Scenario Analysis

Exploring the Macroeconomic Impacts of Information and Communication Technologies on Greenhouse Gas Emissions

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Summary

During the past decade, several macroeconomic studies on the potentials of information and communication technology (ICT) to reduce greenhouse gas (GHG) emissions have been published. The mitigation potentials identified in them vary to a high degree, mainly because they are not consistently defined and diverse methodologies are applied. The characteristics of ICT—exceptional dynamics of innovation and diffusion, social embedment and cross-sector application, diverse and complex impact patterns—are a challenge for macroeconomic studies that quantify ICT impacts on GHG emissions.

This article first reviews principal macroeconomic studies on ICT and GHG emissions. In the second part, we reconsider our own study on this topic and present an in-depth scenario analysis of the future impacts of ICT applications on GHG emissions. We conclude that forthcoming macroeconomic studies could strengthen the state of the art in environmental ICT impact modeling (1) by accounting for the dynamics of new ICT applications and their first-, second-, and third-order effects on a global scale, (2) by reflecting the error margins resulting from data uncertainty in the final results, and (3) by using scenario techniques to explore future uncertainty and its impacts on the results.

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Introduction

Applications of information and communication technology (ICT) are expected to reduce transport volumes, as well as energy and material demand. Such effects of ICT applications are closely coupled to mass flows into the environment, such as emissions into air, water, and soil. In particular, the potential of ICT to reduce greenhouse gas (GHG) emissions is increasingly acknowledged as relevant in intergovernmental policy documents (e.g., Organization for Economic Cooperation and Development 2009). The extent, however, to which ICTs might help governments to achieve GHG emission reduction targets in the mid- to long term is discussed controversially among experts.

ICT components, products, and services are constantly being invented and reinvented (Rejeski 2003), thus providing the basis for an increasing diversity of new applications. If innovation is followed by rapid diffusion, macroeconomic impacts of ICT applications may materialize fast. ICT applications pervade, transform, and link all economic sectors. In improving the efficiency of production and consumption processes and in enabling new activities and societal relations, ICT is an important driver for new lifestyles, structural change (i.e., the share comprised by new industries in the economy increases in relation to old industries), and economic growth.

This particular set of characteristics of ICT is a challenge to deal with in macroeconomic studies on ICT effects on GHG emissions. There are two basic ways to quantify these effects: (1) incorporate ICTs in general macroeconomic models explicitly or (2) build specific macroeconomic ICT impact assessment models.

Studies of the first type commonly conceptualize ICT as a driver of technological efficiency, economic growth, and structural change (Romm et al. 1999; Kuhndt et al. 2003). This article focuses on studies of the second type. They are often built upon a distinction among first-, second-, and third-order effects of ICT on the environment (Fichter 2003; Köhler and Erdmann 2004; Hilty 2008):

1. First-order effects: The impacts of the life-cycle of ICT hardware, for example, the energy consumed by the ICT hardware of an intelligent transport system (ITS).
2. Second-order effects: The impacts of the services provided by ICT applications, for example, the energy saved in transport by using an ITS.
3. Third-order effects (including rebound effects): The emerging effects of ICT in the economic system, for example, increased demand for transport as a long-term implication of efficiency gains induced by ITS applications.

The dynamic impacts of ICT originate from the feedback of third-order effects to first- and second-order effects. If an increase in efficiency (second-order effect) is expected to reduce the environmental impact of an activity, but additional demand (third-order effect) compensates for the reduction, this is a typical rebound effect (Hilty 2008). ICT has the potential to enhance the efficiency of production and consumption processes with regard to cost, time, energy, material, and other factors in the entire economic system significantly. Because one of the core principles of industrial ecology is to view systems in their entirety and full complexity (Allenby 1999), it seems indispensable to account for third-order effects—in particular rebound effects—in any macroeconomic assessment of ICT impacts on GHG emissions.

In the next section, major ICT impact assessment studies are reviewed, taking these particular characteristics of ICT into account. We will then present a new interpretation of our own study, consisting of a scenario analysis for ICT applications based on the system dynamics model developed in that study. In the final section we will draw conclusions for future macroeconomic ICT impact assessment studies.

Review of Existing Studies

In a recent review of research on the environmental impacts of e-business and ICT, Yi and Thomas (2007) identified a diverse body of literature ranging from micro-level to macro-level impact assessments, from sector studies to cross-sector studies, from qualitative to quantitative assessments. The authors of these studies were mainly motivated by the environmental implications of the rise of the Internet and the "new economy." The references dating back to 1998 belong to a period that we classify as the "first green ICT wave."

The publication of the Yi and Thomas (2007) review almost coincided with the issuance of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change in February 2007 (IPCC 2007). Since then we have observed a "second green ICT wave," in which a growing body of literature focusing on the potentials of ICTs to reduce GHG emissions has been published. Almost all of these studies cover new applications of ICT.

The present review looks at the most important macroeconomic cross-sector studies that have been published in the past decade (table 1).[1] We exclude studies that did not break their macro-level assessments down to ICT applications (namely, Laitner and Ehrhardt-Martinez 2008; Madlener 2008). However, we make three exceptions for older studies that stimulated the scientific debate substantially (Romm et al. 1999; Laitner et al. 2001; Kuhndt et al. 2003).

Study Type

The macroeconomic studies reviewed differ in their basic approaches (see table 1). Some studies are based on a "bottom-up" approach. They analyze ICT applications at the micro-level (e.g., efficiency gains in specific processes) and aggregate the impacts to the meso- and macro-level. Other studies follow a "top-down" approach by analyzing macroeconomic indicators in order to isolate an ICT impact. Two studies take a "hybrid" approach. They are anchored in macroeconomic analyses, but attribute the ICT sector impacts to certain ICT applications (Laitner et al. 2001; Matsumoto et al. 2005). Seven studies we analyzed include prospective applications of ICT, whereas three studies did not disaggregate to the level of ICT applications.

Erdmann and colleagues (2004) tailored a system dynamics model. Laitner and colleagues (2001) implemented their calculations in the U.S. National Energy Modeling System. Matsumoto and colleagues (2005) used a computable general equilibrium model to recalculate adjusted input/output tables. Two studies applied statistical methods (Romm et al. 1999; Kuhndt et al. 2003). All other quantitative macroeconomic studies we reviewed calculate their results—to our knowledge—with basic arithmetic.

