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ICTs: Do they contribute to increased carbon emissions?

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ABSTRACT

There is much evidence that the deployment of information and communications technologies (ICTs) can improve economic productivity, reduce energy intensity and exert downward pressure on renewable energy costs. While significant insights have been revealed about each of these effects in isolation, literature has not established their combined implications for carbon emissions. This article uses the International Futures (IFs) integrated assessment system (www.ifs.du.edu) to explore the dynamic impacts of ICT on interacting global systems, including economic and energy systems, and resultant carbon emissions. First, it reviews the literature on the various impacts of ICT; next, it extracts relationships from previously existing quantitative studies on the subject; third, it explains the addition of these relationships to the IFs structure; fourth, it explores the implications of the acceleration of ICT penetration; finally, it frames a range of uncertainty around the analysis through scenarios. The authors argue that ICT can have a downward impact on overall carbon emissions across a 50-year time horizon. However, the net impact of ICT is limited, and if policy makers are concerned with substantial reductions in overall stocks of carbon in the atmosphere, our model shows that ICT promotion must be coupled a global price on carbon.

1. Introduction

It is well documented that information and communication technologies (ICTs) have wide-ranging impacts on key global systems [1–4]. These technologies have been shown to improve productivity, reduce energy intensity and potentially decrease the relative cost of renewable energy production. Each of these links has distinct effects on CO_2 emissions. Consensus on the overall impact of ICTs on climate change has not, however, been achieved. Is the full impact of ICTs on environmental systems one that brings about a reduction or an increase in greenhouse gasses?

Some promote ICT as a tool to mitigate global climate change through its ability to improve energy efficiency and reduce renewable energy costs [5–8]. Other reports document the strong connection between ICT promotion and economic growth, which ceteris paribus would increase energy use and carbon emissions [9–15]. Yet widely accepted conclusions about the overall impact of ICTs on the environment have not been fully realized [16].

This article explores the impact of ICT on global CO_2 emissions by augmenting the structure of the International Futures (IFs) integrated assessment modeling platform (which contains representation of global demographic, energy, economic, and environmental systems). The analysis had three primary steps. First, ICT's relationship to economic, energy and environmental systems was conceptualized, as displayed in Fig. 1. Overall, ICT penetration impacts carbon emissions in three major ways across the aggregate economy – via changing productivity, energy intensity and the cost of renewable energy – identified by the left-most set of arrows in Fig. 1 and the forward paths, ultimately leading to annual carbon emissions. Others have explored pieces of this puzzle, but no one has systematically accounted for the aggregate impact of ICT on carbon emissions in an integrated assessment

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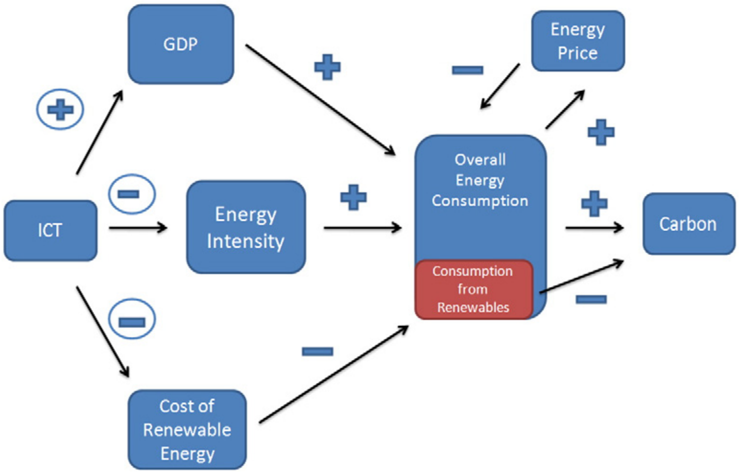

Fig. 1. Conceptualizing ICT's impact on carbon emissions.

model, particularly with a model that considers energy price changes and the feedback effects associated with them (the main one being the "rebound effect" that links reduced energy consumption to lower prices, thereby incentivizing higher energy consumption again and making it difficult to change the system).

Second, the ICT conceptualization fueled a modeling exercise. We first added ICT diffusion forecasts to the model – specifically, broadband penetration rates – to drive the forward linkages, as well as to establish a base-case for analysis. Next, we operationalized the forward linkages between ICT and economic growth and the energy system by exploring extant literature; such formalization and its parameterization are a challenging endeavor, as some of these academic and professional threads are in their infancy.

Third, we used scenario analysis to explore uncertainty around the impact of our base case ICT forecasts on environmental systems. This inquiry explored two axes of uncertainty: 1) ICT can diffuse throughout a society at different rates; and 2) the impact of ICT on productivity, energy intensity and the cost of renewable energy can be higher or lower than our base-case parameterization. Varying these two sets of parameters frames four stories about the possible future of the world vis-à-vis ICT and CO_2.

We concluded that higher ICT penetration rates can reduce CO_2 emissions (and we mapped the extent of that reduction dependent on the levels of diffusion of ICT within a society and the strength of the individual impacts of ICT on economic and energy related variables). We find, however, that while ICT can play an important role, if governments wish to reduce carbon emissions they should use accelerated ICT diffusion in conjunction with a carbon price.[2] Specifically, if high ICT adoption is combined with a global carbon price to address both its contribution to economic growth and the rebound effect, then CO_2 significantly decreases relative to the base. The combined impact is significantly greater than the impact of ICT or carbon pricing alone. In such a scenario, acceleration of advance in ICT usage can have generally the same impact on the overall stock of carbon in the atmosphere as a $100 increase in the price of carbon.

2. Modeling method

2.1. International Futures (IFs)

IFs is a large-scale, long-term, integrated global modeling system. It represents demographic, economic, energy, agricultural, socio-political, and environmental subsystems for 183 countries interacting in the global system out to the year 2100 [17–20]. See Fig. 2 for a representation of the overall system. The central purpose of IFs is to facilitate exploration of global futures through alternative scenarios. The model is integrated with a large historic database containing values for nearly 2000 data series since 1960. IFs is freely available to users both on-line and in downloadable form and is housed in the Frederick S. Pardee Center for International Futures (www.ifs.du.edu).

