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The relevance of information and communication technologies for environmental sustainability – A prospective simulation study

Lorenz M. Hilty [a,*], Peter Arnfalk [b], Lorenz Erdmann [c], James Goodman [d], Martin Lehmann [a], Patrick A. Wäger [a]

[a] *Technology and Society Lab, Empa, St. Gallen, Switzerland*
[b] *IIIEE, University of Lund, Lund, Sweden*
[c] *Institute for Futures Studies and Technology Assessment, Berlin, Germany*
[d] *Forum for the Future, London, United Kingdom*

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Abstract

Information and Communication Technologies (ICT) have relevant positive and negative impacts on environmental sustainability on various levels: First-order effects such as increasing electronic waste streams; second-order effects such as improved energy-efficiency of production; third-order effects such as a product-to-service shift in consumption or rebound effects in transport. In the simulation study described in this article, all known relevant effects on all three levels were modeled using a System Dynamics approach in combination with scenario techniques and expert consultations. The prospective study for the European Union with a time-horizon until 2020 revealed great potential for ICT-supported energy management and for a structural change towards a less material-intensive economy, but strong rebound effects in the transport sector whenever ICT applications lead to time or cost savings for transport.

Keywords: Information technology; Communication technology; Environmental impact; Sustainable development; Information society; Socio-economic modelling and simulation; System dynamics; Structural change; Material intensity; Rebound effect; Prospective technology assessment

1. Introduction

Information and Communication Technologies (ICT) have a great potential to support sustainable development. However, most of the ICT-related trends, such as the trend towards pervasive computing or policies for 'the information society', are not exploiting this potential (Som et al., 2004; Hilty et al., 2006). On the contrary, there is some risk that ICT will become counterproductive with regard to environmental sustainability (Hilty et al., 2004a; Köhler and Erdmann, 2004; Wäger et al., 2005; Widmer et al., 2005; Kräuchi et al., 2005). Systematic approaches to develop ICT and its application in view of the goal of sustainable development are therefore essential.

Political decisions made with regard to ICT or sustainable development (hopefully taking into account the interactions between the two fields) must be based on a prospective analysis of the positive and negative environmental effects of ICT. Such an analysis would be almost useless if it ignored the dynamics both of the development of ICT and of its impacts on the socio-economic system and its interactions with the environment.

For a prospective study in this field, it is therefore more important to analyse the causal structure of the system than to rely on time series from the past. Retrospective data, although quantitatively exact, may lead to incorrect results if simply extrapolated into the future without considering the causal relationships accounting for the dynamics of the system. Constructing a causal model creates at least the opportunity of being 'roughly right' in a medium to long-term perspective – as opposed to being 'precisely wrong' when no causal structure is in place.

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* Corresponding author. Tel.: +41 71 274 7345; fax: +41 71 274 7862.
E-mail address: lorenz.hilty@empa.ch (L.M. Hilty).

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In a project commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission, the authors developed a System Dynamics model to assess the impact of ICT on environmental sustainability in the European Union within a time horizon until 2020. It was clear from the beginning that it would not be realistic to try to *forecast* the development (i.e. to describe one most plausible development path). Instead, we explored possible, internally consistent development paths (scenarios) and showed how the development can be influenced. The final goal of the project was to formulate policy recommendations based on new insights about the relative relevance of ICT application fields for environmental sustainability.

Environmental sustainability was defined by the contractor with reference to the following set of environmental indicators, which had been developed in response to the conclusions of the European Council in Gothenburg and reported to the Spring European Council in March 2002 (see also Ruddy, 2005):

- greenhouse gas emissions,
- energy intensity of the economy,
- volume of transport to gross domestic product,
- modal split of transport,
- urban air quality,
- municipal solid waste landfilled or incinerated.

Some simplifications of this set of indicators were admitted during the project. ‘Modal split of transport’ was only taken into account for passenger transport, but not for freight transport. The former was done using a time-use approach in combination with known elasticities of demand, treating virtual forms of mobility (telecommuting, teleconferencing, etc.) as additional modes of transport. ‘Urban air quality’ was excluded because this was the only indicator which would have required relating mass flows to geographic space, a task which was unrealistic under the given budget constraints.

The basic idea of the model was to build a conceptual bridge from the use of ICT in a set of economic sectors to the environmental indicators listed above, accounting for the following three types of ICT impacts or effects (EITO, 2002; Köhler and Erdmann, 2004):

- ‘First-order’ or ‘primary’ effects: effects of the physical existence of ICT (environmental impacts of the production, use, recycling and disposal of ICT hardware).
- ‘Second order’ or ‘secondary’ effects: indirect environmental effects of ICT due to its power to change processes (such as production or transport processes), resulting in a modification (decrease or increase) of their environmental impacts.
- ‘Third order’ or ‘tertiary’ effects: environmental effects of the medium- or long-term adaptation of behaviour (e.g. consumption patterns) or economic structures due to the stable availability of ICT and the services it provides.

ICT use in each sector considered can, in principle, have first-, second- and third-order impacts.

Both ICT use in the sectors considered and ICT impacts are influenced by a number of external factors, such as gross domestic product, population, number of households, labor force, total number of desk workers, etc. The results of the model are therefore only valid with respect to the assumptions made about the development of these external factors. Internally consistent sets of such assumptions, called scenarios, were used as a framework to construct and run the model.

This article gives a condensed description of both the methodology used in the project and the main results that were derived. However, due to space restrictions, our description has to remain quite abstract, with a few exceptions where examples can be provided. The reader who is interested in a more comprehensive view is referred to the five original interim reports (Erdmann and Würtenberger, 2003; Erdmann and Behrendt, 2003; Goodman and Alakeson, 2003; Hilty et al., 2004b; Arnfalk, 2004) and the synthesis report (Erdmann et al., 2004) which are all accessible online. Since these reports add up to a total of 560 pages, the article at hand may also serve as a guide to the original material.