The studies differ in other key characteristics, namely, (1) goal, scope, and system boundaries, (2) data and methodologies, and (3) results.

Goal, Scope, and System Boundaries

The goal of all the studies reviewed is to analyze the macroeconomic impact of ICT on GHG emissions and/or on energy consumption. Most of the studies put particular emphasis on ICT applications that produce environmental gains. The geographic scope ranges from national to global. The two global studies (Buttazoni 2008; Webb 2008) also provide a geographic resolution of world economic regions. The time horizon of the studies with disaggregated ICT applications spans 10 to 25 years.

There is a core of ICT applications that are covered by almost all studies, whereas some applications are considered by one or a few studies only.

ICT in the production sector is broadly addressed by the topics process automation and smart motors. Several studies address ICT applications in the energy sector by considering smart grids, smart metering, and smart appliances, which comprise a basis for an optimized electricity supply and demand management. Webb (2008) also examines the impact of ICT on energy conversion efficiency explicitly.

Smart buildings are covered by most of the studies. Applications range from ICT-controlled heating, ventilation, and air conditioning (HVAC) systems (e.g., Labouze et al. 2008) to presence-based power management of electronic devices (Mallon et al. 2007). Only Buttazoni (2008) quantifies the impact of smart city planning on transport.

Intelligent transport systems comprise ICT-supported infrastructure and in-vehicle navigation systems, and are included in most of the

Table 1 Synopsis of the Studies Reviewed

Characteristic of the study	*CECS study*	*EPA/LBNL study*	*Digital Europe study*	*IPTS study*	*NEC study*	*Telstra study*	*Ecofys study*	*WWF Canada study*	*Biointelligence study*	*GeSI study*
Reference	Romm et al. (1999)	Laitner et al. (2001)	Kuhndt et al. (2003)	Erdmann and colleagues (2004)	Matsumoto and colleagues (2005)	Mallon and colleagues (2007)	Buttazoni (2008)	Gibson and colleagues (2008)	Labouze and colleagues (2008)	Webb (2008)
Study type										
Basic approach	Top-down (and sector studies)	Hybrid	Top-down (and case studies)	Bottom-up	Hybrid	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Granularity	High-level indicators	High-level sector categories	High-level indicators	ICT application	ICT application	ICT application	ICT application	ICT application	ICT application	ICT application
Calculation method	Statistical time series analysis	Integrated modeling system (NEMS)	Statistical decomposition analysis	System Dynamics model	Computable General Equilibrium model	Basic arithmetic	Basic arithmetic	Basic arithmetic	Basic arithmetic	Basic arithmetic
Scope										
Geographic focus	USA	USA	Europe	Europe	Japan	Australia	Global	Canada	Europe	Global
Geographic resolution	USA	USA	Germany, Italy, UK	EU 15 and the 10 Accession Countries	Japan	Australia	Varying economy groupings	Canada	EU 27	China, Europe, India, North America
Base year	1998	2000	1995–1997 (D) 1995–1998 (UK)	2000	2000	2005	2005	2006	2005	2002
Time horizon	2007	2010	—	2020	2010	2015	2030	2020	2020	2020
Coverage of effects quantitatively	Structural change and technology	Technology, structural change, integrating/ rebound	Growth, structural change, technology, private households	First, second and third order	First and second order/ technology, structural change	Second order (first order excluded from aggregation)	Second order	Second order (first order excluded from aggregation)	First and second order	First and second order

Continued

Table 1 Continued

Characteristic of the study	*CECS study*	*EPA/LBNL study*	*Digital Europe study*	*IPTS study*	*NEC study*	*Telstra study*	*Ecofys study*	*WWF Canada study*	*Biointelligence study*	*GeSI study*
Data and methodology										
Key data sources and assumptions	EIA	EIA, Romm et al. (1999), own assessments	Official NAMEA data	Official EU data. Expert and own assessments.	Input/Output table, adjusted by own assessments	Official Australia data. Own assessments.	WEO, WBCSD. Own assessments.	"realistic assumptions"	Official EU data. Own assessments.	McKinsey. Own assessments.
Treatment of data uncertainty	Unsystematic, qualitatively; final estimation as a data range	Unsystematic, qualitatively	Unsystematic, qualitatively	Best case/worst case simulation	Unsystematic, qualitatively.	Unsystematic, qualitatively.	Systematic, qualitatively. Unsystematic quantitatively.	Unsystematic, qualitatively.	Unsystematic, quantitatively.	Unsystematic, qualitatively.
Treatment of future uncertainty	One estimation of energy intensity change	Forecast (reference case, adjusted reference case)	No projections quantified	Scenarios (Technocracy, Government First, and Stakeholder Democracy)	Scenarios (WLAN, Seamless mobile network, Cooperative device network, Context sensitive network)	One opportunity per application	Potentials (low, medium, high)	Goals (short term, stretch)	Scenarios (Baseline, BaU Eco)	Scenarios (BaU, SMART 2020)
Baseline	1998 energy intensity value	2010 GHG emissions in reference case forecast	1995 GHG emissions	2020 GHG emissions with ICT development "frozen" in 2000	2000 GHG emissions	2005 GHG emissions	Unclear total 2030 GHG emission baseline	Canada's Kyoto obligations (−6% of 1990 GHG emission levels 2008–2012)	EU 27 electricity consumption projection 2020 with 2005 GHG emission factor	2020 GHG emissions in BaU scenario
ICT impact measure against baseline	2007 energy intensity change	2010 GHG emissions in adjusted reference forecast	1997/1998 GHG emission balance of effects	2020 GHG emissions for scenarios	2010 GHG emissions for scenarios	2015 GHG mitigation potentials	2030 GHG mitigation potentials	GHG mitigation goals	2020 GHG emissions for scenarios	2020 GHG emissions for scenario

