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Jussi Ahola, Toni Ahlqvist, Miikka Ermes, Jouko Myllyoja
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ICT for Environmental Sustainability

Green ICT Roadmap

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Abstract

This report presents a VTT roadmap on ICT for environmental sustainability, based on the assessments and evaluations made by VTT technology experts. We adopt a broad and systemic view to the issue; in other words, we believe that ICT's effectiveness depends on mutual understanding and changing the system level activities, i.e. the complex web of behaviour of people, institutions, organisations and political jurisdictions, like nation-states. We use the term ICT for environmental sustainability or environmentally sustainable ICT, instead of green ICT, and defined it as: *Use of ICT for optimising societal activities in order to improve environmental sustainability*. The roadmap is divided into three themes. *Empowering people* means using ICT to raise people's awareness of the environmental impact of their actions and to channel their behaviour in a more environmentally-friendly direction. *Extending natural resources* involves reducing the use of diverse environmentally unsustainable re-sources through ICT-based solutions. *Optimising systems* refers to minimising the environmental load of diverse systems by optimising their operation. As a synthesis, we identified four focal topics within the roadmap themes that are most promising for further investigation. These are: 1) *environmentally sustainable consumption*, 2) *smart energy and buildings*, 3) *lifecycle efficient production*, and 4) *optimised and adaptive networks*.

Executive summary

Green ICT, or sustainable ICT, is a hot topic and initiative that has recently emerged to address the problematic role of ICT for environmental sustainability. That is, in the past few years, ICT has increased sustainability by decreasing resource intensity but has at the same time encouraged resource-consuming lifestyles. Consequently, the aim of green ICT is to make the overall impact of ICT clearly environmentally sustainable and positive.

Originally, green ICT was understood to be limited to the direct effects of ICT on the environment, but nowadays, it is often considered to include the use of ICT to improve the environmental efficiency of other industries and domains. In this report, we adopt the latter, broader view and take a systemic viewpoint on the subject. In other words, we believe that ICT's effectiveness depends on mutual understanding and changing the system level activities, i.e. the complex web of behaviour of people, institutions, organisations and political jurisdictions, like nation-states.

To emphasise a wider view of the subject and to avoid confusion in the terminology, in this report we will use the term ICT for environmental sustainability or environmentally sustainable ICT, instead of green ICT, and will define it as: *The optimal use of ICT for managing the environmental sustainability of societal activities*. In other words, the aim is to use ICT to minimise the environmental load caused by humans. The report provides an outlook of potential developments in the field based on VTT's technological competence; it aims to create a structure of ICT solutions and, furthermore, to identify some central themes and topics that have the most untapped potential from a technological perspective.

The roadmap is divided into three themes that were defined during the early stages of the roadmapping process. *Empowering people* means using ICT to raise people's awareness of the environmental impact of their actions and to channel their behaviour in a more environmentally-friendly direction. *Extending natural resources* involves reducing the use of diverse environmentally unsustainable resources through ICT-based solutions. *Optimising systems* refers to minimising the environmental load of diverse systems by optimising their operation.

By carefully analysing the roadmaps, we were able to identify four focal topics within the themes. These topics summarise the key findings of the roadmap concretely and in detail. In other words, they present our view of the most relevant research topics that have both significant potential in terms of environmental sustainability and great application opportunities for ICT. The focal topics are presented as the final conclusion of the report:

1. **Environmentally sustainable consumption**. Novel ICT tools are needed to help average consumers make environmentally sustainable decisions in their daily lives. Such tools may include

automatic calculators of carbon footprints and other individual measures as well as social media applications that promote ecological behaviour. The ICT tools that support sustainable consumption must simplify this complex information and also present it in more personal and motivating manner. To present and distribute information, online communities and user-driven design are essential. The standards and respective databases and marketplaces for exchanging, processing and reporting environmental information between different operators, systems and even devices are of crucial importance. Currently, the lack of governmental actions and other guidance is limiting consumer motivation to use ICT technologies for environmental sustainability. Future challenges also include coping with the complexity of the ICT systems and networks, and the lack of standards that define and provide for the exchange of information on environmental sustainability.

2. **Smart energy and buildings**. Smart metering – i.e. solutions that are able to measure energy consumption in greater detail than current systems and also communicate that information further through network(s) – is a technology that is developing quite rapidly. The new information paves the way for novel business models and the provision of new digital services for diverse stakeholders. In the long run, smart metering together with other technologies, such as home area networks, smart appliances, and building automation, enables direct feedback from the energy consumption information to load control, which is the ultimate goal. Furthermore, the smart grid concept will enable distributed, small-scale energy generation in buildings or at the neighbourhood level, using mainly renewable energy sources. Finally, there are some major practical challenges to be solved in order to successfully implement smart meters, grids and buildings, such as the prediction and optimisation models, the building and (low voltage) distribution network automation, standardisation and information security.

3. **Lifecycle efficient production**. For the process and manufacturing industry, there will be new production paradigms requiring a more extensive and systemic way of utilising ICT. For example, integrated production results in facilities where several different products are manufactured in a single factory and digital product processes that result in the digitalisation of information and even products, especially in product development. Large-scale simulation and modelling as well as integrated product information systems are needed to assess and manage the environmental impact of the products throughout their lifecycle, and their operation should be optimised while minimising the impacts of the individual lifecycle phases. ICT-enabled optimisation can provide great savings in production through tailored mass production, the utilisation of production lines, the optimisation of raw material usage, preventive maintenance, etc. Recycling is also gaining popularity all the time and it will be increasingly seen as a source of raw material. In terms of energy production, the use of renewable energy sources is definitely increasing, mainly due to reasons related to the politics of global warming.

4. **Optimised and adaptive networks**. ICT brings intelligence to all sorts of networks, including the transportation, telecommunications, energy, delivery chain and water networks, and requires new solutions for network management. ICT enables network optimisation at multiple levels; structure, energy consumption, throughput, etc. As the networks provide more up-to-date information, more detailed and accurate forecasts can be made. Novel network management solutions will emerge that can even be applied to many different networks. For example, telecom network solutions can

readily be tailored to energy networks. The need for more advanced intelligent transportation systems (ITS) is undeniable. ITS will contain solutions for following up, taking the snapshot, processing the control response, and enforcing the control of traffic flows and individual vehicles. They will also support recent concepts, such as electric cars, demand-responsive public transport, eco-driving, etc. One central technology is remote collaboration, which reduces the need for transportation and thus arguably had the greatest impact on the environmental sustainability of mobility.

Terms and abbreviations

Artificial intelligence (AI) = Concept for providing machines with the capability to mimic human properties and activities that require intelligence, such as cognition.

Automatic meter reading (AMR) = Technology for remotely accessing and collecting data over a data network from utility (water, heating, electricity etc.) meters.

Carbon footprint = An indicator of total greenhouse gas emissions caused by an entity. A carbon footprint is only one ecological footprint; other indicators include e.g. water footprint and footprint.

Combined heat and power (CHP) = The generation of electricity and heat simultaneously in the same power plant.

Cloud computing = A type of computing where the computing resources are provided as a service over the Internet. In other words, instead of local servers or personal devices, the distant servers or server farms are utilised to handle applications.

Cross-reality applications = Services or solutions that combine the physical and virtual worlds. For example, user interaction can add virtual features to enhance the physical surroundings.

Demand-responsive transport (DRT) = Public transport that is not bound to fixed schedules and routes; instead, passengers are picked up and dropped in accordance of their needs.

Distributed energy production = The decentralised generation of energy using many small, local energy resources. Often this is associated with small scale power production using renewables, such as sunlight, wind and geothermal power.

Empowering people = Using ICT to raise people's awareness of the environmental impacts of their actions to help steer people's behaviour in a more environmentally friendly direction.

Extending natural resources = Involves reducing the use of diverse environmentally unsustainable resources through ICT-based solutions.

Environmentally sustainable ICT/Green ICT = The use of ICT for optimising the environmental sustainability of societal activities. In other words: utilising ICT to minimise the environmental load caused by humans.

Information and communication technologies (ICT) = Technologies for information transfer, management, processing and sharing using computers and telecommunications equipment. ICT basically includes all activities related to information technology (IT) and telecommunications (telecom).

Intelligent transportation systems (ITS) = Systems that employ ICT technologies in traffic infrastructure and/or vehicles in order to improve the efficiency and safety of the transportation networks. ITS include a wide variety of applications, from car navigation and traffic signal control to container management and bridge de-icing systems.

Lifecycle assessment (LCA) = A technique for determining the environmental impacts of products, processes or services throughout their lifecycle; from the extraction of raw materials to processing, transport, use and disposal. The LCA procedures are standardised in ISO environmental management standards.

Optimising systems = Minimising the environmental load of diverse systems by optimising their operation.

Parallel computing = A form of computation where several processors are used simultaneously to execute a program. The basic idea of parallel computing is to divide large computing problems into smaller ones and run different segments simultaneously on different processors.

Product data management (PDM) = A function for creating, managing and publishing product data to ensure information consistency throughout the lifecycle of a product. See also Product lifecycle management (PLM).

Product life cycle management (PLM) = The process of managing the entire lifecycle of products; from the design, production, support, and use to final disposal. The goal of PLM is to minimise waste and maximise the efficiency of a product.

Remote collaboration = An activity that allows several people who are physically in different locations to communicate and interact with one other utilising telecom networks and presence technologies.

Radio-frequency identification (RFID) = Technology for wirelessly transmitting the identification label (in the form of a unique identifier) of an object. RFID systems consist of tags that carry the identifier information and readers that offer long-distance identification.

Smart grids = The next generation, intelligent energy distribution networks. Smart grids are less centralised and more consumer-interactive than the present grids and they increase the connectivity, automation and coordination among different stakeholders.

Smart metering = Measuring the consumption of utility (water, heating, electricity etc.) meters. Smart meters are able to measure energy consumption in greater detail than current systems and can also communicate that information through network(s). See also AMR.

Visionary socio-technical roadmaps = Visionary socio-technical roadmaps are visualisations of knowledge based on expert assessment. They combine societal and technological issues in relation to explicitly stated visions of the future. A roadmap usually integrates knowledge-content layers (e.g. drivers, markets, solutions, enabling technologies) with temporal dimensions (e.g. present, middle term, long term).

Web 3.0 = The third generation of the internet. What it will include and when it will be launched is not yet clear. However, it has often been said that Web 3.0 will be, e.g., semantic, personal, ubiquitous, and intelligent and that it will appear gradually over the coming years (some components already exist).

Contents

1. Introduction

Environmental sustainability is a very hot topic at the moment. Topics such as climate change and global warming have generated a lot of discussion and even some international regulations aimed at reducing the human environmental load. For example, in January 2008, the EU commission launched a climate and energy package in which the EU commits to decrease its overall emissions by at least 20 percent below 1990 levels by the year 2020, improving energy efficiency by 20 percent and increasing the share of renewables in energy use to 20 percent. A concrete measure for achieving this goal is the EU Emissions Trading Scheme (EU-ETS). The implementation of ambitious climate policies and ambitious reduction targets in the long term (an 80% reduction by 2050) requires new approaches and tools that go beyond the current portfolio of policies and measures.

The ICT sector has also been forced to evaluate its impact on the environment. Without a doubt, ICT has played a major role in decreasing the resource intensity in society and hence has had a positive impact on environmental sustainability. At the same time, however, ICT has enabled and accelerated development towards more resource-consuming lifestyles, including the rapidly increased resource consumption of ICT itself, and therefore laid stress on the environment. Thus, it is fair to say that ICT is part of the problem. However, it is important to note is that ICT can also be part of the solution.

Green ICT is a topic and initiative that has emerged recently to address this problematic role of ICT. Its main objective is to change the overall impact of ICT, making it environmentally sustainable and positive. Although the term has been widely used, the contents of green ICT have yet to be clearly established. Originally green ICT was understood to encompass only the direct effects of ICT on the environment, i.e. the design, manufacture, use, and final disposal of ICT equipment and services. Nowadays, however, it is more common to consider the use of ICT as a way to improve the environmental efficiency in other industries and domains. This view is, in a way, well-justified due to the ubiquitous nature of ICT i.e. it is embedded pretty much everywhere. In this roadmap, we will adopt this broader view of green ICT.

The aim of the roadmap is to form a perspective on the issue of green ICT based on VTT's technological expertise. This report offers an outlook of the potential developments of green ICT based on VTT's technological competence. More precisely, the report aims to create a structure of green ICT solutions and, furthermore, to identify some central themes and topics that have the most untapped potential from a technological perspective. The roadmap is not just outlining a strategy for VTT. Instead, we have tried to offer a general assessment of ICT's potential for the future in order to enable different actors and organisations to locate and navigate their own activities. We have chosen some focal areas, like industrial production, as the basis for visionary ventures.

The roadmap has a systemic viewpoint. In other words, we believe that ICT's effectiveness depends on mutual understanding and changing the system level activities, i.e. the complex web of behaviour of people, institutions, organisations and political jurisdictions, like nation-states. The impact of technologies should thus be compared with their systemic effects. We do not believe that any separate solution or application can trigger systemic changes. Instead, inducing systemic change requires an understanding of technologies in societies, markets and in the context of human behaviours. Technologies should be approached as socio-technologies, not merely as the technical applications of individual solutions.

