AEC_{PC}$$

Equation 2

The annual energy consumption of a PC is estimated by dividing its state into three operating modes: active, when the device is on and the processor can be functioning; sleep, when the processor is on a standby mode; and off, when the device is switched off but remains plugged into the electrical socket. The annual energy consumption for a PC in each of these modes can be obtained, in turn, by multiplying the average power consumption in that mode with the annual usage factor, which is defined to be the number of hours per year that a PC is in a particular mode.

This methodology, as summarized in Figure 1, can be applied to any type of a device from the ICT space. While we tried to follow this methodology as far as possible in our analysis, scarcity of reliable data forced us to adapt this methodology further in a few cases, notably in the energy estimation of mobile phones as we will see in the sequel.

B. Sub-sectors of ICT and Their Annual Energy Consumption

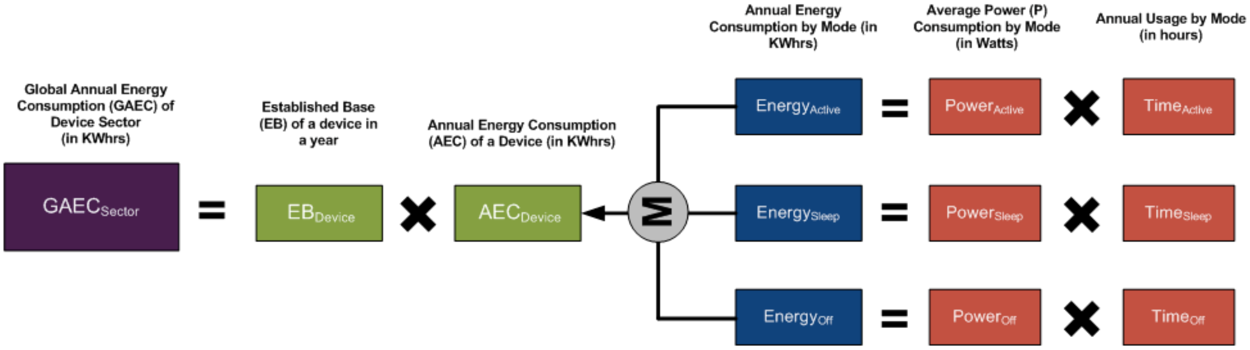
We chose to broadly classify ICT into four main sub-sectors as shown in Figure 2: data centers (DC), personal computers (PC), mobile devices (M), and gaming consoles (GC). In order to produce an estimate of the total global energy consumption of ICT and thus, estimate resulting carbon emissions, we analyzed the trends and projections in each of the subsectors separately.

<u>Personal Computers (PCs)</u>: We consider the PC sector to consist of a wide range of devices, from netbooks and laptops to desktop computers, with widely varying energy consumption values. We classify PCs into two broad categories for our estimates: laptops, which consist of all portable and mobile PCs, and desktops, which are fixed PCs connected to an external monitor.

For our projections, the historical PC-established base numbers were obtained from the sales numbers provided by consultancies Gartner [26] and IDC [27]. The established base was measured based on a sliding window of a life cycle of an individual PC derived from [3].

Annual usage factors as to how the active, idle, and off modes quantitatively relate to each other in a day were obtained from estimates published by the U.S. Department of Energy [6]. Lower bound values of the active mode power consumption of representative desktop and laptop models were obtained from [7-9], while the idle and off mode power consumption values were obtained from the Energy Star ratings [10]. Using these sources, we make the projections on the total PC sector energy consumption using the methodology from Figure 1.

Figure 1: Methodology for Computing the Global Annual Energy Consumption of an ICT Sector



<u>Data Centers</u>: A data center is a facility used to house computer systems and associated components, such as telecommunications and storage systems. Using the methodology described in Figure 1, the two primary measures that must be ascertained are the established base of components and their average power consumption within a data center. Our estimate for the historical data for the established base of data centers is based on the sales figures for server computers from market intelligence firm IDC [18]. Using this historical data yielded projections on the established base until 2020.

A typical data center is always in the "on" mode, and, therefore, to estimate the energy consumption of a data center, we only consider the active mode of power consumption. In order to accurately estimate the power consumed in this mode, we divide all data center servers into three different categories following Koomey's thinking [18]: volume servers, mid-range servers, and high-end servers. The power consumption in each category is estimated using a weighted average of the power consumption (Figure 1) of the top six server models in each category, determined by the sizes of their respective established bases.

