SUSTAINABILITY REQUIREMENTS IN INFORMATION & COMMUNICATIONS TECHNOLOGY

CHRISTOPHER J. PAVLOVSKI AND JOE ZOU **(Refereed)**

IBM Corporation
Sydney, NSW Australia
chris_pav @ au1.ibm.com, jouzou @ au1.ibm.com

Abstract

This paper raises the issue of formally addressing sustainability during the development of ICT solutions. Several environmental themes in ICT sustainability are presented including electronic waste, carbon emission, and energy consumption trends. The existing frameworks and standards that are in use for alternative industries are analyzed and their applicability to ICT is discussed for policy development. This includes carbon trading frameworks, energy emission reporting standards, and the ICT eco-efficiency guidelines. We build upon the eco-efficiency indicators and suggests several new indices for modeling ICT sustainability, including electronic waste, radio emissions, and waste heat. Together with existing models based on CO_2 emission, the proposed indices serve as a basis for modeling the sustainability of ICT. The frameworks and tools presented provide a useful foundation for the development of more robust solutions that address sustainability with current and emerging ICT innovations. This may also assist government, industry, and research in developing policies that will help organizations meet their regulatory and social obligations in environmental sustainability.

Key Words: ICT, Information & Communications Technology, e-sustainability, CO_2, carbon emission.

1. Introduction

Recently, the impact of drawing energy from fossil fuels and its environmental impact has received considerable attention. The issue of sustainability is increasingly becoming a major policy issue for government, industry, and society around the world. In Australia, the National Greenhouse and Energy Reporting Act has been effective from the 1 July 2008. What that means is that around 1,000 organizations in Australia will be required to disclose details regarding their greenhouse gas emissions, energy consumption, and energy production [1]. In addition, the Australian government has brought forward the national carbon trading scheme to 2010 [1], also announcing a long term target of 60% emission reduction by 2050 [2].

The distribution and presence of Information & Communications Technology (ICT) has increased significantly over the past several decades. The rapid introduction of ICT into every aspect of human life has occurred without detailed consideration to environmental impacts such as the energy consumption associated with deployed technologies. While sustainability has been addressed more broadly in transportation, energy generation, and in general household goods, the literature in ICT sustainability is comparatively sparse.

Globally, the ICT sector contributes some 2.0 to 2.5% of total greenhouse gas emissions, with this expected to increase over time [3]. Within Australia, an ACS audit on ICT carbon emissions shows that the industry generated 7.94 metric tons of carbon dioxide in 2005 [4]. The report notes that ICT has an overall contribution of 1.52% of the total national carbon emissions, which is considerable when compared to other key industries such as metal production and civil aviation, which are 2.3% and 1% respectively. Furthermore, carbon emission is only one aspect of sustainability. A more complete assessment requires consideration of further issues such as electronic waste, toxic materials, and waste heat.

In this paper, we discuss the notion of sustainability in ICT, referring to this as sustainability requirements. We present the ways in which ICT usage has contributed to environmental impacts observing the need to address sustainability in line with general industry trends. The standards and guidelines for assessing the sustainability of ICT solutions are outlined and several new indices are proposed that consider the broader impact of ICT upon the environment. We view the main contributions of this paper as follows.

- Evaluate the emerging tools and techniques that have applicability in addressing sustainability requirements.
- Identify the key sustainability issues and proposes several additional indices for measuring sustainability of ICT solutions.
- Outline the emerging ICT solutions that have the potential for a positive impact to sustainability and the environment.

The next section presents the literature related to sustainability in ICT. Section three identifies the general principles and indicators associated with sustainability in the broader domain. In section four we examine further the sustainability issues and how these pertain to ICT, suggesting additional indicators for assessing ICT sustainability. In section five, we outline the various emerging initiatives that are underway that attempts to address sustainability. The final section summarizes the key observations made and suggests areas of further work.

2. Background and Related Literature

Before outlining the concepts, standards and frameworks that relate to the broader domain of sustainability, we review the related work that addresses the focused area of ICT sustainability.

Hasna proposes a combined design model that integrates science and engineering to advance sustainability [5]. The main idea is to address sustainability within regular engineering projects with sustainability performance criteria clearly defined.

In [6], it is suggested that the information age is substantially different to the industrial age and hence a new socioeconomic system is required that is sustainable and community based that is able to accommodate newer information technologies. The volume combines several papers in sustainability that address research, policy making, and economics with a focus on global communities. For instance, it is suggested that ICT is able to assist in promoting decentralised local communities [7]; which may be considered more sustainable for the environment when compared to the impact of centralised large cities upon the environment.

Forge examines the contribution of ICT to climate changes, surveying the impact energy consumption and management of hazardous materials [8]. The work points out that many current ICT trends are unsustainable, in particular the growing power consumption trends in data centres.

There is detailed work on how ICT is able to facilitate reductions in travel via telecommuting and hence reduce CO_2 emissions [9]. Toomey points out that the notion of telecommuting has been largely overlooked as a source for carbon reduction by organisations. Recent advances in video, messaging, shared white board, and other collaboration tools are now readily available and adequate provision of these tools is required to enable telecommuting to function effectively.

In [10], an analysis is conducted on the un-intended consequences of ICT, due particularly to the recent evolution and strength of ICT innovations. The paper outlines a number of factors that contribute to the unintended results of technology adoption. This includes consequential impact to individuals, society, and the environment. A key point raised is how a technology assessment method may help identify such consequences, so that remedial actions may be put in place to mitigate harm.

A further study on the future impact of ICT on environmental sustainability estimated a range of impacts areas of ICT in the year 2020 [11]. This included areas such as greenhouse gas emissions, energy intensity, transport intensity, air quality, waste, and renewable energy. The study concluded that the impact of ICT is relevant and needs to be taken into account for environmental policies.

3. Principles, Indicators & Standards

In this section the general principles and concepts of sustainability are presented. In addition, the standards and frameworks that are available to assess ICT sustainability are outlined. Although the traditional viewpoint on sustainability has emerged form an ecological and environmental perspective, the term has now broadened to accommodate a general industry wide view that all aspects of society have a sustainability theme; this includes the economical, technological, and ecological aspects.