To emphasise our broader view of the subject and to avoid confusion in the terminology, we will henceforth use the term ICT for environmental sustainability or environmentally sustainable ICT instead of green ICT. Furthermore, we define ICT for environmental sustainability as "Use of ICT for optimising societal activities in order to improve environmental sustainability". In other words, the aim is to use ICT to minimise the environmental load caused by humans. The approach of the report is to concentrate on the activities and solutions that currently have high potential for significant impacts on environmental sustainability. Solutions that are seen to have only marginal environmental impacts on a global scale are considered in lesser detail. The overall target used for guiding the roadmapping work was to separate overdriven resource use from economic growth.

The roadmaps presented in this report are structured around three themes that were defined in the flow of the roadmapping process, which is described in the next section. *Empowering people* refers to using ICT to raise people's awareness of the environmental impacts of their actions to steer their behaviour in a more environmental-friendly direction. *Extending natural resources* involves reducing the use of diverse environmentally unsustainable resources through ICT-based solutions. *Optimising systems* considers minimising the environmental load of diverse systems by optimising their operations.

In the next section, the roadmapping process is outlined. After that, in section 4, a short recap of the main reports and studies regarding the field of ICT for environmental sustainability is presented. In section 5, the main drivers of the subject are considered. Sections 6–9 present the actual roadmaps; the sub-roadmaps for the three themes mentioned above preceded by the meta-roadmap that integrates their central contents. Finally, the key findings of the report are summarised in Section 10.

2. The roadmapping methodology and process

The roadmaps presented in this report were constructed by emphasising the following three criteria. Firstly, roadmaps are *visionary socio-technical roadmaps*, i.e. they are constructed to combine examinations on societal and technological issues in relation to explicitly stated visions of the future (see Ahlqvist et al. 2007: 86–87). The idea is that the combined elements of the roadmaps have strong potential for producing the outcomes that each vision presents. Roadmaps strive to describe relations and potential causalities between the technological and societal issues mainly from the viewpoints of companies, R&D actors (research institutes, universities), governmental actors and non-governmental actors. However, it should be mentioned that the roadmaps are not intended to depict the future in a deterministic way, i.e. we do not assume that any of the visions or roadmap explorations presented in this report will in fact become a reality. Thus, future development is likely to include some elements that are presented in these roadmaps, but there will also be new and surprising elements that obviously could not be taken into account when creating these roadmaps.

The second criterion for the ICT for sustainability roadmaps was to organise development paths and possibilities around three themes: empowering people, extending natural resources and optimising systems. The themes of the roadmaps are quite broad. This sets some limits on the applicability of the roadmaps. The roadmaps presented here should not be read like product roadmaps or action plans, i.e. as the presentations of definite causal structures or temporal paths to realise some concrete goals. These roadmaps describe some of the key transformations and elements in transition within each theme. Therefore, roadmaps should be approached as strategic tools for creating deeper understanding and setting agendas for the utilisation of environmentally sustainable ICT.

Thirdly, the roadmaps are the outcomes of the expert workshop process and core group iterations. The roadmaps therefore crystallise the views of a group of experts that were collected in a systematic process and re-worked by the core group of the project.

The research questions of the social media roadmapping project can be formulated as:

1. What are the most important possibilities and challenges for ICT in terms of environmental sustainability?
2. Which roadmap levels are they affecting? The roadmap levels are: drivers, bottlenecks, services, products and markets, and enabling technologies.

3. What are the temporal sequences of the possibilities and challenges identified on the roadmap? The temporal levels of the roadmaps are: present (current state-of-the-art activities), middle term (about 5–10 years) and long term (over 10 years).

The roadmapping process was completed in three working phases (Figure 1). Phase I was a landscaping phase that depicts the field of ICT for environmental sustainability. In the first step, desktop research and the relevant literature, such as reports and studies, were mapped and positioned. After the desktop step, there was a discussion workshop. In this workshop, the first core group was formed and the process themes were discussed. In the third step of phase I, relevant themes for the roadmapping phase were formed. The themes chosen for the roadmapping were: empowering people, developing demand-side management and optimising systems. The reason behind this selection was the desire for broad themes that would emphasise extensive multi-technological and cross-industry solutions.

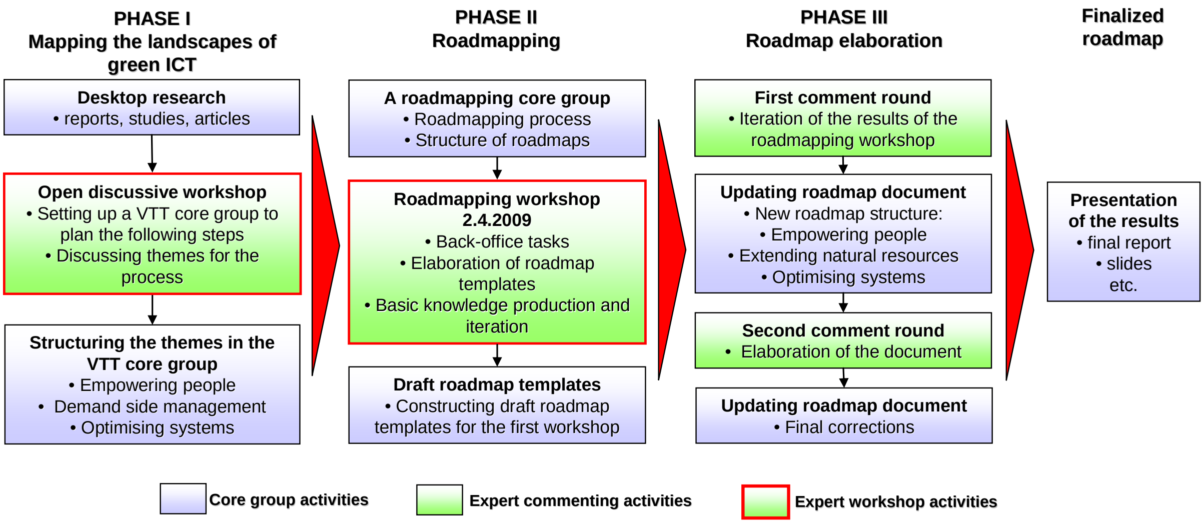

Figure 1. The roadmapping process.

The first step of phase II, roadmapping, involved setting up a specific roadmapping core group. The task of this core group was to plan the roadmapping process, to decide upon the structure of the roadmaps and to plan a roadmapping workshop. The second step was an expert workshop that provided the basic content of the roadmaps. A total of 16 expert participants participated in the workshop with the core group members (see acknowledgements). As an outcome of the workshop, roadmap templates were drafted.

Phase III involved roadmap elaboration. The first step was a round of comments in which VTT experts iterated and reflected on the results of the roadmapping workshop (see acknowledgements). In step two, the roadmap document was thoroughly updated. In addition, the roadmap structure was elaborated and our roadmapping structure was changed a bit. Practically this meant that the second roadmap template, "developing demand-side management" was transformed into "extending natural resources" due to its content emphasis. The third step was a second extensive round of commenting on the document. After this second round of comments, further corrections and changes were made and the roadmap was finalised.

3. Desktop survey on ICT for environmental sustainability

In the following, we discuss and present some of the most relevant reports related to the field of ICT for sustainability.

Pathways to a Low-Carbon Economy report by McKinsey (McKinsey & Company 2009) provides a global greenhouse gas abatement cost curve, which estimates the potential and costs of more than 200 GHG (Green House Gas) abatement activities across 10 sectors and 21 world regions (Figure 2). According to this report, there is potential to reduce the GHG emissions by 38 GtCO_2e by 2030. This means a 35 percent reduction compared with 1990 levels or a 70 percent reduction compared to a business-as-usual scenario for 2030. The activities are divided into four categories (the estimated abatement potential in parenthesis): energy efficiency (14 GtCO_2e), low-carbon energy supply (12 GtCO_2e), terrestrial carbon (forestry and agriculture, 12 GtCO_2e), and behavioural change (3.5–5 GtCO_2e). Regarding the three first categories, the report estimates that 33 percent of the abatement potential lies in land-use sectors (agriculture, forestry), 29 percent in energy supply sectors (electricity, petroleum and gas), 22 percent in sectors with significant consumer influence (transportation, buildings, waste), and 16 percent in the industrial sector. Regarding the last category, the report claims that changing behaviour is difficult and will greatly depend on the kind of incentives policy makers are able to offer.

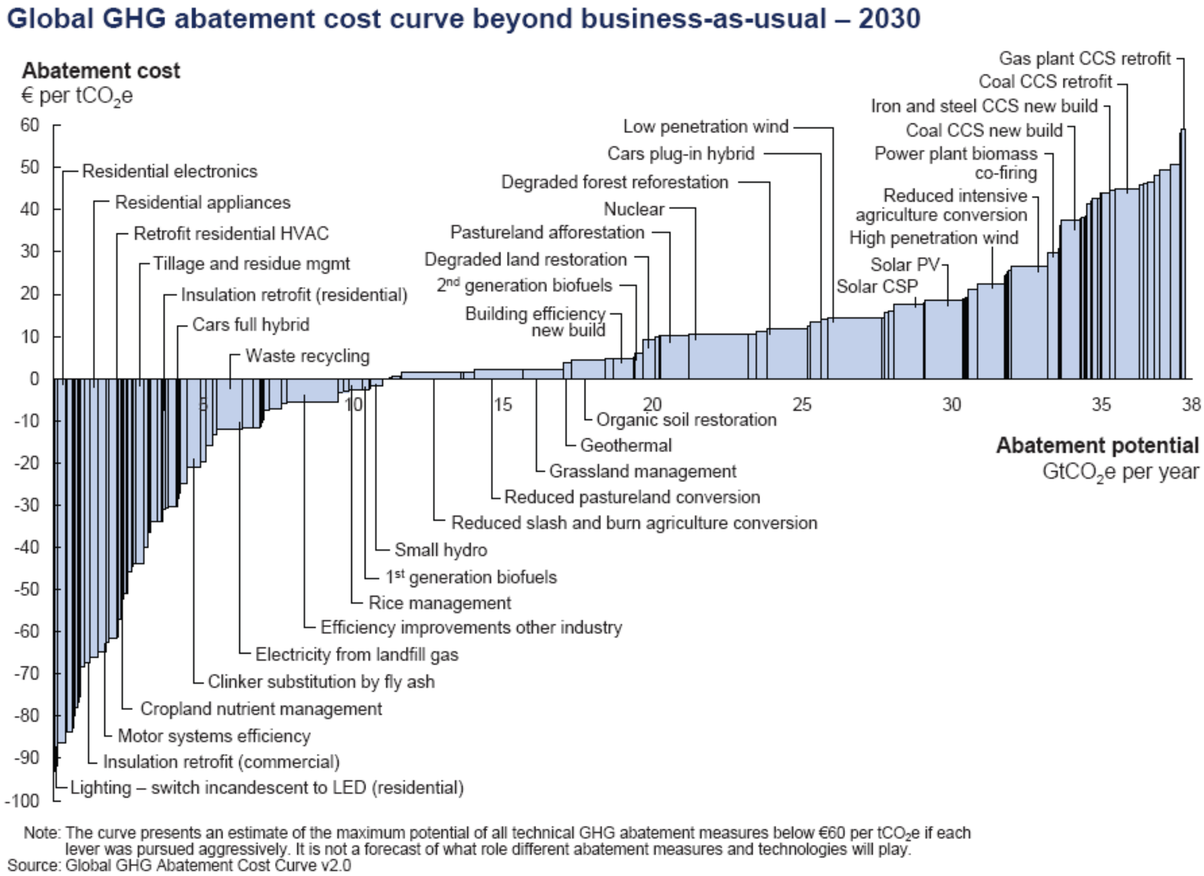

Figure 2. Global GHG abatement curve (McKinsey & Company 2009: 7).

In the report *SMART 2020* (Global eSustainability Initiative 2008), the Global eSustainability Initiative (GeSI) evaluated the impacts of direct emissions of ICT products and services based on expected growth in the ICT sector. It also assessed areas where ICT could enable significant emission reductions. The report states that ICT's largest influence will involve enabling energy efficiency in other sectors and not in increasing the energy efficiency of ICT products and services as such. The biggest role ICTs could play is in helping to improve energy efficiency in electricity supply infrastructure, the power consumption of buildings and factories and the use of transportation to deliver goods. Consequently, by realising the opportunities in smart motor systems, smart logistics, smart buildings, and smart grids, ICT could produce emissions savings of approximately 7.8 $GtCO_2e$. This amounts to carbon savings five times larger than the total emissions from the entire ICT sector in 2020, translating into savings of approximately €600 billion. The report also stresses that in order to capitalise the potential of ICT for sustainability, major policy, market and behavioural changes are required.

Gartner's report Green IT – *The New Industry Shock Wave* (Gartner 2007a) concentrates on the potential changes that greener ICT could have on business practises. The report also raises the issue of "green fatigue" on the agenda, i.e. the over-exposition of green information and the attitude people could adopt towards this information. The report also presumes that green IT will go through the same hype cycle as every new emerging technology. Only after a big hype it is possible to realistically evaluate the actual roles of green IT in society. Gartner notes that the motivation of midsize enterprises in moving towards green IT is mainly cost savings. Importantly, the report notes that the big opportunity for the IT industry lies in the use of ICT to reduce the overall environmental impact of enterprises instead of focusing on the footprint of the ICT hardware.

Another Gartner's report, *Green IT – Where to Invest* (Gartner 2008) aims at defining those "green industry" segments that investors should consider prominent while green values are promoted in almost all products. Gartner has worked with its clients to define the most prominent topics of green IT (Figure 3).