Mobile Devices: Mobile computing, or the evolution of digital cellular communication, has grown to be the most ubiquitous form of computing on the planet, with more than 60 percent of the world's population now using some sort of handheld, connected computing device [15]. Despite their widespread usage, such devices contribute a small share of global ICT energy consumption, owing to their dependence on battery capacity that hasn't grown significantly over the last few decades when compared to the computing power [19]. In this study, we constrain ourselves to an estimate of the energy consumption and the resulting estimate of the carbon footprint of mobile ICT devices themselves (smartphones, etc.), and will ignore the back-end infrastructure, including antennae, base station computing, and fixed links.[1] We do note that not all of the costs associated with cell phone usage are ignored in our study, since the components that are computational tasks being performed on data centers are accounted for through the estimates in Section III-B, above. For the projections of energy consumption in this sector, the size of the established base was obtained from the world mobile usage statistics from the CIA World Factbook [4] and from sales numbers provided by Gartner [26].

Referring back to our overall methodology in Figure 1, we need an accurate estimate of the energy consumption per-device. To estimate this, we use the battery capacity (BC) of a mobile device and its charging frequency (N). As mobile devices are seldom used while they are plugged in, we will assume that the annual energy consumption of the mobile device is the product of its battery capacity and it's charging frequency. Favoring a conservative approach that potentially underestimates this value, we will use the anecdotal measure that a typical mobile phone is charged only once in two days—a figure many current generation smart phone users will argue to be quite low. Based on this approach, the annual energy consumption due to a single mobile device can be estimated as shown in Equation 3, below.

$$AEC_M = BC_M \times N_M \qquad \textbf{Equation 3}$$

Gaming Consoles: Video game consoles are interactive entertainment computers that can be used with a display device—typically a television or a monitor. A rapidly growing component of

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[1] We believe due to scarcity of reliable data for this sector among all the sectors, the projections here are likely to be less accurate. However, as the contribution of this sector to the total ICT emissions is quite low as shown in Table 2, we believe that the overall impact is not noticeable.

computing, we believed video game consoles warranted analysis of their carbon footprint, especially owing to their increasing popularity. We found that in isolation, gaming consoles such as Xbox and Playstation without the (television) display consume as much power as a desktop PC and hence, only estimated the energy consumption of the gaming consoles without including the TV energy consumption values.

To estimate the energy consumption of the gaming consoles sector, the methodology described in Figure 1 was used. The projections are built on historical established base data obtained from the reported annual sales numbers [20] with an assumption of a four- to five-year life cycle (based on the average life cycle of a gaming console version before a newer version is released). The annual average energy consumption of a gaming console is computed from the product of the weighted average power consumption of a console in each of the three modes as before, obtained from [16], and the time spent in each mode over the course of a year from [17].

Summary of Energy Consumption Across Sectors: Summarizing our effort above, the energy consumed due to the electricity used by various parts of the ICT sector during the year 2009, and projections for the years 2015 and 2020 are encapsulated in Table 1.

Table 1: Summary of Results for ICT Sector Energy Consumption in Billions of KWhrs

	2009	2015	2020
Data Centers	205.28	399.78	660.86
PCs	214.39	386.79	923.91
Mobiles	2.61	6.51	11.77
Total	441.30	838.36	1668.49
Gaming Consoles	19.00	45.28	71.94

C. Converting Energy Consumption into a Carbon Footprint

We found that the conversion of energy consumed into the corresponding carbon emitted is not a simple process since the amount of carbon dioxide–carbon is the result of carbon dioxide–emitted per unit energy consumed varies over time, and depends on the source of electricity production ranging over coal, natural gas, nuclear energy, and others. To try and consolidate this, we define a metric called the carbon conversion number (CCN) through which we intend to denote the amount of carbon emissions (usually in lbs or kgs) per unit of energy consumption (usually in joules or kilowatt hours [KWhrs]).

$$CCN = \frac{\text{Carbon Emissions}}{\text{Electricity Consumption}} = \frac{lbs(or)Kgs}{KWhr}$$ **Equation 4**