Sustainability is defined as ‘a characteristic of a process or state that can be maintained at a certain level indefinitely’ [12]. The term implicitly relates to a level of balance in the presence of activity. This poses the immediate question of how a system is able to maintain balance in the presence of activity. A common human activity is growth and development; hence the term *sustainable development* is applied. The most widely accepted definition of sustainability, referred to as *sustainable development*, originated from the 1987 world commission on environment and development [13]; see Table 1 below.

Table 5 Sustainable Development

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

3.1 Principles of Sustainable Development

The definition in Table 1 has been widely accepted and cited by many scholarly works, treaties, and declarations. The UN definition also goes on to elaborate upon two key concepts.

> 1) The concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given; and
>
> 2) the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs.

The world commission report also observed that growth and development is often destructive, which needs to be moved to a sustainable path [13]. As such, several strategic imperatives were identified as critical objectives (or principles) for environmental and development policies [13, chapter 2]; these are:

- reviving growth;
- changing the quality of growth;

- meeting essential needs for jobs, food, energy, water, and sanitation;
- ensuring a sustainable level of population;
- re-orienting technology and managing risk;
- conserving and enhancing the resource base; and
- merging the environment and economics in decision making.

The fundamental objectives have been extended with several further principles [14], and serve as a foundation for guiding policy makers. Given the definition of sustainability, the issue of how to measure or assess whether a given activity is sustainable is raised. In the following sections we elaborate upon some of these methods.

3.2 Indicators of Sustainable Development

Several mechanisms have been proposed in order to assess sustainability. These are both qualitative and quantitative in nature and often ranked to a single sustainability figure [15]. While numerous methods exist, we discuss several of the key approaches.

3.2.1 Environmental Impact Assessment

The Environmental Impact Assessment (EIA) was originally introduced in 1969 by the USA and is now widely used for assessing the environmental impact of a proposed project [16]. The EIA is defined as the 'the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made' [17]. Dalal-Clayton points out that while the assessment is sometimes extended to account for social cost benefit [16], he suggests that the EIA be modified to draw from methods in social impact analysis, environmental economics, and participatory techniques that ensure involvement from project beneficiaries. As a starting point, he suggests that the sustainable development indicators of Holmberg *et al* be expanded upon. This includes indices on the following [18].

- The use of energy and materials;
- Ecological Processes and Biological Wealth;
- Policies, Economics, and Institutions; and
- Society and Culture.

3.2.2 The Bellagio Principles

The *Bellagio Principles* were defined by a group of international experts and provide guidelines for determining the sustainability assessment process [19]. A comprehensive report was prepared, and rather than naming explicit indices, the principles guide choice and design of indicators, their interpretation, and the method for communicating results. The ten principles are:

1. Guiding Vision and Goals,
2. Holistic Perspective,
3. Essential Elements,
4. Adequate Scope,
5. Practical Focus,
6. Openness,
7. Effective Communication,

8. Broad Participation,
9. Ongoing Assessment, and
10. Institutional Policy.

These principles are also designed to deal with four aspects of assessing sustainable development, these are the establishment of clear vision and goal (principle 1), the content of the assessment method (principles 2–5), the process of assessing (principles 6–8), and to ensure an ongoing assessment capability (principles 9 and 10).

The principles are intended to help measure and assess activities associated with sustainable development. They were also fashioned in order that they may be applied by community groups, industry, and government.

3.2.3 OECD Pressure State Response Framework

The OECD has published a core set of indicators for evaluating environmental change, as part of the Pressure State Response (PSR) framework [20]. This framework attempts to measure the change to the environment due to human activities. Moreover, the framework observes that human activities place pressure upon the environment, changing its state, and that society needs to respond adequately. As such three general types of indicators exist to address these aspects of sustainability, these are as follows.

1. Indicators of environmental pressure such as CO_2 emission, CH_4 emission, consumption of CFC (halons), and N_2O emission.
2. Indicators of environmental condition such as atmospheric concentration of greenhouse gas, mean global temperature, and ozone depletion.
3. Indicators of societal response such as energy efficiency programs, tax on energy/CO2 emission, and funding for alternative energy.

Around 50 indicators are described and it is anticipated that the indicators are tailored to the specific environmental issue. This may be climate change, ozone depletion, acidification, toxic contamination, waste, water resources and forest resources. Annually, the OECD defines a subset of the core indicators as the *key indicators* [21]. These are used to communicate status to the general public and to highlight issues for policy makers.

3.2.4 Environmental Sustainability Index

The Environmental Sustainability Index (ESI) proposes 21 indicators for tracking the status of the environment [22]. The report was prepared in 2005 by the Yale and Columbia Universities in collaboration with the World Economic Forum and the European Commission Joint Research centre. The indicators are intended to cover a broad range of environmental issues and enable countries to measure their performance in sustainable development.

The ESI method is also based upon the OECD pressure-state-response framework and countries are ranked based upon their ESI score. The higher the ESI score, the better the environmental disposition of the country. The ESI index has been refined further and superseded by the Environmental Performance Index (EPI) [23]. The key difference is that ESI is a relative measurement of each country, whereas the EPI is based upon a benchmark.

3.3 ICT Standards & Frameworks

The previous section outlined the indicators applicable to the broad domain of sustainable development. Whilst these indicators are also generally applicable to ICT, we now focus the discussion to indicators and frameworks that have been designed specifically to address the ICT sector.

3.2.1 Emergy Based Sustainability Index

Brown and Ulgiati propose a sustainability index that monitors both technology and economic conditions when developing environmentally sustainable solutions [24]. They build upon work in *Emergy* systems [25], a term that was original introduced by Scienceman and Odum [26, 25]. Emergy fundamentally refers to the sum of all input energy required by a process to yield a given output product [10].