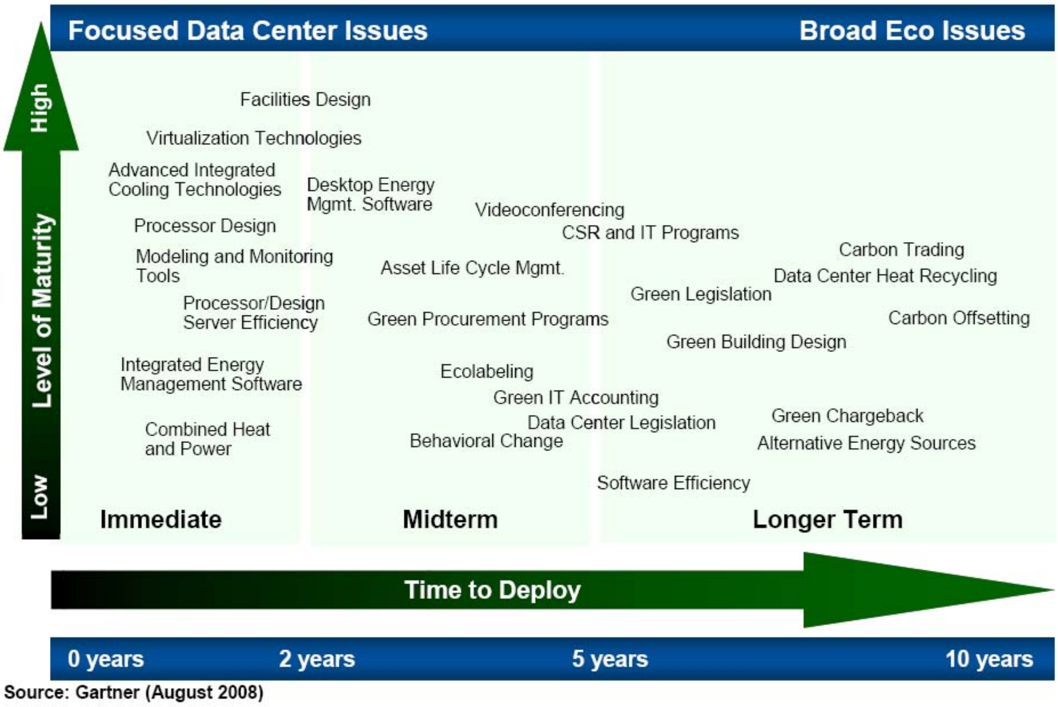

Figure 3. Development of green IT according to Gartner (Gartner 2008: 2).

The key finding of the third Gartner report *IT's Role in a Low-Carbon Economy* (Gartner 2007b) is that the ICT industry is the winner in the future low-carbon economy as new business opportunities are opening in many fields. The current contribution of ICTs to low-carbon economy is considered modest, with the exception of teleconferencing solutions. The report lists some of the fields where ICT can make substantial environmental impact: 1) fuel-efficient vehicles, 2) energy-efficient buildings, 3) forest management, 4) transportation management, 5) travel substitution, 6) carbon accounting and eco-labelling, 7) flexible working, 8) process analysis and optimisation, 9) supply chain management, 10) e-business and e-government, and 11) environmental management systems.

The Potential Global CO_2 Reductions from ICT Use report (WWF 2008) is the result of collaboration between WWF (the World Wildlife Fund) and HP (Hewlett-Packard). The purpose of the report is to identify ICTs that could contribute to billion ton reductions in CO_2 emissions. The following solution areas were identified: 1) smart city planning, 2) smart buildings, 3) smart appliances, 4) dematerialisation services, 5) smart industry, 6) i-optimisation, 7) smart grid, 8) integrated renewable solutions,

9) smart work, and 10) intelligent transport. The report is written from a positive perspective instead of merely listing the problems. It concentrates on new business opportunities initiated by climate change. On Table 1 (below), the potentials of different green ICT solutions for emission reduction are presented and compared. It is quite difficult to provide estimates of the potential and for that reason three different values (low, medium, high) are presented for each solution area.

Table 1. Estimated incremental potential for GHG emission reduction by ICT by 2030 (WWF 2008: 4).

	Estimated incremental potential for GHG emission reductions enabled by ICT by 2030 $MtCO_2$		
	Low	**Medium**	**High**
Smart buildings – ICT in legacy buildings	121	545	969
Smart buildings – ICT for planning and operating new buildings	46	439	832
Transport mode switching enabled by smart urban planning	38	190	380
Telecommunications and virtual meetings (smart work)	68	159	404
In vehicle ICT and intelligent transport infrastructures (smart vehicles and intelligent transport)	581	1 486	2 646
E-commerce and dematerialisation	198	927	1 822
ICT for energy efficiency in industry (improving day by day operations; smart industry plant and process design; I-optimisation)	100	815	1 530
ICT in energy supply systems (removal of network constraints – 2020)	17	59	128
Estimated total potential for CO_2 emission reductions	**1 168**	**4 620**	**8 711**

In the report *Saving the Climate at the Speed of Light* (ETNO & WWF 2006), the European Telecommunications Network Operators' Association (ETNO) and WWF present a roadmap for reducing CO_2 emissions in the EU and beyond. The report states that in order to achieve the necessary reductions of CO_2 dramatic structural changes in infrastructure, lifestyles and business practise are required. The effects of ICT are divided into three groups: direct, indirect and systemic (see Figure 4). The gap between the academic studies (discussing theoretical potentials of technologies) and policy makers (requiring specific information of what needs to be done) is noted and the roadmap report attempts to bridge this gap.

Currently, the focus of environmentally sustainable ICT is mostly on products instead of services, and ICT companies do not recognise green ICT as a business opportunity. The roadmap outlines two phases for actions:

- The first phase is a goal for 2010: to keep emissions below 50 million tonnes of CO_2 annually. This can be done by implementing several strategic ICT applications, e.g. virtual meetings, e-dematerialisation and flexi-work as well as some additional tasks like policy revision (e.g. energy, tax, transport, innovation, etc.).
- The second phase is a target for 2020 and should include more services and system solutions that combine a number of services, as well as a more ambitious target for CO_2 reduction. Possible fo-

cus areas for the second phase are sustainable consumption, production, city planning and community development.

The report presents three real-world case studies of ICT for environmental sustainability in the areas of 1) travel substitution, 2) sustainable consumption and 3) new combined services. Reducing the need for travel is identified as the most obvious (short-term) way for ICT to reduce CO_2 emissions. The report also emphasises the need for decision-making at the high-level governmental level and for policies related to sustainable development.

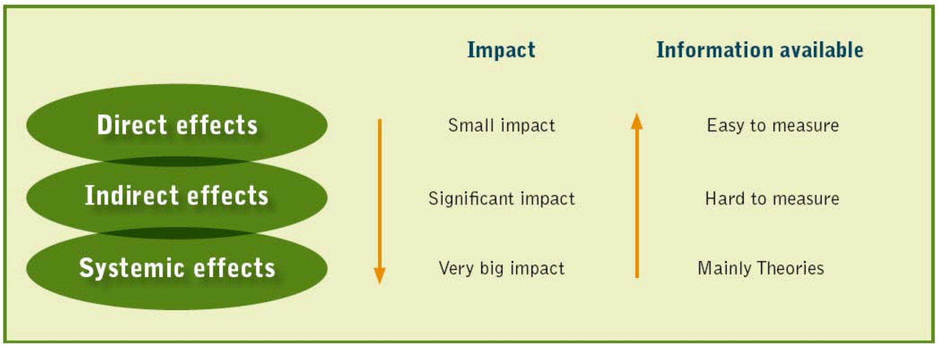

Figure 4. The effects of ICTs (ETNO & WWF 2006: 11).

Round-up

There are some general conclusions that can be drawn from the reports presented briefly above. For instance, most of the reports focus on the potential of ICTs in other sectors instead of the ICT sector itself. In other words, the environmental impacts of applying ICT in other economic sectors are estimated to be greater than those of intensifying and gearing up the ICT sector itself. The reports also point out that the environmental footprint of the ICT sector is the most rapidly growing one, so it cannot be neglected.

Another view shared by the reports is that making a significant impact and changing the state-of-affairs requires that society make major systemic changes in both structure and behaviour. The reports seem to approach environmentally sustainable ICT from the viewpoint of industry but do not consider how people, as citizens and consumers, can contribute to the low-carbon economy. Still, new incentives and policies that steer both the companies and citizens/consumers towards more sustainable behaviour are needed. Consequently, policy-makers and governments will play a central role in this equation.

Finally, most of the reports and the corresponding research is now concentrated on just climate change, the mitigation of GHG-emissions and adaptation. Although this is unquestionably an important issue, sustainability is a topic that goes far beyond climate change. For example, more thought should be give to topics such as efficient resource use (both non-renewables and renewables, energy, water and land-use), the emissions and use of hazardous substances, and the conservation of biodiversity and "ecosystem services."

4. Drivers of ICT for environmental sustainability

New environmentally benign technologies are facing many challenges, changes and possibilities. Globalisation, population growth, drastic changes in lifestyles, and climate change are all contributing to this situation. Limited oil resources, the consequential energy price fluctuations and their significant impact on vital markets (other fuels, food, logistics etc.) and thus on the selection of energy sources are key issues for all of the world's countries and regions. Political decision making and legislation – with a constantly shifting variety of new regulations, standards and recommendations – is another important aspect in the development of environmental innovations. From this perspective, ICT has a two-fold role as a consumer of electricity and scarce natural resources and as an enabler of environmentally friendly solutions, to encourage positive social practises and develop an ecologically sustainable society.

Globalisation is a vital part of the challenge. Along with intensive competition, the markets are increasingly favouring solutions which can contribute both environmental and economical benefits (Ministry of the Environment 2007). Environmental aspects should no longer be seen as something that has to be dealt with: instead, it should be viewed as a source of process enhancement, product quality improvement, material savings and competitive advantage. In other words, organisations should become increasingly convinced that greener solutions can also be a source of profits (UNEP 2001). As a consequence of globalisation, it is becoming increasingly hard for a single player to innovate (Hermansson 2007). This also means that good engineering alone is not enough to make an innovative breakthrough: cross-boundary thinking is also required among various actors such as complementary solution providers, vendors, financiers, research institutes and competitors. There is a need to focus: no single actor can be the best at everything (Hermansson 2007). For nations, for example, clear national strategies are required, and increasingly, a specific competition advantage analysis is required for different countries or regions, such as the Nordic countries and the EU. In these strategic efforts, it is useful to look at the development from the value chain perspective as well. Although it is an acknowledged fact that production and its detrimental environmental effects are increasingly moving to Asia, it is important to remember that most of the sales profits still stays with the brand owners, developers and delivery chain (Tekes 2009).

A recent Tekes report (2009) recounts the crystallisation of six sweeping mega trends that have crucial impacts on the demand for innovative activities. As can also be seen on Table 2, these crystallised mega trends also have a direct affect on the development of environmentally sustainable ICT. What is important to note is that many of the identified mega trends are linked to consumer behaviour or to the consequences of user activities. Therefore it is important to realise – especially in the Finnish context, which is still very technology-driven – that the most important changes happen at the systemic user level and involve consumer behaviour. These changes cannot be tackled by incrementally developing separate applications or solutions alone. Instead, the development activities should be directed at large business concepts that combine technology and service perspectives and are aimed at system-level changes, i.e. enabling technologies to drive more intelligent and sustainable consumption.

The basic material behind these mega trends was produced in collaboration with four organisations: The Finnish Funding Agency for Technology and Innovation Tekes, VTT Technical Research Centre of Finland, The Research Institute of the Finnish Economy (Etla) and the National Consumer Research Centre of Finland. After the initial material was prepared, the identified mega trends were presented on the web for evaluation. All in all, 6,000 evaluations were done. The material thus provides a sound basis for identifying key mega trends in the future.

Table 2. Six crystallised mega trends that will affect innovation activities in the future (adapted from Tekes 2009: 37–38).

Mega trend	Key content
New division of shopping habits and shopping customs	• Costs of shopping in Finland is estimated to be around 10 billion € yearly at the level of macro economy • The rise of the sustainable consumption as a value sets pressures to minimise and divide these costs • Solutions could be based on logistic technologies and ways to calculate logistic costs: are e.g. lifecycle costs, environmental costs or energy costs included in the per unit cost of goods?
Minimalism as an innovation driver	• Sustainability is rising as a lifestyle and as a value • Consumption is more and more directed towards services • Ethical consumption is at the core of the perspective of minimalism • In order to be realised, requires social and technological innovations that foster sustainability and conservation
Leisure consumption is the pacesetter of consumer changes	• Consumption happens in three temporal spheres: work time, everyday time and leisure time • In terms of the possibilities of individual citizens to modify their consumption, the sphere of leisure is most important • Leisure as a target of spending is on the rise • Changes in leisure behaviour could also spread to working life
New kind of consumer movement leads to global innovations	• Resource scarcity leads to the search for new and sustainable energy sources • Markets are changing due to cost pressures and ecological pressures • A new kind of consumer movement could change the energy and environmental development in a sustainable direction through market mechanisms • The core of this new movement is formed by networked, conscious consumers and knowledge infrastructure instead of official organisations or proclamations • Environment and energy sectors are pioneering the development, but the practises are rapidly spreading to others sectors
Competence is at the core of economic activity	• Change and renewal of economy is accelerating • Success is dependent on the competence and focusing of competence • The global economy is becoming an innovation economy – innovations are born everywhere, but their development and utilisation requires competences • Competition on competence leads to focusing and alternatives
Technological discontinuities and new technological paradigms	• Changes in consumption and in values increase the need for new technologies • Paradox: consumption is increasing, yet minimalism as a life choice is also increasing • This paradox is creating a demand for new technologies • Biotechnology and nanotechnology are still seen as viable paradigms to resolve this paradox

Environmental policies play a crucial role by providing policy framework to develop and disseminate new environmentally friendly ICTs. Existing policies are meant to ensure that production meets the high environmental standards. An obligatory regulation has also been completed with a different kind of market-based and voluntary instruments, such as eco-labelling and environmental management systems (EC 2004: 5). As a matter of fact, stricter environmental legislation can be considered the most significant factor in terms of catalyzing the markets of environmental technologies (Sitra 2006: 17). However, it seems that literature on environmental innovations focuses mainly on the role of regulation as a stimulus for technological innovations while not enough attention is paid to the innovation process itself – its features and determinants at the industry and company levels (Oltra & Maïder 2008). However, some detailed studies linking sustainability and innovation activities have also been conducted at VTT (e.g. Hongisto et al. 2001).