IFs was a core component of a project exploring the New Economy sponsored by the European Commission [21]. Forecasts from IFs supported Project 2020 of the National Intelligence Council [22] as well as the NIC's Global Trends 2025 [23] for the newly elected US presidential administration. The IFs project provided driver forecasts for the fourth Global Environment Outlook of the United Nations Environment Program [24]. IFs has been used increasingly for analysis within the African context [25]. IFs was also the primary tool for a research project on ICT trends and sustainability supported by the Information Society and Media Directorate General (DG INFSO) of the European Commission, the project on which this current study is based (SMART 2008/0031).

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[2] The IFs model does not consider the political feasibility of achieving a global price on carbon and unanticipated material and political costs.

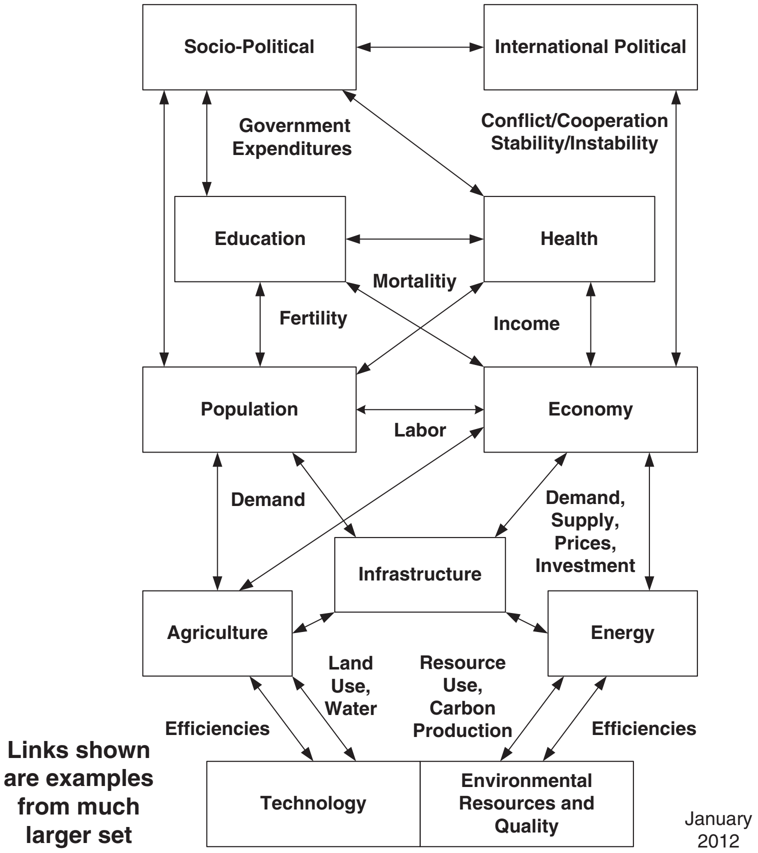

Fig. 2. International Futures (IFs) model structure.

2.2. Modeling steps

Previous to this project, the IFs system included an ICT sector within the economic model; the model's sectoralization was based on data from the Global Trade Analysis Project (GTAP). In addition it included the ability to explore the impact of changing communication technology on productivity across all sectors. There existed a basic representation of ICT-related variables (namely, the number of networked persons and the percent of people on the internet), but these were inadequate for our purposes.

Three steps were required to add a more complete ICT sub-model to IFs. First, we identified a critical variable that would represent ICT as a whole and drive the forward linkages. Although we also added forecasts of mobile phone penetration and ICT spending as a percentage of GDP to the model, we chose to initialize our forecasts using ICT broadband penetration rates, as defined by the International Telecommunication Union [26] and forecasted as a hybrid between wireless and wired technologies (see Appendix A). We chose broadband penetration for the following reasons. First, unlike mobile phone penetration, the trend has yet to approach saturation in the large majority of countries. Second, it is a technology that has been either theorized or demonstrated to improve productivity, reduce energy intensity and lower the cost of renewable energy. Third, there were adequate data – both as a historic time series and across countries – to operationalize this variable within a global model. Fourth, it is a leading-edge technology with a wide range of applications for industry, households, governments and other key sectors.

The method used to forecast broadband penetration involved exploring the relationship between income, governance and technology development. Broadband is expected to diffuse along an S-curve pattern, where initial levels are low, then grow quicly, reach a peak growth rate in the middle range of penetration and then eventually slow and asymptotically approach an upper limit. To forecast this, we needed to identify the upper limit of penetration (100% of the population), the inflection point (50% of penetration), the relationship between broadband and both income and governance as key variables driving the advance, and what we call the technology shift factor. This last factor measures the annual shift in penetration rates at a fixed level of country income (the entire relationship of income with broadband penetration has, of course, shifted upward over time as the technology has advanced).

Second, we structured the forward relationships between broadband penetration and economic productivity, energy efficiency, and renewable energy cost, three variables already forecast in the IFs model in relationships with other drivers. We added broadband penetration to the model's exisiting forecast formulations (described in the Help system of IFs) using an elasticity approach: increases or decreases of broadband penetration relative to "expected" advance in the base forecast of IFs accelerate or slow the change in the three critical economic and energy variables (see again Fig. 1). These three key economic and energy variables themselves affect carbon emissions in a largely mechanical manner. For instance, higher renewable energy production, all else being equal, decreases the carbon emissions of the energy mix (IFs assigns specific carbon emissions to each energy source). All else will not, of course, always be equal and we return later to the complicating implications of energy price changes. And not all additional relationships are fully mechanical; for instance, the cost of renewables affects renewable production and contribution to the consumption mix via dynamics of the IFs energy model (see the Help system of IFs for documention).

Third, we tested the model extensively to make sure that the results that we obtained were consistent with the literature and reasonable expectations.

3. The three paths of ICT impact

Specifying the three relationships linking ICT with economic productivity, energy efficiency and renewable energy production and use was critical to the analysis, and the literatures addressing the three relationships are mixed with respect to usefulness and are identified below in detail. The relationship between ICT and productivity is well researched. The link from ICT to energy efficiency, and ultimately energy intensity, is less clear. The linkage between ICT penetration and the cost of renewable energy is even less well quantified with an unfortunate dearth of sources. We discuss each in turn.