2. Methodology

The principle challenge of the project was to produce quantitative estimates of how environmental indicators might be influenced by ICT development and application in 2020 and to formulate policy recommendations on that basis. The time horizon involved a great degree of uncertainty, not just with regard to the type of ICT in use and the scale of penetration of ICT into everyday life in Europe, but also with regard to a wide range of other factors not directly related to the production and use of the technology.

Much of the uncertainty was addressed through the use of qualitative estimation and validation from experts. Specifically, the development of scenarios is a qualitative means of accommodating uncertainty, and in this case formed the basis for the construction of the simulation model.

The methodology applied can be described by the following steps, which were in practice not executed in strict sequential order because of various interdependencies:

1. Screening for relevance: Identify economic sectors in which ICT applications have relevant environmental effects and list the types of applications.
2. Data collection: Collect existing data about environmental effects of ICT in the selected sectors and for the identified application types systematically.
3. Scenario building and validation: Create the scenarios which the model should be able to simulate and test the plausibility of the scenarios with experts.
4. Model building: Identify the main parts and variables of the system and their basic causal relationships, design the structure of the conceptual model, refine the conceptual model, implement and test the model.
5. Model validation: Compare the output the model generates for each scenario with expert judgments and test the

robustness of the main results, correct the model based on new insights.
6. Simulation: Select an experimental design and run the simulation experiments for all scenarios with the final version of the model.
7. Evaluation of results: Evaluate the model output with regard to the specific questions the simulation study was intended to answer.
8. Policy recommendations: Evaluate and interpret the results in the context of the existing political framework and formulate recommendations for future policies.

Each of the following sections describes one of these steps.

2.1. Screening for relevance

To reduce the complexity of the task, a matrix of economic sectors and the given environmental indicators was created in order to identify the combinations of sectors and indicators (cells of the matrix) that are most sensitive for ICT applications and therefore most relevant for further consideration. The sector/indicator combinations were chosen based on literature reviews and expert discussions. The (slightly simplified) result is shown in Table 1, which can be explained as follows:

- Transport sector: The most relevant effect of ICT on transport is that it can modify the transport intensity of the economy (freight or passenger transport per unit of gross domestic product) and the modal split. Effects on energy intensity or greenhouse gas emissions are mainly indirect, i.e. derived from transport intensity and modal split.
- Industry, domestic (private households) and service sector: In these three sectors, ICT most directly influences how energy and materials are dealt with. The former implies an effect on energy intensity, the latter (at the end of all material products' life cycles) an effect on municipal solid waste.
- Agriculture: There is a relevant effect of ICT applications in agriculture on energy intensity. However, since most of the energy used for agricultural products is consumed in the industrial sector (production of fertilizers etc.) and in the transport sector, the influence of ICT on agriculture is not treated as a distinct category.
- Energy industry: The supply of energy, in particular electric energy, is influenced by ICT supporting more decentralized energy supply structures, which may influence the share of renewable energy sources used and have an effect on greenhouse gas emissions (mainly CO_2) of energy supply and use.

Table 1
Combinations of economic sectors and environmental indicators considered most sensitive to ICT applications

	Greenhouse gas emissions	Energy intensity	Transport intensity	Modal split of transport	Municipal solid waste
Transport sector	(x)	(x)	x	x	
Industry sector	(x)	x			x
Domestic sector		x			x
Agriculture		(x)			
Energy industry	x				
Service sector		x			x

An 'x' indicates a most relevant and direct effect, an '(x)' a less relevant or indirectly covered effect of ICT. An effect may be positive or negative with regard to the indicator. (Adapted from Erdmann and Behrendt, 2003.)

All chosen sector/indicator combinations (cells marked with 'x') were then searched for ICT applications with potential environmental effects, including first-, second- and third-order effects (Erdmann and Wuertemberger, 2003). Based on this screening, the following list of ICT application types was compiled (Erdmann and Behrendt, 2003):

- e-business,
- virtual mobility (telework, teleshopping, virtual meetings),
- virtual goods (services partially replacing material goods),
- ICT in waste management,
- intelligent transport systems,
- ICT in energy supply,
- ICT in facility management,
- ICT in production process management.

These types of ICT application were then treated as the most relevant candidates for further analysis in the succeeding steps of the project.

2.2. Data collection

An extensive literature search was done to identify:

- trends in ICT development,
- trends in ICT penetration and application (focusing on the types of applications mentioned above),
- available data in the field of environmental effects of ICT (quantified first-, second- or third-order effects).

The results were compiled to a comprehensive 'script' serving as a reference for all succeeding steps of the project (Erdmann and Behrendt, 2003). However, during the modelling process, additional data had to be collected because the model revealed data requirements that could not have been anticipated in advance. All data that were fed into the model (i.e. used to set model parameters or to initialize model variables) are referenced in the fourth interim report (Hilty et al., 2004b).

2.3. Scenario building and validation

Acknowledging the complexity and uncertainty of future developments, scenario methodology was applied to assess the future impact of ICT on environmental sustainability. Three plausible scenarios describing alternative future courses of ICT until 2020 were created, taking the complex interactions of economic, social and ecological aspects into account.

The scenario development process identified the most important factors likely to influence the development and use of ICT in the future. This process was mainly based on expert interviews. Out of these factors, the most uncertain ones (classified as highly unpredictable) were used to create the difference between the three scenarios called 'Technocracy', 'Government First' and 'Stakeholder Democracy'. Table 2 shows a condensed characterisation of the scenarios. The scenarios are described in detail in the third interim report (Goodman and Alakeson, 2003).

Assuming that each uncertain factor can be varied over several levels, it would easily be possible to create hundreds of scenarios even from this small set of factors. In order to avoid combinatorial explosion, scenario development seeks for specific combinations of factor levels that are viewed as internally consistent.

To ensure consistency and to validate assumptions, the scenarios were discussed and adjusted by a panel of experts.

It was challenging to represent the scenario characteristics later in the form of quantitative parameter settings of the model. For some of the scenario characteristics it was possible to find an operational representation. For example, a ''highly accepting'' attitude to ICT was represented by shorter service lives for ICT (higher churn rates because customers will adopt new ICT products faster). ''High awareness and interest'' regarding the environment in combination with ''Government intervention'' was represented by substantially higher prices for fossil energy (internalisation of the associated external costs). However, we must admit that the model had to reduce the qualitatively rich scenarios to a few parameters that might not fully reflect what the experts had in mind when they created the scenarios.