We note in passing that this metric can be generalized where the source of energy can be more broadly defined and need not be tied to electricity. We base our estimates of CCN on the projections of global electricity consumption and global carbon emissions due to electricity generation until 2030, published by the International Energy Agency [22]. Based on the information available from these sources, we computed the CCN, expressed as lbs of CO_2 per KWhr of electricity consumption. Next, using the CCN values and combining them with the findings summarized in Table 1 earlier, we are able to compute the carbon footprint expressed in Mega tonnes of carbon. The results are summarized in Table 2, for each of the four ICT sectors, and also as cumulative amount for all of ICT.

IV. Computing the SIQ

In the previous section, we projected the global carbon emissions of the ICT sector looking ahead until 2020. To compute the sustainable innovation quotient (SIQ) of the ICT sector, we now need to determine the GDP of ICT over the same time period. In the context of global carbon emissions, reliable retrospective data in various forms such as the installed base of computers, their usage patterns and others, was essential. Through our study, we could unearth data we consider reliable, for ICT’s share of GDP for the United States [23], United Kingdom, and Canada [24]. As a result, we focus our attention on developing and demonstrating the SIQ concept for the United States. In principle, given access to the worldwide GDP data and ICT’s contribution to it, our methodology can be extended to the global context. To complete the determination of the SIQ, since we already computed ICT’s carbon footprint and its projection to 2020, the GDP component remains to be extrapolated. From these projections, we derive the SIQ of the ICT sector in the U.S.

Table 2: Summary of results for ICT Sectors Carbon Footprint in Megatonnes of CO_2

	2009	2015	2020
Data Centers	121.30	229.87	369.48
PCs	126.69	222.41	516.55
Mobiles	1.54	3.74	6.58
Gaming Consoles	11.23	26.04	40.22
Carbon Conversion Number (CCN)	1.3	1.265	1.23
Total	260.77	482.06	932.84

A. Computing the Carbon Emissions of ICT in the United States

To derive the ICT carbon emissions in the United States, we tailor the methodology used in Section III. The change involves using U.S. sales data in each subsector as opposed to using global sales data. Also, care was taken to specialize the CCN value to be specific to the United States. Based on this, the summary of the carbon emissions of the ICT sector in the United States is shown in Table 3.

Table 3: Summary of Results for ICT Sector's Carbon Emissions in the United States in Megatonnes of CO_2

	2009	2015	2020
Data Centers	40.72	68.48	93.92
PCs	27.55	41.48	79.95
Mobiles	0.13	0.32	0.58
Gaming Consoles	4.56	12.13	20.61
Carbon Conversion Number (CCN) for USA	1.251	1.217	1.176
Total	72.95	122.41	195.06

B. Computing the GDP of ICT in the United States

Using the historical data of the share of ICT sector in GDP of the United States [23], we project the GDP share of the ICT sector until 2020. Due to wide fluctuations in the historical data, it is difficult to project the future values. Hence, GDP values of a subset of the historical data set (years 2002-2008) are taken as the basis to project the future values of the GDP of the ICT sector. (Readers are cautioned that, as with majority of economic projections, this projection is only a simple business-as-usual projection and the actual values might deviate significantly from the projected values due to fluctuations in the economic data analysis.) A summary of some of the projections of ICT's future GDP values is given in Table 4.

Table 4: Summary of results for ICT Sector's GDP in the United States

	2009	2015	2020
ICT's GDP (Billions of USD)	461.46	571.13	662.5

C. Computing the SIQ of ICT in the United States

Once we projected carbon emissions, as well as the GDP of the ICT sector, we computed the SIQ of the ICT sector using the equation (1) described in Section II. While the data representing the change in the carbon emissions as well as the change in GDP are discrete sets, we characterize the trends that they represent by interpolating a continuous function. This allows us to use a differential as a basis for the SIQ and, should discrete values be desired, we can replace this with a similar definition using finite differences instead.

It should be noted that since the thrust of our paper is on demonstrating the value of SIQ and its novelty, these estimates given in Tables 2, 3, and 4 could be looked upon as illustrative examples to accomplish our goals. If other, more reliable estimates may seem appropriate, those could be used instead without affecting the overall methodology and demonstrate the value of the SIQ.

