Estimating Environmental Costs

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Abstract

Added demands on natural resources and proposed environmental regulations could potentially have a significant impact on the production and operational costs of information technology (IT). In this paper, we utilize an Economic Input-Output Life-Cycle Assessment (EIO-LCA) framework to model projected changes in the cost structure of a portfolio of IT products due to increased electricity prices and a carbon tax on producers and consumers. Our analysis suggests that the Total Cost of Ownership (TCO) for IT in a large enterprise could increase by up to 13% depending on the incidence of taxation. We conclude by discussing how this changing IT cost environment will further incentivize the design of energy- and carbon-efficient IT products.

1. Introduction

Additional constraints on our natural resources, climate change and the impacts of effluents such as greenhouse gas (GHG) emissions, air particulates, and water pollutants on society and the environment are a growing global concern for governments, corporations, and consumers. Over the next ten years, electricity prices are predicted to rise approximately 2% and 4% annually for consumers and producers, respectively, and by 2019 consumers are predicted to expect a 15% increase in the cost of electricity relative to 2009 baseline costs [1]. For the growing IT industry, its environmental impact is an increasing concern, as aggregated information and communications technologies—including personal and enterprise communications technologies—have been estimated to emit approximately 2% of global carbon emissions, roughly as much as the aviation industry [2].

As a result of increasing environmental and economic pressures, producers and consumers are increasingly concerned with the environmental impacts and operational cost of products. Consumers are demanding sustainable products that are "green" and energy efficient. Industry is also facing an increasingly regulatory environment that is demanding sustainable business practices. Proposed regulatory schemes seek to address many of these environmental problems by imposing policies that may force companies to internalize the environmental costs associated with their production.

Consequently, sustainability is becoming an increasingly important component of corporate business strategy. In the face of the growing green economy, the IT industry needs to be aware of the changing demands and needs of consumers, and develop sustainability initiatives to address these demands internally as well as along their supply chain.

Currently, businesses lack a framework that provides a quick and easy way to analyze the effect that changing producer and consumer cost structures may have on corporate business strategy. We propose a hybrid modeling framework that assesses the impact of rising electricity prices and carbon taxes on production and operational costs for a portfolio of IT products. Our modeling approach provides a framework for businesses to access the sustainability of their products so that they can update their business strategy accordingly (product design/green design, etc).

We make three key contributions in this work. First, we present a framework that enables producers of IT products to easily evaluate the impact of environmental regulation on their cost structures, not just internally but also along their entire supply chain. Second, we show how potential cost changes in the utility industry affect the IT industry, both in terms of the cost of production but also in terms of the cost of ownership for end users. Finally, we suggest a methodology to leverage our framework for purposes of evaluating the potential economic impacts that 'green design' might enable.

The rest of this paper is organized as follows. Section 2 provides a review of the life-cycle assessment (LCA) and economic input-output (EIO) methods used in this paper. Section 3 discusses how we use a hybrid EIO-LCA framework to assess future costs. Section 4 illustrates application of the approach for a portfolio of IT products, including the potential cost implications for a sample enterprise supporting 50,000 users. Section 5 concludes by discussing limitations of the present work, as well as ongoing work to further refine the methodology to incorporate elasticity of supply and demand estimates of the IT industry.

2. Life-Cycle Assessment (LCA)

Life-cycle assessment (LCA) is a method for assessing the environmental impacts of a product, process, or service from cradle to grave—including the extraction of raw materials, manufacturing, transportation, use, and end-of-life [3-8]. LCA is thus a system-wide model across the breadth of the life cycle from the inputs (materials, energy, and water) to the outputs, both the valuable (usefulness, recovered materials, and recovered energy) and non-valuable (water effluents, airborne emissions and solid waste).

Various approaches have been developed over the years to help quantify life-cycle impacts. The "process LCA" approach is among the most rigorous. This approach essentially involves a detailed process of compiling an inventory of material and energy flows across the life-cycle, evaluating each of the data sources (usually manually), assigning impact factors individually to each process or product, and subjectively weighing the results into an overall environmental interpretation. Since this type of assessment can be quite time-consuming, laborious and expensive to implement many practitioners opt to implement a streamlined LCA, where the designer makes baseline assumptions about the scope, boundaries, and significance of different aspects of the lifecycle. Since the model is streamlined, results from such an analysis are generally more of an approximation than those from detailed process LCAs. Thus, streamlined LCAs are often considered most appropriate for preliminary evaluations or environmental hot-spot analysis.