Brown and Ulgiati propose several indicators for evaluating eco-technological processes. The proposed indices are:

- Emergy Yield Ratio (EYR): ratio of emergy output and the emergy input.
- Environmental Loading Ratio (ELR): ratio of purchased/non-renewable emergy and the free environmental emergy.
- Emergy Investment Ratio (EIR): ratio of emergy fed back and the indigenous emergy inputs.
- Emergy Sustainability Index (ESI): an aggregate measure of yield and loading upon the environment, given by EYR/ELR.

The indices above provide insight to the net sustainable value of an engineering process. Given that ICT is an inherent engineering activity, the sustainability index also has applicability.

3.2.2 ICT Eco-Efficiency Guidelines

The eco-efficiency of information and communications technology is a recent topic of interest for many organisations. The ICT eco-efficiency evaluation guidelines have been developed in Japan by the environmental efficiency forum [27]. Although these guidelines are emerging, there is much interest in the evaluation criteria [28].

The key objective of the guidelines is to assess the environmental impact of ICT. This is achieved largely through assessing the CO_2 emission related to the ICT innovation. The fundamental approach in conducting the ICT evaluation is to apply the ISO Life Cycle Assessment (LCA) method. This involves the following key steps:

1. definition of goal and scope,
2. life cycle inventory analysis,
3. life cycle impact Assessment, and
4. life cycle interpretation.

There are three main assessment guides outlined within the framework. These are the environmental impact assessment, an eco-efficiency assessment, and a comparative evaluation of ICT with respect to its environmental impact.

The impact assessment evaluates a number of activities related to ICT development. This includes material and energy consumption, use of ICT devices, use of network, use of software, shipping, travelling, storage, and the workplace. The environmental impact is given as the sum total of CO_2 emission of each activity. The eco-efficiency is a measure of the value provided by the ICT divided by its (CO_2) environmental impact.

$$\text{Eco-efficiency} = \frac{\text{Value provided by ICT}}{\text{ICT Environmental Impact}} \quad (1)$$

The comparative assessments are applied to evaluate different forms of ICT, or to compare this with respect to existing technologies and means for achieving an outcome. The comparative assessments are conducted for environmental impact, eco-efficiency, and the quantitative change to the environment. For example, the *Quantitative change in environmental impact = Environmental impact of the target ICT − Environmental impact per functional unit of baseline service*. Moreover, the comparative evaluation of eco-efficiency is given by the following.

$$\text{Comparative evaluation of Eco-efficiency} = \frac{\text{Eco-efficiency of target ICT}}{\text{Eco-efficiency of baseline service}} \quad (2)$$

3.2.3 ITU Standards and Emerging Indices

The International Telecommunications Union (ITU) has also supported the need for addressing sustainability, observing the impact that ICT has to climate change [29]. In addition to hosting several symposiums, a working group has been initiated in 2008 [30]. The objective is to work upon standards related to the impact of ICT on climate change. More specifically, their stated objective is '*to develop internationally agreed methodologies to describe and estimate the impact of ICTs on climate change, both directly and through their application in other industry sectors*' [30].

In meeting this objective, the focus group will also attempt to conduct most of its work using collaboration tools in order to minimise emissions from activities such as travel.

While the existing indicators have related the evaluation largely to that of CO_2 carbon emissions, we suggest here that additional criteria may be drawn upon when evaluating the sustainability of ICT. This includes factors such as:

- ICT waste (or e-waste), both toxic and non-toxic waste;
- carbon emission;
- impact of excessive radio emission upon the environment; and
- heat convection from ICT devices.

In order to evaluate the applicability of such criteria we conduct an analysis of these and other factors that constitute a sustainability issue for ICT.

4. Sustainability Indicators in ICT

With an understanding of the indicators and factors associated with sustainability we analyse further the contributing issues that influence ICT development. While much of the emerging work is focused on greenhouse gas emission, in practice ICT may exhibit several additional impact areas. This invariably involves issues such electronic waste, energy consumption, hazardous materials, and radio emissions. By examining these issues we then identify several further coefficients that may be applied to evaluate an overall sustainability index for ICT.

4.1 Electronic Waste

The rapid advance in the development of new devices means that the incumbent technology becomes outdated quickly. This creates a high churn and turnover of devices which leads to the problem of dealing with devices and hardware which are no longer required. Electronic waste is now viewed as a major problem for society and an environmental risk. For instance, while 180 million new computers were sold during 2004, in the same year 100 million became waste [31]. Furthermore, such waste often contains toxic materials such as lead, mercury, arsenic, and cadmium [31, 32].

Unfortunately, in today's society the notion of repairing broken ICT equipment has been superseded with replacing goods at volume. This is perhaps a consequence of a global economy that yields benefits in low cost electronic goods – cheaper to buy a new one rather than to repair. When one extends the e-waste trend to other devices such as mobile phones, cathode ray televisions, and household goods, it is straightforward to see that e-waste is a significant environmental concern. Moreover, e-waste now constitutes 8% of local waste and is quickly increasing in proportion [32].

Electronic waste contributes to toxic concentrations and forms part of the OECD core sustainability indicators. In addition, these factors will contribute to soil degradation, another OECD core indicator. Considering the growing trend of e-waste impacting the environment, an index that measures the balance of waste produced and recycling seems a worthy statistic for assessing ICT sustainability.

4.2 Carbon Emission

The key contributors to carbon emission are deforestation, power generation, and fuels used in transportation. The increase use of ICT throughout society has also resulted in increased power requirements. A 2007 Gartner report suggests that ICT was responsible for 2% of global carbon emissions [33]. A similar finding was also reached by the Smart2020 Climate Group report [34]. This footprint may be partitioned with telecommunications contributing 31% and information technology 69% [33]. While 2% may appear as a marginal contribution, this footprint translates to 830 million tons of CO_2 and is estimated to increase by 6% each year until 2020 [34].

In the observation that some 60% of personal computers are left on after hours [33], there appears to be considerable opportunity to reduce the ICT impact. Furthermore, it is estimated that from the energy source, only 15% is productively used by power supplies, with 6% reaching the server, and only 1% of the original energy source productively applied by a central processor [33].

Greenhouse gas carbon emission is perhaps the most widely discussed sustainability issue and is presently addressed by the eco-efficiency index for ICT by measurement of CO_2 output [27].