Each of these relationships enters the model via an elasticity approach. An elasticity is a ratio of percentages, and it identifies how much change in one variable will impact change in another variable. For the purpose of this article, we were interested in establishing the elasticities of productivity, energy demand and the percent of renewable energy in total energy production (the numerators in the elasticities) to change in broadband penetration (the common denominator). The next three subsections identify how we derived our three elasticities.

3.1. ICT and productivity

It is widely accepted that ICT investment leads to real-world productivity gains [27,11]. While this was not initially observed on a macro level in the early 1990s, productivity gains began to clearly emerge at the beginning of the 21st century. The “Solow Paradox” – stated in 1987 – noting that more investment in computing and communication devices did not appear to lead to more productive industry, was shown to be fallacious, and many peer-reviewed studies have identified a strong link between ICT and productivity [3,4,9–15,27,28].

The work of Qiang, Rossotto and Kimura [10] identified GDP growth rate improvements of 1.38% for OECD and 1.21% for non-OECD countries when broadband penetration increases by 10%. This result emerged from regressing the average per capita GDP level between 1980 and 2006 against a range of independent variables. The Climate Group on Behalf of the Global Sustainability Initiative (CESifo) reported that a 10% increase in broadband in OECD countries increases GDP per capita anywhere from 0.9%–1.5% [7]. An additional review of OECD countries indicated that ICT has contributed consistently to improvements in economic growth: “Over the past two decades, ICT contributed between 0.2 and 0.5 percentage points per year to economic growth, depending on the country. During the second half of the 1990s, this contribution rose to 0.3 to 0.9 percentage points per year” [28].

Based on this literature analysis, we concluded that a reasonable parameterization of IFs would link a 1% increase in broadband penetration relative to the base case with a 0.12% increase in GDP growth rate (an elasticity of 0.12).[3]

3.2. ICT and energy demand

Considerable literature explores the strength of the relationship between ICT promotion and energy demand [29–31].[4] We built upon two reports: one authored by the Bio Intelligence Group [32] and the other, the Brattle Group [33]. In analyses of these reports, we estimated how much energy demand would be affected with a change in broadband penetration of 10%, all else equal.[5]

The Bio Intelligence report indicated that ICT could save 111.3 TWh of electrical energy demand when comparing two scenarios for the EU to 2020. The two scenarios used by this group were a *baseline scenario* and a *business as usual scenario*. The *baseline scenario* quantified a world of no additional ICT penetration. The *business as usual scenario* studied base-case growth in ICT penetration. We used two IFs broadband penetration scenarios to proxy these Bio Intelligence scenarios: for the Bio Intelligence

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[3] We calibrated a model parameter named “mfpinfict” to a value of 0.0075 to implement this linkage. It is sometimes necessary to calibrate model parameters via an iterative process because the exact relationship used in the model (in this case between broadband penetration rates above an expected growth pattern and increase in multifactor productivity) does not correspond directly to the calculated elasticity; the calibrated parameter generates the behavior of the elasticity under alternative scenarios for growth in broadband penetration.

[4] Unfortunately, this literature is not nearly as comprehensive as the literature tracing the linkage between ICT and productivity. Many of these sources are not peer-reviewed. We have also conducted sensitivity analysis around the strength of parameters, found in Appendix C.

[5] In these studies we are not able to consistently trace the micro-foundations of these improvements in energy efficiency, but instead are interested in the macro-level impacts irrespective of the micro characteristics.

baseline scenario, we kept EU broadband penetration in IFs fixed at the 2005 level of 12%; for the Bio Intelligence *business as usual scenario*, we used our own base-case scenario in which broadband penetration grows for the EU to 49% in 2020.[6] That is, the difference in broadband penetration between the two scenarios in 2020 is 37%.

For the numerator of our elasticity, we divided the decrease in EU electricity demand that the Bio Intelligence report associated with increased ICT (namely 111.3 TWh) by an estimate of the total EU energy consumption in 2020 (3975 TWh[7]), yielding 2.8%. This analysis thus associates each 10% of incremental broadband reduction with a decrease of 0.77% of energy demand (2.8/3.7).

The Brattle Group produced a report for the Edison Foundation [33] that we used as a second study to establish this parameter. It focused on the US, thereby providing an opportunity to expand the analysis beyond the EU. Using the Regional Capacity Model (RECAP), researchers produced scenarios with different levels of ICT investment (among other variables) driving energy consumption. We compared two of their scenarios: the *reference scenario* (no additional ICT investment) and a *realistically achievable potential scenario* (base case ICT investment). We again used two IFs broadband penetration scenarios as proxies for these two scenarios: for the Brattle Group *reference scenario* with no additional ICT investment, we let US broadband penetration stagnate at the 2005 values of 16.1%; for the *realistically achievable potential scenario* we used the (generally aggressive) broadband penetration pattern for the US of the IFs base case, in which it climbs to 94.5% in 2030. That is, the difference in broadband penetration between the two scenarios in 2030 is 78.4%.

The Brattle Group provided straightforward assessment of the overall expected change in electricity demand with different levels of ICT penetration. For the *reference scenario* with no additional ICT investment, electricity demand grew to 1378.9 GW. For the *realistically achievable potential scenario*, this number was less, at 1297.8 GW. That is, the difference in consumption between the two scenarios is (1378.9 GW - 1297.8 GW)/1297.8 GW or 6.2%. This analysis thus associates each 10% of incremental broadband increase with a decrease of 0.79% of electricity demand, nearly identical to the result from our analysis of the Bio Intelligence report.[8]

Thus the two studies suggest that each percentage point increase in broadband penetration (our admittedly rough proxy for their ICT variables) is associated with a reduction in energy demand of about 0.077–0.079%, yielding an elasticity of approximately −0.08.[9]

3.3. ICT and renewable energy cost

For this relationship we did not directly focus on energy cost, but on the result of lower costs, namely increased renewable production and consumption (in terms of Fig. 1, we examine the relationship between ICT penetration and consumption of energy from renewable, which runs through the cost of renewable energy). Moreover, we looked to the study of the impact of “smart grids” for help with the parameterization of that relationship.