A summary of SIQ values of the ICT sector over a few years is shown in Table 5. This can be interpreted as: In 2009, we are obtaining an economic output of \$2.831 per kilogram of CO_2

emitted by the ICT sector, while in 2020 we only obtain an economic output of $1.06 per kilogram of CO_2 emitted.

Table 5: Summary of Results for ICT Sector's SIQ in the United States

	2009	2015	2020
SIQ	2.831	1.657	1.060

D. Innovation as a Driver for Improving the SIQ

As evident from the previous subsection, the value of SIQ, or the resulting GDP dollars for a unit of carbon emitted, is decreasing over the years. In order to curb this phenomenon and increase the net resulting GDP, we anticipate that the role of innovation in ICT is critical. As demonstrated in Figure 3, innovation can play a critical role in increasing the economic value of the ICT sector.[2] Intuitively, a higher value of SIQ is meant to imply that more efficient systems are the result and, therefore, for the same carbon budget, more of them can be deployed in the marketplace.

A significant caveat is to note that as innovation results in such efficiencies, it is important to ensure that in the process, the functionality of the resulting devices is preserved. For example, a reason for increased sales and GDP growth in the business-as-usual scenario is that each year, newer models and more features are offered to customers—one need only look at the cell phone market to understand this. This constraint is expected to be implicitly true of our SIQ formulation, in that a more efficient system ought to be realizing such efficiencies while preserving the increased functionality relative to the business-as-usual model. In our cell phone example, this would imply that innovation would embody additional features comparable to the business-as-usual scenario, resulting in increased sales and concomitant GDP growth, while being more energy efficient at the same time. However, we wish to point out that unusual approaches in which the concept of functionality is modulated by need—the emerging probabilistic CMOS technology (PCMOS) that, for the first time, allows computational hardware to trade off errors that we might be willing to live with, in return for significant energy savings,

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[2] Note that, the *with Innovation* case shown in Figure 3 is done a more aggressive growth rate (quadratic) than the business-as-usual (linear) growth rate to demonstrate this concept.

and the I-Slate platform it is meant to enable—are examples [25, 28]. We considered adding these constraints on functionality to the formulation of SIQ, but chose not to do so since we felt it would compromise the simplicity and, therefore, its broader utility of the definition.

V. Remarks

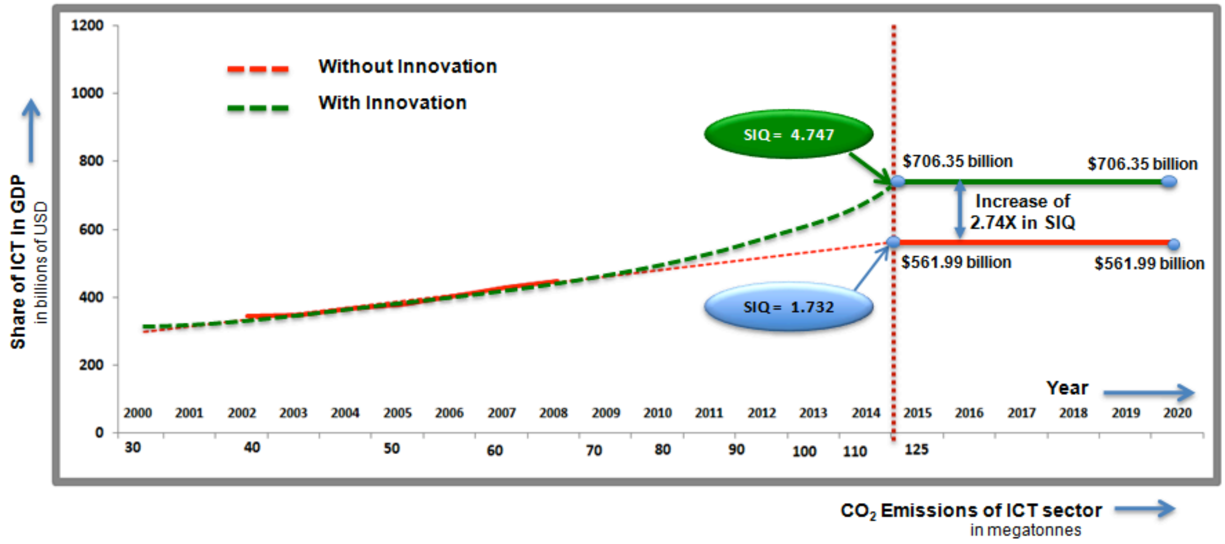
As seen from Table 5, the economic output of ICT as represented by GDP for a fixed carbon budget is diminishing. The underlying cause of this can be attributed to the steadily increasing CO_2 emissions of the ICT sector where the efficiencies are lagging the concomitant growth in the GDP. A typical response would be a call for a need to take stringent measures to curb the steadily increasing CO_2 emissions of the ICT sector.

