KTH Centre for Sustainable Communications

Simulating the future impact of ICT on environmental sustainability

validating and re-calibrating a system dynamics model
- Background Data

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Working Paper - from the KTH Centre for Sustainable Communications
Stockholm, Sweden 2014

ISSN: 1654-479X
TRITA-SUS 2014:3

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ROYAL INSTITUTE
OF TECHNOLOGY

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TRITA-CSC-SUS Report 2014:3

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Abstract

This report serves as supplementary material to the book chapter, *Modeling the Effects of ICT on Environmental Sustainability: Revisiting a System Dynamics Model Developed for the European Commission*, published in ICT Innovations for Sustainability (edited by L. M. Hilty & B. Aebischer. Springer, 2015). The current report was referred to in the book chapter whenever the data to be presented exceeded the space provided for the book chapter.

Introduction

This report serves as supplementary material to the book chapter "Modeling the Effects of ICT on Environmental Sustainability: Revisiting a System Dynamics Model Developed for the European Commission" (Achachlouei and Hilty 2015)[1] published in the book "ICT Innovations for Sustainability" (Hilty and Aebischer 2015)[2]. This report was referred to in the book chapter whenever the data to be presented exceeded the space provided for this chapter.

Achachlouei and Hilty (2015) revisited the assumptions and the results of a previous study commissioned in 2002 by the European Commission's Institute for Prospective Technological Studies (IPTS) to explore the current and future environmental effects of ICT. The aim of that study (here called "the IPTS study") was to estimate positive and negative effects of the ICT on environmental indicators with a time horizon of 20 years. The method applied was to develop future scenarios, build a model based on the SD approach, validate the model and use it to run quantitative simulations of the scenarios.

This report, which provides supplementary material for the book chapter (Achachlouei and Hilty 2015), is organized into four sections:

1. Overview of original and new scenarios
2. New assumptions based on empirical data
3. New simulated trends compared to empirical data
4. New simulation results compared to original results

[1] Achachlouei, M. A., & Hilty, L. M. (2015). Modeling the Effects of ICT on Environmental Sustainability: Revisiting a System Dynamics Model Developed for the European Commission. In *ICT Innovations for Sustainability* (pp. 449-474). Springer International Publishing.

[2] Hilty, L. M., & Aebischer, B. (2015). ICT Innovations for Sustainability. *Advances in Intelligent Systems and Computing*. Springer International Publishing.

1. Overview of Old and New Scenarios

Original assumptions in 2003: Scenarios A, B, and C[3]

The task of the original study was to make a prediction about the future effect of ICT on environmental sustainability. When building the System Dynamics model, it soon became clear that this prediction would depend on conditions that were external to the model, called "external factors," in particular: the development of the general economic activity level (usually represented by the Gross Domestic Product, GDP), the labor market, energy prices, the climate for innovation, the general attitude of the population toward ICT and toward environmental issues, spatial dispersion, and the speed of some technological developments.

Given the fundamental difficulty to forecast these factors over 20 years, the project team applied a scenario approach to deal with the uncertainty. In expert and stakeholder workshops, three possible futures were developed in the form of scenarios, each of them representing a development that was internally consistent and plausible according to the participants' assessment. Brief descriptions of the original scenarios are repeated here [4]:

- Scenario A, called "Technocracy," was characterized by strong economic growth, leading to an increase in the workforce which is also reflected in an increase in desk workers due to the service-based nature of the economy. Strong growth also leads to a significant increase in the total number of households and buildings due to increased economic activity. Collusion between government and business in determining the framework for business activity is dominated by large companies, which is reflected in a fall in the number of SMEs.
- Scenario B, called "Government first," was characterized by weak economic growth which is reflected in the lack of growth in the number of households, buildings, and desk workers. The total labor force decreases due to stagnating economic growth and the flight of industry from Europe. The settlement pattern becomes more dispersed due to the development and high take-up of environmental and social applications of technology, for example ITSs, smart homes, and virtual conferencing. This also leads to an increase in the percentage of SMEs.
- Scenario C, called "Stakeholder democracy," was characterized by steady economic growth, leading to an increase in the number of households and desk workers and the total labor force. A reduction in the levels of inequality between the developed and developing worlds and the expansion of the EU to 35 Member States reduce immigration to Europe and, as a result, the expected rise in population does not materialize. The settlement pattern becomes more dispersed due to business investment in applications that can improve virtual conferencing and smart home technologies.