2.4. Model building

As a first step towards a simulation model, we decomposed the system under study in the components shown in Fig. 1. The arrows connecting the boxes denote material flows (solid lines) or information flows (dashed lines) between these subsystems.

This structure served as the first blueprint for the model. The box 'External factors including policies' at the bottom was later refined by defining a set of external variables (used to differentiate between scenarios), the box 'Environment' at the top by defining variables representing the environmental indicators. The other subsystems were refined to more complex (sub-) models.

This conceptual model structure basically allows for modelling the following effects of ICT on the environment:

- ICT is produced (subsystem 'ICT industry').
- ICT is used (subsystem 'ICT use').
- ICT supports energy supply management or energy demand management (subsystem 'Energy').
- ICT changes transport by offering virtual forms of mobility and by supporting traffic management (subsystem 'Transport')
- ICT changes the production of goods and services by supporting 'virtual goods', i.e. services meeting needs that otherwise would be satisfied by material goods. It also changes the business processes that are used to supply all types of goods and services by enabling e-business (subsystem 'Goods and Services').
- ICT supports waste management (e.g. by enabling more 'intelligent' recycling systems) and contributes to the waste stream by its hardware, i.e. it creates electronic waste (subsystem 'Waste').

This structure was derived from the second interim report (Erdmann and Behrendt, 2003) and covers – at a higher level of abstraction – the types of ICT applications that were listed in Section 2.1 of this article.

In the next step, the subsystems were modelled using causal loop diagrams and integrated into one comprehensive model, which was then refined to a System Dynamics model and implemented using the 'Powersim Studio 2003' simulation system. The modelling process is described in more detail in the fourth report (Hilty et al., 2004b).

To give one example, Fig. 2 shows the causal loop diagram for the sub-model 'Waste', which is the simplest one. This causal loop diagram is based on the following considerations.

- The municipal solid waste stream grows with the gross domestic product (GDP), because economic growth implies a higher level of consumption. However, this correlation is modulated by the material intensity of the economy: If more services are consumed instead of material products or if the products are manufactured using less material, there will be less waste per unit of GDP. A structural change or dematerialization, resulting from the sub-model 'Goods and Services', could lead to a 'decoupling' of the waste stream from economic growth.
- ICT itself adds to the stream of electronic waste (e-waste). The ICT waste stream is derived from the ''ICT Use''

Table 2
Main characteristics of the three scenarios (Erdmann et al., 2005)

Uncertain Factor	'Technocracy' Scenario (A)	'Government first' Scenario (B)	'Stakeholder democracy' Scenario (C)
Technology Regulation	Incentives for innovation	Government intervention	Stakeholder approach
Attitudes to ICT	Moderate, conservative	Open and accepting	Highly accepting
ICT in business	High level of cooperation	High level of competition	Between A and B
Attitudes to the environment	Moderate/controversial	High awareness and interest	High awareness and interest