Smart grids are energy infrastructures that use ICT to continuously monitor and match the supply and demand of energy, including intermittent renewable resources and changing demand patterns (which it can also partly control by providing real-time price information). This type of infrastructure can promote reduced renewable energy costs by improving transmission efficiency, dealing with intermittency, and allowing de-centralized individuals and firms to both buy and sell to the grid.

The Brattle Group report exploring US investment in energy infrastructure to 2030 measured changes in electricity consumption related to – among other things – investment in advanced metering infrastructure (AMI), a central element of much smart grid technology. It argued, in part, that different levels of AMI investment would lead to different levels of renewable energy production. We therefore focused on the relationship between change in levels of AMI and change in renewable energy production as an, admittedly very crude, proxy of the relationship between ICT and renewable energy production/consumption.

For the denominator in the elasticity, we looked to the same two scenarios that the above section described in the analysis of broadband's impact on energy demand. The IFs base-case forecast for broadband in the US (90.8% penetration) was a proxy for the *realistically achievable potential scenario* (*RAP*). This was compared with the base year development of broadband (21.1% penetration), for an increment again of 69.7%.

The Brattle Group report estimated that in 2030 the renewable share in new electricity production of the US would be 29.5% as compared to 18% in a scenario with stagnant ICT investment. The report did not, however, provide sufficient additional data to calculate renewable energy production as a percentage of total energy consumption. We looked to the U.S. Energy Information Agency website to determine the changing share of renewable energy relative to total energy production for the different scenarios. These estimations, outlined in detail in Appendix B, resulted in the percentage of renewable energy to total energy production being 6.2% in the base case and 8.8% in the realistically achievable potential scenario. Our final estimation led to an elasticity of 0.037, indicating that a 10% change in ICT penetration would lead to a 0.37% change in renewable energy's share of total energy production. We needed to scale this down, though, as the Brattle Group did not only attribute ICT to changes in renewable penetration, and arbitrarily decided to cut the elasticity in half to 0.0185.

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[6] Forecasts of access to ICT technology are heavily contingent on the original data source methodology. Different data sources have different thresholds for measuring access to different levels of ICT. For example, EuroStat measures broadband with a threshold of 144 Kbit/s. International Telecommunication Union places this threshold at 256 Kbit/s, leading to very different outputs.

[7] This estimate of total energy demand came from the *European Energy and Transport Trends to 2030* [34]. ICT may, of course, have an impact on other components of the demand beyond electricity use. Comparing reduction in electricity demand with total energy demand may underestimate the impact of ICT.

[8] The numerators in these two analyses are different, however, the former looking at change in electricity demand relative to total energy demand and the latter looking at change in electricity demand relative only to total electricity demand. The former analysis therefore may somewhat underestimate the elasticity.

[9] We set the parameter “elendemict” to −0.0008 to represent this elasticity, the difference being a scaling factor.

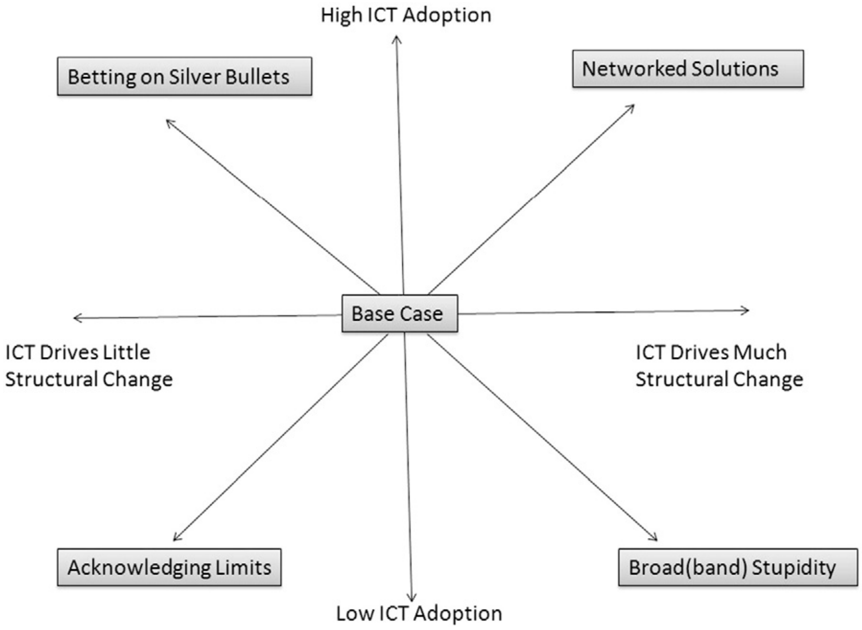

Fig. 3. ICT scenario space.

Sensitivity Analysis was conducted on the impact of each of the forward linkages on atmospheric carbon concentrations. The results of this can be found in Appendix C.

4. Analysis

Turning to analysis, we begin by mapping two major dimensions that frame uncertainty and building and exploring scenarios that represent that uncertainty. We then add a further element to the analysis, namely the critical issue of carbon pricing.

4.1. Development of scenarios

The discussion above indicated that there is considerable difficulty in establishing the parameterization of relationships linking ICT (broadband penetration) to critical economic and energy variables. Not only is the literature of mixed help across the relationships, but some of those parameters may, in fact, actually be variables, responsive to the continued unfolding of technology or governmental policy. We explore the impact of ICT on carbon emission with high and low sets of these parameters, effectively undertaking Sensitivity Analysis via the scenarios. Specifically, for high parameters, we double the size of our forward linkages. For the low parameters, we have cut their size in half.

The second major uncertainty is the speed of ICT diffusion. Broadband penetration rates will depend on technology, government policy, and other variables. It is a key variable that many governments wish to influence, minimally with the expectation that it will influence economic growth, and sometimes with the hope that it will prove helpful for the environment. For high scenarios, broadband rates grow by 3.5 times their base case rate for the years 2010–2015 (pushing, for example, the EU's base-case broadband penetration from nearly 35% to over 70% by 2015[10]). For low broadband penetration scenarios, penetration growth rates stagnate from 2010 to nearly 2015.