New assumptions in 2014 based on empirical data: Scenario D

The new Scenario D is directly based on empirical data (see Table S-1): For the years 2000-2012, statistical time series were used, and for 2013-2020, the CAGR values drawn from this data (also shown in Table S-1) were used for trend extrapolation.

[3] The summary in this subsection is taken from the book chapter (Achachlouei and Hilty 2015)

2. New assumptions based on empirical data

Table S-1 presents more details on the empirical data (more details on Table 1 in Achachlouei and Hilty 2015) for EU-15 over 2000-2012: both time-series values and CAGR[4] values (CAGR values were used when the data were missing for some years between 2000 and 2013. They were also used as estimates for 2013-2020). The values in Table S-1 were used as assumptions in the new scenario (D).

Table S-1: Empirical data for EU15 over 2000-2012 used as assumptions in Scenario D

No	External variable	Empirical data for EU15 2000-2012	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
			2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
M2	GDP Annual Growth Rate	1.11 % (14.2% increase over 2000-2012)	2.0	1.2	1.3	2.4	2.0	3.2	3.0	0.1	-4.6	2.0
			1.5	-0.5	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
M4	Labor Demand Annual Growth Rate	0.67 % (8.3% increase over 2000-2012)	1.47	0.69	1.01	0.86	1.56	1.84	1.75	0.96	-1.76	-0.41
			0.40	-0.33	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
M7	Population Annual Growth Rate	0.46 % (5.7% increase over 2000-2012)	0.46	0.55	0.61	0.64	0.61	0.58	0.63	0.58	0.44	0.40
			0.39	-0.39	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
M9	Number of Households Annual Growth Rate	1.51 % for 2005-12 (11.1% increase over 2005-2012)	1.51	1.51	1.51	1.51	1.51	2.42	1.03	0.99	3.36	0.94
			1.24	0.62	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51
M15	Number of SMEs Annual Growth Rate	0.78% for 2005-12 (5.6% increase over 2005-2012)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	-1.28	3.76
			-0.76	-2.20	0.82	3.10	0.78	0.78	0.78	0.78	0.78	0.78
M16	Office Work Demand Annual Growth Rate	1.28 % for 2008-2011	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
			1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
E400	Fossil Energy Price Annual Change Rate	2.8 % Automotive gas oil price as proxy	CAGR over 2000-2012 is about 2.8%									
U400	Shift to Energy-Efficient ICT Half-life	~ 7.5 a	~ 7.5 a									
T400	ICT-Induced Spatial Settlement Dispersion	20% increase in average commuting distance over the period 2000-2010 in Finland as proxy	25% over the period 2000-2020 Since the empirical proxy indicator shows a growth of 20% over the period 2000-2010, we chose to use the assumption made in Scenario B and C, which was a growth of 25% estimated over the period 2000-2020.									
E12	D&T Electricity Use Efficiency Potential	~ 30 a (7.9% increase in efficiency over 9 years 2000-2009 in EU-27)	*E12*=50%, f(t)=*E12**(1-(0.5^(t/*E13*))) Given 7.9% increase in efficiency over 9 years 2000-2009, f(9)=7.9%, *E13* is about 30 years									
E13	D&T Electricity Use Efficiency Half-life											
E17	D&T Electricity Price Annual Growth Rate	3.9 % (35% increase over 2005-2013)	3.9	3.9	3.9	3.9	5.43	9.83	0.43	4.07	-0.41	5.16
			4.21	2.54	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
E19	Electricity Supply Efficiency Potential	~ 20 a (7.1% increase in efficiency over 10 years 2000-2010)	*E19*=25%, f(t)=*E19**(1-(0.5^(t/*E20*))) Given 7.1% increase in efficiency over 10 years 2000-2010, f(10)=7.1%, *E20* is closer to 20 years (as assumed in Scenario A and C)									
E20	Electricity Supply Efficiency Half-life											