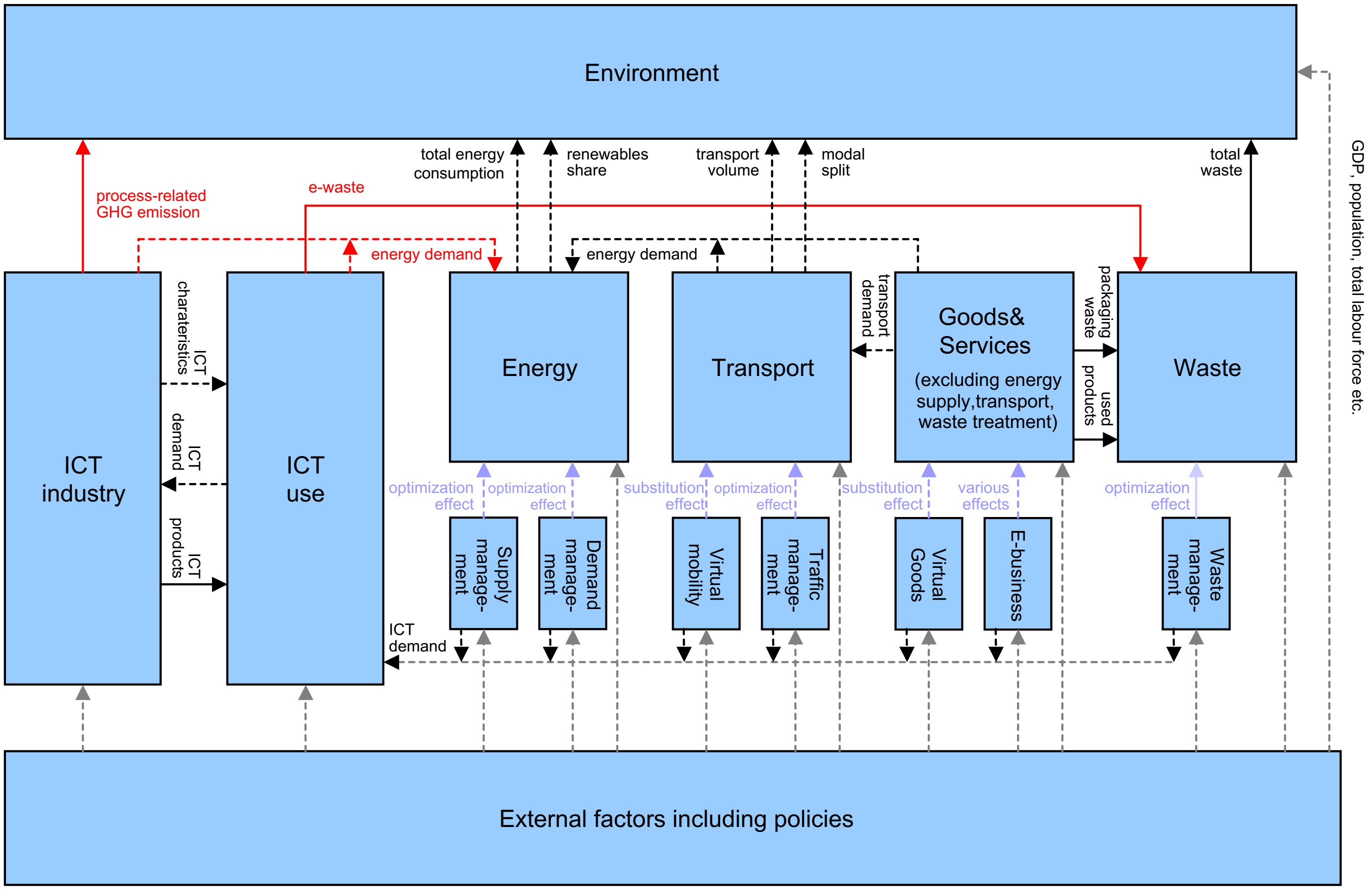

Fig. 1. Decomposing the system under study into subsystems (Hilty et al., 2004b).

sub-model. The 'Non-ICT e-waste' is almost impossible to derive from other sub-models.[1]

- ICT applications in waste management can contribute to more effective and efficient recycling of all municipal waste, e.g. by intelligent sorting technologies and improved waste logistics. If the share of recycled waste increases, it is taken into account that waste is transported over longer average distances if recycled, because specialized recycling facilities are not as close on the average as landfill sites or incinerators. The transport intensity of the waste sector is linked to the 'Transport" sub-model as a component of the overall freight transport demand.
- Waste that will not be recycled is landfilled or incinerated. Assuming a constant share of incineration in waste treatment, the resulting greenhouse gas emissions (GHG) can be calculated.

The dashed rectangle around the two variables 'ICT E-Waste' and 'ICT Applications for Waste management' emphasizes the 'causal entry points' of ICT into the waste system.

After refining the 'Waste' causal loop diagram, a System Dynamics model with 43 equations resulted, 37 of them being needed for auxiliary calculations. The overall model (including the other, more complex sub-models as well as the external variables and the environmental indicators) grew to more than 3000 equations, among which 85% were auxiliary. Running the model required 60 Megabytes of RAM and 21 s CPU time for a simulation run of 20 years length on an Intel Pentium M processor with 1.6 GHz clock rate.

2.5. Model validation

A model validation workshop with 10 international experts in the field of ICT and environment was held on September 18, 2003, at the Swiss Federal Laboratories for Materials Testing and Research (Empa) in St. Gallen, Switzerland. Descriptions of the scenarios, input data and simulation results were presented to the participants and discussed in smaller groups.

First, the participants discussed the input data (values for external variables and for parameters) which the project team presented in lists similar to the tables the reader will find in Chapter 4 and Appendix 1 of the fourth report (Hilty et al., 2004b). This step was introduced to deal with the

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[1] We later assumed that it will grow proportionally to ICT waste, because the borderline between ICT and other electric and electronic devices is expected to become irrelevant in the future. According to the vision of 'pervasive computing', all electric equipment will be ICT in about 10 years, and even other, formerly non-electric devices will be made "smart" by embedding ICT components. Therefore, the assumption that ICT waste will dominate the future e-waste stream is conservative. It may even include parts of other waste streams, too, which then will have to be classified as e-waste (Hilty, 2005).

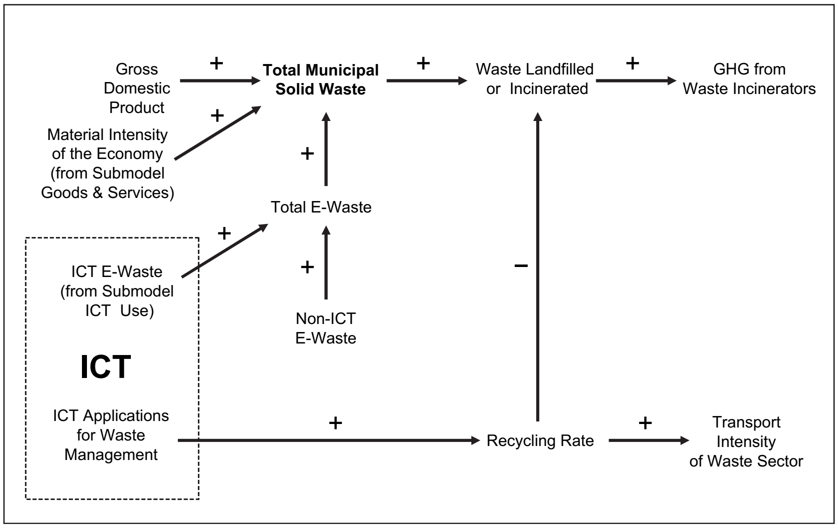

Fig. 2. Causal loop diagram for the sub-model 'Waste' (Hilty et al., 2004b).

uncertainty of a large part of the input data. If the experts agreed on a parameter, it was assumed to be confirmed by this procedure. Larger error margins were assumed if the estimates of the experts showed relevant deviations. Example: The parameter 'Household Internet Penetration Potential' was set to 'between 70% and 99%' based on the workshop discussions, because some of the experts believed that Internet penetration would reach its saturation level at 70% of the private households, while others believed that 99% of all households would finally be reached by the Internet. (We will explain in the following section of this article how we dealt with input data uncertainty.) Similar error margins had to be admitted for a large subset of the model parameters.

Second, the participants were asked to estimate the results for the environmental indicators for the year 2020 relative to the levels of 2000 for each scenario. The estimates were made by groups working on different scenarios. Each group was supposed to try to find a consensus. The participants were familiar with the scenarios, but neither with the model nor with the simulation results.

Using scenario A as an example, Table 3 shows how the simulation output (calculated for average parameter values in case of uncertain parameters) compares to the expert estimates for the most important output variables.

Altogether the results were roughly consistent with the expert judgements. On closer examination, the model seemed to underestimate energy consumption slightly and to overestimate passenger transport in scenario A, compared with the experts' estimates. Furthermore, it seemed to overestimate transport and waste (particularly e-waste) in scenario C.