As an example, the Networked Solutions scenario doubles the parameters connected to our forward linkages (see the discussion earlier in this article) while also substantially increasing ICT penetration globally. Fig. 3 shows the four scenarios that the two dimensions create (in addition to the base case at the origin of the two dimensions of uncertainty).[11]

4.2. Scenario analysis

Within the framework of the four scenarios and the base case, this analysis proceeds in three steps. The first step considers economic growth across the five scenarios, as it is a key variable in the path between ICT and carbon emissions (see again Fig. 1). The second analyzes the overall implications of economic growth, energy intensity and the cost of renewable energy on

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[10] Broadband penetration rates in IFs are lower than typically discussed within the EU context. This is because IFs uses ITU data, and the EU uses Eurostat data with a lower threshold to identify broadband.

[11] The four scenario files are available in the Scenarios\World Integrated Scenarios folder of the installed IFs system (itself available at www.ifs.du.edu) and the interventions are outlined in Appendix 4query.

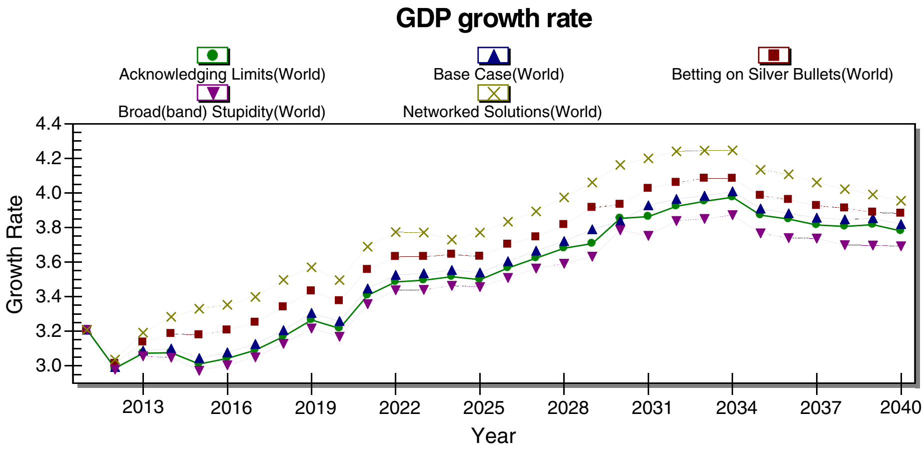

Fig. 4. GDP growth across scenarios.
Source: IFs Version 6.37.

total energy consumption and production. This step also requires that we consider how the changes in demand and price influence each other in a negative feedback loop also known as the rebound effect. The third step considers the consequences of that energy pattern for carbon emissions and accumulation in the atmosphere; it is there that we look also at the possible interaction of ICT and carbon pricing interventions.

4.2.1. Step 1: economic growth

The range of variation in global GDP growth rates across our five scenarios is about 0.4% (see Fig. 4). That variation characterizes the entire time period, reflecting ICT's ability to improve productivity on an ongoing basis. The Networked Solutions scenario produces the highest level of global GDP growth, because it represents both increased strength of ICT impact in its parameterization and a faster overall rate of ICT penetration. The Betting on Silver Bullets scenario produces the next strongest growth pattern, but the rate is about 0.2% lower on an annual basis than in the Networked Solutions scenario. The final two scenarios – Acknowledging Limits and Broad(band) Stupidity – cluster together with lower growth rates.

4.2.2. Step 2: energy consumption and production

The changes in GDP noted in Step 1 interact with changes in energy intensity and with the cost and production of renewable energy, also affected by ICT (see again Fig. 1) to determine the patterns of country-specific, regional, and global energy consumption and production. With respect to overall global energy demand (see Fig. 5), the Networked Solutions scenario initially produces the lowest rates of growth, but the scenario ends the 30 year time horizon with higher overall energy demand than we find in the other four scenarios. Slower demand growth initially for this scenario – even though GDP growth was the highest – reflects ICT's ability to decrease overall energy intensity. The higher demand by the mid 2030s, however, represents heavily the effect of higher overall levels of GDP, which more than offsets the increased efficiency of energy demand.

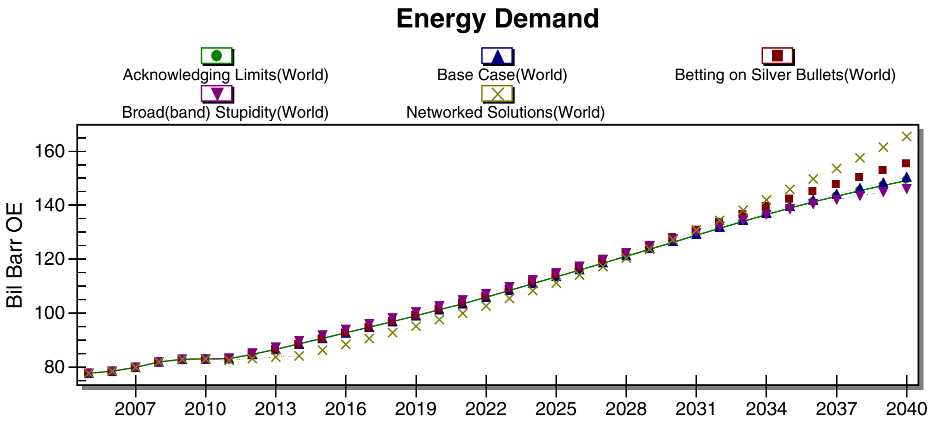

Fig. 5. Energy demand across scenarios.
Source: IFs Version 6.37.