[4] compound annual growth rate

U201	Average Useful Life of ICT Annual Change Rate	-7.3% over 8 years 2000-2008	-
W31	MSW Recycling Potential	~ 10 a (28% recycling rate in 2011)	*W31*=53%, f(t)=*W31**(1-(0.5^(t/*W32*)), Given 28% for recycling rate in 2011, f(11)=28%, *W32* is about 10 years
W32	MSW Recycling Half-life		

3. New simulated trends compared to empirical data

This section provides more comparisons between the simulated trends in the new scenario (D) and the real-world trends observed over 2000-2011. This is related to the following research question addressed in Section 6 in the book chapter (Achachlouei and Hilty 2015):

> RQ2: Are the main trends (in energy, transport, etc., as shown in Figures 6-2, 6-3, 6-4, 6-5, 6-6, 6-7, 6-8, and 6-9 in Hilty et al. 2004) that the IPTS model predicts for a realistic scenario consistent with the currently available data?

Since none of the three scenarios dominantly represents the reality over the past years, we defined a new scenario (Scenario D) based on the empirical data available today. Figures S-1, S-2, S-3, S-4, S-5 and S-6 show selected trends in energy, transport, and waste, electricity consumption, greenhouse gas emissions, and modal split in passenger transport, comparing the simulated development in Scenario D with the real world trends.

As shown in Figures S-1, S-2, S-3, S-4, S-5 and S-6, the predictions were roughly plausible, but cannot be taken as precise predictions, which is not surprising because the purpose of the model was not to predict the development of transport and energy demand and other environmental indicators in absolute terms, but the relative impact of ICT on these indicators.

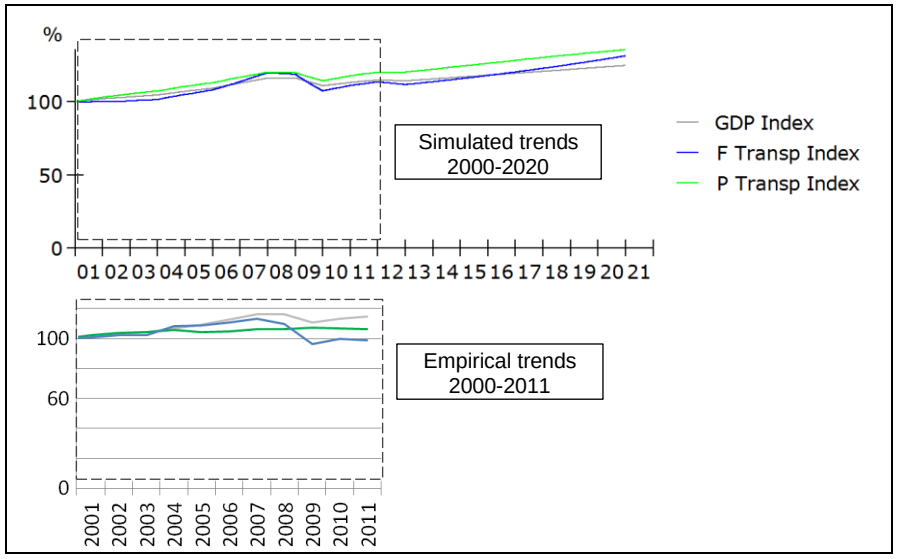

Fig. S-1. Comparison of simulated trends (Scenario D, mean sub-scenario) with empirical trends[5] of: freight transport performance ("F Transp Index") and passenger transport performance ("P Transp Index"), compared to GDP index. (2000 = 100 %)