Continued

Table 1 Continued

Characteristic of the study	CECS study	EPA/LBNL study	Digital Europe study	IPTS study	NEC study	Telstra study	Ecofys study	WWF Canada study	Biointelligence study	GeSI study
Results										
Overall ICT impact	−1.5 to −2.0%	−107 Mt CO_2e/a	D: decrease; UK: increase	+2% to −19% [in 2020 GHG emission levels]	+0.6% to −2.1%	−27.3 Mt CO_2e	−1168 to −8711 Mt CO_2e	−19.1 to −36 Mt CO_2e [7%–13.3% of Canada's Kyoto obligations]	+0.1% to −5.5% without CE +1.5% to −4.6% including CE [in 1990 GHG emission levels]	Up to −15%
Impact by application	No disaggregation	No disaggregation	No disaggregation	Some positive, some negative, some ambiguous	All positive	All positive	All positive	All positive	All positive	All positive

Note: BaU = business as usual; CE = consumer electronics; EIA = U.S. Energy Information Administration; GHG = greenhouse gas; ICT = information and communications technology; Mt CO_2e = metric megatons CO_2 equivalents; NAMEA = National Accounting Matrix with Environmental Accounts; NEMS = National Energy Modeling System of the EIA; WEO = World Energy Outlook; WBCSD = World Business Council for Sustainable Development.

studies. Few studies consider personal travel assistants for public transport explicitly (Mallon et al. 2007). Buttazoni (2008) and Webb (2008) also examine ICT-enhanced fuel efficiency of vehicles.

E-commerce is dealt with in all studies. Business-to-business (B2B) e-commerce includes ICT in supply chain management and logistics and business-to-consumer (B2C) e-commerce covers, for example, teleshopping. Virtual mobility (telework, mobile work, virtual meetings, and also teleshopping) and dematerialization effects of ICT (by virtualization or ICT-based services) are treated by all studies.

Some studies distinguish between the growth, structural change, and technology effects of ICT, and other studies build upon the classification into first-, second-, and third-order effects. A few partially account for both conceptual frameworks. A complete coverage of the growth, structural change, and technology effect is provided by Kuhndt and colleagues (2003), while Matsumoto and colleagues (2005) do not account for the growth effect. Laitner and colleagues (2001) account for rebound effects, but the report does not disclose a value for economic growth. First-, second-, and third-order effects are covered quantitatively by Erdmann and colleagues (2004) only; all other studies focus on second-order impacts, some also considering first order effects.[2]

Data and Methodology

Data sources, assumptions, and methodologies of the studies vary broadly. The bottom-up studies typically combine data for ICT uptake with estimated data for ICT impact. Uncertainty is dealt with in many ways. We distinguish between data uncertainty (incomplete data about facts that could be known in principle) and future uncertainty (developments that are not determined and can be influenced in principle).

Both Labouze and colleagues (2008) and Buttazoni (2008) do quantitative data uncertainty analysis at selected points only, but not for all ICT applications and impacts under study systematically. Erdmann and colleagues (2004) conceptualize data uncertainty as differences among expert estimates that could not be resolved by discussion, propagating the error margins quantitatively to the final results.

The consideration of future uncertainty ranges from parameter estimations at the desk to complex participatory scenario building exercises. In general, scenarios are used to define a measure for the future macroeconomic impact of ICT against a baseline. The diverse definitions used for ICT impact measures, baselines, differences in geographic focus, and time horizons as well as the different methodologies used all impede a direct comparison of numerical results.

Results

Six of the studies reviewed postulate unambiguous overall reductions of GHG emissions due to ICT. Four studies show an ambiguous picture. In the study of Erdmann and colleagues (2004), the ICT impact can range from a slight increase to a strong reduction, depending on data and future uncertainties. In both the Matsumoto and colleagues (2005) and Labouze and colleagues (2008) studies, the negative first-order effects outweigh the positive second-order effects under certain conditions. Kuhndt and colleagues (2003) show that the impact of ICT on GHG emissions can be positive or negative for a country, depending on the relative sizes of the three effects considered (technology, structural change, and growth effect) and the contribution of private households.

All studies that disaggregate ICT effects to ICT applications postulate net GHG-reducing impacts for each single application, with the exception of the study by Erdmann and colleagues (2004), which will be discussed in detail in the section “Scenario Analysis.”

Discussion

The pervasive character of ICT requires inclusion of all economic sectors in macroeconomic assessments of ICT impacts. The inevitable complexity of such an assessment is aggravated by the exceptional dynamics of ICT innovation and diffusion. To cope with this problem, mid- to long-term studies often introduce broad ICT application domains such as ITS (medium level of abstraction) or treat ICT as a monolithic sector (high level of abstraction).

The studies reviewed all cover ICT impacts on the industry, transport, and building sectors and agree on the relevance of most ICT applications concerning GHG emissions, but some ICT applications such as smart city planning are only treated by one study quantitatively. Other ICT applications such as precision farming are not treated by any of the studies, although they are likely to be relevant. The main reason is presumably the studies' major focus on energy efficiency.

The two conceptual frameworks used, growth/structural change/technology effect and first-/second-/third-order effects, have some overlap and some differences. While the first conceptual framework treats ICT as a driver of economic growth, the studies of the second type either treat growth as an external variable or indirectly as a third-order effect (additional growth induced by ICT). Second-order effects include both ICT-fostered dematerialization (by substitution effects) and ICT-enhanced process efficiency (by optimization effects). First-order effects are not explicitly addressed in the first conceptual framework but can be accounted for in principle.

We did not find any discussion of the implications of choosing a certain metric for the ICT impact on GHG emissions. Even if a common metric were agreed upon, the different scopes would still make it difficult to compare results.

We found that the five older references are rich and diverse in methodology, whereas the five more recent studies take the simpler approach of quantifying GHG reduction potentials at the level of second-order effects, ignoring first- and/or third-order effects.

In view of the various sources of uncertainty in this field of study, it seems indispensable to disaggregate the uncertainty as far as possible (by breaking it down to specific ICT application fields) and to make a clear difference between future uncertainty and data uncertainty. Only Erdmann and colleagues (2004) make a systematic attempt to treat data uncertainty quantitatively. As contributors to this study, however, we have to concede that data uncertainty is merged with future uncertainty in the presentation of the results. Therefore, we will reinterpret the results of this study in the next section and demonstrate the benefits of separating scenarios from data assumptions at the level of ICT applications.