A hybrid LCA model is essentially a combination of different types or LCA approaches, designed using the tacit knowledge of the assessor usually with the codified knowledge of some level of process detail. Most commonly, hybrid LCAs are segregated by applying a particular type of LCA across select stages of the life-cycle. For example, if one expects that system operation might be the dominant source of environmental impact, then an LCA practitioner may choose to implement a detailed process LCA model for the operational phase of the lifecycle but a more streamlined or generalized approach during the other lifecycle stages. Such hybrid LCA models are the most common type of LCA, since they are generally easier to implement than process LCA but retain much of the rigor and relative analytical accuracy of the latter. We will revisit the creation of hybrid LCAs for IT systems specifically in Section 2.3.

2.1. Economic Input-Output (EIO)

An Economic Input-Output (EIO) model, commonly referred to as the Input-Output (I-O) or the Leontief Model[1], is used to analyze the interdependence of industries/sectors in an economy (*interindustry analysis*). The model consists of a set of linear equations that describes the distribution of the industry's product throughout the economy and tracks the activity of industries that both produce goods (outputs) and consume goods from other industries (inputs) during production.

The basic form of the model consists of a system of linear equations whereby each equation describes the distribution of a sector's product throughout the economy, and the economic activity between sectors in the economy. This data is displayed in an interindustry transaction table and is generally measured for a particular period of time (usually years) and in monetary terms ($ value). Once the economic activity of all sectors has been documented, an EIO matrix can be constructed. Such an EIO matrix exhibits the flows of products from each industrial sector considered as a producer to each of the sectors considered consumers. The rows describe the distribution of a producer's output throughout the economy, while the columns describe the combination of inputs required by a particular industry to produce its output.

For example, computer manufacturing requires semiconductors as an input. In addition, television manufacturing also requires semiconductors. Then, for a simplified 3-sector economy (consisting of computers, televisions, and semiconductors), we might construct an EIO matrix wherein, along each row: (i) computer manufacturing consumes a small number of computers themselves, since people building computers do use computers themselves; computer manufacturers use some fraction of output from the semiconductor industry; and (to a first order) computer manufacturers use a negligible amount of televisions. In addition, computer manufacturers sell their output to directly address the demand of consumers. Similarly, (ii) semiconductor manufacturing uses a small number of computers; some amount of semiconductors in their own manufacturing processes; and a relatively small number of televisions in their industry; and there is almost no demand for semiconductors directly by end consumers. Lastly, (iii) television manufacturing uses a small number of computers; a reasonable fraction of semiconductors; a small

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[1] Wassily Leontief received the Nobel Memorial Prize in Economic Sciences in 1973 for this work.

number of televisions; and mostly produce output to meet the final demand of consumers.

Using such a representation, it becomes possible to represent in a simplified matrix form (for example) how a perturbation in the manufacturing of semiconductors might affect the manufacturing of computers and televisions; or, how a change in the amount of spending by consumers might affect the output from the computer or television industries (or, by extension, how much stimulus in consumer spending might be required to prevent revenue declines in the computer industry etc).

The simplified input-output transactions table above can be generalized for the case of *n* sectors. For such an economy of *n* sectors, sector *i*'s output (x_i) is used as an input in the production of sectors 1, 2, … n. This amount of output purchased in the intermediate market (i.e. the amount purchased by other industries as inputs to their own processes) is represented by $z_{i,1}$, $z_{i,2} \ldots z_{i,n}$ while *y* represents the total amount of sector *i*'s output purchased by final markets. In such a model:

x_i is the total output (production) of sector *i*
y_i is final (consumer) demand for sector *i*'s product
such that $x_i = z_{i1} + z_{i2} + \ldots + z_{in} + y_n$ (1)