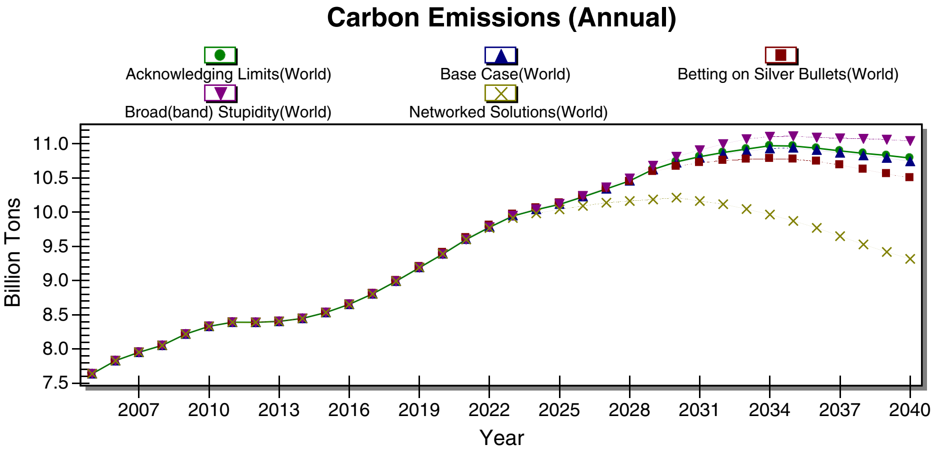

Fig. 6. Global carbon emissions for ICT scenarios.
Source: IFs Version 6.37.

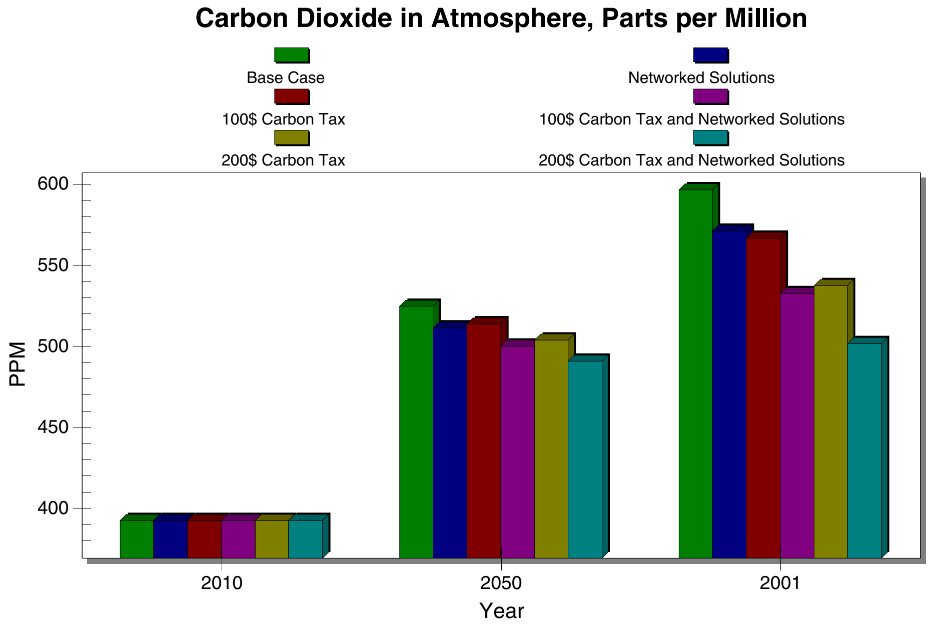

Fig. 7. Global carbon PPM for six scenarios.
Source: IFs Version 6.37.

The demand patterns also reflect, however, the dynamics around energy prices across the alternative scenarios (with prices responsive to both the overall energy demand and to the mix of energy supply sources including renewable ones). Energy prices vary considerably across the scenarios. Because of the reduced cost of renewable energy in the Networked Solutions scenario, energy prices stay relatively stable through 2040.[12] The highest growth in energy prices occurs in the Broad(band) Stupidity scenario, eventually doubling the prices seen in the Networked Solutions scenario. Significantly higher global renewable energy production is a critical underlying driver of the relatively stable energy prices in the Networked Solutions scenario.

These substantially lower world energy prices of Networked Solutions relative to other scenarios, and the rise in demand that they bring about, reflect increases in renewable energy production. Initially, levels of global renewable energy production are quite low, and no scenario passes 10 billion barrels of oil equivalent (BBOE) until 2025. However, by 2040, overall renewable energy production for the Networked Solutions scenario is nearly 50% more than that of the next closest scenario, and it peaks at

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[12] The IFs energy model computes energy prices in a partial equilibrium structure that is responsive to economic growth and representations of energy efficiency improvements, energy resource base, and supply and demand elasticities, among other factors. Full documentation accompanies the model.

over 70 BBOE. As a point of comparison, the worst performer in terms of global renewable energy production/consumption was Broad(band) Stupidity, in which it does not exceed 30 BBOE by 2040.

4.2.3. Step 3: carbon emissions and atmospheric levels

The final variable in our causal diagram was overall carbon emissions. Annual global emissions, highlighted in Fig. 6, continue to grow in the base case until nearly the end of our time horizon. In contrast, the Networked Solutions scenario shows the substantial overall impact that a structural shift in the production of energy can have: the faster we begin to seriously build our renewable production base, the more overall carbon emission reduction we will see. The other four scenarios diverge from one another only slightly, at the most, by 5%.

Annual global carbon emissions pass through to the overall stock of carbon in the atmosphere. Many have argued that we need to avoid moving above 450 parts of carbon per million to mitigate the most extreme impacts of climate change. None of our five scenarios achieves this target. The best scenario – Networked Solutions – sees continued growth in carbon PPM by 2040, passing 450 by 2030 and reaching 485 by 2040.

While Networked Solutions does not achieve the often proposed "safe" level of 450, there is good news. Although ICT alone – even promoted strongly – cannot lead to the target levels often discussed (in part because of the price rebound effects, as well as because it also increases GDP), it can have a significant impact on overall carbon in the atmosphere. That impact can be increased significantly when it is coupled with a global carbon price.