4.3 EM Radio Wave Pollution

The concept of pollution has traditionally been applied to waste and its disposal, particularly hazardous materials. More recently this has been applied to excessive sound, referred to as noise pollution. We also observe that due to the volume of radio wave emitting technologies, such as wireless LAN, mesh networks, cellular mobile, and wireless broadband a new consideration is required as Electro Magnetic (EM) radio wave emission pollution. Moreover, the intent is to observe the increases in radio wave emission and to assess the cumulative impact to the environment.

There is very limited work in the area of impact assessment of electro magnetic emissions upon the environment. In one example, while it has been demonstrated that radio emission have disrupted the behaviour of insect colonies [35], there appear to be other factors that contribute to colony collapse [36]; however the possibility remains that EM emission is a contributor to immune system dysfunction. Nevertheless, the potential for a casual relationship between radio emission and the environment may be useful to consider as a sustainability factor. Given that the rate of radio wave based technologies continues to increase, it seems prudent to consider that such emissions may play a role in sustainability.

It is suggested that a cumulative radio wave emission index be considered as an ICT sustainability factor. This may form part of a core set of indices that are drawn upon when appropriate, similar to the OECD core indices from which a subset are drawn upon when relevant to the evaluation conducted.

4.4 Waste Heat Discharge

Industrial waste heat has been actively studied for some time. Waste heat discharges have an atmospheric impact [37], and incur an energy cost to run cooling systems. There are however, several ways in which waste heat may be productively applied. This includes power generation [38], waste heat recovery systems [39], and heat conservation through efficient design.

Sanderson points out that there is minimal work to recover low and medium grade heat, less than 500^{o}C, and that this accounts for over 50% of the total heat generated by industry [40]. ICT radiates heat, often requires extensive cooling apparatus and there appears to be little (if any) work on the productive conversion of ICT heat discharge.

The automotive industry has already started to embrace energy recovery systems in their designs [41]. The same principles may also be applied to ICT. For instance, recent research into thermo-acoustic devices converts waste heat, via an acoustic pathway, that may be used to generate electricity for cooling computers [42]. Considering the multi-faceted benefits in harnessing and reducing heat, the eco-efficiency of waste heat is suggested as a further indicator for ICT sustainability.

4.5 Proposed Indices

The eco-efficiency handbook outlines a broader applicability of the eco-efficiency guidelines to product development in general industries [43]. The handbook observes the use of additional factors such as waste, energy consumption, and resource consumption as inputs to the eco-efficiency indicator for environmental impact. In light of this, we build upon the ICT eco-efficiency guidelines [27] and propose several additional metrics for monitoring and evaluating ICT sustainability. We first note that the original eco-efficiency assessment in [27] of environmental impact is one based upon CO_2 and hence rename this accordingly.

$$\text{ICT } CO_2 \text{ eco-efficiency} = \frac{\text{Value provided by ICT}}{\text{ICT } CO_2 \text{ Environmental Impact}} \qquad (3)$$

The proposed sustainability indices for e-waste, EM pollution, and waste heat are given by the following general formulae.

$$\text{ICT e-waste eco-efficiency} = \frac{\text{ICT Waste Recycling}}{\text{ICT Waste Output}} \qquad (4)$$

$$\text{ICT EM Emission eco-efficiency} = \frac{\text{Ambient EM Emission}}{\text{Ambient EM Emission + EM Emission of ICT}} \qquad (5)$$

$$\text{ICT Waste Heat eco-efficiency} = \frac{\text{ICT Heat Recovery}}{\text{Radiated Heat of ICT}} \quad (6)$$

Computation of denominator and numerator values may be achieved via the process-sum or input-output table methods as outlined in [27, 43]. However, it is suggested that this is as an area of further work with input sought widely from the ICT industry to ensure agreement and transparency on standardized methods for quantitatively evaluating sustainability.

Given the above general indicators in assessing ICT, then the cumulative eco-efficiency and eco-efficiency factor then become an assessment of the cumulative indices outlined above, with respect to the value provided by ICT and the baseline service respectively. Hence we re-write the original eco-efficiency protocols in [27] as follows.

$$\text{ICT Cumulative eco-efficiency} = \frac{\text{Value provided by ICT}}{\text{ICT Cumulative Environmental Impact}} \quad (7)$$

$$\text{ICT eco-efficiency Factor} = \frac{\text{ICT Cumulative eco-efficiency}}{\text{Eco-efficiency of baseline service}} \quad (8)$$

5. ICT Sustainability Initiatives

While ICT is part of the problem in contributing to global warming, accounting for 2% to 2.5% of total greenhouse gas emission [3], research shows that ICT can be a very effective tool to reduce greenhouse gas emission. This is evident in a report produced by the American Council for an Energy Efficient Economy (ACEEE), which suggests that 'for every extra kilowatt-hour of electricity that has been demanded by ICT, the U.S economy increased its overall energy savings by a factor of about 10' [44]. The ITU also recognises that ICT may have both a positive and negative impact to climate change.

We now outline the solutions that address sustainability, that have the potential to yield a positive impact to the environment. The ICT solutions can be grouped into two general categories. The first category of solutions, are those that address the sustainability problem caused by the growth of ICT. The second solution category includes innovations that assist other industries. Through the use of smarter technology it is suggested that ICT has the potential to reduce global emissions by 15% [45, 34].

5.1 Solutions to Address the ICT Industry

The issues to be addressed by the ICT industry have generally focused upon energy consumption in data center and computer hardware, and to some extent, the environmental impact caused by e-waste. Solutions to these problems are further defined below.

5.1.1 Virtualization

Virtualization is emerging as a key design pattern for building *green* data centres. Broadly speaking, virtualization is intended to provide a logical representation over physical resources without the related physical constraints [46]. There are three sub-patterns in virtualization:

1. Virtualization of a single physical resource to multiple-logical resources.
2. Virtualization of multiple physical resources to one single logical resource.
3. Virtualization of multiple physical resources to multiple logical resources.