Table 3
Output comparison for Scenario A

Environmental indicator	Expert estimate for Scenario A	Simulation result for Scenario A
Total energy consumption	130–200%	129%
Total volume of passenger transport	150%	171%
Total volume of freight transport	160–300%	233%
Total volume of waste generated	100–250%	150%
Volume of e-waste generated	200–500%	485%

The task to solve both by the experts and by the simulation model was to estimate the level of each environmental indicator in 2020, expressed in % of its level of the year 2000, under the conditions specified in Scenario A.

In a third step of the validation workshop, the simulation results were shown to the participants and discussed in groups and in the plenary. The aim of this step was to collect arguments for and against the plausibility of the results and identify potential errors in the model.

The following aspects of the model were changed in reaction to the model validation workshop:

- Correct an error in the calculation of freight transport development.
- Include a shift of energy consumption from the industrial to the domestic and service sector, if the former decreases by a product-to-service shift (not for other causes of decrease). The idea is that saving energy in industry due a shift to services must be reflected in the energy demand of the service sector.
- Introduce a level variable for e-waste which reflects the fact that there is a stock of ICT at the beginning of simulation which will be waste after a certain delay, depending on the average useful life of the equipment.
- Correct an error in e-waste calculation.

We could not follow a recommendation to calculate the results for EU25 instead of EU15 because of a lack of data for the Acceding Countries. However, this suggestion caused us to include a section on the enlargement of the EU into the results discussion for each indicator in the fourth report (Hilty et al., 2004b).

2.6. Simulation

In order to account for the uncertainty of the parameters, we created sub-scenarios that exploit parameter uncertainty to maximize or minimize the environmental indicators. These are called 'worst case' or 'best case' sub-scenarios, respectively. Given an environmental indicator, all parameter values are selected within their min/max boundaries in such a way that the indicator is maximized or minimized. We selected energy as the leading indicator for this optimization. A third sub-scenario was created by just setting each parameter to the average of its min and max values, called the 'mean' sub-scenario. (This sub-scenario has already been used to calculate the results shown in Table 3.)

Since the goal of the project was to identify and quantify *the impact of ICT* on environmental indicators, we introduced the possibility of freezing ICT development and application in all sectors at the level of the year 2000 for the purpose of comparison.

The experimental design for the simulation therefore has three dimensions:

- Scenario (A, B or C, as described in Section 2.3).
- Sub-scenario (worst case, mean, or best case, using total energy demand as a leading indicator).
- 'ICT as expected' or 'ICT freeze' (dynamic development of ICT according to the respective scenario vs. ICT frozen at the level of 2000).

This design results in 18 values for each output variable.

2.7. Evaluation and interpretation of the simulation results

Table 4 shows an example of the simulation output, integrating all three dimensions (i.e. all 18 values per indicator for the year 2020) in each line of the table. We show only intensities here, i.e. absolute indicators such as greenhouse gas emissions (GHG) are divided by the gross domestic product (GDP). Furthermore, we replaced the given indicator 'municipal solid waste landfilled or incinerated' by the more general indicator 'material intensity' for this view. Material intensity is the total material throughput of the economy divided by GDP.

First, it can be seen that energy intensity, greenhouse gas intensity and material intensity decrease considerably in all scenarios and sub-scenarios. The effects express a structural change towards a relatively 'dematerialized' economy.[2] In each case (first three lines of Table 4), the values in parentheses ('ICT freeze') are higher than the regular values, indicating that ICT has a decreasing (environmentally favorable) effect on these three indicators: Energy, GHG and material intensity would be higher if ICT were 'frozen'.

Second, it can be seen that there is no general decrease of transport intensity, except for freight transport intensity in scenario B and – only under best-case assumptions – for passenger transport intensity in the same scenario. With a few exceptions, ICT has an *increasing* effect on transport intensity.

Such results were then explained by tracing them back to the causal mechanisms and – finally – to the basic assumptions they are based on. In the case of the transport, the explanation can be summarized as follows:

- Freight transport: ICT investments will be made where higher efficiency decreases the cost per tkm. Since freight transport is a highly competitive market, it must be assumed that lower production cost will lead to lower prices. Lower prices will, given the known elasticities of demand with regard to price in the freight transport market, induce an increase of demand.
- Passenger transport: ICT will lead to various sorts of time-saving innovations in passenger traffic (both for private car and for public transport). Since time cost is a relevant part of the effective price a consumer pays for a pkm, this immediately leads to an increase in demand, based on the empirical elasticities embedded in the model.

Results like the ones shown in Table 4 can be evaluated further by calculating an 'ICT impact index', filtering out what is invariant across the scenarios and sub-scenarios (see Hilty et al., 2004b, for more details). More results and explanations are provided in Section 3 of this article.

2.8. Policy recommendations

Based on the evaluation of the simulation results, the project team derived political recommendations. The recommendations were put through an intensive process of consultation and validation with experts in the field. They suggested measures that if taken could maximise the environmentally positive contribution of future ICT to the environmental indicators.

The methodology for setting the simulation results and other project outputs in a policy context is described in detail in the fifth interim report (Arnfalk, 2004). We cannot elaborate on this part of the project methodology here due to space restrictions.

3. Results

In this section, we summarize the results of our simulation experiments in a highly aggregated form. For more detailed results, please refer to the synthesis report (Erdmann et al., 2004) and to the fourth interim report (Hilty et al., 2004b).

Fig. 3 shows two versions of the simulated development of the environmental indicators to 2020, both in terms of a relative increase or decrease on their values in the year 2000. The dark bars show the results of the simulation for our projected development of ICT. The lighter bars show the estimated impacts *if ICT application remained as it was in 2000*. The comparison

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[2] However, this does not imply that the absolute level of environmental stress would decrease, because the scenarios are associated with considerable GDP growth which largely compensates or even overcompensates for the progress in ecological efficiency in our simulation of scenarios A and C. The only decrease in absolute environmental indicator levels occurs in scenario B – which is characterized by weak GDP growth – and for some indicators also in scenarios A and C under best-case assumptions. This cannot be derived from the information given in this article; see Hilty et al. (2004b), Chapter 6, for details.