Four new scenarios were created. Two scenarios just modeled a ramped-up increase in carbon from 0$ in 2010 to either 100$ or 200$ by 2030. The Networked Solutions interventions were then added to these. Fig. 7 shows these four new scenarios, along with the original Base Case and Networked solutions scenarios out to 2100.[13]

The base case involves no significant intervention to promote reduction in green house gasses, and its atmospheric carbon levels approach 600 PPM by the end of the century, well above the 450 target. The next two clusters of scenarios (those saturating around 560 and 540 ppm) highlight the relative impact of the Networked Solutions scenario relative to the price of carbon. Comparing the 100$ carbon price and the original Networked Solutions scenarios finds general parity, as does comparing the 200$ carbon price with the 100$ carbon price and Networked Solutions. This indicates that aggressive but reasonable promotion of ICT can have a similar impact on carbon parts per million as a 100$ carbon price.

5. Discussion of findings and next steps

Advance in ICT (represented here in terms of penetration of broadband) has a generally positive potential to reduce carbon emissions via two paths (reduction in energy intensity and increased production of new renewable energy forms) that should outweigh the negative impact it has as a result of also contributing to the increase of GDP. The net positive affect is, however, not large. One of the key reasons is that the positive paths also tend to reduce energy prices and lead to offsetting increases in energy demand and increased competition of carbon-based fuels with new renewables. This rebound effect is important in leading our analysis to the conclusion that it is only in combination with some form of carbon pricing that ICT advance can truly enable reductions in carbon emissions.

These results may be disheartening for those who believe that ICT can bring about substantial overall reductions in carbon emissions on a global level on their own. They should not be, for two reasons. First, it is important and energizing that the net effect of acceleration in the advance of ICT, across multiple pathways of impact (economic productivity, energy efficiency, and renewable energy production and use), can be a reduction in carbon emissions. That is true in spite of ICT's positive impact on

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[13] We assessed the IFs treatment of carbon prices and their impact on carbon parts per million in relation to the work of Nordhaus and the DICE model [35]. We imposed on IFs the world carbon prices represented by Nordhaus in five scenarios: a Base Case, an Optimal Price scenario (increasing to 187.68$ in 2095), Kyoto with US involvement (increasing to 11.43$ in 2095), the prescription of Stern (increasing to 958.01$ by 2095), and the prescription of Gore (increasing to 873.52$ in 2095, but growing sharply to over 900$ by 2050). The table below compares the resultant atmospheric carbon level (PPM) results from the two models in 2100 across the five scenarios:

	Base case	Optimal price	Kyoto with US involvement	Stern review	Gore proposal
Nordhaus' DICE model	685.9	586.4	660.3	404.4	399.2
International Futures	596.5	564.3	588.9	458.2	472.8

Two major differences fall out of the table. First, the IFs base case is lower than the DICE base case. The IFs base case anticipates a significant rise in world energy prices by 2100, equivalent to as much as 500$ per ton of carbon To put this in context, a DICE scenario that caps global emission growth at 2% annually requires a carbon price that rises to more than 400$ per ton by the end of the century; the scenario produces a carbon level similar to the IFs base case. A more significant difference between the two models is the results that they produce for the Stern and Gore proposals, where the IFs forecasts are less optimistic about the achievable reductions (in absolute terms relative to Nordhaus and especially in absolute terms relative to the respective base cases). There are at least two likely explanations for this. The first relates to the treatment of the backstop price and the transition to a carbon free economy. Unlike in DICE, reaching the DICE backstop price in the IFs model would not lead to a full elimination of carbon emissions, because of the elasticity structure in IFs (with elasticity structure progressive reductions in carbon-based energy use require geometrically higher energy prices) and because of delays inherent in energy systems that contain longer-term fixed investments (which IFs represents). Second, it appears that the DICE model represents a considerably more rapid removal of carbon from the atmosphere into the biosphere and the upper oceans than does IFs. Our estimates indicate that in DICE as much as 8.5 Gt of carbon per year can be removed (this is apparent in scenarios and time periods without carbon emissions)[let's check this again and perhaps provide some detail], while the annual removal in IFs is 3 t per year. Collectively, modeling differences makes direct comparison of results from DICE and IFs difficult, but our analysis gives us considerable confidence in the general behavior of IFs.

economic growth and associated carbon emissions when energy consumption is mostly derived from fossil fuels, and it remains true in spite of the rebound effect's tendency to undercut gains in energy consumption reduction that result in lower energy prices.

Second, when we model changes in carbon prices in conjunction with increased penetration of ICT, the overall reduction in global carbon emissions is complementary. Thus, a global carbon price of around $200 in conjunction with accelerated ICT advance would lead to peak atmospheric carbon parts in per million of around the 500 level, still above what many analysts feel is "safe", but considerably below the current path of global development. These results indicate that it may be possible to promote both high growth and environmental sustainability, if managed correctly, though this is far from a certainty.

There are many limitations of an analysis of this type. Among these is considerable uncertainty in the literature around the magnitude of impacts of ICT within each of the three paths to carbon emissions that we have explored, especially that via renewable energy production. We have tried to address this uncertainty via scenario analysis and found that the results generally stand up to variations in parameterization. Another limitation is our inevitable omission of additional possible paths of importance. For instance, ICT might also enable the production of additional fossil fuels (for instance, via its support for techniques such as hydraulic fracturing, perhaps even undercutting its contribution to reduction in the cost of renewables). Future research could productively expand the pathways analyzed. There are also data limitations of many sorts, surrounding both ICT and energy variables. Finally, we have relied heavily on the broader International Futures (IFs) modeling system and its representations of economic, energy, and environmental systems, like all models, do have weaknesses. Much more research needs to be conducted to replicate and extend the study here of the relationship between ICT and the future of carbon emissions. Nonetheless, this integrated, multiple-path, scenario-augmented analysis has broken a new ground in helping us understand that important relationship.