From the point of view of R&D related activities, there seems to be strong potential for mixing different approaches to the systemic nature of innovation activities. The broader approach would have the potential to affect products and services on a more fundamental level. This in turn could generate more information about critical and generalisable dimensions of environmental innovations (Hellström 2007). For example, the social dimensions of new ICTs have much untapped potential although these dimensions are rarely the highest priority when it comes to new product development at companies. In this respect, the innovation process is closely linked with the concept of sustainable product design and eco-design. Sustainable product design means balancing all the variables of sustainable development – economic, environmental and social – in the context of innovation process. In respect to new ICT solutions, there is, for example, an increasing need for ICT applications that respond to new societal drivers such as the aging population and new generations already immersed in ICT, networks and emerging virtual environments. At the same time, the role of the customer is changing towards increasing participation in the innovation process. The aspects of service science have also risen significantly in terms of better understanding customer experiences.

If consumer views are taken at a glance, there are certain developments that are relevant to new ICT solutions. The move towards a more individualistic society, for example, enhances the need for more customised services and different kinds of social media and virtual communities. Simultaneously, consumers are seeking more engaging experiences related to their fields of interests, a development which sparks challenges for service developers and content providers. The development of mobile technologies enables new “remote forms of living” in terms of both work and leisure time. Constantly changing features of products require that consumers learn constantly. Improvements attract the consumers to acquire new products before old ones have reached the end of their lifecycle, which adds some pressure in terms of recyclability and modularity.

Still, since a purchase decision is usually a complex combination of multiple economic, functional, imagined and social factors, there is one thing to be emphasised: “greener” solutions need to outperform competing products in features other than environmental impacts. They must be better in terms of how customers experience the overall benefits when compared to alternative solutions. These overall benefits may be a combination of improvements which will be profitable in the longer run, or they may be a combination of an aggressively marketed simple solution with a promise to enhance the environment in some minor way – or something else altogether. Consumers might perceive and evaluate environmental and social impacts of the supply chain as an extended dimension of the quality of the product at hand. ICT solutions could have a strategic role in helping consumers link and evaluate the benefits (quality) of the product or service itself and the external environmental impacts of its production (externalities) that impinge on third parties through non-market channels. The bottom line is that customer preferences should be surveyed properly, understood correctly, and responded to in a way that suits both customer needs and the provider's own strategy.

Along with the debate on climate change, the discussion about sustainable development has pervaded all levels. Without elaborating on the causes of climate change in more detail, it should be stated that beside the possibilities resulting from several positive market factors, the societal acceptance for advancing environmentally sound technologies appears to be generally very favourable (see EU 2008). In other words, environmental awareness and ethical consumption are rising significantly, or in other words, society values are increasingly turning green. This should be seen as an important possibility in the ICT sector: as people want to act in more environmentally friendly fashion, the ICT field could provide solutions to measure and deliver environment-related information in easy-to-use and customised forms. However, it should be remembered that although attitudes are becoming greener, actual practises are slower to change (Tekes 2009). From this perspective, ICT could fasten the transition from "thinking to action" by offering tools and applications that provide users with the means to consider their actions as "sustainable consumers". Still, active citizens and local communities have a central role in promoting sustainable everyday practises. ICT solutions can be utilised to provide channels to influence other people as well as policy makers.

There is also an apparent need for governmental support and incentives for promoting environmentally sustainable ICT. The government could play several roles. Firstly, it could continue to support the creation of innovations and environmental information contents via existing mechanisms, especially those with global potential. Secondly, it could take actions to support the creation of environmental knowledge and innovations with specific measures to advance greener alternatives through regulations and subsidies, comparative frameworks, databases and verification systems. Thirdly, it could support research attempts to build methods to understand and structure the ties between sustainable development and innovation design e.g. by making these ties more visible. Simultaneously, the government would increase producers' interest in applying these benefits and turning them into actions. And fourthly, it could act as a key customer and lead the way by taking into use the state-of-the-art and environmentally sustainable ICT solutions.

In the future, ICT will increasingly be present in our everyday lives, and as users we have more and more possibilities to customise products and services to reflect our individual needs. Simultaneously, background systems are globally interconnected and optimised, working faster, and collecting more and more small-scale information. And as the development of ICT integration continues, it might not be too bold to predict that e.g. tomorrow's car producer could be Intel or Microsoft instead of GM. Despite uncertainties in terms of predicting the future, one thing seems to be apparent: environmental sustainability is here to stay, since the challenges it involves are ongoing, and increasingly, it is also becoming a competitive factor.

5. Structure of the roadmaps

The roadmap of ICT for environmental sustainability is structured on two levels (Figure 5). The first level is the meta-roadmap, a combination that synthesises the most pivotal themes that were identified in the roadmapping process. The second level is the sub-roadmaps. The roadmap is split into three sub-roadmaps: empowering people, extending natural resources and optimising systems.

The sub-roadmap of empowering people considers the possibilities of ICT to provide people, as citizens and consumers, with more information and tools to assess their actions and decisions from the environment point of view. This includes e.g. solutions for intelligent consumption, smart housing and open social platforms to ensure the wide acceptance of empowering tools. One major objective in this theme is to help people concentrate on the activities that really matter the most from an environmental perspective.

Extending natural resources deals with reducing the use of a range of environmentally malign resources through ICT-based solutions. The aim is to use as few resources as possible over the whole lifecycle of products, systems, and services – from design to operation to decommissioning. The focus also includes solutions for eco-efficient production, smart energy generation and delivery, and remote collaboration.

Optimising systems refers to increasing the operational efficiency of products, systems, and services resulting in order to reduce their environmental load. The solutions in focus include intelligent mobility and traffic systems, efficient production processes and optimised telecom, energy, traffic, etc. networks. The systems in question may be new or existing ones and optimisation may be aimed at different levels of the systems, from individual measuring devices to large-scale processes.

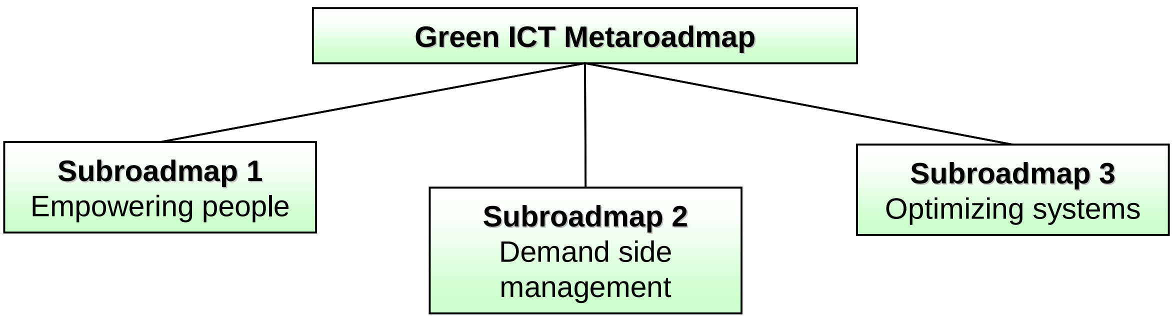

Figure 5. The structure of the roadmap of ICT for environmental sustainability.

6. ICT for environmental sustainability: the meta-roadmap

Setting the scene

During the last few years, climate change has made a breakthrough in both political decision-making and business. Whether this relates to seeing new environmentally benign solutions as a source for cost reduction, environmental protection, image construction or the means for advancing social responsibility, it seems that greener values have become a constant in both politics and business. This means that the R&D of new ICTs has to adapt to new environmental claims. This concerns the optimisation of a wide variety of environmental, economical and societal aspects in attempts to gain competitive advantage. Recyclability and LCA (lifecycle assessment) analysis are also important pieces of the environmental puzzle. As the outcome of this, development attempts to support technologies that are consuming less energy are highly endorsed.

The recession has caused a sudden break with some of the basic assumptions concerning economic development. While about a year and a half ago, most economists drummed the dogma of continuous growth, many economies and business sectors are now struggling with recession, collapse and survival strategies. Even though the consequences and the entire duration of this trend are unknown, it could be argued – since different organisations are continuously striving for enhanced operational and structural effectiveness – that the significance of ICT solutions is likely to grow during the slump. At the same time, the global economy will be forced to make new arrangements in places where both mass production and consumption are emphasised in rapidly growing economies, especially in China.

Technological development appears to be dominated by a trend towards smaller, faster and more capable. More knowledge can be included in an increasingly smaller chip; processors and servers are faster, and more information is transferred faster both through cable and wireless. The infrastructure is also developing more extensively. Information processing technology struggles with the great amount of information, and therefore the improvement of information processing and management systems is a key issue. The rapid development of web, mobile, and battery technologies are signs of the time as well. From the viewpoint of users and customers, it is no news that Internet is the most important platform for new product and service innovations. New social media and virtual communities are continuing the transformation of communication started by mobile phones.

The most important effects of new technologies happen in systemic level activities, which involve the complex web of behaviour of people, institutions, organisations and political jurisdictions, like nation-states. The effects of technologies should thus be compared with their systemic effects. Inducing systemic change requires an understanding of technologies in societies, markets and human behaviours. Technologies should be approached as socio-technologies, not merely as the technical applications of separate solutions.

The vision of the meta-roadmap (Figure 6) is the following:

Vision

ICT will increasingly be present in our everyday private and business life. It has contributed to decreasing the resource consumption and resource-intensive lifestyles in many ways. ICT offers achievable data and easy-to-use tools for the people to decrease their ecological footprint and to select more environmentally sustainable products and services. Smart production and recycling technologies have resulted in optimised products, processes and systems that consume as few resources as possible at every stage of their lifecycle. Smart metering and grid technologies have enabled flexible, accessible and economical energy generation (using renewables), distribution and consumption both in households and business/industry. Intelligent transportation systems and remote collaboration technologies have reduced unnecessary traffic and minimised the energy usage of transportation in general. ICT devices and networks themselves will naturally be highly optimised. Sustainable decisions are also supported by governmental regulation and other incentives.

Present

Drivers: There are currently four important drivers for environmentally sustainable ICT. The first is increasing awareness of the global consequences of climate change. This awareness is beginning to spread globally, even to nations and regions that previously seemed unaware of this phenomenon. The second is the economic recession. Recession is empathetically a two-sided phenomenon: it can be a driver for environmental solutions by focusing on issues such as the reduction of materials in the production processes or the streamlining of production lines, but it can also be a bottleneck, especially if firms and organisations modify their environmental agendas in the future and deem investments in this area as unnecessary. The third driver is the emission trading, which is currently starting to have an effect on companies. The fourth driver is the rising living standards in BRIC countries. The rising living standards will require increased efforts to cut down the environmental impacts.

Markets, services and products: For private citizens, there are a number of separate products and services available, e.g. carbon footprint calculators, car navigators, ecodriving instructors. The basic versions of home automation systems are currently utilised, for example in heating and ventilation.

AMR (automatic meter reading) is currently one of the key solutions; to date, this has mainly benefitted energy companies. Basic LCA (lifecycle assessment) software is already in use for increasing the environmental efficiency of industrial production. One important market for ICT-enabled services and products for environmental sustainability is currently transport and traffic. Also, high-end videoconferencing solutions and services are crucial to making ICT more environmentally sustainable along with simulation solutions for e.g. industrial production and manufacturing. The energy management of ICT infrastructure is increasingly embedded in the devices and networks.

Enabling technologies: Enabling technologies are basically different fields of ICT. Sensors and measurement devices provide the basic data for various applications. Modelling and simulation enable the consequent data interpretation and optimisation that is needed, e.g. in LCA and environmental impact assessment solutions. The required number crunching is enabled by multicore computers and solutions for parallel processing (e.g. cloud computing). Fast telecom networks and Internet are used for accessing, transferring and sharing information in real-time.

Bottlenecks: The key bottlenecks at present can be condensed into three categories. The first category involves social issues. Currently, people and companies are not ready to change and there are not sufficient regulations or other incentives for such change. The second category is systemic issues, which mainly refer to the current knowledge of the systemic impacts of ICTs. In the current situation, there is a lack of standards and openness regarding the information on environmental sustainability resulting in closed local solutions and poor information interoperability in general. The third bottleneck category is technological issues. This refers especially to the capacity of telecommunication networks and to battery technology, which are crucial bottlenecks for the utilisation of ICT in general.

Middle term

Drivers: In the middle term, global warming is expected to be the major driver at the global level. There will be global treaties, initiatives and campaigns on environmental issues. Consequently, more concrete regulation and incentives (such as taxation) for both citizens and companies will be utilised to steer their behaviour and to limit the exploitation of natural resources. There will be a significant rise in the green value among citizens, increasing e.g. demand for the improved duration, upgradeability and recyclability of products and services. It is likely that there will be pressure to change the current culture of disposable ICT, where mobile phones, laptops and other electronic devices are frequently exchanged for new ones. The increasing price of energy and raw materials is also a significant driver that could have effect on the values as well. The structural changes in resource-intensive industries that lead to a more sustainable track are important middle-term drivers.