Through virtualization, operators can consolidate the number of required physical servers, improving computing power utilization. Thus the power consumption of computing devices may be reduced. In addition, the floor space required within the data center may also be reduced, which leads to a reduction of the cooling and lighting power consumption by the facility. In theory, virtualization patterns may be applied to many aspects of ICT. This includes applications, communication channels, operating systems, firmware/hardware resources such as I/O ports, CPU, memory and storage assets.

In practice, virtualization is applied in the areas of desktop, web applications, networks, firewall/load-balancer, servers and storage. In addition to the traditional VLAN and VPN technologies, network virtualization enables virtualization of network ports, cables, network adapters and host-bus adapters, which increases network resource utilization and reduce network maintenance overhead. From a storage perspective, different tiers of storage devices can also be virtualized to present as a single logical storage device to the end users, reducing the cost associated with storage media migration, backup and recovery.

Given the range of virtualisation scenarios, the potential impact to sustainable solutions may be significant. A case study shows that in 2007 an electric company achieved 80% energy saving in the data centres through a server consolidation and virtualization initiative [46]. Further studies from virtualization vendors suggest that virtualization can achieve an equipment consolidation ratio of 10:1 and cut energy consumption up to 85% [47].

5.1.2 Cloud Computing

Cloud computing is an emerging technology that may improve data centre efficiency further. Gartner defines cloud computing as 'a style of computing where massively scalable IT-enabled capabilities are delivered 'as a service' to external customers using Internet technologies' [48]. While other may define the term differently, cloud computing typically builds upon virtualization solutions. When building upon a Service-Oriented Architecture (SOA), ICT capabilities and even business process capabilities can be provided as services to business. Thus business can have the alternative of acquiring ICT services as required without owning the underlying infrastructure. If the cloud computing model becomes wide-spread, then the number of data centers may be further consolidated, and the overall greenhouse emissions are likely to be reduced further. Example of services provided by Cloud computing providers are 'storage as a service', 'computing power as a service', 'software as a service' and 'business process as a service'.

5.1.3 Waste Heat, Cooling, and Power Management

Cooling, power management, and addressing wasted heat are vital in addressing the sustainability problem in ICT. While innovations in chip technology, systems, power suppliers and cooling systems design continue to drive down power consumption per computation, power consumption in data center continues to grow. A report from the US Environmental Protection Agency (EPA) shows that from 2000 to 2006, the energy consumption associated with the nations' servers and data centers has more than doubled in the period [48]. A key factor is the inefficiency in data center design. EPA's report suggests that improving operation in data center can achieve 22% less energy consumption compared to the current trend, whereas applying best practice in data center design can consume 56% less energy; and if the business adopts the state-of-art technologies, data center can achieve a 70% energy savings [49].

Energy consumption metering and monitoring within data centers help the operator to identify power usage inefficiencies. Advanced thermal distribution monitoring and analysis also provide insight for the operator to mitigate hot spots and rectifying imbalances within the data center. New cooling technology can also significantly reduce the energy consumption of the cooling devices. For example, research shows that a data centre using the water-based cooling technology saves around 20% energy consumption than one using the air-based cooling approach [50]. In addition, emerging waste heat recovering systems based upon thermo-electrics [41] and thermo-acoustics [42] may also provide opportunities for utilizing waste heat to generate power for device cooling or to perform other functions.

5.1.4 Material, Packaging, and e-Waste Management

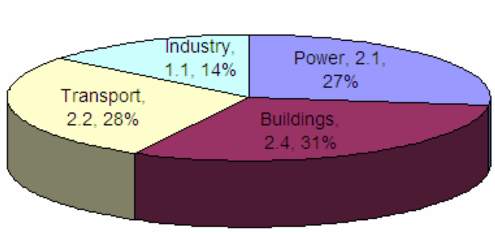
An important green factor in ICT is whether the materials used to manufacture devices and packaging create a harmful environmental effect or excessive greenhouse gas emission. Thus, minimizing toxic elements in the materials, reducing packaging volume, and promoting the use of energy efficient or recyclable materials are important areas for green technology innovation.

Traditional advances in flat panel monitors, printers, servers, and storage systems can contribute to energy savings. Alternatively, new approaches include changes from paint to powder coatings on computer covers that can avoid significant emission of Volatile Organic Compounds (VOCs) [51]. In addition, the use of recycled resins in computer manufacture can increase the proportion of recyclable content. Finally, Product End-of-Life Management (PELM) is a critical step to ensure environmentally responsible e-waste disposal. While largely overlooked by the industry, PELM includes computing asset recovery, refurbishing, recycling and disposal of computer product wastes; which not only reduce harmful environmental impact, but also recover value from the e-waste.

5.2 ICT Solutions in Other Industries

There are a variety of issues that may be addressed through the application of ICT to improve the sustainability of general industry. For instance, a recent report by the Global e-sustainability Initiative (GeSI), suggested that ICT is able to reduce carbon emissions in other industries by up to 7.8 billion tons by 2020 (see Figure 1 below); as pointed out in the report this figure is five times the footprint of ICT [34].

Figure 3 Potential Carbon Emission Reduction due to ICT (Gigatons CO_2)



While carbon management is a key aspect of sustainability, in practice there are many further areas that may be addressed. This includes collaboration tools, disaster monitoring solutions, resource management, and improving efficiencies in business processes.

5.2.1 Carbon Management

The Kyoto agreement effectively starts the era of carbon management in business. A carbon Emission Trading Scheme (ETS) will put a price tag on carbon, which will directly impact the bottom line. As such, carbon management presents a new challenge to business. To a large extent, business is not ready to embrace the new carbon regulatory environment. A recent survey conducted by the Australian Institute of Management (AIM) suggests that 88% of the CEOs in Australia have little or no knowledge of a carbon emission trading system; while 76% said their organization has not started any planning for the requirements of ETS [52]. The use of ICT will be critical to enabling industry to respond to the carbon management challenge.