Scenario Analysis

In this section we present a new assessment of the future impact of ICTs on GHG emissions based on the study by Erdmann and colleagues (2004), which was commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission. This study (in the following referred to as the IPTS study) included a system dynamics model of the causal relationships between relevant ICT applications and a set of given environmental indicators.

The subsequent scenario analysis did not involve any change to the model or the input data. Instead, now in a new way, the two types of uncertainty were separated in the calculation at the level of ICT applications:

- data uncertainty indicating research demand;
- future uncertainty indicating a need for political action.

In doing this analysis, we want to show that a systematic treatment of uncertainty can improve the practical utility of simulation results in that it makes a contribution to setting research agendas and policy agendas.

We will first summarize the integrated assessment methodology of the IPTS study and then present the new scenario analysis.

Integrated Assessment Methodology

The methodology of the IPTS study has been described by Erdmann and colleagues (2004) and contains a modeling focus by Hilty and colleagues (2004, 2006). Here we recapitulate the methodological elements necessary to understand the subsequent analysis.

Goal Definition and Scope

The aim of the study was to explore qualitatively and to assess quantitatively the way that ICT can influence a set of given environmental indicators within the time horizon of 2020.

The geographical coverage of the study was the European Union at the time the study was put out to tender (EU 15). For each result, the generalizability to an enlarged European Union has been discussed qualitatively (Hilty et al. 2004). Impacts caused outside the European Union (such as emissions from ICT production in Asia) were not covered by the study.

The basic approach was to model the effect of ICT application domains on the sectors energy, transport, production, and waste, and then to aggregate the effects to estimate the overall ICT impacts. Table 2 lists the application domains considered and examples of established and newer applications. An ICT impact was defined as a net change—caused by applying ICT—of one of the following given indicators: total freight transport volume (tonne-kilometers per year, tkm/a), total passenger transport volume (passenger kilometers per year, pkm/a), the share of private cars in the modal split of passenger transport (pkm-%), total energy consumption (terajoules per year, TJ/a), the share of renewables in electricity supply (TJ-%), total municipal solid waste not recycled (tonnes per year, t/a), and total GHG emissions (CO_2-equivalents in metric tons per year, t/a). For the purpose of this article, we will focus on the last indicator.

The strength of an integrated assessment approach is that it is comprehensive with regard to sectors and can address the dynamic changes implied by the long-term diffusion of a technology. In practice, an integrated assessment of ICT impacts is so comprehensive that it cannot consider as much technological detail as an LCA study of ICT products or services does. Our study therefore relied on abstractions of ICT devices ("client-type device," "server-type device," and "network-type device"; Hilty et al. 2004) and their application in generically defined domains to cope with technical progress. It was assumed that if more specific ICT devices and applications had been included, they would have become obsolete during the simulation period.

Scenario Building

There are many drivers other than ICT that may change the environmental indicators (such as energy prices or governmental regulation) and drivers that influence the diffusion of ICT applications. To reduce the number of possibilities spanned by these drivers (or external factors), three plausible scenarios were created and validated in an expert workshop (Goodman and Alakeson 2003). These scenarios differed in the factors the experts considered both most influential with regard to the system under study and most uncertain at the same time:

- Scenario A, called "Technocracy," assumed strong economic growth and employment driven by large companies in the service sector and is enabled by low regulation.
- Scenario B, called "Government first," assumed strong environmental regulation, resulting in only moderate growth, no progress in employment, but good conditions for small and medium-sized enterprises.
- Scenario C, called "Stakeholder democracy," was characterized by steady economic growth, leading to an increase in the number of households, desk workers, and total labor force.

The scenarios were formulated qualitatively and had to be quantified to be used as parameter settings for the ICT impact model (for details see tables S1-1 and S1-2 in the supplementary material on the Journal Web site).

Modelling ICT Impacts Under Given Scenarios

The basic approach of the model was to cover all three types of ICT effects on the environmental indicators in the following way:

- First-order effects: A generic model of the energy consumption of ICT in the use phase and of the ICT waste produced was built (key parameters: the growth rate of the energy efficiency of ICT equipment and the [negative] growth rate of the useful life of ICT equipment). The production of ICT hardware was neglected because most of the impacts of production would occur outside the given system boundaries.
- Second-order effects: Potentials of ICT applications (see table 2) for optimization and/or substitution of products and

Table 2 Generic Description of Information and Communication Technology (ICT) Application Domains and Relevant Examples of ICT Applications

ICT application domain	*Generic description*	*Examples of established ICT applications*	*Examples of newer ICT applications*
Production process management (PPM)	ICT applications increasing the energy and material efficiency of production processes	Production planning and control systems	Networked multisensor regulators for high-temperature processes
Power generation and distribution management (smart grids)	ICT-supported measures to improve the coordination of electricity supply and demand	ICT-based load detection	Electricity consumption feedback (smart metering) and demand-side management (smart appliances)
Intelligent transport systems (ITS)	ICT applications assisting drivers and managing transport infrastructure (all modes)	In-vehicle navigation systems	Real-time road traffic routing
Supply chain management (SCM)	ICT applications supporting the coordination of the processes and the optimization of the physical mass flows in the supply chain	Electronic data interchange along the supply chain	RFID-based supply chain management
Virtual goods (de-materialization)	ICT applications supporting a product-to-service shift and the digitization of physical products	ICT-enabled services (e.g., Web-based car sharing)	E-paper, e-books
Teleshopping	Demand-side e-commerce, allowing the purchase of physical goods away from retail	Online ordering and payment	Peer-to-peer merchandise exchange networks
Telecommuting	ICT-supported work away from the firm's premises, which replaces commuting travel	Personal computer and Internet access at home	Virtual workspace at home
Teleconferencing	A mode of telecommunication which replaces business travel	Audio conferencing	High-definition video conferencing
Mobile work	ICT devices making it possible to work while travelling	PDAs	WLAN hotspots in trains
Building management	All "soft measures" supported by ICT to reduce the energy consumption of buildings	Intelligent HVAC management	Energy consumption feedback (smart metering)
Waste management	ICT applications supporting the separation of waste fractions	Sensor-based sorting	RFID-based sorting

Note: HVAC = heating, ventilation, and air conditioning; PDA = personal digital assistant; RFID = radio frequency identification; WLAN = wireless local area network.
Source: Erdmann et al. (2004).

processes were modeled. The speeds at which these potentials would be realized were determined by parameters depending on the scenarios.