Markets, services and products: In the middle term, there will be different kinds of services that utilise data from ICT embedded in our everyday environment. For consumers, personalised information services that integrate diverse activities (housing, transportation, nutrition etc.) and handle complex data on environmental sustainability (automatically) are entering the markets. Services related to housing and traffic that were previously used only for businesses have extended to private consumers.

In industry, new manufacturing paradigms are evolving and new ICT-based tools and processes are available for the whole production lifecycle. ICT plays a major role in the design and operation of factories. The product processes are mainly digitalised and more integrated production facilities are emerging. Automatic disassembly and recycling solutions are also emerging. Some aspects of the smart grid concept are maturing, e.g. distributed, sustainable small-scale energy production based on renewables are emerging.

Remote collaboration services provide a real feel of telepresence over the Internet, resulting in a more extensive use of teleworking and virtual conferencing. The ICT sector is getting more and more active in clean technology markets, using its technologies to provide environmentally sustainable solutions for eco-efficiency. Innovative ICT companies like Google, Nokia and Apple are getting even stronger and will begin co-operating with one other and also with companies in diverse sectors other than ICT teleconferencing

Enabling technologies: The technologies that are currently emerging are stronger than ever. Sensor networks and networked measuring devices allow data to be obtained from our daily surroundings. Data management and analysis and consequent automation technologies are utilised to handle this massive and multi-directional data flow. Modelling and simulation generally enable more complex optimisation, recognition and other tasks required in many products and services. 3-D environments and virtual worlds are crucial enablers of telepresence and other advanced services. Advances in hardware, especially battery technology, are likely to be made, and if so, this will definitely enable the large-scale utilisation of ICT. Social media, parallel computing (e.g. cloud computing) and telecom technologies are also key enablers in the middle-term.

Bottlenecks: The most important bottlenecks in the middle-term are, on the one hand, information overload and on the other hand, the complexity of the integrated systems. These bottlenecks are also very important right now, but in the middle and long term, when more and more information systems are likely to be connected to our living environments, it will probably reach new heights. The complexity and lack of standards limit transparency and result in poor interoperability of information and systems. They also sets challenges for privacy and data security issues. In the middle term, the immaturity in terms of both business models and people’s attitudes will still limit to some extent the utilisation of ICT for environmental sustainability.

Long term

Drivers: In the long term, drivers other than just climate change will have a bigger role globally. The scarcity of some critical resources, such as fresh water and rare earth metals, will have a major effect both in political terms and at the market level. International treaties, laws and regulations must thus be implemented to ensure increasing environmental sustainability. Consumption fees, taxes and other incentives are used to control user behaviour. Public opinion has changed drastically and non-radical environmentalism has moved – in the western countries – from marginal to mainstream.

Markets, services and products: The small scale environmental sustainability services offered for individual consumers are scaling up to large-scale systems. Telepresence and other virtual services have expanded from the company level to the consumer level. Users can design new services through social media to make them reflect their personal values. There will also be new products in the consumer markets, e.g. smart appliances that assess their own lifecycle.

The manufacturing industry is efficient and agile in terms of lifecycles, leading to integrated industrial production and easily configurable processes. A number of joint ventures and company mergers in and between industrial sectors have occurred. Considerable business has arisen around recycling and it has become quite automatic and robotics-based. A considerable portion of the energy is generated and distributed in buildings or at the neighbourhood level; renewable energy sources are increasingly used and consequently aggregators are introduced on energy markets. ITS have enabled more intelligent and more automated traffic services. New ecomobility solutions, such as hybrid and electrical vehicles, are common and their performance has been optimised.

Remote collaboration solutions that seamlessly integrate the virtual and physical will emerge. Also, different kinds of cross-reality applications and advanced virtual products and services are available on the market. These solutions might have significant impacts e.g. in health sector. In the ICT market, agile small companies can be successful by narrowing their expertise and honing their capacity to master the “big picture”, making big global players even bigger.

Enabling technologies: Parallel and cloud computing technologies have further developed, enabling the modelling, optimisation and AI methods that will be needed in various next generation services and products, e.g. context-aware products, intelligent recycling and energy grid solutions. Virtual/augmented reality and consequent 3-D Internet technologies allow for novel remote collaboration solutions, virtual products and post-PC era graphical user interfaces. Open social platforms and communication technologies will also be key enablers in the long term.

Bottlenecks: In the long term, the complexity of systems and services will continue increasing; interoperability and information availability will remain a major bottleneck. The reliability of information, along with security and privacy issues, become really critical aspects. The danger that humans may be forgotten in the midst of this entire technology boom does exist. Therefore, people may get frustrated and demotivated, especially if they do not see the changes in environmental attitudes and behaviour. Of course, economics always sets limits on the extent to which technological solutions can be implemented in practise.

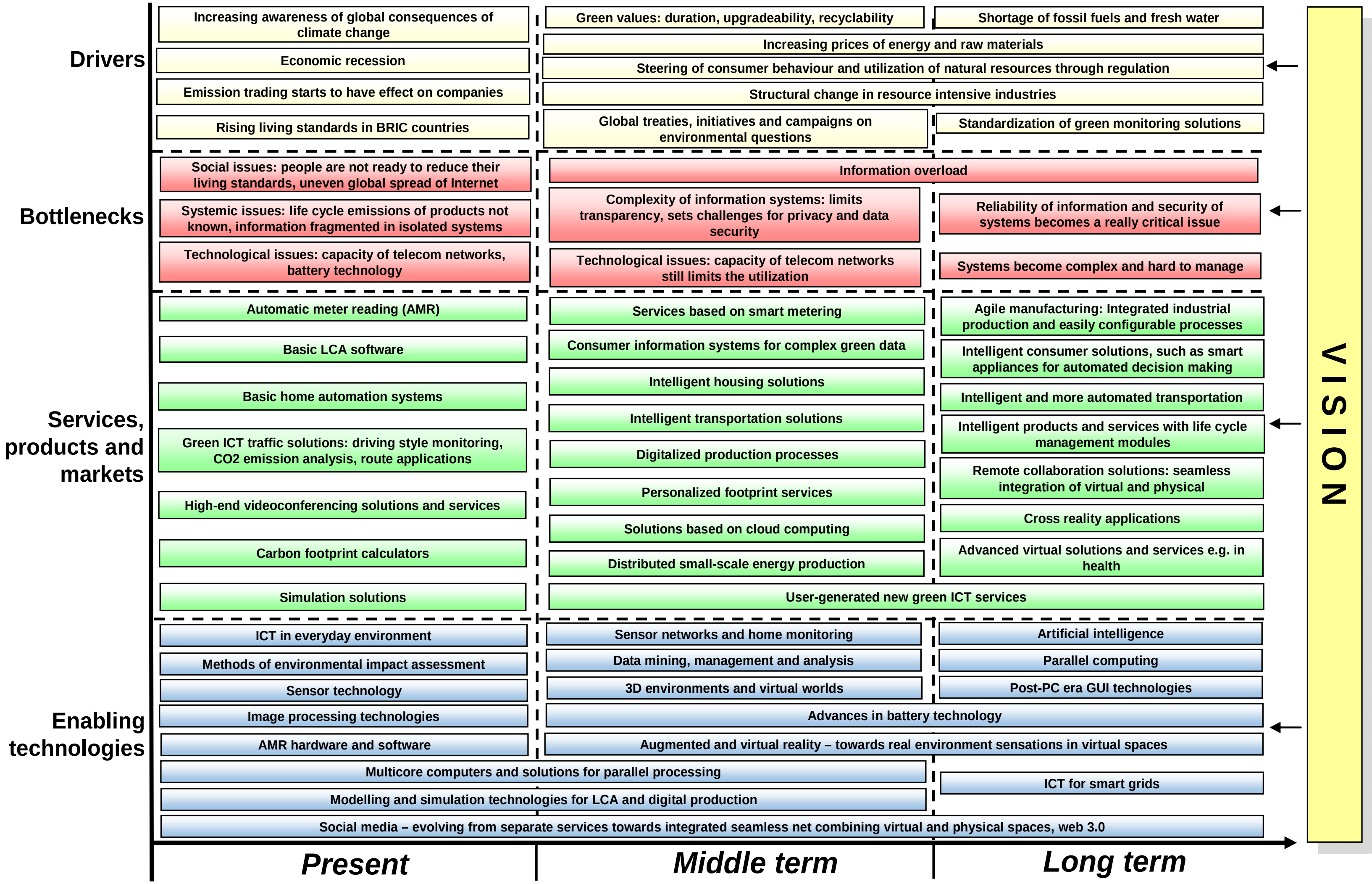

Figure 6. The meta-roadmap of ICT for environmental sustainability.

7. Sub-roadmap 1: Empowering people

The vision of the *Sub-roadmap 1: Empowering people* (Figure 7) is the following:

Vision

Because of changing personal values, social and media influences and governmental guidance, people are more motivated to make green choices in their daily life. Environmentally sustainable ICT offers achievable data and easy-to-use tools for people to decrease their ecological footprint and to select environmentally more sustainable products and services. It enables a less material-intensive lifestyle in general. This is achieved by providing consumers with accurate information about the ecological burden of every decision they make. Sustainable decisions are also supported by governmental regulation and incentives. People design new sustainable practices and social innovations through social media and take responsibility for their personal emissions, in the vein of industries. The consumption information of individuals and the emission information of products and services (supply chains) are monitored, collected, processed and shared through international databases and marketplaces for commercial applications that provide information for increasingly conscious consumers.

Present

Drivers: The current drivers for consumer-targeted and environmentally sustainable ICT are increasing awareness of climate change and increasing energy prices. Water and air pollution and the reduction of biodiversity can also be regional drivers in various geographical areas. Economical recession might temporarily decreases the trend towards ethical consumerism.

Markets, services and products: Although the demand for consumer-targeted ICT products for environmental sustainability is developing, the current ICT applications that are marketed as green are existing technologies which are approached from different and "greener" angles. For example, personal navigation devices are marketed as eco-friendly as they are shown to decrease the fuel consumption of transportation vehicles.[1] Solutions for the monitoring of driving style and economic advisors have been available for a while for heavy duty vehicles because there is a clear business motive for reducing transportation costs. For passenger vehicles and private users, similar products have now started to appear. For example, there is also a more advanced ICT for analysing driving style and its

[1] http://investors.tomtom.com/environment.cfm

effect on CO_2 emissions.[2]. Existing web-based route planning applications are already marketed for similar reasons. Another technology branch labelled "green" is home automation systems that control the efficient use of e.g. lighting and heating.

Carbon footprint calculators are the most prominent field of ICT solutions that were designed to increase people's environmental awareness. The current web portal solutions on market depend on manual input from the user.[3] Users enter estimates of recent trips, housing and other consumption. The web application then provides an assessment of the user's CO_2 emissions based on the input. Currently, ICT solutions which involve wearable sensors (including GPS) and other information sources used to estimate a person's carbon footprint are entering markets.[4] In addition, tools for estimating the CO_2 emissions of our metered electricity consumption and food consumption are being developed. An example of a system of this kind is presented in the text box below.

Research example: Climate feedback system

The "demonstration version" of the "Climate feedback system" combines carbon footprinting, multi-sectoral monitoring, consumer feedback and reward systems for households. The piloted ICT service enables consumers to monitor and follow the accumulated greenhouse gas emissions of their households purchases (Hongisto et al. 2008). Users of the service can also compare their results with target levels and with the results of other users of the system. They can acquire bonus points (credits), e.g. on the basis of reducing greenhouse gas intensity. VTT's demonstration version of the service covers emissions from foodstuffs, transport fuels and services, energy consumption at home, and a category called "other consumption." It combines several approaches and data sources (lifecycle analysis, input/output analyses and data from emissions trading schemes). Foodstuff purchases are automatically registered with the service through a special system (www.nutritioncode.com) that uses a dedicated key card and the information systems of the Kesko retail chain. The rest of the purchases are recorded manually via a computer interface or using the optical barcode recognition capabilities of Nokia mobile phones. The project also introduced the basic structure of a system to produce data for generating product-oriented "certified carbon footprints."

Feedback from the pilot has been encouraging: consumers believed that the use of a monitoring and feedback system for consumption-induced greenhouse gas emissions could change the consumption patterns of households and reduce greenhouse gas emissions from consumption. The authors of the study believe that feedback systems like Climate Bonus could activate significant reductions in voluntary emissions if disseminated for extensive use. The accuracy and tractability of carbon footprint data should be adequate in order to maintain credibility among consumers, retailers and producers. Consequently, the approval of carbon footprints should be based on transparent and comparable methods and impartial third party verification if used for crediting purposes. Up-to-date, reliable and comparable carbon footprint data of products and services is seldom available, slowing the commercial introduction of these kinds of ICT services. Due to the challenges related to the emission monitoring of international real world supply chains, the expansion of such systems is expected to be gradual, starting with selected products, product categories and sectors (For more information and publications, see http://extranet.vatt.fi/climatebonusfin/publications/).