Carbon metering and monitoring solutions lay down the groundwork for carbon management, establishing a baseline for improvement. Australia's National Greenhouse and Energy Reporting (NGER) ACT prescribes four methods to measure greenhouse gas emission [53]. The first method (known as the default method) is derived from the Australian National Greenhouse Account methods and is based on national average estimates. The second and third are facility specific methods. The fourth method adopts direct measurement of greenhouse gas emission. In any of these methods, ICT provides the key capabilities such as metering, monitoring, sampling, analysis and reporting to enable accurate measurement of the carbon footprint. As such, several solutions have already emerged to address this business challenge.

5.2.2 Collaboration and Telecommuting Tools

Employee travel and commuting contributes to the overall carbon emissions. Collaboration technology such as teleconferencing, video conferencing, and on-line chat is able to reduce the demand for staff travel as well as office space. Recent developments in virtual world technologies (e.g. Second Life) provide an environment where the collaboration experience resembles closely that of face-to-face meetings. Web 2.0's social networking sites also provide an efficient avenue for information sharing and dissemination. Advanced collaboration solutions enable business to choose alternative operation models such as off-shoring, outsourcing or even home-sourcing in the new carbon regulatory environment.

It is estimated that such teleworking solutions are able to reduce carbon emission by up to 360 million tons [34]. When considering the reduction in using paper assets, these tools may contribute further to carbon savings. There is also the positive impact to the environment in reduced deforestation. Furthermore, broadband technology is able to provide new services such as high-definition video services. As observed in a recent report on telecommunications and climate [54], face-to-face meetings rely upon several forms of communication including body language, facial expression and spoken words. These traits can be met by such high definition video conferencing solutions [54].

5.2.3 Intelligent Transportation and Energy

ICT solutions can contribute to the construction of intelligent network in the energy sector. Remote metering, monitoring and intelligent decision support enhance the efficiency of energy transmission and distribution. The ICT solution is also a factor to reduce energy usage and outage, improving the overall efficiency of grid management.

ICT solutions have also been applied to build intelligent transportation systems for the transport industry. Solutions are available today to enable intelligent routing and scheduling in mass transit systems, reducing traffic congestion and hence carbon emissions. While efficiencies in traffic flow management, transport optimization, and vehicle improvements may reduce emissions by 760 million tons, advances in power distribution and management may contribute to some 2.15 billion tons in emissions savings [34].

5.2.4 Ecoinformatics and Resource Management

The branch of information technology that concerns environmental science, or the ecology of the environment, is referred to as ecoinformatics. Through increasing the material understanding of the environment, ICT is able to play a more critical role in providing data on changes to our environment. This data is able to assist planners in how best to use our finite resources whilst protecting the environment.

The existing ecoinformatic solutions are focused upon large databanks that report on the environment. The range of environmental themes include: forestry, wildlife, fisheries, agriculture, and the conservation of eco-systems. As the issue of sustainability increases in intensity, new areas in restoration of many ecological processes will perhaps also emerge as a further area that these ecoinformatic solutions will need to address.

5.2.5 Disaster Monitoring and Response

Natural disasters exert a tragic human loss and have the potential for catastrophic impact to the environment. Further to this, man made disasters contribute further stress to our environment. ICT is able to assist in a unique way to mitigate the damage inflicted by both natural and unnatural disasters. This is through the application of both monitoring and response solutions.

Disaster monitoring solutions have now been proposed to monitor and provide early warning to natural disasters such as tsunamis'. Solutions exist to manage incident response for rescue and response crews that include fire, police and medical services. For example, recent advances in Mesh Network technologies allow communications, command and control infrastructure to dynamically accept new nodes as fire and rescue crews arrive at an incident. This contributes to a more effective response to the danger, hence mitigating both the human and environmental losses.

The emerging technologies may also be applied to several forms of disaster response, and will assist in providing a more effective and efficient means to deal with threats to the environment. In addition to the traditional carbon based systems, interventions such as these enable ICT to make further contributions to the sustainability of human activities.

5.2.6 Indicator Monitoring Tools

A key observation of the 2008 EPI report is that advances in information technology have fuelled the ability to make data-driven decision making, in particular for those relating to the environmental performance index (EPI) [23]. Thus, a further contribution that ICT is able to make is in the tools that monitor and report upon the sustainability indices outlined in the previous sections. As pointed out by the Balaton group 'in order to develop the aggregated indicators, information systems are required for each step' [55].

There are numerous tools available now and emerging to monitor the key sustainability indicators. A sample of some of the most recent tools is shown at [56]. As the requirements of the industry change, so too will the need for ICT to adapt to monitor and report the environmental statistics accordingly.

6. Conclusions and Discussion

In this paper, the issues of sustainability and how this relates to ICT is discussed. The principle indicators of sustainability are presented and several indicators specific to ICT are outlined. We also observe that the environmental burden of ICT goes well beyond an assessment of CO_2 greenhouse gases and suggest a more complete assessment may consider waste, heat, and radio emissions. While ICT impacts the environment, contributing to global carbon emissions, ICT also has the potential to have a significant positive impact to the sustainability of the environment, particularly in the area of telecommuting, energy efficient designs, and ecoinformatic solutions.

A recent Forrester report points out that sourcing and procurement teams need to add green requirements for suppliers with some 35% of enterprise IT professionals citing that 'environmental concerns are very important in planning IT operations' [57]. Furthermore, Gartner gives top predictions for IT organizations and users suggesting that going green will no longer be just a phrase, but rather suppliers will need to be certified green to remain on supplier shortlist [58]. Finally, Garnaut points out that the inertia of climate change will continue to occur after the cause has been removed [59]. Given the significance of sustainability to society, industry, and government, it is hoped that that the indicators, environmental issues and solutions discussed in this paper will serve as input for policy development.

6.1 Further Work

There is further work to design the method for calculating the numerators and denominators of the eco-efficiency general formulae proposed. This may build upon the process-sum methods outlined in [27], or based upon other statistical methods that include averaging the sum of co-efficient squares as suggested in [52]. There is also further work in identifying modeling indices in addition to the indicators presented in this paper. Finally, we suggest that the modeling of sustainability requirements as non-functional requirements be investigated further.

6.2 Acknowledgements

We thank Michael Shallcross for his insightful feedback and comments on this paper. We also thank the anonymous reviewers for their helpful suggestions to this work.