- Third-order effects (including rebound effects): Realized efficiency potentials change market prices or time-use and can therefore change demand, depending on elasticity parameters (see table S1-3 in the supplementary material on the Journal Web site).

All parts of the model could interact with one another; for example, the substitution of virtual for material goods could decrease freight transport demand and increase ICT use. The overall impact of ICT was calculated by creating a second variant of each scenario in which all variables concerning ICT were "frozen" during the simulation run. By comparing the two variants of each scenario, the overall net effect of further ICT development and diffusion was calculated.

Figure 1 shows groups of variables that were used in the model. The details of the model, which was implemented using the simulation system *PowerSim*, have been published in the original interim report to IPTS (Hilty et al. 2004).

Figure 2 shows the basic causal structure used by this model to account for the dynamic impacts of ICT on the environmental indicators. This causal-loop diagram is basically an interpretation of the definitions of first-, second-, and third-order ICT effects.

The scenario differences were expressed by different settings of the external variables; these were thus used to represent future uncertainty (for details see table S1-2 in the supplementary material on the Journal Web site). In order to account for data uncertainty, the scenarios were combined

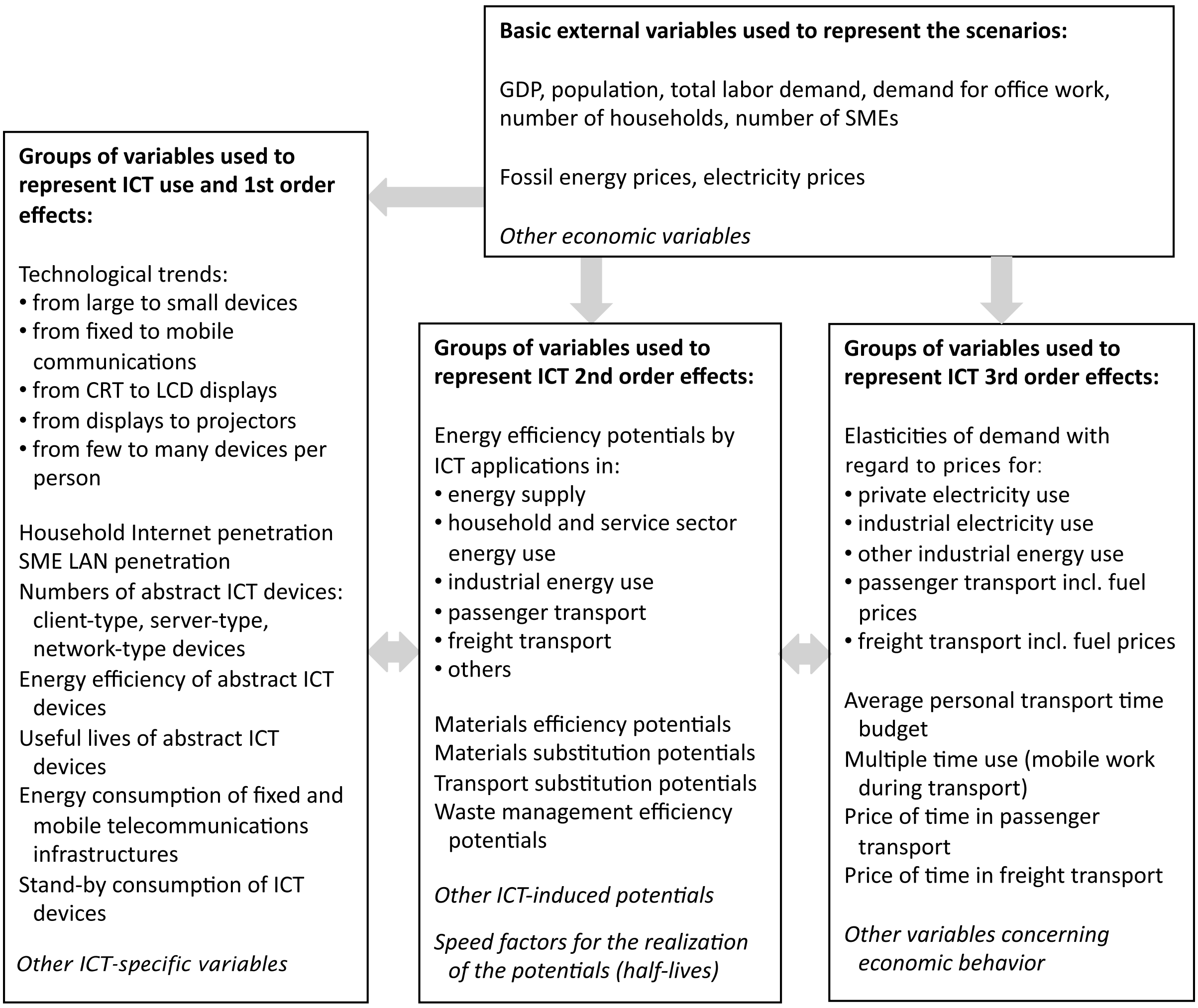


Figure 1 Groups of variables used to represent the scenarios and the three levels of information and communications technology (ICT) effects (see Hilty et al. (2004) for a description of all variables).
CRT = cathode ray tube; GDP = gross domestic product; LAN = local area network; LCD = liquid crystal display; SMEs = small and medium-sized enterprises.