[5] European Commission: Statistical pocketbook 2013, http://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2013_en.htm

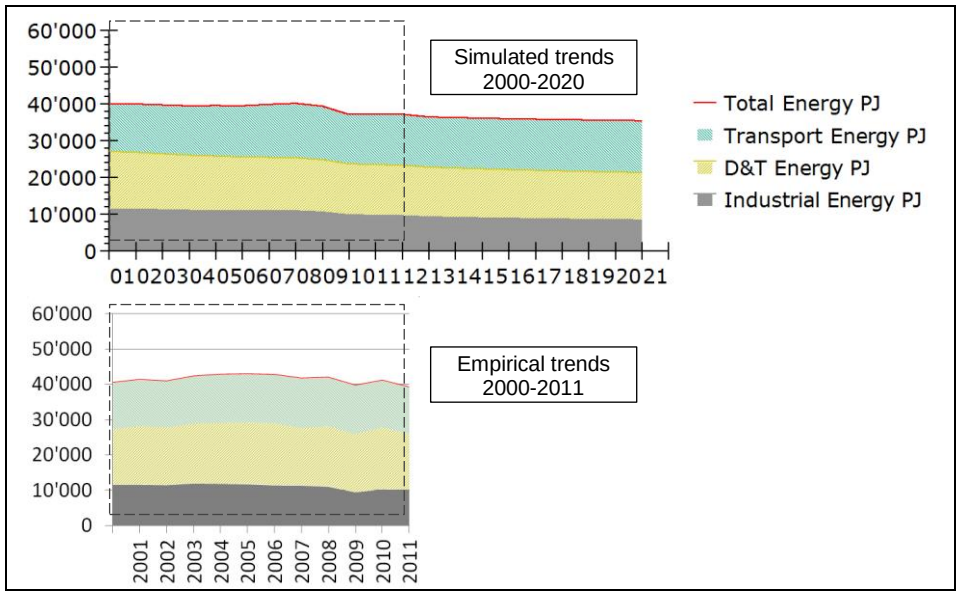

Fig. S-2. Comparison of simulated trends (Scenario D) with empirical trends[6] of: energy consumption by the sectors transport, domestic and tertiary, and industry. Abbreviations: PJ: Petajoule; D&T: Domestic and tertiary sector.

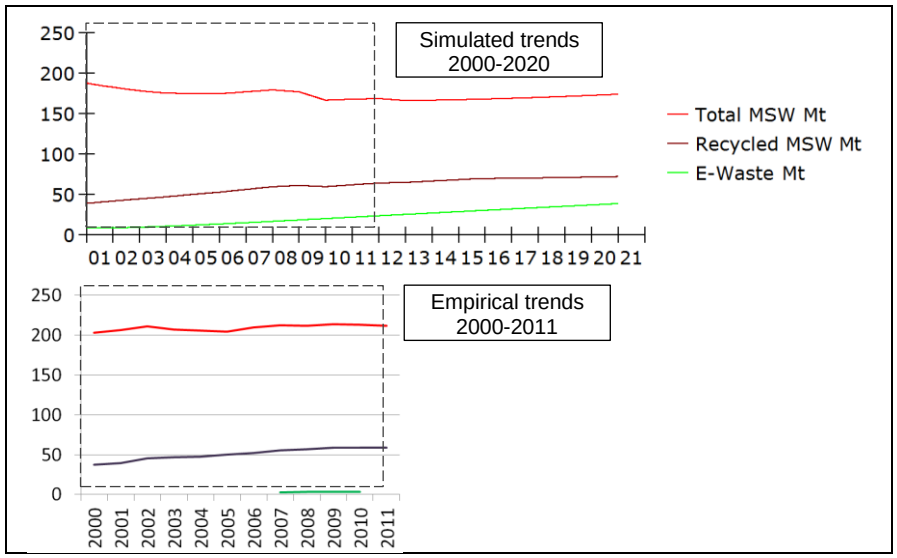

Fig. S-3. Comparison of simulated trends (Scenario D) with empirical trends[7] of: municipal solid waste (MSW), the recycling rate, and the e-waste fraction in megatonnes (Mt).