Our notion of SIQ, however, informs us that this can have a deleterious effect on the continued potential of ICT technologies to be a dominant contributor to the future growth of the GDP, in the context of an acceptable ceiling on the total amount of carbon from any sector. This is shown in Figure 3 where, with a hypothetical ceiling of 117.5 Mt of carbon for the ICT sector. Our rationale for choosing this value is based on the following two observations. First, we can use the current proportion or share that the ICT sector has in the U.S. GDP as a fair basis to determine the corresponding fraction that it could have in the carbon emissions in the future. Next, we note that, for environmental sustainability, the United Nations recommends an annual cap of 14.5 Gigatonnes of CO_2 [21] of which the EIA indicates that the United States contributes to about 19.8 percent [29]. Combining these factors yields a ceiling of 117.5 Mt of CO_2.

As shown in Figure 3, with an SIQ of 1.732 and with this ceiling, the contributions from the ICT sector will be limited to $561.99 billion dollars by 2020 and would not grow past this amount starting mid-2014. In stark contrast, and in conjunction with innovations and an improved representing an improvement of a factor of 2.74X, the ICT sector has the improved potential for contributing an additional $144.36 billion to U.S. GDP by 2020, while respecting an overall ceiling on the expended carbon. Keeping in mind that the final value of SIQ is entirely dependent on the quality of historical data, and not being economists ourselves, we viewed this excursion as one taken by technologists with a strong interest in the sustained positive economic impact of the

ICT sector. We consider this not so much as a final numerical prescription, but rather as a way of comparing the relative values of different technology scenarios from the perspective of potential GDP growth. In this sense, it is an empirical observation through which we would like to extend the reach and economic benefits of Moore's law, to encompass the increasing constraints that we are likely to face from limits on carbon emissions.

Figure 3: Scenario when ICT's carbon emissions are frozen at 117.5Mt for the United States and the value of innovation to improving IC



Acknowledgments

The authors wish to thank all of the students in our Rice University spring 2009 class, "Sustainability, Energy and Information Technology: An Interdisciplinary Approach." Very special thanks are extended to Kirthi Krishna Muntimadugu for participating in the study during the course leading to the model shown in Figure 1. We also wish to express our deep appreciation to our summer 2009 intern, the late William Holt Weeks.

References

1. U.S. Energy Information Administration. *Greenhouse Gases, Climate Change & Energy*. http://www.eia.doe.gov/emeu/aer/envir.htm.
2. Prahalad, C.K. 2004. *The Fortune at the Bottom of the Pyramid: Eradicating Poverty Through Profit*. Upper Saddle River, NJ: Wharton School Publishing.
3. European Commission. *Personal Computers (desktops and laptops) and Computer Monitors.* http://extra.ivf.se/ecocomputer/downloads/Eup Lot 3 Final Report 070913 published.pdf.
4. University of Missouri-St. Louis. Archive of CIAWorld Factbooks, 1990-2008, in "Alphabetical List of Online Government Documents." http://www.umsl.edu/services/govdocs/alpha_list.html.
5. The Climate Group. *Smart2020: Enabling the low carbon economy in the information age.* http://www.smart2020.org/_assets/files/02_Smart2020Report.pdf.
6. TIAX. 2006. *U.S. Residential Information Technology Energy Consumption in 2005 and 2010.* http://www.tiaxllc.com/reports/residential_information_technology_energy_consumption_2006.pdf.
7. University of Pennsylvania, Information Systems and Computing. "Approximate Desktop, Notebook, & Netbook Power Usage." http://www.upenn.edu/computing/provider/docs/hardware/powerusage.html.
8. Apple Computer, Inc. "Apple and the Environment." http://www.apple.com/environment/reports/.
9. Bray, Megan. 2006. *Review of Computer Energy Consumption and Potential Savings*. http://www.dssw.co.uk/research/computer_energy_consumption.html.
10. Energy Star. "Energy Star Rating of Computers." http://www.energystar.gov/index.cfm?c=revisions.computer_spec.
11. Baudchon, Hélène. December 2002. "The aftermath of the 'New Economy' bust: A case study of five OECD countries." *Observatoire Français des conjectures Economiques* no. 2002-08.
12. Jorgenson, Dale. 2001. "Information Technology and the U.S. Economy." *The American Economic Review*.