For calculation purposes, the model can be generalized by assuming that the inter-industry flows between sectors are represented as a percentage of sectoral output. This flow is represented by dividing the economically valued flow from sector *i* to sector *j* by the total output of sector *j*. Thus, the inter-industry flow can be represented as follows:

$$a_{ij} = \frac{z_{ij}}{x_j} \qquad (2)$$

where a_{ij} is a unitless technical coefficient that ranges in value from 0 to 1. As a set of linear equations:

$$x_i = a_{i1}x_1 + a_{i2}x_{i2} + \ldots + a_{in}x_n + y_i \qquad (3)$$

Now, let the matrix *A* contain all the technical coefficients (a_{ij} terms), vector *X* all the output (x_i) terms, and vector *Y* the final demand (y_i) terms. Then:

$$X - AX = [I - A]X = Y \text{ , or } X = [I - A]^{-1}Y \qquad (4)$$

A decomposition of the general *n* x *n* form of $[I–A]^{-1}$ gives: $[I - A]^{-1} = [I + A + A^2 + A^3 + \ldots + A^n]$ (5)

so that: $X = Y + AY + A^2Y + A^3Y + \ldots + A^nY$ (6)

Equation (6), a power series approximation of the model, shows the total supply chain effects of producing goods and services in an economy, where the individual terms represent the magnitudes of the round-by-round effects. In the *first* round, *Y* represents the production of the desired output. This would be a simplistic model of an insular economy, where no inter-industry flow is required in order to produce goods or services that meet the final demand. In reality, however, production of *Y* would require inputs from other sectors. In this *second* round, *AY* is needed to produce *IY* of final demand. But, extending the same argument, a demand for *AY* output would require *A(AY)* worth of input, so that in the *third* round, A^2Y is needed to produce *AY* from the second round, etc. The sum of these round-by-round effects, including the final demand, is the total output (*X*).

Alternatively, *AY* represents the contributions from the direct or first level suppliers, while *AAY* is the second level of indirect suppliers, and $[I–A]^{-1}$ (also known as the 'Leontief inverse') represents the entire supply chain. When this demand is aggregated across all sectors, we get a recursive process whereby the individual terms of the power series approximation represent the magnitudes of the round-by-round effects. Additional information regarding the I-O model can be found in Raa [9] and Miller and Blair [10].

2.2. EIO-LCA

The Economic Input-Output Life Cycle Assessment (EIO-LCA) is a macroscale modeling framework that combines the comprehensiveness of EIO with the environmental meaning of an LCA. Such a model begins with the Leontief model of a given economy. Once the economic output for each sector (*x*) has been determined, a vector of direct environmental outputs is then obtained by multiplying the output at each stage by the environmental impact per dollar of output:

$$b_i = R_i x \qquad (7)$$

where b_i is a vector of environmental burdens (such as toxic emissions or electricity use) for each production sector, and R_i is a matrix with diagonal elements representing the impact per dollar of output at each stage. In practice, environmental impacts per sector are obtained using estimates of various environmental burdens per dollar output for each commodity sector. For example, energy use can be derived by aggregating the heating values of individual fuels using I-O data on fuel purchases based on average prices of individual fuels. CO_2 estimates may then be derived using emissions factors from fuel use for each sector. Thus, for example, once we know the volume of commodities consumed by a specific sector (from an EIO model or otherwise), the environmental impacts related to that sector can be calculated. Normalizing these impacts to the economic activity in that sector gives the R_i matrix. Combining Eq. (7) with Eq. (4):

$$b_i = R_i(I - A)^{-1} y \qquad (8)$$

The total effect of an environmental impact of a process or service can then be generated by summing sector specific impacts across the entire supply chain. This process includes both direct and indirect effects of production. For example, given the total dollar output of a sector, EIO-LCA can be used to estimate the total CO_2 emissions generated by this sector and trace these emissions across its complete supply chain from cradle to gate (raw material gathering and processing to manufacturing). Further details regarding this approach can be found in the discussion by Hendrickson et al. [11].

3. Assessing Future Costs

In the present work, we combine prior work related to hybrid EIO-LCA modeling with a forward looking EIO-based projection of environmental costs.

Specifically, we begin by using EIO-LCA to create cradle-to-gate (i.e. extraction, manufacturing and transportation) models of IT systems [12]. We then approximate the operational and end-of-life impacts using process LCA models. Such a hybrid LCA model thus provides a cradle-to-grave view of the environmental impacts of a given system. Past work on IT systems, such as desktop computers [13], has shown such a model to be quite accurate; we extend such a model across a portfolio of IT products in the present work.