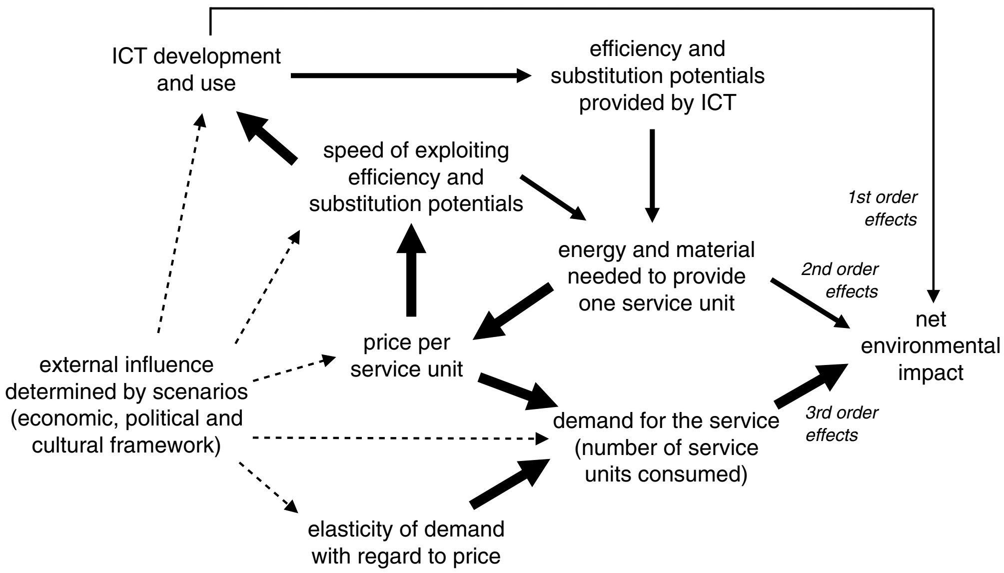


Figure 2 Abstract representation of the causal structure used in the system dynamics model of information and communication technology (ICT) environmental effects by Hilty and colleagues (2004).
Dotted arrows = influence from outside the system boundaries; thin solid arrows = first-order effects of ICT; medium solid arrows = second-order effects of ICT; thick arrows = third-order effects of ICT.

with three parameter settings representing best-, mean-, and worst-case data assumptions.[3] The best-/worst-case variants were calculated with the parameter vector that minimized/maximized total energy consumption, which means total energy consumption was chosen as a lead indicator. For the mean variant, each parameter was set to the mean of its best- and worst-case values.

Results and Discussion of the Scenario Analysis

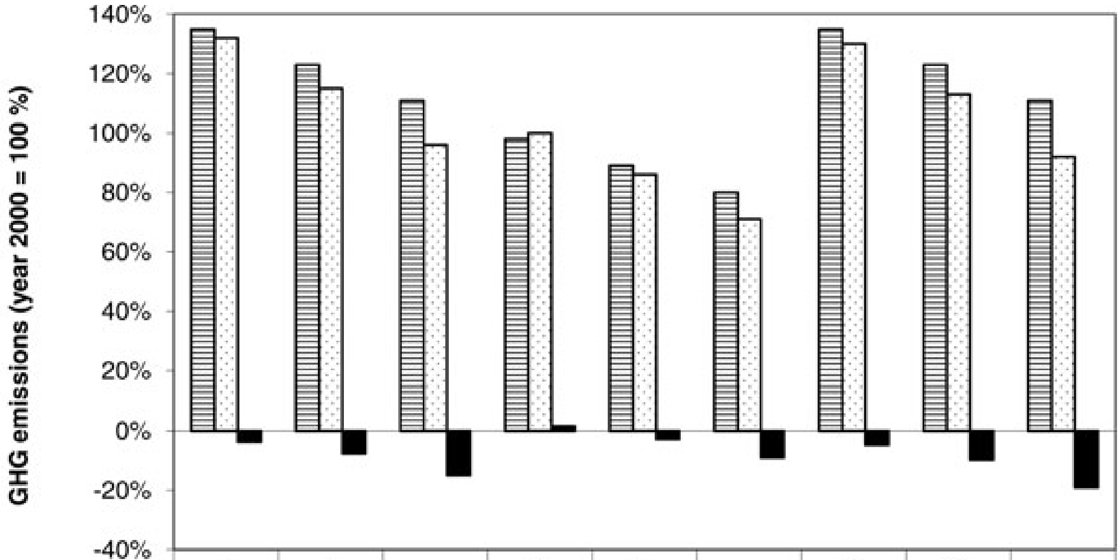
We will first show the overall ICT impact on GHG emissions that have been calculated and discuss the associated data uncertainty and future uncertainty. Then we will look into individual ICT application domains and discuss their contributions to the overall impact with regard to their varying extent and uncertainties.

Overall ICT Impacts

Simulating the three scenarios in three variants yields the nine value sets of total GHG emissions in 2020 shown in figure 3. All GHG emissions are expressed in percent of the year 2000 level. The left bar of each value set shows the GHG emissions in 2020 that occur if ICT is "frozen" at the 2000 level. The second bar shows the GHG emissions in 2020 with the projected ICT development (2000–2020). The third bar shows the difference between these two values, representing our metrics of ICT impact.[4]

As figure 3 shows, there is only one case (scenario B combined with worst-case data assumptions) in which this value is positive (indicating that the net impact of ICT is an increase in GHG emissions). As can be seen, the variation caused by ICT is smaller than both future uncertainty and data uncertainty.

Future uncertainty is represented by the differences among the scenarios A, B, and C. Data uncertainty is represented by the best-, mean- and worst-case variants of each scenario. An example may illustrate the origin of this type of uncertainty: A parameter called "virtualization potential for information products," expressing how much of the total physical mass of all information products (books, newspapers, DVDs, etc.) could potentially be replaced by online services (in EU 15 by 2020), was estimated on a modeling workshop to range from 30% to 90%. Dozens of such uncertainty ranges combine into the overall data uncertainty reflected by the difference between the best- and worst-case scenarios (all data published by Hilty et al. 2004).



	A worst	A mean	A best	B worst	B mean	B best	C worst	C mean	C best
ICT "freeze"	135%	123%	111%	98%	89%	80%	135%	123%	111%
ICT development	132%	115%	96%	100%	86%	71%	130%	113%	92%
ICT impact	-3.7%	-7.6%	-15.0%	1.6%	-2.8%	-9.0%	-4.7%	-9.8%	-19.0%

Figure 3 Simulated developments of greenhouse gas (GHG) emissions by 2020 in EU 15 (year 2000 = 100%) for the three future scenarios in three data uncertainty variants. ICT = information and communication technology.