[6] Eurostat: Supply, transformation, consumption - all products - annual data. Product code: nrg_100a (2013)
[7] Eurostat: EuroStat: Municipal waste. Product code: env_wasmun (2014)
Eurostat: Waste Electrical and Electronic Equipment (WEEE). Product code: env_waselee (2014)

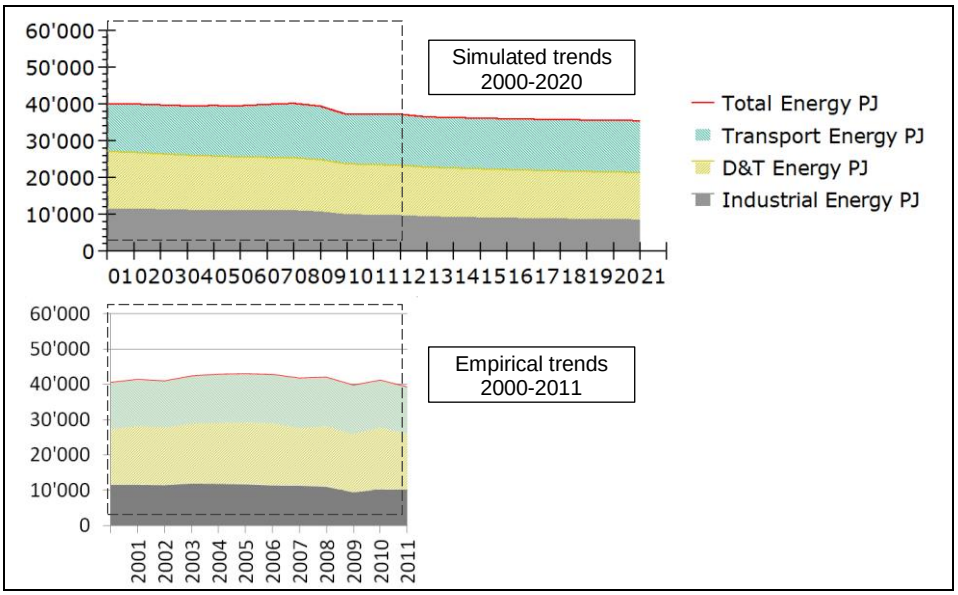

Fig. S-4. Comparison of simulated trends (Scenario D) with empirical trends[8] of energy consumption

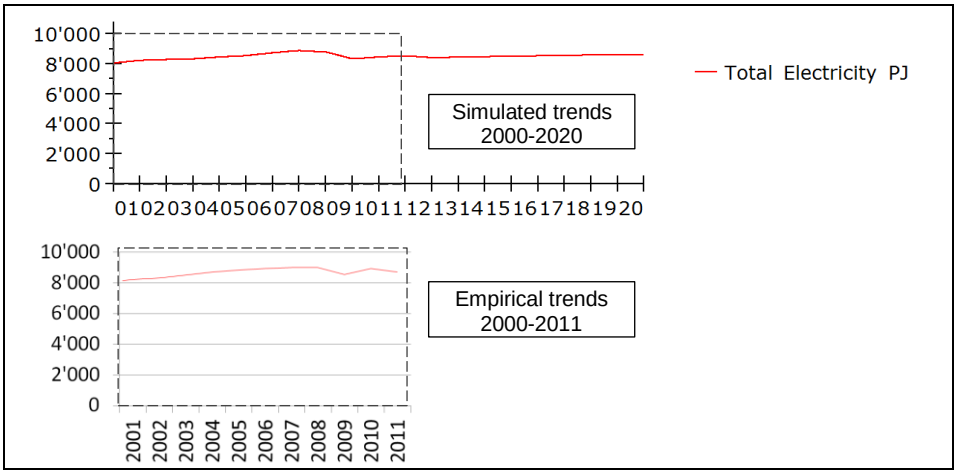

Fig. S-5. Comparison of simulated trends (Scenario D) with empirical trends[9] of total electricity