Table 4
Simulated values for environmental indicators divided by GDP in the year 2020, expressed in % of the values of the year 2000

% (100% in 2000)	A worst	A mean	A best	B worst	B mean	B best	C worst	C mean	C best
Energy intensity	82.9 (85.0)	76.5 (80.4)	68.5 (77.1)	67.6 (65.8)	62.3 (62.6)	55.4 (60.2)	87.2 (90.2)	79.6 (85.3)	69.6 (81.8)
GHG intensity	79.7 (81.8)	69.7 (74.1)	58.5 (67.3)	65.8 (64.1)	56.9 (58.2)	47.2 (52.6)	83.1 (86.0)	72.0 (78.3)	59.2 (71.2)
Material intensity	80.3 (89.4)	74.9 (84.9)	63.2 (79.9)	65.6 (65.8)	60.1 (62.5)	51.2 (58.9)	80.3 (89.4)	73.1 (84.9)	59.0 (80.0)
Freight transport intensity	144.9 (139.5)	134.1 (132.6)	112.3 (125.1)	74.1 (56.1)	67.8 (53.2)	55.8 (50.1)	170.3 (165.7)	154.1 (157.6)	123.5 (148.7)
Passenger transport intensity	103.3 (100.4)	100.4 (98.0)	96.6 (95.6)	106.0 (102.0)	102.4 (98.8)	97.9 (95.8)	118.7 (115.8)	115.1 (113.2)	110.7 (110.4)

The values in parentheses show the results for the ‘ICT freeze’ simulation runs.

of the two gives an impression of the aggregated impact of ICT. The length of the bars indicates the uncertainty of the results that is caused both by future scenario variation and data uncertainty.

As Fig. 3 shows, the variation caused by ICT seems to be small compared to the overall uncertainty in most cases.

The reason for the low overall impact is that positive and negative environmental impacts of several ICT applications cancel each other to a great extent. This observation as such is one of the most important results of the project, since it implies that there is no such thing as a “general ICT policy for environmental sustainability”. Instead, a set of *specific* ICT-related policies is necessary to unfold the potential of ICT to support sustainable development – and to inhibit ICT’s negative environmental impacts at the same time.

We will give a short description of each indicator and the most relevant ICT applications in terms of a positive or negative impact on the indicator.

3.1. Total freight transport

Freight transport is measured as the product of freight weight and distance transported (measured in tons times kilometers = tkm). Freight transport is closely connected to changes in the throughput of economic activity as well as in changes in industrial structure, production/distribution organization and logistics. The particularly strong growth in road transport results from its speed and flexibility in meeting such demands, and also its ability to service out-of-town factories and shopping centers.

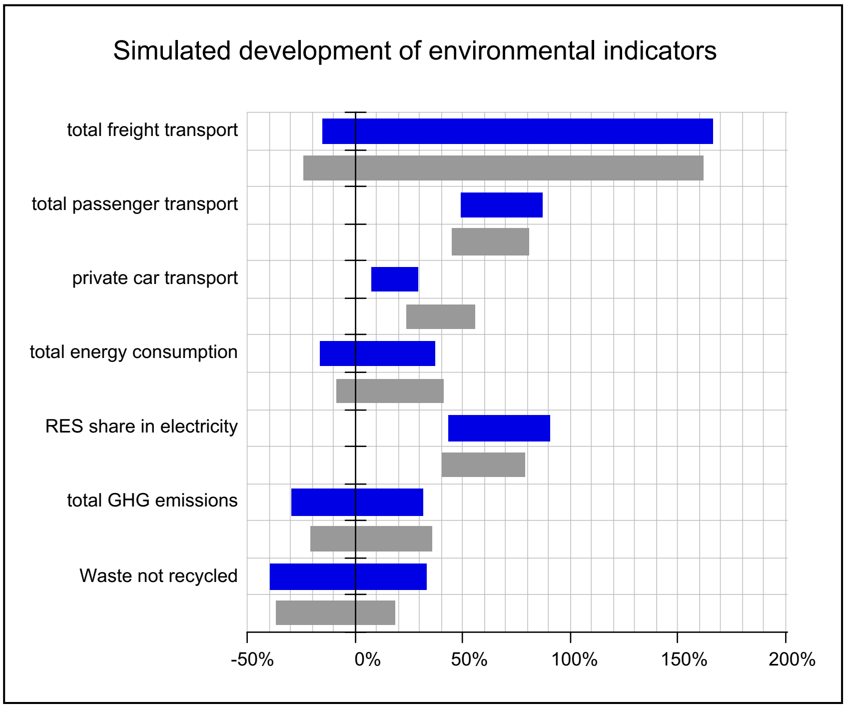

Fig. 3. Simulated development of environmental indicators by 2020 in % increase or decrease of their values in the base year 2000. The length of the bars indicates the uncertainty of the results that is caused both by future scenario variation and data uncertainty. There are two bars per indicator, the upper (dark) bar showing the results for the projected ICT development, the lower (light) bar showing the results for the so-called “ICT freeze” simulations (i.e. ICT applications remain at the level of 2000). Private car transport is included in total passenger transport, but also displayed separately to show the modal split in passenger transport. Abbreviations: RES = Renewable Energy Sources, GHG = GreenHouse Gas.

As shown in Fig. 3, freight transport performance could more than double under worst-case assumptions, but slightly decrease under best-case assumptions.

The high uncertainty in the development of freight transport does not imply that the future impact of ICT on this indicator is as uncertain, which can be shown by disaggregation. The effects of five areas of ICT application on freight transport were considered in the model:

- Supply chain management: higher efficiency due to ICT.
- Teleshopping: structural changes in freight transport demand (and an effect on passenger transport, see below).
- Virtual goods: ICT as an enabler for a shift from material goods to services (product servicizing).
- Intelligent Transport Systems (ITS): higher time and space efficiency of transport.
- Production process management: higher materials, energy, and time efficiency of production processes.