13. Koomey, Jonathan, Chris Calwell, Skip Laitner, Jane Thornton, Richard E. Brown, Joe Eto, Carrie Webber, and Cathy Cullicott. 2002. "Sorry, wrong number: The use and misuse of numerical facts in analysis and media reporting of energy issues." In *Annual Review of Energy and the Environment 2002*, 119-158.
14. Holtz-Eakin, Douglas and Thomas Selden. 1995. "Stoking the Fires? CO_2 emissions and economic growth." *Journal of Public Economics* 57: 85-101.
15. Wray, Richard. 2008. "Half world's population 'will have mobile phone by end of year.'" *The Guardian UK*, Sept. 26, 2008. http://www.guardian.co.uk/technology/2008/sep/26/mobilephones.unitednations.
16. The Energy Saving Trust. 2007. *The Ampere Strikes Back*. http://www.energysavingtrust.org.uk/Publication-Download/?p=4&pid=1085.
17. Roth, Kurt and Kurtis McKenney. 2007. *Energy consumption by consumer electronics in U.S. residences*. Final report prepared for the Consumer Electronics Association. http://www.ce.org/pdf/Energy Consumption by CE in U.S. Residences (January 2007).pdf.
18. Koomey, J.G. February 2007. *Estimating total power consumption by servers in the U.S and the world*. Lawrence Berkeley National Laboratory.
19. Warwick, C. April 1995. "Trends and limits in the talk time of personal communicators." *Proceedings of the IEEE* 83(4).
20. VGChartz. "Hardware Annual Summary." http://www.vgchartz.com/hw_annual_summary.php.
21. United Nations Development Programme. 2007-2008. *Fighting climate change: Human solidarity in a divided world.* Human Development Report. http://hdr.undp.org/en/media/HDR_20072008_EN_Complete.pdf.
22. International Energy Agency. 2007. *World Energy Outlook*. http://www.worldenergyoutlook.org/2007.asp.
23. Centre for the Study of Living Standards. "The Canada-U.S. ICT Investment Gap in 2008: Gains in Communications Equipment and Losses in Computers." http://www.csls.ca/data/ict.asp .
24. Industry Canada. "ICT Sector Gross Domestic Product (GDP), 2008." http://www.ic.gc.ca/eic/site/ict-tic.nsf/eng/h_it05864.html.

25. Jonietz, Erika. 2008. "TR10: Probabilistic Chips." *Technology Review*, March-April. http://www.technologyreview.com/read_article.aspx?ch=specialsections&sc=emerging08&id=20246

26. Gartner, Inc. 2010. Press releases. http://www.gartner.com/it/section.jsp?type=press_releases&format=xhtml&year=2010&show_archived=true

27. International Data Corporation. 2010. Press releases. http://www.idc.com/getdoc.jsp?containerId=prUS22383910

28. Jones, Willie D. 2009. "Researchers Use Low-Power Chips to Tackle High-Powered Problem." IEEE, July 7, 2009. http://www.ieee.org/portal/site/tionline/menuitem.130a3558587d56e8fb2275875bac26c8/index.jsp?&pName=institute_level1_article&TheCat=2201&article=tionline/legacy/inst2009/jul09/featuretechnology.xml&;jsessionid=ws2TMCLbRQB6CvV4mq6Vx8bYnhzJ2KlGGfx51ZgrwGD8.

29. U.S. Energy Information Administration. 2009. *Annual Energy Review*. http://www.eia.doe.gov/emeu/aer/envir.html.