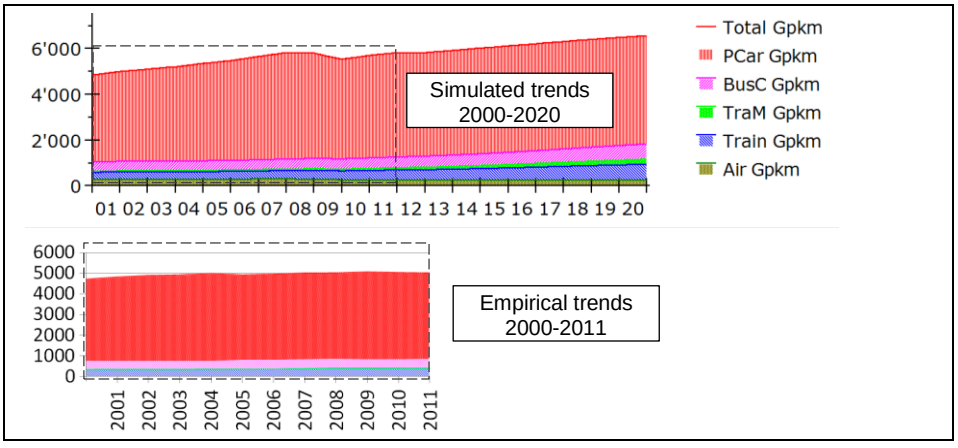

Fig. S-6. Comparison of simulated trends (Scenario D) with empirical trends[10] of passenger transport performance by traffic mode (Note: empirical trend for air passenger transport is missing). Abbreviations: Gpkm=10^9 passenger-kilometer, PCar=Privat car, BusC=Bus and Coach, TraM=Tram and Metro.

[8] Eurostat: Supply, transformation, consumption - all products - annual data. Product code: nrg_100a (2013)
[9] REF???

4. New simulation results compared to original results

This section presents quantitative results of the simulation modeling using the new assumptions described in Table S-1 (Scenario D). Simulation results for Scenario D are compared with the results for the original three scenarios (A, B, and C).

For each scenario, the results for three sub-scenarios are presented. These sub-scenarios express best-case, worst-case, and mean assumptions about model parameters that were specified with a range of uncertainty. The "mean" sub-scenarios simply used the arithmetic mean of the best- and worst-case values of each (input) parameter.

Moreover, for each scenario, the results for two versions of simulation runs are presented: the reference (or regular) run and the "ICT Freeze" run. The reference run simulates the development of ICT as it is predicted over the simulation period. The "ICT Freeze" run "freezes" ICT diffusion and use at the level of the year 2000.

In this section we revisit the results presented

Table 1. Simulated values in Scenario D for environmental indicators divided by GDP in the year 2020, expressed in % of the values of the year 2000. This table provides updated results compared to Table 4 in Hilty et al. (2006)

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Energy intensity	**Reference Run**	**398.91951**	**77.6%**	**71.1%**	**61.6%**
	ICT Freeze		82.2%	78.7%	75.3%
GHG intensity	**Reference Run**	**33.746827**	**62.6%**	**63.2%**	**51.3%**
	ICT Freeze		77.4%	71.3%	65.0%
Material intensity	**Reference Run**	**1.88**	**87.0%**	**74.2%**	**56.4%**
	ICT Freeze		77.5%	73.6%	69.3%
Freight transport intensity	**Reference Run**	**1**	**114.6%**	**105.2%**	**84.6%**
	ICT Freeze		115.8%	110.3%	104.0%
Passenger transport intensity	**Reference Run**	**1**	**111.9%**	**108.6%**	**103.8%**
	ICT Freeze		108.3%	103.5%	99.5%