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Appendix A. Representation of broadband in IFs

Construction of a forecast of broadband levels involved the following steps:

1. Analysis informed by the literature and based on generally accepted statistical analysis practices led to specification of a multivariate relationship. Two variables that were both theoretically and empirically relevant were a World Bank measure of governance, as well as GDP per capita at purchasing power parity. These were used to construct the coefficients in our analysis.
2. In the model's base year (2005) this multivariate regression produces a calculated value from the initial conditions of the independent variables.
3. The model compares the 2005 value thus forecasted with actual 2005 ITU Broadband Subscribers data.
4. The model adds a shift-term to the multivariate forecast so that the first year of data matches the most recent actual data value. This represents the first year's forecast.
5. We determined a technology shift factor, based on comparative cross-sectional analysis over time. The annual technology shift at the inflection point was 3% in our base case.
6. For the second year forecast, and all subsequent years:
    a. The cross-sectional relationship indicates the "expected" broad-band penetration rate for each country. That relationship is $\text{Broadband Subscribers} = -4.9 + 0.7 * \text{GDPPCP}/1000 + 0.12 * (\text{EXP}(\text{GovernanceRegQual} + 2.5) + 0.32 * (\text{ICT Expenditures}/\text{GDP}))$.
    b. Determine a country's technology advance/diffusion up the S-curve. That process takes into account the inflection point; this is the mid-point in the technology diffusion process, at which the initial exponential curve turns into a log curve (the point at which annual increments cease to grow and begin to decline). The base-case inflection point is 50%. It also takes into account the expected value of a country with respect to penetration.
    c. Add the technology shift increment to the previous year's penetration rate and its rate of movement up the S-curve. This produces a forecast of the expected penetration rate in the current year.

If history is a good indicator the diffusion pattern for a wired technology for each country should follow a similar pattern to the development of telephone lines per capita, which saturated well below 100 lines (in many cases, around 0.3 lines per person). However, because the ITU measurement of broadband subscribers takes into consideration any device that connects to the internet at speeds over 256 kb/s, the unique characteristic of Broadband as a wired technology cannot be usefully exploited. 3G mobile technology already allows users to connect at speeds greater than the ITU threshold. We set the saturation point at 100%. The forecast of broadband is thus a hybrid between mobile and fixed technologies. It is initialized using the ITU value, but is forecasted with the inclusion of a technology shift value which pushes penetration rates up exogenously, a pattern typically found in the diffusion of wireless ICT.

Appendix B. Establishing the link to renewable energy

1. Total electricity generating capacity for the US in 2007 was taken from the US Energy Information Administration data (http://www.eia.doe.gov/fuelelectric.html) was 1,104,486 MW. Total Generated Electricity for the US was 4,156,745,000 MWh. Dividing the two gives us the utilization of the capacity over the year: 3763.5 h per year, or 10.3 h per day.
2. The percentage of US electricity generation to total generation was taken by converting the MegaWatt Hours (4,156,745,000) to Billions of Barrels of Oil Equivalent. The unit of conversation was 1 MW is $5.88235 * 10^{-10}$ leaving us with 2.445 BBOE. This conversion was then compared to the IFs Total Energy Production for the US, 11.712 BBOE. Dividing the percentage of total electricity production in BBOE for the US (2.445) by total energy production for the US (11.712) produces 20.9%.
3. For the 2030 forecast for renewable energy production by scenario, the two Brattle Group scenarios were used. The Base Case shows no additional investment in ICT for Energy Efficiency and Demand Reduction strategies (of which Advanced Monitoring Infrastructure is a pivotal component) and produces an additional electricity generating capacity of 214,000 MW. The Realistic Achievable Potential scenario produces has a reasonable investment in Energy Efficiency and Demand Reduction strategies and requires an additional generation capacity of 139,000 MW. The key difference between these scenarios is the new renewable energy required, which is 18% in the base-case and 29.5% in the realistically achievable potential scenario.
4. Knowing the ratio of new electricity production from renewable energy by scenario and the ratio of total energy production to electricity production in 2030 (taken from an IFs base-case forecast), we calculate the percentage of new energy that comes from renewable. Knowing the percentage of total energy that currently comes from renewable energy sources (again, taken from IFs) along with the above information, we can calculate the total energy from renewable to 2030 by different scenarios.

	Percent of new electricity from renewables	Percent of total electricity generation to total energy generation in 2030	Percent of total new energy from renewables	Percent of renewable to total energy generation in 2010	Total energy from renewables in 2030
Base case	18.0%	27.0%	4.9%	1.3%	6.2%
Realistically achievable potential	29.5%	25.5%	7.5%	1.3%	8.8%

5. Next, we identified different levels of ICT to determine our elasticity. The main difference between the two scenarios is an emphasis on energy efficiency and demand reduction strategies, of which ICT is an important component. The Base Case assumes that there is no additional investment in these activities, so we compared base-case ICT diffusion in IFs with no additional ICT investment, or an ICT scenario that stagnated in development.

Low ICT	21.1%
High ICT	90.8%

6. We determined our elasticity by dividing the change in renewable energy penetration by our ICT penetration.

$$(8.8\%-6.2\%)/(90.8\%/21.1\%) = .037$$

Therefore, a 10% increase in broadband penetration would lead to an increase additively of 0.37% of renewable's share of total energy production.

Contributing the entire increase in the share of renewable energy's portion of total energy production to ICT within these scenarios would be a great stretch. The Brattle Group scenarios placed heavy emphasis on the role of Energy Efficiency and Demand Reduction, two general themes that we picked up on in the exploration of energy intensity reduction. As no other measure of this kind exists in the literature, we were forced to arbitrarily reduce the elasticity that we found by half to 0.0185.

Appendix C. Sensitivity analysis with parameterization and carbon parts per million

Carbon parts per million, peak level out to 2100 by ICT scenario: sensitivity analysis					
		Energy demand and productivity			
		High ICT penetration			
Renewable energy cost	High ICT penetration	Forward linkage treatment	Double	Base-case	Off
		Double	575.6	573.4	570.3
		Base-case	587.6	586.1	583.9
		Off	594.1	594.7	593.8
			Double	Base-case	Off
	Low ICT penetration	Double	596	595.8	596.3
		Base-case	595.8	596.3	595.1
		Off	592.5	592.5	593.8

Appendix D. Parameterization of relationships in IFs model

	Calibrated parameter in IFs	1% increase in broadband penetration leads to:
GDP growth (IFs parameter ictbroadm)	0.0075	0.12% increase in GDP
Energy demand (IFs parameter elendemict)	0.0008	0.08% decrease in energy demand
Renewable energy (IFs parameter elenrenict)	0.00085	0.0185% increase in renewable's share of total energy production

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