Supply chain management, production process management and virtual goods can avoid a part of freight transport growth. On the other side, ITS contribute significantly to an increase in freight transport performance because they make transport faster, more flexible and cheaper, inducing additional demand. (This typical rebound effect is represented in the model by demand elasticities for freight transport.) Less important are the freight transport effects of teleshopping.

The conclusion from the entirety of our simulation results for this indicator is that – even under best-case assumptions – ICT is not the key factor that could stabilize freight transport. There are other factors – e.g. energy prices – that have much greater influence on freight transport development. But in connection with other transport policy elements and guided by them, ICT can be a relevant factor.

3.2. Total passenger transport

Passenger transport is measured as the product of number of passengers and distance transported (measured in persons times kilometers = pkm). Passenger transport is closely connected to individual time use patterns, mobility requirements and preferences as well as transport infrastructure. The strong growth in road transport results from its speed and flexibility in meeting mobility demand, and also its ability to reach out of town shopping centres and off the beaten track leisure and holiday destinations.

As can be seen in Fig. 3, total passenger transport performance is expected to increase by roughly 50%–80% between 2000 and 2020. The increase would be less with no additional ICT. So the overall future impact of ICT on passenger transport, according to our model, is an increase.

Here again, the overall ICT impact is a result of counteracting effects that have to be separated. ICT has three main interactions with physical passenger transport:

- Virtual mobility (telework, teleshopping, virtual meetings), which mainly serves as a loophole when the time used for travel tends to exceed an acceptable limit,
- Several applications of ICT that make physical transport more efficient, including ITS,
- Better possibilities for *time utilization during transport* due to ICT (time utilization effect).

Virtual mobility is estimated to avoid additional passenger transport in the range of 6% to 8% *of the future (2020) level*, i.e. of the level we would expect with virtual mobility frozen at the level of the year 2000. On the other hand, ITS and the time utilization effect of mobile ICT applications contribute significantly to passenger transport growth by creating a time rebound effect.

3.3. Private car transport

Looking only at private car transport,[3] the effect of ICT surprisingly reverses. One of the most unexpected results emerging from our model was that ICT has – below the line – an *increasing* effect on passenger transport in general, but a *decreasing* effect on private car transport in particular. According to our simulation, ICT could avoid 10% to 19% of the expected future (2020) car traffic. Given the increasing effect on total passenger transport, this implies that ICT would *heavily stimulate* the growth of public transport and *slow down* the growth of private car transport (which could still be considerable).

This result is a consequence of two ICT effects represented in our model:

- ICT-induced time efficiency gains for the user of the future public transport (ITS for public transport).[4]
- An ICT-induced time utilization effect that increases the share of activities the passenger can perform during travel time, except when driving a car.

These two effects are realized when the physical limits to the expansion of traffic become relevant. Private car traffic needs more space per unit of transport than all other modes of land traffic. In conurbations, where space is rare, the car is in competition with bus and light rail, which are much more space efficient. Approaching capacity limits of individual transport generally slows down traffic, whereas in collective transport, more users lead to a higher density of the

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[3] As the most important component of the indicator 'modal split', we show private car passenger transport. The full details of the modal split (including different types of public transport) are documented in the fourth interim report (Hilty et al., 2004b).

[4] The ITS efficiency potential is assumed to be slightly higher for public transport than for private cars, because there are more unexploited efficiency potentials in public transport, in particular regarding customer information, seamless integration of various systems of public transport, more flexible and dynamic demand/supply co-ordination, optimum infrastructure utilization, and electronic payment at minimum transactions costs.

service in space and time, i.e. greater time efficiency for the user.

While taking into account these causalities, the model assumes that traffic modes are only changed when there is pressure to do so. This pressure comes from the time budget constraint, if individual mobility grows. Instead of changing to a faster mode of transport, it is also possible to better utilize the time spent in traffic. Different modes of transport offer different time utilization potentials, and ICT development also creates new potentials. Below the line, public transport grows faster than private car transport and virtual mobility grows moderately.

3.4. Total energy consumption

Total energy consumption is closely connected to changes in the level of economic activity as well as changes in transport patterns and energy consumption by buildings.

As shown in Fig. 3, total future energy consumption could increase by 37% under worst-case assumptions, but decrease by 17% under best-case assumptions. Without our projected development of ICT, both the best- and worst-case values would be higher, i.e. ICT has a decreasing effect on the future energy consumption.

The overall effect of ICT on energy consumption is the result of many effects working in either direction and partially canceling each other out when aggregated. The main *increasing* effects on energy consumption are:

- The overall effect of ICT on freight transport (see Section 3.1).
- ICT's own electricity demand in the use phase.

The main *decreasing* effects of ICT on energy consumption are due to the following areas of application:

- Virtual goods: ICT as an enabler of a shift from material goods to services.
- ICT-supported facility management, in particular intelligent heating systems.
- ICT-supported production process control.
- ICT-supported supply chain management.

If ICT is to enable a decrease in absolute energy consumption despite strong GDP growth and high employment, it will be necessary to find a way of promoting the "energetically positive" impacts of ICT, while inhibiting the negative ones. There is no simple overall strategy for minimizing energy demand with ICT.

3.5. Share of renewable energy sources in electricity generation

The noticeable growth in the share of renewable energy sources (RES) in electricity generation shown in Fig. 3 is mainly driven by policy incentives.

ICT enables decentralised electricity generation supporting renewable energies (RES) and combined heat and power generation (CHP). The future impact of ICT on RES ranges from a 2% to 7% increase of the RES share in electricity generation. Under best-case assumptions, 9.7% of total energy consumption would be covered by electricity from RES in 2020. Other uses of RES than power generation are not covered by the model.

3.6. Total greenhouse gas emissions

Total greenhouse gas emissions (GHG) consist of GHG from electricity production (power generation), from non-electric heating in the domestic and service sectors, from energy use in the industrial sector, from transport and from waste incineration. All emissions are calculated based on cumulated emission factors from the Life Cycle Inventory database ecoinvent (Ecoinvent, 2003).[5] Emissions of non-CO_2 GHGs (CH_4, N_2O, SF_6, HFCs, HCFCs) are converted to CO_2-equivalents according to their relative global warming potential.