Table 2. Simulated results for Scenario D in energy consumption by the sectors transport, domestic and tertiary, and industry. Compare this with original scenarios in Table 6-1 in Hilty et al (2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Total Energy PJ	**Reference Run**	**39892**	**38642**	**35408**	**30654**
	ICT Freeze		40927	39177	37468
Transport Energy PJ --	**Reference Run**	**12854**	**15104**	**14110**	**12496**
	ICT Freeze		15425	14486	13677
D&T Energy PJ --	**Reference Run**	**15666**	**13633**	**12876**	**12660**
	ICT Freeze		14441	14716	14942
Industrial Energy PJ	**Reference Run**	**11372**	**9905**	**8423**	**5499**
	ICT Freeze		11061	9976	8848

[10] European Comission http://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2013_en.htm

Table 3. Simulated results for Scenario D in electricity consumption, total and for ICT. Compare this with original scenarios in Fig 6-3 in Hilty et al (2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Total Electricity PJ	**Reference Run**	**8020**	**8501**	**8608**	**9014**
	ICT Freeze		7814	8198	8554
ICT Electricity PJ	**Reference Run**	**519**	**1520**	**966**	**623**
	ICT Freeze		519	519	519

Table 4. Simulated results for Scenario D in energy-related greenhouse gas emissions by the sectors transport, domestic and tertiary, and industry. Compare this with the results of original scenarios in Table 6-1 in Hilty et al (2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Total GHG Mt	**Reference Run**	**3375**	**2638**	**2663**	**2162**
	ICT Freeze		3262	3005	2738
Transport GHG Mt	**Reference Run**	**905**	**1054**	**996**	**881**
	ICT Freeze		1082	1017	958
D&T GHG Mt	**Reference Run**	**1507**	**980**	**1096**	**971**
	ICT Freeze		1319	1269	1196
Industry GHG Mt	**Reference Run**	**963**	**604**	**571**	**310**
	ICT Freeze		861	719	583

Table 5. Simulated development of freight transport performance (tkm) compared to GDP and passenger transport performance in Scenario D (Compare with Fig 6-8 in Hilty et al 2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
99 GDP Index	**Reference Run**	**100.0**	**124.8**	**124.8**	**124.8**
	ICT Freeze		124.8	124.8	124.8
01 F Transp Index	**Reference Run**	**100.0**	**143.0**	**131.3**	**105.6**
	ICT Freeze		144.5	137.6	129.8
02 P Transp Index	**Reference Run**	**100.0**	**139.7**	**135.6**	**129.6**
	ICT Freeze		135.1	129.1	124.2
07 MSW not recycled Index	**Reference Run**	100.0	**80.2**	**68.4**	**52.1**
	ICT Freeze		71.4	68.7	64.7
08 Materials Index	**Reference Run**	100.0	**86.1**	**79.4**	**64.1**
	ICT Freeze		100.7	95.7	90.1

Table 6. Simulated development of passenger transport in 10^9 passenger km for private car (PCar), bus and coach (BusC), tram and metro (TraM), train, and air transport in Scenario D. (Compare with Fig 6-6 in Hilty et al 2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Total Gpkm	**Reference Run**	**4839**	**6758**	**6560**	**6271**
	ICT Freeze		6539	6247	6010
PCar Gpkm	**Reference Run**	**3789**	**5070**	**4737**	**4478**
	ICT Freeze		5375	4892	4588
BusC Gpkm	**Reference Run**	**411**	**568**	**662**	**678**
	ICT Freeze		449	520	557
TraM Gpkm	**Reference Run**	**53**	**188**	**226**	**232**
	ICT Freeze		15	109	133
Train Gpkm	**Reference Run**	**305**	**662**	**691**	**689**
	ICT Freeze		421	458	481
Air Gpkm	**Reference Run**	**281**	**269**	**243**	**195**
	ICT Freeze		278	268	251

Table 7. Simulated results of municipal solid waste (MSW), the recycling rate and the e-waste fraction in Mt. in Scenario D. The second table shows the same variables and the GDP for comparison as an index with 100 % in 2000. (Compare with Fig 6-9 in Hilty et al 2004)