Enabling technologies: Current technologies are enabled by the general increase of ICT in our everyday environment: People are constantly carrying many electronic devices, such as mobile phones and GPS devices, and ICT is increasingly present in both cars and houses. All of these contain an increas-

[2] http://www.fiat.com/ecodrive/, http://www.driveco.fi/
[3] See for example: http://www.carbonfootprint.com/calculator.aspx
[4] http://conversations.nokia.com/tag/carbon-calculator/; http://ecorio.org/; http://www.carbondiem.com; http://dub.washington.edu/projects/ubigreen, http://peir.cens.ucla.edu/

ing numbers of sensors which can be used to monitor the behaviour of the user. Mobile services, electronic invoicing and new measurement devices capable of communicating real time information for higher level applications allow fragmented data to be incorporated into meaningful contexts. Internet enables the fast transfer and sharing of information, e.g. through social media services.

Bottlenecks: Governmental actions do not currently encourage consumers to utilise the existing environmentally sustainable ICT – there are no major economic benefits or other incentives except for fluctuating energy prices and some indirect taxes. The implementation of ICT services for environmental sustainability requires business models which are currently in their infancy. For now, people are not willing to pay much more for more environmentally sustainable ICT products and services, which means that “common goods” are often purchased instead due to “free riding” mentality. Most of the world’s population does not yet have access to the Internet. In general, ICT solutions for environmental sustainability designed in developed countries will probably not work in developing countries. Slow improvements in terms of battery technology is seriously limiting the emergence of mobile solutions that target consumers.

Middle term (1–5 years)

Drivers: Environmentally sustainable values are becoming increasingly important to consumers and companies: the duration, upgradeability, and recyclability of products are valued. The transparency of supply chains is improved (the origin of foods, electricity and products is increasingly important). Global warming remains a major driver at the global level. Energy and raw material prices increase further, and start to also have an affect on consumer budgets. The steering of consumer behaviour through taxing and consumption fees has become more common.

Markets, services and products: Consumer information systems for integrating diverse activities (housing, transportation, nutrition etc.) and handling complex environmental sustainability data (automatically) are entering the market. At the same time, services that utilise the information from these systems are appearing, such as bonus/reward systems to promote green choices. Measures for environmentally friendly products that go beyond just carbon footprints are emerging. These measures, like the water footprint and biodiversity footprint, bring about personalised services that reflect users’ personal values. Intelligent housing solutions that regulate the energy use of houses are embedded in most new houses in Finland. In houses, smart metering systems provide a limited means for communication with every consumption point of the utilities. Intelligent transportation solutions have developed further. ITS services previously used only for commercial traffic, such as in-vehicle eco-driving instructors, have extended to private traffic. Solutions enabling hybrid transportation, which integrates public and private transportation, are more generally available. More consumer services (eGovernment, eCommerce, eHealth) have been transferred to the Internet. This applies also to entertainment services, where the importance of the physical media has decreased significantly. Local communities are maintaining services that encourage the community to take care of the environment.

Enabling technologies: Sensors networks (wearable sensors and home monitoring) are everywhere in our daily environment. Automation systems for housing and mobility are developing fast. Data management and analysis technologies enable the emergence of more complex services. Most people in the world have access to fast Internet connections. Social media is used to disseminate sustainable practises and to network people. Augmented and virtual reality technologies enable diverse e-services. Advances in battery technology are enabling new mobile and environmentally sustainable ICT solutions.

Bottlenecks: Once the markets are established for environmentally sustainable ICT, privacy problems in terms of information will become a major obstacle in developing new related services. The lack of standards will reduce the possibility for creating database solutions which combine information from multiple sources. For example, building automation is in many cases too expensive and often lacks the interfaces, functionalities and quality necessary for efficient energy management. Consumers are not willing to adopt several separate services, but integrated systems may also grow too complex and difficult to use in order to be accepted by consumers. Information systems are also becoming extremely complex. This may limit their transparency and it also sets challenges for privacy protection and data security.

Long term (over 5 years)

Drivers: The major long term drivers are the shortage of fossil fuels and fresh water. Legislation and consumption fees are used to control user behaviour. As an ideology, non-radical environmentalism has moved – in the western countries – from marginal to mainstream, resulting in a clear change in the overall demand of products and services. The monitoring solutions for environmental sustainability information have been standardised and they have reached technical maturity. Therefore, the information they provide can also be used for levying taxes and offering incentives.

Markets, services and products: The small-scale environmental sustainability services offered for individual consumers are evolving into large-scale systems that are able to evaluate the environmental effects of products and services throughout their lifecycle. Intelligent consumer solutions, such as smart appliances, have emerged in many areas (housing, transportation, etc.) enabling automated decision-making on behalf of consumers. Users design new services for environmental sustainability through social media to make them reflect their personal values. Transportation is more automated, which maximises its efficiency. Virtual services have expanded from the company level to the consumer level, so that they are widely used in many areas – like telehealth, virtual travelling, social events, and sports - significantly decreasing the need for transportation.

Enabling technologies: Open social platforms are evolving in terms of increasing people's support for green applications. Technology for creating augmented and virtual reality has developed enough to provide people with sensations similar to those provided by the real environment, thus enabling many new virtual services. Artificial intelligence enables, e.g., context-aware products that adapt to user behaviour to save energy.

Bottlenecks: Constantly increasing productivity results in a situation where people have more money than they are allowed to spend because of governmental restrictions that limit the use of natural resources by a single consumer. People may get tired and frustrated if they do not see changes in the attitudes and behaviours of people, companies and countries at the global level. Strict governmental restrictions that limit the use of natural resources by a single consumer may demotivate consumers' voluntary actions.

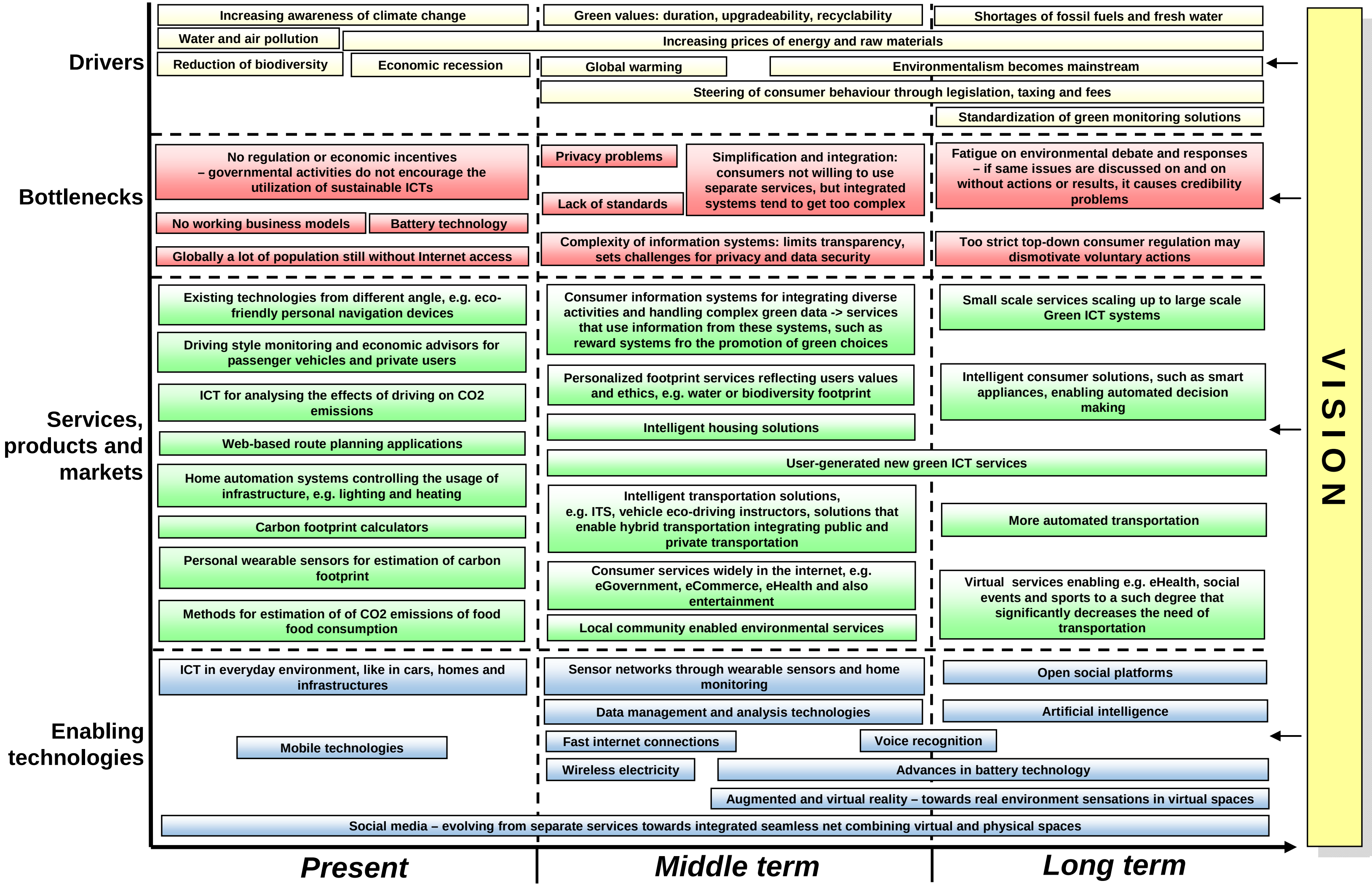

Figure 7. Sub-roadmap 1: Empowering people.

8. Sub-roadmap 2: Extending natural resources

The vision of the *Sub-roadmap 2: Extending natural resources* (Figure 8) is the following:

Vision

The consumption of non-renewable natural resources has decreased considerably, yet the overall prosperity of society has continued to grow globally. ICT has contributed to the decrease of resource-intensive lifestyles in many ways. Smart production and recycling technologies have resulted in products, processes and systems that consume as few resources as possible during every stage of their life-cycle, from product development to decommissioning. For example, integrated production facilities have enabled the efficient use of raw material and energy, resulting in a minimal generation of waste. Smart metering and grid technologies have enabled flexible, accessible and economical energy generation, distribution and consumption both in households and in industry, a great part of which is based on renewable energy sources. Remote collaboration technologies have made efficient and resource-saving work possible by reducing the need for travel and office premises.

Present

Drivers: The prices of diverse resources are increasing in the short term despite the global recession. On the other hand, the recession has enhanced resource and energy efficiency due to the increase in operational efficiency by companies. Separate laws and mechanisms, such as emission trading, will also start to set limits on companies and individuals to increase resource efficiency. The digitalisation of products and services arguably has a positive effect on resource usage.

Markets, services and products: LCA is a standardised method (ISO 2006a and ISO 2006b). Many types of LCA software (e.g. KCL-ECO) are available and are widely used in both the public and private sector in strategic planning, product development, marketing, etc. Some preliminary solutions for the automatic recycling of certain products are already available. The basic automatic meter reading (AMR) services are maturing. Many of the energy network companies have launched campaigns to replace existing meters with AMR-enabling ones. The legislation will enforce AMR roll outs in the western countries; Finland, for example, has established that the meters must be installed in every household by 2014. Skype and other digital communication channels are challenging solutions dedicated solely to teleconferencing. Above all, individuals will use Skype for long-distance video calls.

Companies will do so only on a small scale. On the other hand, high-end videoconferencing solutions and services are gaining ground within larger companies and organisations, which use them for travel substitution.

Enabling technologies: Much emphasis is placed on developing methods and processes for the environmental impact assessment of products and services, including carbon footprinting. The modelling and simulation technologies required for LCA methods are also available. Wireless sensors as well as image processing technologies help in the object recognition needed for automatic waste recycling. AMR hardware and software are available commercially, on-the-shelf. The bandwidth of both mobile and fixed telecom networks is increasing all the time.

Bottlenecks: The price of the resources is not yet high enough to radically limit resource utilisation. The majority of people, both in developed countries in the West and in developing counties, are still not ready to reduce their standard of living. The emissions caused by products and services during their entire lifecycle are not yet known. Support for energy saving services and information has only partially been taken into account in the smart metering systems and related EU and national requirements. The development of energy saving applications is also limited by inadequate standardisation and restricted openness of the data communication interfaces. The capacity of the telecom networks and computing services limits the use of more advanced telepresence technologies.

Middle term (1–5 years)

Drivers: The scarcity of certain natural resources is becoming evident and has an increasing influence on production systems and choices. The prices of resources are rising rapidly due to the increased demand, especially due to the rise of the new economies. Legislation and treaties are passed to manage scarce resources. There are worldwide campaigns and initiatives to encourage recycling and energy saving, similar to those during the 70s energy crisis. An intense structural change is emerging in many industries, especially in high resource-intensity industries.

Markets, services and products: Resource efficiency is changing from a marketing pitch towards a decision criterion for the product and service acquisition of individuals and businesses alike. Ecodesign tools are widely used in product development to minimise the environmental impacts of products over their lifecycle. New ICT-based tools and processes are available for the design and operation of factories. The production processes are mainly digitalised, including solutions such as virtual prototyping. More integrated production facilities are emerging, with a goal of zero-loss utilisation of the most scarce and valuable raw materials. Robotics-based automatic disassembly and recycling solutions are also appearing. Products that are based on renewable resources are gaining more and more popularity. They are substituting traditional products, as in the case of biofuels vs. fossil fuels. User services based on smart metering are maturing and thus enabling e.g. real demand elasticity. Distributed small-scale energy production based on renewables is emerging. Thus, new service providers are also sprouting on energy markets in addition to the traditional energy grid companies. Players like Google enter the markets with new business models that cash in on saving energy. In general, the ICT sector is getting more and more active in clean technology markets, using their technologies to provide environmentally sustainable solutions for eco-efficiency in resource intensive industries, e.g. in energy and manufacturing sectors. Remote collaboration services utilise virtual and augmented reality. These products provide, to some extent, a real feel of telepresence over the Internet. Teleworking and virtual conferencing become common. The shift from physical products to digital ones is speeding up.