Once the environmental impacts of an IT portfolio have been estimated using the hybrid LCA model, we use projected electricity price data from the U.S. Department of Energy (DOE) [1] and historical data on a range of levied carbon taxes worldwide [14] as inputs to the EIO model to simulate the impact of rising electricity prices and carbon taxes on operational and production costs. Specifically, we forecast electricity prices for residential, commercial, and industrial IT users over the next 5 years using DOE models that project energy price estimates for these sectors over the next 25 years. We consider three future scenarios: (A) a baseline, involving approximately constant electricity prices, normalized to current (2009) industrial rates, (B) a modest price increase, involving an approximately 3% increase in prices based on DOE projections for the cost of electricity in 2015, normalized to current industrial rates, and (C) a high price increase, corresponding to an approximately 3% increase in prices but normalized to current residential rates. Interpreted differently, scenario A involves no change in today's electricity prices (i.e. essentially a representation of where we are today); scenario B corresponds to a nominal price increase in electricity rates; and scenario C may be representative of a scenario involving restructuring of the utility industry such that current subsidies for industrial and commercial users is eliminated due to environmental taxation rules (since these categories of users generate the highest fraction of environmental effluents on a per-dollar basis). It should be noted that these scenarios are considered only to provide a representative range of possible outcomes, and the resulting prices for electricity from all the scenarios considered are within the range of possibilities forecasted by the US DOE. (Historically, actual prices over the last 50 years have generally been within this range of predictions.)

In addition to the increase in electricity prices, we consider an additional case of an imposed carbon tax on the electric utility industry [14]. Specifically, we consider a range of possible taxes based on historical indicators of similar taxation schemes: (A) \$0 tax (i.e. legislation fails to pass); (B) a low tax (\$10 per metric ton of CO_2 emissions); and (C) a high tax (\$50 per metric ton of CO_2 emissions). Our carbon tax model makes two important assumptions: (i) the total incidence of a tax on utilities is borne by producers and consumers—that is, the entire tax on utilities is passed on in the form of higher electricity prices, leading to a proportional increase in operational and production costs of IT systems; and (ii) the seller of equipment passes on any increase in their environmental costs to the consumers. We consider in scenario B that the supply chain of computer manufacturing absorbs any cost increases internally, so that the only cost increase the consumer sees is related to increased costs at the IT equipment vendor. In scenario C, we assume that suppliers to IT equipment vendors see an increase in electricity costs, and pass these along to the equipment vendor. Section 4 discusses the impact of these assumptions in detail.

3.1. Operational Impact Model

Operational power use models for all types of equipment have been adequately discussed in the literature [15-18], and can be summarized as predominantly a function of the number of states, the power consumption in each of the states, and the load (demand) over time which determines the state of the machine at any point of time. That is, for any given IT system:

$$\dot{W}_{\substack{sys\\op}} = \sum_{i=1}^{n} \left(\int_{0}^{T} \dot{W}_i X_i(t) dt \right) \qquad (9)$$

where $\dot{W}$ represents power use, the subscript *sys* corresponds to the system, the subscript *op* corresponds to operation of the equipment, *n* represents the number of states available for the machine, T is the total operational lifetime of the system, $\dot{W}_i$ represents the power consumption in that state, and $X_i(t)$ is an indicator of the machine states over time. Nominally, $X_i(t)$ may correspond to 1 for any time *t* when the machine is in the *i*-th state, and 0 when the machine is in any other state. However, for certain situations—such as those with power management using low-power states—fractional values of $X_i(t)$ may also be appropriate. If desired, Eq. (9) could be replaced by more detailed system models, such as those based on service demand, utilization, hardware properties (including voltage- or frequency-scaling characteristics) or other considerations. For example, Eq. (9) can be modified by considering $X_i(t)$ in terms of fractional utilization numbers across two states (idle and peak) to obtain the following model (which has been shown to be accurate for the case of large numbers of enterprise servers) [17, 18]:

$$\dot{W}_{\substack{servers\\op}}(t) = \int_{t=0}^{T} \left[\dot{W}_1 + \left(\dot{W}_2 - \dot{W}_1\right)U(t)\right]dt \qquad (10)$$

where the subscripts *1* and *2* correspond to the power utilized at idle and peak operating states, respectively, and *U(t)* is the utilization of the system.