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Total MSW Mt	**Reference Run**	**188.00**	**204.02**	**174.09**	**132.43**
	ICT Freeze		181.73	172.67	162.63
Recycled MSW Mt	**Reference Run**	**38.92**	**84.47**	**72.07**	**54.83**
	ICT Freeze		75.24	70.28	66.19
E-Waste Mt	**Reference Run**	**8.13**	**56.25**	**38.57**	**25.78**
	ICT Freeze		0.80	0.80	0.80
Waste not recycled Mt	**Reference Run**	**149.08**	**119.56**	**102.01**	**77.60**
	ICT Freeze		106.49	102.39	96.44

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
99 GDP Index	**Reference Run**	**100**	**124.8**	**124.8**	**124.8**
	ICT Freeze		124.8	124.8	124.8
16 Total MSW Index	**Reference Run**	**100**	**108.5**	**92.6**	**70.4**
	ICT Freeze		96.7	91.8	86.5
17 Recycled Index	**Reference Run**	**100**	**217.0**	**185.2**	**140.9**
	ICT Freeze		193.3	180.6	170.1
18 E-waste Index	**Reference Run**	**100**	**691.5**	**474.2**	**317.0**
	ICT Freeze		9.9	9.9	9.9

Table 8. Simulated results in Scenario D for the electricity mix. CHP is not included because it is not an energy source, but a way of using the heat that is produced in some modes of power generation (usually natural gas). Compare with Fig 6-5 in Hilty et al (2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Electricity PJ	**Reference Run**	**8020**	**8501**	**8608**	**9014**
	ICT Freeze		7814	8198	8554
Renewables PJ	**Reference Run**	**1211**	**3666**	**2172**	**2600**
	ICT Freeze		1658	1978	2312
Nuclear PJ	**Reference Run**	**2695**	**2158**	**2306**	**2506**
	ICT Freeze		1984	2196	2378
Natural Gas PJ	**Reference Run**	**1500**	**2170**	**2839**	**3803**
	ICT Freeze		1994	2704	3609
Oil Products PJ	**Reference Run**	**505**	**766**	**458**	**142**
	ICT Freeze		709	436	134
Solid Fuels PJ	**Reference Run**	**2109**	**0**	**832**	**0**
	ICT Freeze		1469	883	120
RES share in electricity	**Reference Run**	**0.15**	**0**	**0.25**	**0.29**
	ICT Freeze		0.21	0.24	0.27

Table 9. Simulated results in Scenario D for virtual mobility in weekly hours per capita for home-based telework, teleshopping and virtual meetings. There is an interaction with the physical traffic modes through the time budget constraint (saved time can be used for other transport) and with infrastructure capacity. Compare with Figure 6-7 in Hilty et al (2004).

		Initial 1.1.2001	D worst 1.1.2021	D mean 1.1.2021	D best 1.1.2021
Telework h	**Reference Run**	**0.31**	**0.69**	**0.70**	**1.14**
	ICT Freeze		0.06	0.17	0.26
Teleshopping h	**Reference Run**	**0.15**	**0.57**	**0.55**	**0.53**
	ICT Freeze		0.03	0.07	0.08
V Meetings h	**Reference Run**	**0.04**	**0.13**	**0.13**	**0.12**
	ICT Freeze		0.02	0.03	0.04
Telework pkmE	**Reference Run**	**1.5E+10**	**3.7E+10**	**3.8E+10**	**6.1E+10**
	ICT Freeze		3.05E+09	9.33E+09	1.37E+10
Teleshopping pkmE	**Reference Run**	**5.88E+10**	**2.4E+11**	**2.4E+11**	**2.3E+11**
	ICT Freeze		1.24E+10	2.88E+10	3.29E+10
V Meetings pkmE	**Reference Run**	**1.29E+11**	**4.1E+11**	**4E+11**	**4E+11**
	ICT Freeze		7.3E+10	9.71E+10	1.19E+11

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