Enabling technologies: Large-scale modelling and simulation technologies enable system-level LCA, digital product processes (e.g. PDM, PLM and digital manufacturing tools), and smart energy supply. There are advanced identification and recognition technologies (RFID, machine vision, etc.) for waste management and recycling. AMR systems will be rolled out throughout the most advanced countries, providing large amounts of metering data. Web technologies (web 3.0) are utilised in both energy consumption monitoring and remote collaboration solutions. For the former, data mining technologies allow data to be transformed into useful information and measures for saving resource and implementing new business models. For the latter, 3-D environments and virtual worlds enable a more authentic telepresence.

Bottlenecks: The acceptance of the resource-efficient life style is generally still too low. Not all of the solutions, e.g. related to recycling, are economically feasible as of yet. The creation of business models that encourage resource saving is essential. The cyber security of smart grids, smart metering and smart homes become increasingly important as the amount of controllable distributed energy resources increases. There is a growing threat of widespread blackouts caused by the need to control huge amounts of small loads simultaneously. Telecom network capacity and the price of heavy computing power still limits the features of the new remote collaboration products to some extent.

Long term (over 5 years)

Drivers: The shortage of natural resources is really influencing society. In particular, pure water has become a limited resource in some parts of the globe. Water issues also affect international politics. Public opinion has changed towards sustainability, especially in developed countries. Wasting energy and material has become unpopular among the citizens. International treaties and regulation further enforce the increases in recycling and energy-efficiency.

Markets, services and products: Integrated industrial production has gone mainstream. That means that different types of products – e.g. water stream and electricity – are produced in the same facilities to ensure a maximal use of resources, i.e. industrial by-products are effectively turned into raw material in the same facility, e.g. plywood and pellets. This also results in a number of joint ventures and company mergers across industrial sectors. Intelligent products and services are emerging with embedded lifecycle management modules. For instance, intelligent products are able to optimise their operations to minimise long-term environmental impacts and also to indicate the correct decommission time. A considerable business has arisen around recycling due to the high material costs. Consequently, recycling has become quite automatic and robotics-based both in households and industry. A considerable portion of the energy is generated in a distributed manner in buildings or at the neighbourhood level, using mainly renewable energy sources. New players responsible for aggregating the distributed energy resources to the electricity grids and markets are entering the energy markets. In general, energy-efficiency has improved across society, resulting in a decrease in the final consumption of energy. This is mainly due to intelligent, automatic solutions that enable high-quality services with less energy in areas such as housing, traffic, manufacturing and telecom. Remote collaboration solutions provide virtual presence, integrating physical and virtual worlds into a single seamless user experience. ICT solutions have significantly decreased work-related travelling, reducing the need for office premises, etc. There are electronic versions of nearly all physical products that can be virtualised.

Enabling technologies: Advanced modelling, optimisation and AI methods enable intelligent products, recycling and energy grid solutions. Smart grids with controllable distributed energy resources enable high penetrations of intermittent or non-controllable renewable generation (e.g. wind, photovoltaic, non controllable hydro) and distributed generation (e.g. CHP). They benefit from diverse ICT solutions from cloud computing to communication technologies. Electricity storage also aids in the development of smart grids. 3-D internet technologies enable novel remote collaboration solutions and virtual products.

Bottlenecks: In the long term, systems become very complex and hard to manage. The interoperability and information availability of the heterogeneous systems and sources of data will remain a major bottleneck. The reliability of the information and security of the solutions also limit the implementation of technology, e.g. in the smart grids. Smart metering systems are still limited in terms of required functionalities and adequate, truly open interfaces. Economics always set limits on the extent to which technological solutions can be implemented in practise.

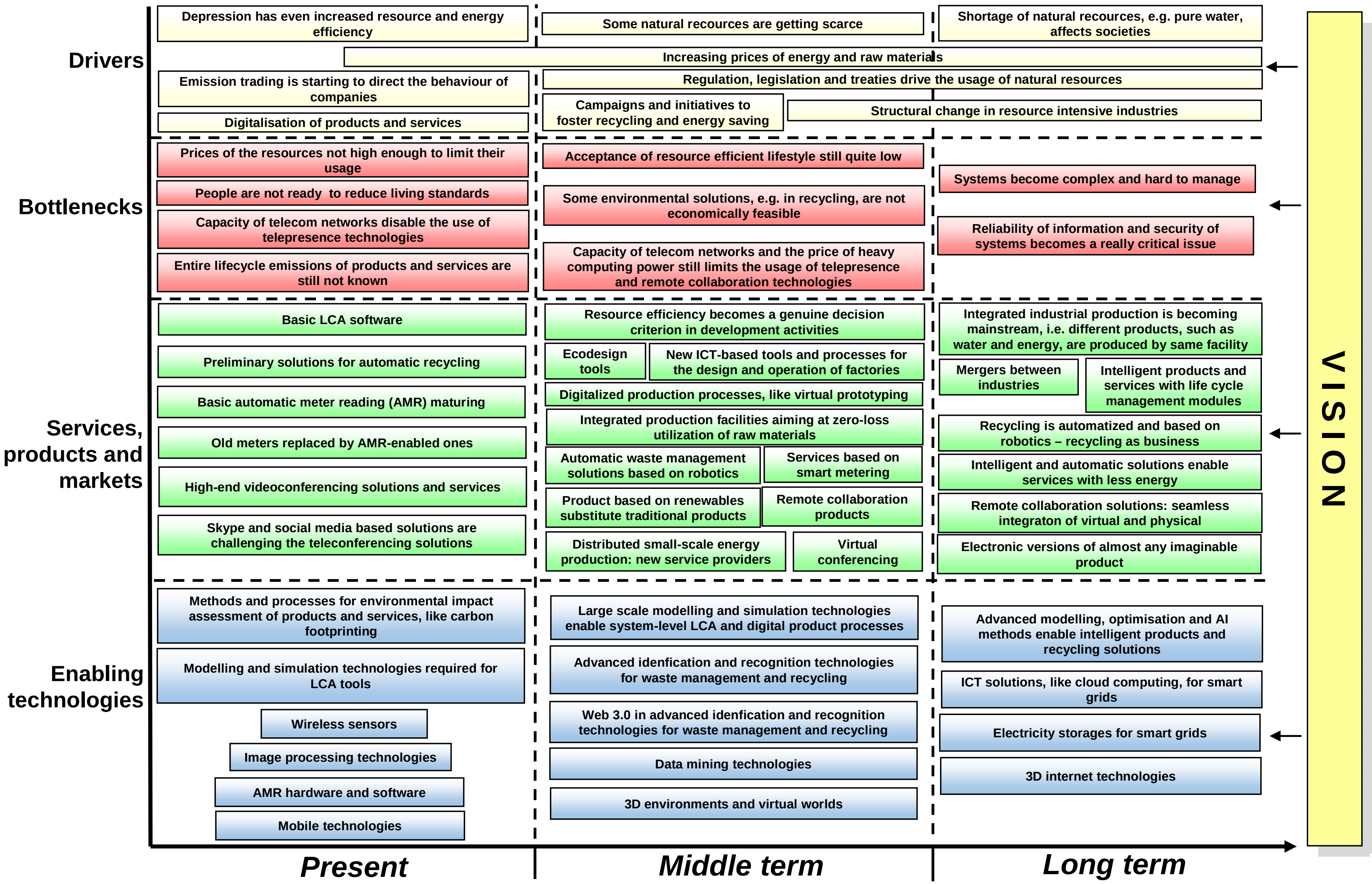

Figure 8. Sub-roadmap 2: Extending natural resources.

9. Sub-roadmap 3: Optimising systems

The vision of the *Sub-roadmap 3: Optimising systems* (Figure 9) is the following:

Vision

Optimisation is applicable to every field of life and thus everything is optimised to some extent. The principle of optimisation is applied to everything from small devices and embedded systems to smart services and very complex systems. There are diverse incentives to optimise the economics of these systems and the services are also optimal in terms of environmental sustainability. In industrial production, the resource use is minimised throughout production processes. The production systems are intelligent and agile. In traffic, telecommunication and optimisation enable intelligent transportation systems (ITS) that both minimise the energy usage of transportation and reduce unnecessary traffic. Optimisation is a key factor of success in the sustainable and distributed energy production systems as well. The ICT devices and networks themselves will naturally be optimised along the way. Citizens have access to versatile and extensive services whose added value is optimisation.

Present

Drivers: People have become aware of climate change, generating pressure on decision-makers to take action to reverse it. International treaties are being drafted. At the same time, the standard of living is going up in China, India, Brazil and Russia, thus creating more CO_2 and greenhouse gases (GHG). The recession of the global economy decreases the emissions only temporarily, but it can result in new thinking. Optimisation is used to gain energy efficiency and maximise resource usage, which usually means advancing environmentally sustainable values.

Markets, services and products: Product life-cycle management companies handle the entire lifecycle of a product from conception to design, manufacture, service and final disposal. The closed loop lifecycle management is economical and environmentally friendly, and it creates a good image for companies. Simulation is a useful tool to design, test and optimise the production system or the delivery chain. Several tools exist for different branches of industry and for different phases of lifecycles: discrete event simulation (e.g. Simul8) are used in discrete production system design and even for production scheduling; steady-state simulators (e.g. Balas) are used in the early stages of production concept design; dynamic simulators (e.g. Apros) are used in detailed process and automation design and testing; finally, system dynamic simulators (e.g. Vensim) are used to study the business environment and analyse its interconnections.

Regarding transportation, there are a rising number of different navigation and route planning solutions. An excellent example of ICT and optimisation product is the lauded YTV Journey Planner, which is a web application containing multimodal route optimisation. In addition to car navigator providers and software houses, new players like Google and Nokia have entered the navigation markets. For example, Google Maps contains embedded optimisation, providing the quickest route calculation service for drivers and pedestrians, as well as public transport routes in selected cities. Software houses provide map-based fleet management applications for industry that can be tailored to a customer's needs. Examples include the forest industry, which uses various approaches to manage the optimal raw material supply to factories and saw mills. Another example is the food industry, which collects its raw material from across Finland and utilises commercial fleet management applications to deliver it. Some solutions also exist for Demand Responsive Transport (DRT) systems, which are utilised in several countries in Europe. ICT companies like Google, Nokia and Apple make products that utilise ICT and embedded optimisation. Telecom network providers and operators optimise the performance of the individual network elements as well as the operation of the network as a whole. For example, BaseN and NetHawk provide solutions that achieve this.

Enabling technologies: A sufficient ICT infrastructure is required for the optimisation. In addition, timely and accurate input data can be obtained. The solutions for parallel processing multicore computers are evolving, making them the main source of computational performance in heavy optimisation solutions. The optimisation and the required modelling algorithms are becoming more effective due to research activities, e.g. multi-objective optimisation (MOO) methods are evolving and simulation-based optimisation tools are available (e.g. OptQuest, ISSOP). Telecommunication technology is making progress and contributing to the performance and coverage of telecommunication. Embedded sensor technology creates "senses" to devices, which is crucial in the industrial automation and robotics.

Bottlenecks: The information currently needed for optimisation is partly isolated in different organisations and generation systems resulting in poor information interoperability. Also, the present models are often inadequate in terms of predicting and optimising systems sufficiently. The interests of people and companies can be quite different. Control is enforced by legislation or directives at the national and EU level and companies then search for the optimal business solution within this domain. However, energy efficiency and environmental impact are not yet common objectives of optimisation. Organisational structures are sluggish and change slowly.

Middle term (1–5 years)

Drivers: Global treaties are major drivers for the behaviour changes of companies. Advanced technology, along with strong political will, is put forth as a key solution to climate change. In addition, and partly as a consequence, the prices of resources and consumer demand are steered towards environmentally sustainable operations and optimisation. Large-scale modelling and optimisation solutions could help to identify good solutions for challenges in society – and particularly, to climate change.

Markets, services and products: In industry, optimisation components are integrated into product control systems (e.g. intelligent motor controllers), production planning, supply chain and business systems (e.g. ERP-systems). New manufacturing paradigms are evolving, like Minimal Manufacturing in Japan and Competitive Sustainable Manufacturing in the European Union. Cloud computing makes it possible to offer small and medium enterprises (SMEs) commercial optimisation services in generic optimisation tasks. In Finland the ideas of e-infra initiative have been realized containing also research and practical application knowledge. Flexible transport services and dynamic car pooling services which supplement public transport are supported by the government, assuring mobility for all and allowing collective passenger transport fleets to be managed. Distributed, sustainable energy production utilises increasingly optimisation at all levels: energy network companies, local energy producers, wind power companies, and households. ICT companies, like Google, Nokia and Apple, are growing even stronger and will soon be co-operating with each other and also with companies in sectors other than ICT. The threshold to build optimisation models will lower when more companies like IBM, AIMMS and Microsoft provide more possibilities to generate large-scale, effective models. Furthermore, the growth of the market demand and the competition between solutions providers decrease licence prices. This new business model favours small software companies.

Enabling technologies: The technology that is presently emerging has strengthened in the middle term. Simulation, optimisation, parallel computing and other such advanced methods form a logical continuum. The simulation model can be transformed into an optimisation model by using well-defined working process. Real-time information about traffic is available for vehicles and mobile devices. Therefore, traffic monitoring across entire road networks has become possible.