If we look only at the mean variant, the positive impact of ICT is lowest in scenario B, with roughly a 3% decrease of GHG emissions, and highest in scenario C, with a 10% decrease. One possible interpretation is that this scenario is more conducive to "decarbonizing" ICT applications than scenario B. However, it should be noted that scenario B already has low GHG emissions for reasons other than ICT, as can be seen in figure 3. These reasons include weaker GDP growth and higher fossil energy prices in scenario B. It is therefore possible that the most favorable development path in terms of GHG reduction is not the one in which ICT contributes most to GHG reduction.

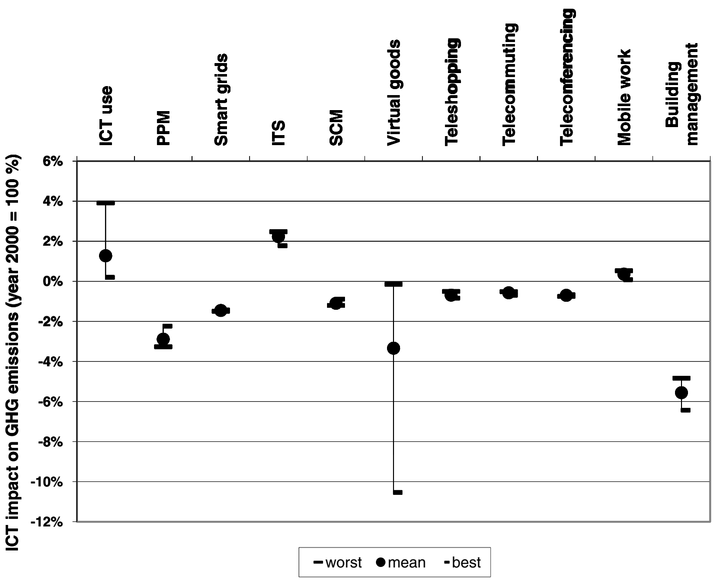
Impacts by ICT Application Domains

In order to show in detail how ICTs affect GHG emissions, we took a look at the disaggregated effects of ten ICT application domains. These results were produced by "freezing" all but one of the ten ICT application domains for each domain. They thus show the net effect of each application domain on the overall GHG emissions. "ICT use," which aggregates the total first-order effects of ICT in the use phase, has been added to figures 4 and 5 for comparison.

To reduce complexity, we selected scenario C for this analysis because it provided the highest GHG mitigation potential by ICT. Figure 4 shows the results. Except for "ICT use," these values are net impacts including first-, second-, and third-order effects. The sum of the impacts across the ten domains does not necessarily add up to the total impact shown in figure 3 because the application domains are interacting in the model.

It can be seen that two application domains *increase* the total emissions according to the IPTS model, namely ITS and mobile work. ITS have, among other effects, the effect of saving time in the transport of passengers or freight. ITS therefore make transport not only more energy efficient and cheaper, but also faster. This creates a rebound effect based on assumed elasticities of demand and the time-use approach included in the model. In a similar way, mobile work is assumed to create a rebound effect by enabling better

Figure 4 The impacts of information and communication technology (ICT) use and ICT applications on total greenhouse gas (GHG) emissions, 2020, in EU 15 for scenario C ('Stakeholder democracy') as a percentage of the GHG emissions 2000. The length of the vertical lines indicates the uncertainty of the results caused by input data uncertainty. ITS = intelligent transport system; PPM = production process management; SCM = supply chain management.



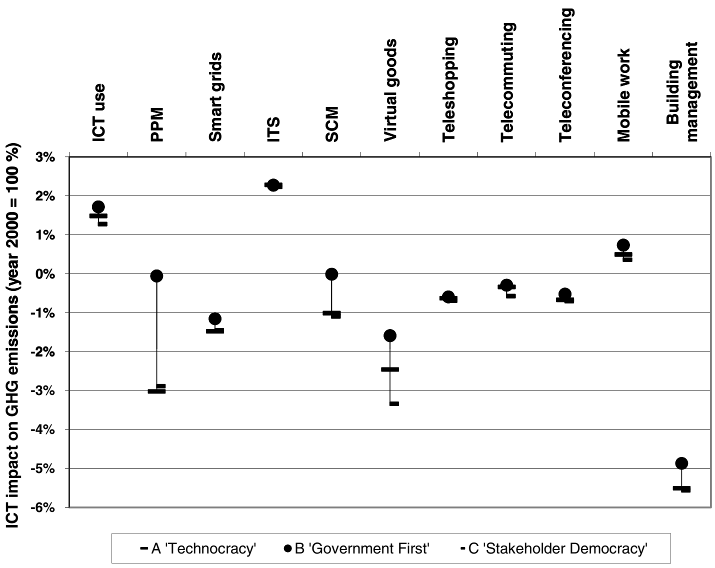
utilization of travel time: When some types of work and travel can be combined, the cost of travel time decreases, which leads to an increase in the demand for travel.

With respect to data uncertainty, our analysis reveals three types of ICT application domains: first, small impacts with small degrees of data uncertainty (smart grids, supply chain management [SCM], teleshopping, telecommuting, teleconferencing, and mobile work); second, significant impacts with low to medium data uncertainty (production process management [PPM], ITS, and building management); third, significant impacts with high data uncertainty (virtual goods and ICT use). The key driver for total data uncertainty (as shown in figure 3 for scenario C) is the data uncertainty of the impacts of virtual goods on GHG emissions (−0.1% to −10.5%). This uncertainty represents a lack of knowledge about the effects of virtualizing goods.

In order to take a closer look at the future uncertainty of the application domains, we selected the mean data values and calculated the impacts of the application domains for all three scenarios (figure 5).