As shown in Fig. 3 and not surprising, total future GHG emissions behave in a very similar fashion to total energy consumption, but with lower growth rates than total energy consumption (because of an increasing share of RES, among other developments).

The impact of ICT on overall GHG emissions is closely linked to energy consumption, as only energy-related GHG emissions are considered by the model.

Therefore, the most relevant impacts of ICT on GHG emissions are the ICT effects on total energy consumption as mentioned in Section 3.4.

3.7. Waste not recycled

The municipal solid waste (MSW) not recycled is the residual waste fraction burnt in incinerators or placed in landfill. Municipal solid waste is generated by households, commercial activities and other sources whose activities are similar to those of households. The amount of MSW is closely connected to the material throughput of the economy as well as to changes in household consumption patterns. The fraction that is not recycled depends on technical, economic, legal and behavioural conditions of recycling.

As shown in Fig. 3, the total physical mass of future MSW not recycled could increase by 33% under worst-case assumptions or decrease by 40% under best-case assumptions. Without the projected developments in ICT, the upper value would be lower. This means that ICT adds significantly to MSW not recycled if no measures are found to limit the growth of electronic waste. For ICT waste in particular high growth rates must be expected because of large numbers of small devices

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[5] Cumulated emission means that the full supply chain of energy is included, which yields emission values that are generally higher than the direct emissions. However, the life cycle of the energy supply infrastructure (e.g. construction of refineries and power plants) is excluded from the cumulated emissions.

and high churn rates (see also Hilty, 2005; Widmer et al., 2005).

4. Discussion

In this discussion, we focus on the methodological approach of the project. A discussion of the results in a policy context can be found in the fifth interim report (Arnfalk et al., 2005).

The project reported on in this article demonstrated that it is possible to model first-, second, and third-order impacts of ICT on environmental indicators with a 'classical' System Dynamics approach in combination with scenario techniques and expert consultations. It was feasible to model aspects of structural change in the economy, and this was possible even without a structural change *in the model* in terms of Beck (2005).

However, some limitations of System Dynamics became apparent during the project. The lack of true modularity made it almost impossible to control the growing complexity of the model. The absence of the concept of a (complex) simulation experiment made it inevitable to mess up the model with control elements and auxiliary equations. Due to these limitations of the approach chosen, the model lost almost all communicative value for discussions, which was contrary to the original intention.

Nevertheless, this project was the first approach to account for the complex causation structure of the environmental effects of ICT in a prospective study; it generated some robust results that pave the way for future research and decision support in this field.

The results should not be interpreted as forecasts of the development of the environmental indicators, because their absolute values in 2020 greatly depend on the three scenarios chosen and on many uncertain model parameters. However, the relative change of the indicators under the influence of ICT, in particular regarding the combined effects of specific ICT application areas, turned out to be quite robust when scenarios and uncertain parameter were varied to test the sensitivity. We therefore think that this project contributes to the general understanding of the environmental impacts of ICT and provides a useful basis for policy-making in the fields of ICT and environment.

5. Conclusion

We demonstrated an approach to model impacts of future ICT on the environment with 'classical' System Dynamics methodology in combination with scenario techniques and expert consultations.

From the simulation results, it can be concluded that ICT applications have relevant potential impacts on environmental sustainability on various levels: First-order effects such as increasing electronic waste streams; second-order effects such as energy savings by ICT-supported facility management; third-order effects such as a product-to-service shift leading to a less material-intensive economy. While the overall impact of ICT on most environmental indicators seems to be weak, the impact of specific areas or types of ICT application can be very relevant in either direction. On an aggregated level, positive and negative impacts tend to cancel each other out. For example, ICT-induced higher energy savings in several areas are nearly compensated by ICT-induced additional energy consumption in other areas. It is therefore essential to design policies that encourage environmentally advantageous areas of ICT application, while inhibiting applications that tend to increase the speed of resource consumption.

Taking all results into account, the project team identified various areas where relevant (positive or negative) environmental impacts of future ICT are expected:

- ICT applications supporting a product-to-service shift (virtual goods). Although there are widely diverging opinions concerning an ICT-supported product-to-service shift and its potential energy saving and dematerialization effects until 2020, it is the high potential for change that makes this issue important. In the model, almost every output turned out to be directly or indirectly linked to the product-to-service shift variables, first of all freight transport, but also waste and the energy used by the industrial sector.
- ICT applications for heating management (intelligent heating). ICT has a high potential impact on the rational use of heating energy. Heating accounts for roughly 30% of total energy consumption and conservation measures using physical materials tend only to be applied to the small annual share of buildings that is renovated or newly built. 'Soft measures' using ICT (such as intelligent heating systems) have the advantage of being applicable in all buildings, and could therefore have a significant effect.
- ICT applications for passenger transport efficiency. All ICT applications that make passenger transport more time efficient (such as intelligent transport systems) will create a rebound effect leading to more traffic and possibly more energy consumption. Induced passenger transport demand has severe environmental consequences in energy use and greenhouse gas emissions, although ICT contributes to lowering the energy and GHG *intensity* of passenger transport.
- ICT applications for mobile work. Mobile work enabled or supported by pervasive computing and other new forms of ICT application can have a significant effect on passenger transport, because it increases the share of time spent in traffic that people can use productively. This can create more transport demand, while stimulating public transport more than private car transport. The effects of ICT on personal time management and time utilization are probably the most underestimated indirect impacts of ICT on the environment, with great potential in either direction.
- ICT applications for freight transport efficiency. All ICT applications that make freight transport more cost efficient (i.e. cheaper) will immediately create more freight transport and more energy consumption. There is no evidence for assuming anything other than a strong price rebound effect here. By making transport more cost efficient, ICT creates freight transport demand, with severe

environmental effects, unless measures are taken to limit demand of transport.

Although the simulation method applied yields quantitative results, we focused in this article on the qualitative outcomes. For any decision-making based on the results of the project reported here, we recommend to focus on substantial numerical differences and on the arguments produced regarding causation structures.

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