The above models assume that the predominant impacts during operation of IT systems stem from the electricity inputs required, which is reasonable because the boundaries of the current analysis have been drawn around the system (and thus, for example, do not include flows such as water consumption required for infrastructure cooling in data centers).

Once the operational power has been calculated, this is then multiplied by the average cost of electricity over the lifetime of the device. Alternatively, if a variable price of electricity is to be considered, then Eq. (9) can be modified as follows:

$$p_{\substack{sys\\op}} = \sum_{i=1}^{n}\left(\int_{0}^{T} \dot{W}_i X_i(t)\hat{p}_{elec}(t)dt\right) \qquad (11)$$

where p corresponds to the total cost (in \$), $\hat{p}$ is the unit price (i.e. $\hat{p}_{elec}$ is the cost of electricity per kWh), and the remaining variables are as defined earlier. Such a time-varying price is particularly relevant for a scenario in which dynamic time-of-use tariffs and rebates may be in place (for example, due to ‘smart grid’ initiatives [22][23]).

Using Eq. (11), it becomes possible to scale the operational demand using an EIO-LCA model to assess the total environmental impact during system operation:

$$\varepsilon_{op} = \hat{\varepsilon}_{elec}(I - A)^{-1} p_{elec} \qquad (12)$$

where ε is the estimated environmental impact, the subscript *op* reflects the operational stage of the lifecycle, the subscript *elec* is indicative that we are only accounting for the cost of electricity, $\hat{\varepsilon}$ is the unit environmental impact (i.e. $\hat{\varepsilon}_{elec}$ is the estimated environmental impact per unit kWh), $(I–A)^{-1}$ is the inverse Leontief matrix, and p_{elec} contains the electricity demand related to operation of the IT equipment.

For the different carbon tax incidences discussed earlier, the total carbon emissions calculated in Eq. (12) can be scaled by the appropriate environmental tax and combined with the costs estimated in Eq. (11) to determine the total cost of operation.

3.2. Production Model

To model the production impact of rising electricity price and imposed carbon taxes, we utilize an EIO-LCA model based on the various economic sectors used in the manufacturing of IT equipment. First, the baseline case (A) is estimated by calculating the producer price for each product by generating a predictive cost model that considers the flow of raw materials and energy which go into a product, aggregate these different costs, attaching typical margin as well as general selling and administrative (GSA) costs. The resulting model is essentially a prediction of the retail cost for a particular item, which can be calibrated against a range of published costs to fine tune estimations such as margin and GSA. For mature products, such predictive models have been found to be surprisingly accurate [19]. Once a validated predictive model has been created, it becomes possible to estimate the cost to produce a given system, which can then be inputted to the EIO-LCA model to obtain the cost to manufacture across the supply chain. Note that in terms of the EIO-LCA model, this calculated producer price corresponds to the economic activity per unit in the computer manufacturing sector (*y*).

Using, a published EIO-LCA database [20], we then obtain R_i for the entire computer manufacturing supply chain for two impact factors: electricity use and CO_2 emissions. The database also specifies A_i based on US Department of Commerce relationships for all 491 sectors, e.g. for a given spend in the computer manufacturing sector of \$1 million, this database conveys how much corresponding economic activity occurs across semiconductor manufacturing; hard disk drive manufacturing; plastics and raw material use; etc. Because EIO databases use historical data, we re-index the economic data to the appropriate year to account for inflation using the Producer Price Index of the United States [21]. In addition, because the EIO database assumes a supply chain that is based in the US, we adjust the data to compensate for sensitivity to regional disparities by modifying the environmental impact factors based on the energy mix of the region being considered.

Combining these adjusted A_i and R_i values with the producer price calculated above (y) and substituting into Eq. (8), we obtain the carbon emissions and electricity use related to computer manufacturing as well as the entire computer manufacturing supply chain. While the estimates are generic industry-level estimates rather than being representative of any company-specific models or company-specific supply chains, we believe such industry-averaged representations are reasonable for purposes of the present work.

Thus, for a given product, we now have a model that predicts the total electricity use and carbon emissions related to the manufacturing of that system, both at the original equipment manufacturer (OEM) as well as across the entire supply chain. Given these values, we are able to estimate production costs for scenarios A, B and C outlined earlier.

We now apply the cost model developed above for the case study of a portfolio of IT products.