REFERENCES

[1] Carbon Pollution Reduction Scheme, Green Paper Summary, Australian Government, Department of the Climate Change, Australian Greenhouse Office, July 2008. Available at: http://www.climatechange.gov.au/greenpaper/ summary/pubs/greenpaper-summary.pdf.

[2] National Emissions Trading Taskforce Report, 'Possible design for a national greenhouse gas emissions trading scheme: Final framework report on scheme design', Australian Government, Department of Climate Change, December 2007. Available at http://www.greenhouse.gov.au/.

[3] ITU and Climate Change, Available at: http://www.itu.int/themes/climate/.

[4] Australian Computer Society (ACS), 'Policy Statement on Green ICT', August 2007. Available at www.acs.org.au.

[5] A.M. Hasna, 'Sustainability in Engineering Design', The International Journal of Environmental, Cultural, Economic and Social Sustainability, 2007, Vol. 4 (1): pp. 69–88.

[6] K. Yamaguchi (Ed.), Sustainable Global Communities in the Information Age Visions from Futures Studies, Praeger Publishers: 1997.

[7] T. Stevenson, I. Burkett, and S. Myint, 'Interconnecting local communities globally: An Australian perspective.' In Sustainable Global Communities in the Information Age: Visions from Futures Studies, 1993, pp. 171–185.

[8] S. Forge, 'Powering Down: Remedies for unsustainable ICT', Journal of Foresight, Emerald Group, 2007, Vol. 9(4): 3–21.

[9] J.P. Toomey, 'Telecommuting and the Road to Sustainability', Masters Thesis, Nicholas School of the Environment and Earth Sciences, Duke University, 2008.

[10] C.J. Pavlovski, 'Information & Communications Technology Evolution and Consequential Damage', Proceedings of the Communications Policy & Research Forum 2007, Network Insight Institute. pp. 337–355.
[11] P.Arnfalk, L. Erdmann, J. Goodman, L. Hilty, 'The future impact of ICT on environmental sustainability', EU-US SEMINAR: NEW TECHNOLOGY FORESIGHT, FORECASTING & ASSESSMENT METHODS-Seville 13–14 May 2004
[12] Sustainability, Wikipedia, Available at http://en.wikipedia.org/wiki/Sustainability.
[13] United Nations, Report of the World Commission on Environment and Development: Our Common Future, World Commission on Environment and Development, Resolution Number A/RES/42/187, 96th plenary meeting, December 1987. Available at http://www.un-documents.net/wced-ocf.htm.
[14] United Nations, Rio Declaration on Environment and Development, Agenda 21, A/CONF.151/26 (Vol. I). Rio de Janeiro, June 1992. Available at http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm.
[15] H. Schroll and B. Kjærgård, 'Sustainable Development and TES', The Journal of Transdisciplinary Environmental Studies, Vol. 5(1–2), 2006.
[16] B. Dalal-Clayton, 'Modifi ed EIA and Indicators of Sustainability: First Steps Towards Sustainability Analysis'. International Institute for Environment and development, Environmental Planning Group, Environmental Planning issues No. 1, May 1993. Available at http://www.iied.org/pubs/display.php?o=7766IIED.
[17] International Association for Impact Assessment, Principles of Environmental Impact Assessment Best Practice, Available at http://www.iaia.org/modx/assets/files/Principles%20of%20IA_web.pdf.
[18] J. Holmberg, S. Bass, S. and L. Timberlake, 'Defending The Future: A Guide to Sustainable Development', IIED/Earthscan, London, 1991.
[19] Bellagio Project, P. Hardi and T. Zdan (Editors), Assessing Sustainable Development: Principles in Practice, International Institue for Sustainable Development, Bellagio Italy, 1997. Available at http://www.iisd.org/pdf/bellagio.pdf.
[20] Organization for Economic Co-operation and Development, OECD Core Set of Indicators for Environmental Performance Reviews, Environment Monographs No. 83, OCDE/GD(93)179, Paris 1993. Available at http://www.nssd.net/pdf/gd93179.pdf.
[21] Organization for Economic Co-operation and Development, OECD Key Environmental Indicators, 2008. Available at http://www.oecd.org/dataoecd/20/40/37551205.pdf.
[22] D.C. Esty, M. Levy, T. Srebotnjak, and A. de Sherbinin, 'Environmental Sustainability Index: Benchmarking National Environmental Stewardship', New Haven: Yale Center for Environmental Law & Policy, 2005.
[23] D.C. Esty, M.A. Levy, C.H. Kim, A. de Sherbinin, T. Srebotnjak, and V. Mara, 'Environmental Performance Index.', New Haven: Yale Center for Environmental Law and Policy, 2008.
[24] M.T. Brown, S. Ulgiati, 'Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation', Elsevier, Ecological Engineering, 1997, Vol. 9, pp. 51–69.
[25] H.T. Odum, 'Self-Organization, Transformity, and Information, Science', Vol. 242, 1988, pp. 1132–1139.
[26] Wickipedia, Emergy, http://en.wikipedia.org/wiki/Emergy.
[27] Y. Matsuno, N. Mochizuki, H. Kob, et al., 'Guideline for Information and Communication Technology (ICT) Eco-Efficiency Evaluation', The Japan Forum on Eco-efficiency, March 2006. Available at: http://www.jemai.or.jp/JEMAI_DYNAMIC/data/current/detailobj-2687-attachment.pdf.
[28] Y. Matsuno, K.I. Takahashi, M. Tsuda, J. Nakamura, S. Nishi, 'Eco-Efficiency for Information and Communications Technology (ICT): The State of Knowledge in Japan,' Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, 2007, pp. 1–5.
[29] ITU, ICTs and Climate Change: ITU background report, April 2008. Available at: http://www.itu.int/dms_pub/itu-t/oth/06/0F/T060F0000070001PDFE.pdf.
[30] ITU Press Release, ITU responds to industry call to accelerate work on cleaner and greener environment: New group to focus on the impact of ICT and climate change, July 2008.
[31] L.M. Hilty, 'Editorial: Electronic waste—an emerging risk?' In Environmental Impact Assessment Review, 2005, Vol. 25, pp. 431–435.
[32] R. Widmer, H. Oswald-Krapf, D. Sinha-Khetriwal, M. Schnellmann, and H. Boni, 'Global Perspectives on e-waste', Environmental Impact Assessment Review, Elsevier, 2005, Vol. 25, pp. 436–458.
[33] Gartner, Green IT: The New Industry Shockwave, presentation at Symposium/ITXPO conference, April 2007.
[34] GeSI Report, SMART 2020: Enabling the low carbon economy in the information age, Global e-sustainability initiative (GeSI), The Climate Group, 2008. Available at http://www.gesi.org/index.php.
[35] W. Harst, J. Kuhn, H. Stever, 'Can Electromagnetic Exposure Cause a Change in Behaviour? Studying Possible Non-Thermal Influences on Honey Bees – An approach within the Framework of Educational Informatics', ACTA SYSTEMICA, International Institute for Advanced Studies, IIAS International Journal, 2006, Vol. 6(1), pp. 1–6.
[36] D.L. Cox-Foster, S. Conlan, E.C. Holmes, et al., 'A Metagenomic Survey of Microbes in Honey Bee Colony Collapse Disorder', Science 12 October 2007: Vol. 318(5848), pp. 283–287.
[37] C.M. Bhumralkar and J. Williams, 'Atmospheric Effects of Waste Heat Discharges', First Edition, Marcel Dekker, New York, 1982.
[38] L. Anatychuk, K. Misawa, N. Suzuki, 'Blocked generators for energy and industrial heat waste use', Proceedings ICT 98. XVII International Conference on Thermoelectrics, Nagoya, Japan, May 1998, pp. 483–485.
[39] J.G. Haidar, J.I. Ghojel, 'Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators', Proceedings of the International Conference on Thermoelectrics, Beijing, China, June 2001, pp. 413–418.
[40] J. Sanderson, 'Waste Heat Recover: Identifying and recovering heat energy', CSIRO, Process, October 2006, p. 3.
[41] J. Yang, 'Potential applications of thermoelectric waste heat recovery in the automotive industry', 24th International Conference on Thermoelectrics, June 2005, pp. 170–174.