Bottlenecks: The future systems become very complex and cause challenges to system development. Information overflow and poor interoperability are two important problems.

Long term (over 5 years)

Drivers: The laws and directives outline the feasible area where the companies can do business while optimising their economic results. In principle, then, public and private interests unite. The effects of globalisation can be alleviated from the 2010 level when the competitiveness of China and India weakens because of the ascending standard of living in those countries (the Estonia phenomenon). It is likely that our efforts to reduce CO_2 and GHG are not sufficient, which creates pressure to work harder on them.

Markets, services and products: Product manufacturing has become very efficient and agile. This means that several products are manufactured in the same factory and the use of all resources is maximised. In addition, factories can easily be configured to produce different products, due to the use of digital manufacturing tools in SME as well. ITS provides road authorities with the means to optimise and to control the traffic flow e.g. by delivering information to mobile information services and dynamic road toll systems. Hybrid and electrical cars are common and their performance is optimised. The situation on the ICT market evolves in two different directions: small, flexible companies can be successful by narrowing their expertise and using business models like that of the Apple iPhone and at the same time, the capability to master the large systemic view makes multitechnology organisations competitive. The big global players, like Microsoft, Google, Apple, IBM and Nokia, have become even stronger. Cross-reality applications enable the virtual shopping experience in which the user can enter the virtual shop and choose articles. As the optimisation models get more and more complex, a new problem emerges: how to understand the results provided by optimisations models. The new virtualisation technology makes it possible to “dive into the resulting information.”

Enabling technologies: Every inhabited area in Finland has access to 100 Mbit/s wlan. Intelligent phones are common and they communicate with servers in the cloud computing environment to start larger optimisation tasks when needed. Parallel computing is the most important feature to increase the computing performance. New dynamic programming languages like Python make the programming effective and fun preserving yet the performance of the target code. The post PC-era user interface technologies have matured. Virtual and cross-reality technologies makes diving into the information more intuitive and natural. The progress of ICT also enables the development of the optimisation models and solutions.

Bottlenecks: The danger is that users may be forgotten in the midst of this technology boom. In optimisation, the final breakthrough always remains on the horizon: the problems are getting more and more difficult and taking new and unexpected turns. Drafting regulations to define the feasible and sustainable areas of economic life is usually a very slow process, but in this case the indications of climate change might be so obvious that the process will advance more quickly than expected. Despite the development of optimisation models, new and more complex problems are always emerging.

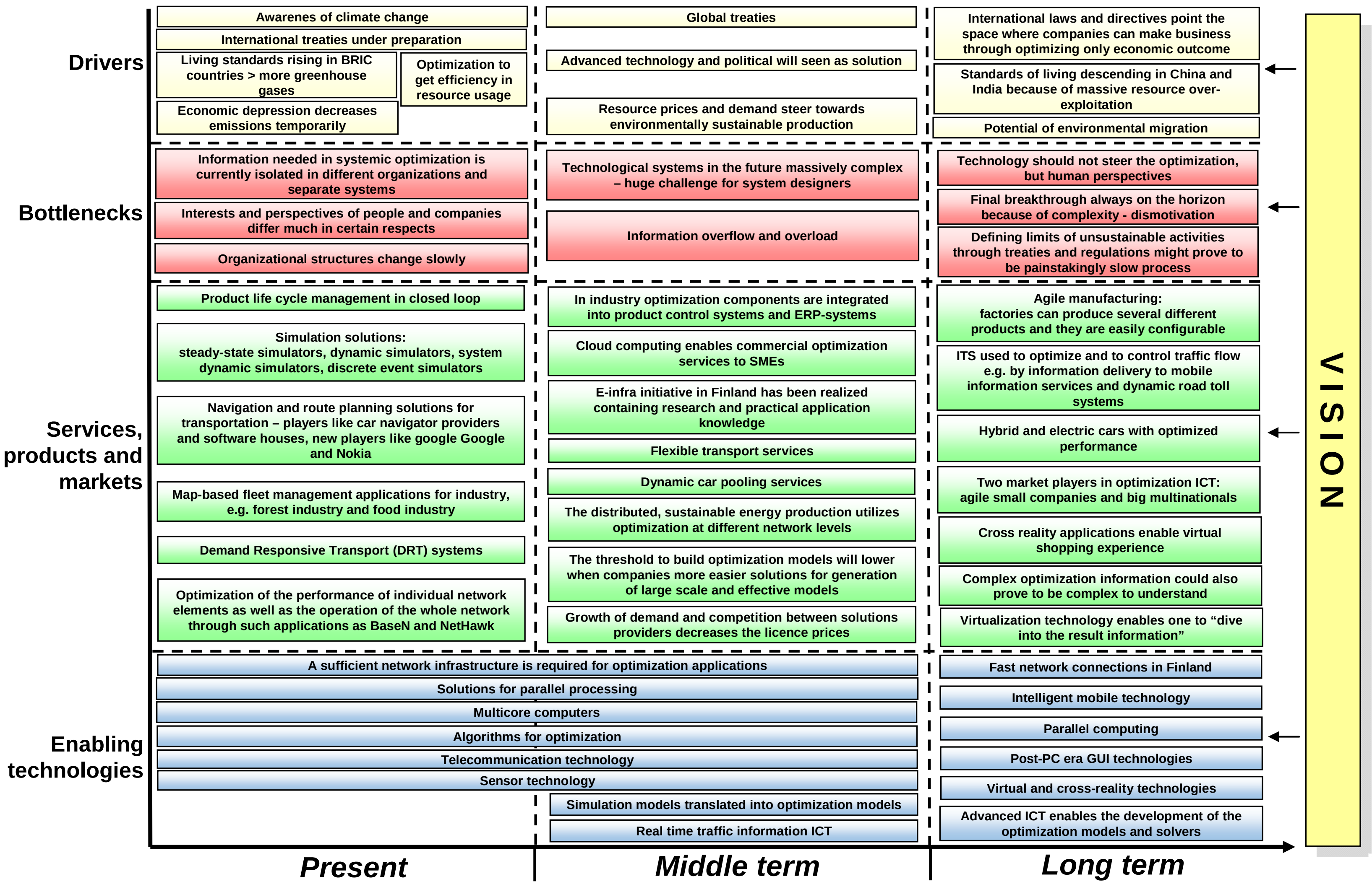

Figure 9. Sub-roadmap 3: Optimising systems.

10. Conclusions

This roadmap report represents the vision for future developments based on three themes; empowering people, extending natural resources, and optimising systems, as seen by the experts of VTT. By carefully analysing the roadmaps, we were able to identify four focal topics within the themes. The topics summarise the key findings of the roadmap concretely and in detail. In other words, they present our view on the most relevant research topics that have both significant potential in terms of environmental sustainability and great application opportunities for ICT. The focal topics are presented in the following as the final conclusion of the report:

1. **Environmentally sustainable consumption**. Consumers are increasingly more willing to change their behaviour to accommodate for climate change, but the overflow and complexity of information on environmental sustainability create some confusion. In addition, the reliability of environmental market information is increasingly challenged. Novel ICT tools are needed to help average consumers make environmentally sustainable decisions in their daily lives. Such tools may include automatic calculators of the carbon footprint and other individual measures as well as social media applications that promote ecological behaviour. The ICT tools that support environmentally sustainable consumption must simplify the complex information and also present it in a more personal and motivating manner – for example, by comparing the consumer's behaviour to a set goal. It is necessary to put personal data and figures into meaningful and understandable contexts and frameworks, e.g. reference-levels. To develop motivating ways to present and distribute the information, online communities and user-driven design are essential. As large amounts of consumption data and the product-specific emission data need to be collected and processed by many sources covering complex production systems, their individual units (and defaults from databases), standards and respective databases and marketplaces for exchanging, processing and reporting environmental information between different operators, systems and even devices are of crucial importance. Currently, the lack of governmental actions and other guidance is limiting consumers' motivation to exploit ICT technologies for environmental sustainability: there are no major economical incentives except for the fluctuating price of energy and some indirect taxes. The future challenges also include coping with the complexity of ICT systems and networks, and the lack of standards that define and provide for the exchange of information on environmental sustainability.

2. **Smart energy and buildings**. Smart metering – i.e. measurement solutions that are able to both measure energy consumption in more detail than current systems and also to communicate that information through network(s) – is a very rapidly developing technology at the moment. Sensors and sensor network-based sub-utility energy measurements will be emerging in the near future; this will result in more elaborate energy consumption information, both in temporal and load profile perspectives. The new information will enable novel business models and the provision of new digital services for diverse stakeholders, such as demand forecasting for energy companies, energy performance benchmarking for building operators, dynamic pricing and energy consumption monitoring for individual residents. These services allow stakeholders to take specific measures to decrease and level off their energy consumption, thus increasing energy efficiency in buildings. In the long run, smart metering together with other technologies – such as home area networks, smart appliances, and building automation – will enable the automation and integration of some of these measures through direct feedback from the energy consumption information to load control, which is the ultimate goal. Furthermore, the smart grid concept will enable distributed, small-scale energy generation in buildings or on the neighbourhood level, mainly through the use of renewable energy sources. Thus, new players responsible for aggregating the distributed energy resources to the electricity grids and markets must enter the energy markets. Finally, there are some major practical challenges to overcome in order to successfully implement smart meters, grids and buildings; these include such as prediction and optimisation models, the building and (low-voltage) distribution network automation, standardisation, and information security.
3. **Lifecycle efficient production**. Current industrial production contains many potential development targets that can be attained while pursuing ecological goals. New production paradigms (e.g. Minimal Manufacturing and Maximum Servicing, Competitive Sustainable Manufacturing) will emerge for the process and manufacturing industry. For example, integrated production results in facilities where several different products are manufactured in a single factory and where digital product processes result in the digitalisation of information and even products, especially in product development (e.g. PLM, PDM, LCA and digital manufacturing tools with sustainability aspects). The new production paradigms require more extensive and systemic methods for utilising ICT. Large-scale simulation and modelling, as well as integrated product information systems, are needed to assess and manage the environmental impact of the products throughout their lifecycle, and well as to optimise their operation and the resulting impacts in the individual lifecycle phases. LCA solutions continuously provide more detailed and accurate information about the diverse impacts for production-related decision making. Related information disclosure policies and associated rules on environmental impact provide yet another driver, inducing dynamic impacts on complex production systems. In the development phase, ecodesign solutions are becoming more common along with virtual prototypes. ICT-enabled optimisation can provide huge savings in production through tailored mass production, the utilisation of production lines, the optimisation of raw material usage, preventive maintenance, etc. Recycling is also gaining popularity all the time, as it will be increasingly seen as a source of raw material. Automated, possibly robotics and smart sensor based, recycling solutions will subsequently emerge, which will not only reduce the amount of

waste but will also enable more effective waste management logistics. Regarding the production of energy, the use of renewable energy sources is increasing, mainly due to reasons related to the politics of global warming.

4. **Optimised and adaptive networks**. ICT brings its intelligence to diverse networks, including transportation, telecommunications, energy, delivery chain, and water networks. As these networks become more intelligent and complex, new solutions for network management are needed. ICT enables network optimisation on multiple levels; structure, energy consumption, throughput, etc. A key requirement for optimisation is forecasting. As the network infrastructure - and in some cases, even the terminals and carriers - provide more up-to-date information about the state of the network and its environment, more detailed and accurate forecasts can be made. In the new energy world, it becomes increasingly important to predict and optimise the dynamic responses of consumption and to maintain the models so that they keep up with fast changes in consumption patterns; existing mainstream modelling techniques are often unsuitable for such changes, and thus new types of models are needed. One aspect of network intelligence will be their adaptive and robust nature, i.e. they must be able to dynamically adjust their structure and control procedures according to the state of the network and its environment, providing maximal throughput. Novel network management solutions will emerge for diverse networks and similar solutions can even be applied to many different networks. For example, solutions for a telecom network can be readily adapted to energy networks. The transportation network is especially interesting due to its great share of final energy consumption and its consequent impacts on the climate. The need for more advanced intelligent transportation systems (ITS) is undeniable. ITS will provide solutions for following up, taking the snapshot, processing the control response, and enforcing the control of traffic flows and individual vehicles. ITS also enable new concepts for ecomobility. They support the long distance use of electric cars, demand-responsive public transport, eco-driving, and many other concepts and services that are currently in their infancy. One central technology is remote collaboration, which reduces the need for transportation and thus arguably has the greatest impact on environmental sustainability.

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Title

ICT for Environmental Sustainability
Green ICT Roadmap

Abstract

This report presents a VTT roadmap on ICT for environmental sustainability, based on the assessments and evaluations made by VTT technology experts. We adopt a broad and systemic view to the issue; in other words, we believe that ICT's effectiveness depends on mutual understanding and changing the system level activities, i.e. the complex web of behaviour of people, institutions, organisations and political jurisdictions, like nation-states. We use the term ICT for environmental sustainability or environmentally sustainable ICT, instead of green ICT, and defined it as: *The optimal use of ICT for managing the environmental sustainability of societal activities*. The roadmap is divided into three themes. *Empowering people* means using ICT to raise people's awareness of the environmental impact of their actions and to channel their behaviour in a more environmentally-friendly direction. *Extending natural resources* involves reducing the use of diverse environmentally unsustainable resources through ICT-based solutions. *Optimising systems* refers to minimising the environmental load of diverse systems by optimising their operation. As a synthesis, we identified four focal topics within the roadmap themes that are most promising for further investigation. These are: 1) *environmentally sustainable consumption*, 2) *smart energy and buildings*, 3) *lifecycle efficient production*, and 4) *optimised and adaptive networks*.

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