4. Results

Table 1 describes the set of representative products considered in the current study. For each of these, we simulate the operational and production changes in economic costs arising from an increase in electricity prices and imposed carbon taxes. Recall that we consider three scenarios: (A), no increase in costs; (B), a nominal increase in the cost of electricity and a $10/ton carbon tax on utilities, but only the direct costs incurred by the IT equipment vendor get passed along to the end user; and (C), a removal of subsidies currently available to industrial and commercial entities, and a $50/ton carbon tax on utilities across both direct *and* indirect (i.e. supply chain) production which gets passed along to the end user.

Table 1. Product profiles considered in case study.

Product	*Est. Producer Price (inflation adjusted)*	*Est. Lifetime Elec. Use (kWh)*
Netbook[a]	$ 273	114
Laptop[b]	$ 478	442
Desktop[c]	$ 581	301
Handheld[d]	$ 342	1204
Server[e]	$ 1,580	8340

[a] 10.1" display, 1.20 kg weight; 1.66 GHz low-power processor, 1 GB 800 MHz DDR2 SDRAM, 160 GB 7200 rpm HDD

[b] 14.1" display, 2.40 kg weight; 2.1 GHz dual-core processor, 2 GB 800 MHz DDR2 SDRAM, 250 GB 5400 rpm HDD

[c] 18" tower, 365-W power supply, 12 kg weight; 2.4 GHz dual-core processor, 4 GB 800 MHz DDR2 SDRAM, 320 GB 7200 rpm HDD

[d] 150-gm (2.5" x 0.5" x 4.5") communications device, 416 MHz processor, 128 MB SDRAM, 256 MB Flash ROM

[e] 1U industry-standard server with 2-socket quad-core processors, 64 GB PC2-5300 DDR2 FB DIMMs, typical enterprise workload [17]

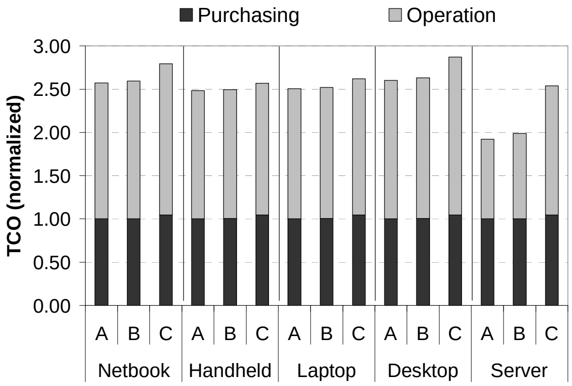

Figure 1. Forecasted TCO for different systems. Costs have been normalized to the purchase price in scenario A.

Note that in all three scenarios, we assume that the end user effectively sees increased production costs in terms of the IT acquisition (or more precisely, depreciation) costs. Thus, we present all results in terms of the total lifetime cost-of-ownership (TCO) seen by the end user. Figure 1 shows the results for the different scenarios considered. For convenience, all of the values have been normalized to the baseline (scenario A) purchase price. Overall, as expected, our models suggest that environmental taxation is likely to increase the TCO for different types of IT systems. The average TCO across the different devices is forecasted to increase by between 1.3% and 12%. The smallest increase was forecasted for handhelds (between 0.3% and 3%), while the highest increase is for servers (up to 32%).

In terms of where the increase in costs comes from within the portfolio, we find that the source differs based on the type of product. For example, in servers, the increase in operational costs accounts for up to 95% of the cost increase. On the other hand, for handhelds, increased manufacturing (acquisition) costs are responsible for up to 56% of the increase in TCO.

For purchasing costs, we find that the typical purchase price is forecasted to increase by between 0.3% and 5% across the range of devices and scenarios considered. Under Scenario B, the purchase price of the portfolio of products would increase from 0.3% to 0.6%, with the laptop, desktop, and handheld experiencing the largest increase in purchase price. Interestingly, in the case of Scenario C, the purchase price of all devices would increase approximately 5%. That is, as the environmental costs become more mainstream and extreme, it is likely that the burden will be more uniformly felt across different product types (rather than initially, where the burden will vary depending on the cost structure intrinsic to the product).