[42] O. Symko, 'A sound way to turn heat into electricity', University of Utah, Press Release, June 2007. Available at http://www.unews.utah.edu/p/?r=053007-1.
[43] Ministry of Economy and Trade and Industry (METI), Eco-Efficiency and Factor Handbook for products, Japan Environmental Management Association for Industry (JEMAI), 2004. Available at: http://www.jemai.or.jp/JEMAI _DYNAMIC/data/current/detailobj-2073-attachment.pdf.
[44] J.A. Laitner and K. Ehrhardt-Martinez, 'Information and Communication Technologies: The Power of Productivity, How ICT Sectors Are Transforming the Economy While Driving Gains in Energy Productivity', American Council for an Energy Efficient Economy (ACEEE), February 2008
[45] Press Release, Smarter technology use could reduce global emissions by 15 per cent and save global industry EUR 500 billion in annual energy costs by 2020, Global e-sustainability initiative (GeSI), The Climate Group, 2008.
[46] R. Bersier, 'Virtualization of IT environments as ecological alternative in the data center', Third International Conference on Lifecycle Management (LCM), 2007. Available at: http://www.lcm2007.org/paper/295.pdf.
[47] GCN, 2008, Virtualization, Priority Report, Custom Supplement to Federal Week, July, Government Computer News, Available at: http://www.gcn.com/acmfiles/ sponsored_papers/PR_VIR_07142008_PDF.pdf.
[48] Plummer, D. C., Bittman, T. J. and et al, 2008, Cloud Computing: Defining and Describing an Emerging Phenomenon, Gartner, Research Report.
[49] EPA, 2007, Report to Congress on Server and Data Center Energy Efficiency, U.S. Environmental Protection Agency ENERGY STAR Program.
[50] M.J. Ellsworth, L.A. Campbell, et al., 'The Evolution Of Water Cooling For IBM Large Server Systems: Back To The Future', 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, 2008.
[51] L.G. MacDowell III, 'History of protective coating development at the Kennedy Space Center', Corrosion and Materials, October–December 2003, Vol 28(5–6).
[52] AIM, 2008, The Introduction of Australia's Emissions Trading Scheme, Level of understanding amongst CEOs/senior executives, Australia Institute of Management, Available at http://www.aimvic.com.au/apps/news/StoryView.php?viewNewsStory=1058.
[53] National Greenhouse and Energy Reporting Act, No. 175, 2007, Australian Government, Department of the Environment and Water Resources, Australian Greenhouse Office, October 2007. Available at http://www.greenhouse.gov.au/reporting/ publications/pubs/nger-fs.pdf.
[54] K. Mallon, G. Johnston, D. Burton, and J. Cavanagh, 'Towards a High-Bandwidth, Low-Carbon Future: Telecommunications-based Opportunities to Reduce Greenhouse Gas Emissions', Climate Risk, Telstra, October 2007
[55] D. Meadows, 'Indicators and Information Systems for Sustainable Development: A Report to the Balaton Group', The Sustainability Institute, September 1998. http://www.balatongroup.org/.
[56] The World Conservation Union. The Learning Consortium on Systems and Sustainability Resource Database. Available at http://cec.wcln.org/index.php?module=pagesetter&tid=2&filter=collection:like:846&tpl=list.
[57] G. Schreck, 'Five Green IT Trends That Will Impact The IT Infrastructure And Operations Professional', Forrester Research, March 2008
[58] D.C. Plummer, C. Smulders, L. Fiering, et al., 'Gartner's Top Predictions for IT Organizations and Users, 2008 and Beyond: Going Green and Self-Healing', Gartner, 8 January 2008. Available at http://www.gartner.com/DisplayDocument?id= 578409.
[59] Garnaut Climate Change Review, 'Interim Report to the Commonwealth, State and Territory Governments of Australia', February 2008. Available at http://www.garnautreview.org.au/.