For most of the domains, scenario B is outstanding as the scenario (1) with the highest adverse impacts (ICT use, mobile work) and (2) the

Figure 5 The impacts of information and communications technology (ICT) use and ICT applications on total greenhouse gas (GHG) emissions, 2020, in EU 15 for mean input values for three scenarios (A, B, and C) as a percentage of the GHG emissions 2000. The length of the vertical lines indicates the variation of the results caused by future uncertainty. ITS = intelligent transport system; PPM = production process management; SCM = supply chain management.



lowest beneficial impacts (PPM, SCM, virtual goods, building management). One application is clearly outstanding in its GHG-reducing effect: building management, which includes intelligent HVAC systems and soft measures such as creating user awareness for energy consumption in buildings. The impacts as well as their variation among scenarios are small for teleshopping, telecommuting, and teleconferencing. These applications seem to be "robust" in having almost no net impact due to rebound effects that compensate for their second-order impact. In general, the impacts of ICT application domains are similar in scenarios A and C, with a significant advantage of scenario C in the domain of virtual goods. The main driver for the outstanding character of scenario B are the higher energy prices assumed in this scenario (see the analysis by Arnfalk 2004).

Conclusions

This article has reviewed principal macroeconomic studies on the impact of ICT on GHG emissions and discussed the challenges encountered in modeling ICT impacts at the macroeconomic level. When assessing impacts of ICT, it is necessary to introduce a baseline: This can be historical data, a "business as usual" scenario, or—in the case of our own study—an "ICT freeze" scenario in which the development and diffusion of ICT were frozen at the beginning of the simulation period. As our review has shown, most of the studies are not comparable due to different baselines.

We have presented an in-depth scenario analysis providing a reinterpretation of the results of our own study. It showed that the impacts of different ICT application domains as well as different types of impacts can compensate for each other as a result of the system's dynamics. ICT applications that are assumed to mitigate GHG emissions may turn out to have an adverse effect, as shown in the cases of ITS and mobile work. The impact of some applications is sensitive to the scenarios chosen and to the data assumptions made, whereas other ICT applications seem to reduce GHG emissions in a relatively robust manner, such as building management and virtual goods, although the extent of the reduction remains uncertain. In the latter case, both types of uncertainty are remarkably high, indicating a great need for further research as well as some political responsibility: Whether the dematerialization potential of ICT will unfold in the economic system seems to depend on framework conditions—otherwise, in the worst case, it will just fizzle out.

In contrast to the other studies, we find both positive and negative net impacts depending on the type of ICT application. We attribute this to the fact that our simulation model treats first-, second-, and third-order effects of ICT in an integrated manner.

Meanwhile, there is a growing body of literature on the extent of *direct* rebound effects (e.g., Sorrell et al. 2009) that could be used to improve the approach. Furthermore, *indirect* rebound effects, which will increase the demand for other goods and services if less money or time is spent on one service, could be easily incorporated into an ICT impact assessment model today as marginal consumption values of expenditure and their related impacts on GHG emissions (Thiesen et al. 2008; Tukker et al. 2006). However, *macroeconomic* rebound effects of energy efficiency measures leading to a series of economy-wide price and quantity adjustments—with energy-intensive goods and sectors gaining at the expense of less energy-intensive ones (Greening et al. 2000)—can hardly be integrated into an ICT impact assessment study, as they affect all industries. Instead, it would be necessary to incorporate ICT in a general macroeconomic model, as done by Laitner and colleagues (2001).

Most of the existing studies on ICT impacts on GHG emissions (including the IPTS study) have a limited geographical scope, both regarding the applications and the impacts of ICT. This we consider a serious limitation, since transboundary effects at any level (first-, second-, or third-order) are then neglected. For example, energy consumption of mining metals abroad to produce ICT hardware may compensate for some of the domestic progress in energy efficiency. Conversely, materials saved due to ICT-enabled efficiency could reduce the demand for resources outside the system boundaries. Finally, resource efficiency induced by ICT can influence world market prices and produce global rebound effects. We therefore think that the next generation of ICT impact models should combine the scope and ambition of the two global studies (Buttazoni 2008; Webb 2008) with a methodology that is able to address effects on all three levels.

A process that adjusts the scenarios used in such assessments periodically to real-world developments and recalculates the implications could provide opportunities for mutual learning between researchers and decision makers.

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Notes

1. The original Global e-Sustainability Initiative study (Webb 2008) was complemented by the U.S., German, and Portuguese addenda and a subsequent industry study focusing on mobile telecommunications (McVeigh et al. 2009). The Gibson and colleagues (2008) study represents a series of ICT industry-sponsored studies of similar methodology involving the World Wildlife Fund (e.g., Pamlin and Szomolányi 2007). The Matsumoto and colleagues (2005) article represents a body of hybrid modeling studies that have been prepared in Japan. We could not analyze some presumably relevant Japanese studies at a meaningful level mainly due to language barriers (e.g., the background of the *Report from Study Group on ICT Policy for Addressing Global Warming* [Ministry of Internal Affairs and Communications 2008]). Because ICTs pervade, transform, and link all economic sectors, any cross-sector definition to capture the impacts of ICT is somewhat arbitrary. For example, it can be argued that e-commerce and virtual mobility are cross-sector ICT application domains. However, the major studies focusing on these domains, we found, do not provide additional insight on the topic of this article.
2. From a life cycle perspective, the studies address mainly the use phase of ICT equipment. Few studies also account for upstream and/or downstream processes (Kuhndt et al. 2003; Labouze et al. 2008; Webb 2008). Erdmann and colleagues (2004) include electronic waste.
3. We are aware that upper and lower bounds based on expert judgment do not imply that the true value is within these ranges. However, if all uncertainty ranges input to the model are selected amply and the simulation still produces some unambiguous results, these results can be considered more credible than individual judgments.
4. These values may differ slightly from those published previously (Erdmann et al. 2004; Hilty et al. 2004) because of a different GHG emission reference year. The former publications took the respective GHG emissions of each ICT "freeze" simulation run by the year 2020 as the reference, whereas in this article the ICT impact for all simulation runs is measured against the GHG emissions in the year 2000 to allow for cross-comparisons of scenarios.

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Supplementary Material

Additional supplementary material may be found in the online version of this article:

Supplement S1: This supplement fleshes out the three scenarios presented in the article, adding brief characterizations for each as well as the specific value assumptions used in the final model. In these scenarios, as efficiency potentials become realized, market prices and therefore demand can change; the extent to which this happens is dependent on elasticity parameters in table S1–3. The final table, S1–4, presents the disaggregated simulation results for all future scenarios and data uncertainty variants.

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