A key assumption in our model was that all cost increases during production get passed along to the consumer in the form of increased prices. At the lower end of the taxation scheme (Scenario B), the increase in purchase price is sufficiently small whereby the impact of absorbing the costs at the manufacturer (instead of passing them along to the consumer) may not be as significant, i.e. the consumers may not necessarily see an increase in costs. At the higher end, however, a 5% increase in the cost to produce is sufficient enough where manufacturers may have to actively manage the carbon emissions across the supply chain (since some system manufacturers have margins that are of approximately this portion). At these levels, the consumer will likely see some increase in the cost to acquire. Whether this increase is the full 5% or only some fraction thereof will depend on the elasticity of demand for these products, which is an area for future work.

One might intuitively expect that the dominant impact of environmental taxation may be on the manufacturers of equipment, particularly in terms of managing the relative increase in costs along their entire supply chain. However, we find that a much larger impact could potentially be the increase in cost of utility prices seen by the end user. That is, an increase in costs passed along by the utility to the end user may have a far more significant impact than any potential increase than any production cost increases which the IT equipment vendors may pass along to the consumer. Specifically, for the different types of devices, we find that operational costs for all devices other than servers increase by between 0.3% and 7% for Scenario B (low end of forecast), with the handheld and the laptop experiencing the smallest cost increase and the server having the largest increase in operational costs. Under Scenario C (high end of forecast), operational costs are predicted to increase between 2% and 14%, with the netbook, desktop, and server experiencing the largest increase in operational costs. For servers, because the operational electricity consumption is sizable (relative to other systems which spend a sizable portion of their lifetime hibernated or in sleep mode), the direct increase in cost of electricity has a much more drastic effect than the indirect increase in cost to manufacture. More specifically, the cost of operation for servers may increase by between 7% and 62%, causing the overall TCO to increase by between 4% and 32%. Note that we only include the cost of operating the server; if the cost of the infrastructure were included, then the increases might be even larger; in addition, we include consideration of varied power states depending on server utilization (had this not been taken into account, the potential increase in server operational costs would be even higher).

Another subtle result in Figure 1 is that in the baseline scenario (A), the operational phase accounts for between 48 and 62 percent of the lifetime costs of each device. By comparison, for scenario C, operation accounts for between 60 and 64 percent of the lifetime costs of each device. Thus, environmental taxation may slightly shift the TCO burden for most IT systems towards the operation of the device. While this is already accounted for today in some systems (e.g. servers in data centers), the cost of operation for many systems (such as handhelds) is often secondary. Considering *total* cost rather than just acquisition cost may become more important for all types of IT systems in the future.

Given the above product-level results, we estimate the change in TCO for a hypothetical enterprise IT department supporting approximately 50,000 employees. We assume that the CIO has an IT fleet consisting of 15,000 handhelds 5,000 netbooks, 30,000 laptops, 20,000 desktops, and 1,500 servers. Given this enterprise portfolio, our models suggest that the operational costs related to IT could increase by around 18% at the lower end to about 1.6X at the higher end. (This increase is important to note, because these costs often occur in terms of increased facility electricity costs, and therefore never get tracked back to the IT equipment.) Simultaneously, the purchase price to replace the fleet would be between 0.4 and 3 percent higher relative to today's baseline acquisition costs. (Note that these numbers have been converted back to nominal 2009 dollars, i.e. already correct for inflation; the actual costs seen by the CIO could be much higher.) Overall, the TCO of the next generation of IT equipment for such an enterprise could increase by between 1% and 13% (i.e. between $0.8 million and $6.5 million).

5. Conclusions

We present a method to evaluate the impact of the changing environmental cost structure on producers and purchasers of IT equipment. Our work suggests that compositional changes in the price of electricity, particularly related to changes in future supply-demand equilibriums and carbon taxes, could have a considerable impact on the TCO of IT equipment, both in terms of the cost to purchase new equipment but also (and more so) in terms of the cost to run the new equipment. For different types of IT systems, we find that the TCO could increase by between 0.3% and 32%; when applied to a representative enterprise IT department supporting 50,000 users, this would correspond to an increase in TCO of up to $6.5 million. Our future work will explore how elasticity of demand might impact the likelihood of a customer purchasing IT equipment at increased costs-of-ownership, and related, the impact of demand response (DR) mechanisms in the Smart Grid market such as time-of-use (TOU) pricing mechanisms on energy efficiency.

As environmental taxation is internalized into existing cost structures, the importance of 'green IT' will likely increase. Our model provides a framework to evaluate the potential impact of such initiatives.

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