Unclassified **DSTI/ICCP/IE(2009)16/CHAP6**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **11-May-2010**

English - Or. English

DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INDUSTRY
COMMITTEE FOR INFORMATION, COMPUTER AND COMMUNICATIONS POLICY

DSTI/ICCP/IE(2009)16/CHAP6
Unclassified

English - Or. English

Working Party on the Information Economy

INFORMATION TECHNOLOGY OUTLOOK 2010
Chapter 6. Smart sensor networks for green growth

The draft Chapter 6 of the Information Technology Outlook 2010 is circulated for comments and finalisation.

Comments should be provided within 2 weeks of the OLIS date. As for previous editions, the ITO 2010 will be declassified under the written procedure.

Graham Vickery, tel: +33 1 45 24 93 87; Email: graham.vickery@oecd.org

JT03283348

TABLE OF CONTENTS

SMART SENSOR NETWORKS FOR GREEN GROWTH

Sensor and sensor network applications can contribute significantly to more efficient use of resources, tackle environmental challenges and reduce impacts of climate change. In the field of smart buildings, minimum standards of energy efficiency coupled with the use of sensor technology can be a major factor in reducing electricity use and greenhouse gas emissions. However, rebound effects have to be taken into account, particularly in transportation, and increased efficiency due to the use of sensor technology should be paralleled with demand-side management to internalise environmental costs, for example by raising CO_2*–intensive energy and fuel prices, and encouraging systemic change in consumer and user behaviour. Government policies and initiatives are crucial in fostering the positive environmental effects of the use of sensors and sensor networks. Government programmes demonstrating and promoting the use of sensor technology beyond pilot projects and support for the development of open standards can contribute to tapping the potential of sensor technology.*

Introduction: Sensor technology for green growth[1]

1. Environmental degradation and climate change are among the major global challenges facing us. These challenges include improving the efficient use of energy and tackling global warming. ICTs and the Internet play a vital role in tackling these challenges in three ways.[2] They have:

- *Direct impacts* on the environment and can be part of the problem, for example they consume energy and are a source of pollution;
- Major potential to *enable* improved environmental performance in other sectors, for example through "smart" applications in energy, buildings and transport (the focus of this chapter);
- Capabilities to catalyse and support *systemic behavioural* change, for example for consumers to radically increase their consumption of non-renewable energy.

2. This chapter gives an overview of sensor technology and fields of application of sensors and sensor networks. It discusses in detail selected fields of application that have high potential to reduce greenhouse gas emissions and reviews studies quantifying environmental impact in these fields. The chapter provides a detailed followup to Chapter 5 in one application area.

3. Sensor applications can contribute to more efficient use of resources, mitigate climate change, and improve environmental performance. Various examples illustrate the role of ICTs as an enabling provider of solutions to environmental challenges. *Smart grids and smart power systems* in the energy sector can improve energy distribution and optimise energy usage (Adam and Wintersteller, 2008). *Smart housing* can contribute to major reductions of energy use in hundreds of millions of buildings. *Smart transportation systems* are a powerful way of organising traffic more efficiently and reducing CO_2 emissions. All of these applications rely on sensor technology and often on sensor networks.[1]

---

[1] This chapter was prepared in conjunction with Verena Weber, consultant. See also OECD, 2009a.

[2] A detailed analysis of policies focusing on direct and enabling impacts of ICTs is given in OECD, 2009b. This analysis is operationalised in the OECD *Recommendation of the Council on Information and Communication Technologies and the Environment*, OECD, 2010 and www.oecd.org/sti/ict/green-ict.

4. The chapter opens with some technological fundamentals in describing sensor technology and sensor networks. This is followed by an overview of different fields of application. Selected sensor and sensor network applications are discussed and their environmental impact analysed.

Technology overview of sensors, actuators and sensor networks

5. Sensors measure multiple physical properties and include electronic sensors, biosensors, and chemical sensors. This chapter deals mainly with sensor devices which convert a signal detected by these devices into an electrical signal. These sensors can be regarded as "the interface between the physical world and the world of electrical devices, such as computers" (Wilson, 2008). Their counterparts are actuators that convert electrical signals into physical phenomena (*e.g.* displays for quantities measures by sensors such as speedometers, temperature reading for thermostats). Table 1 shows that sensors which measure different properties can have the same form of electrical output (Wilson, 2008).

Table 1. Examples of sensor types and their outputs

Physical property	Sensor	Output
Temperature	Thermocouple	Voltage
	Silicon	Voltage/current
	Resistance temperature detector (RTD)	Resistance
	Thermistor	Resistance
Force/Pressure	Strain Gauge	Resistance
	Piezoelectric	Voltage
Acceleration	Accelerometer	Capacitance
Flow	Transducer	Voltage
	Transmitter	Voltage/current
Position	Linear variable differential transformers (LVDT)	AC voltage
Light Intensity	Photodiode	Current

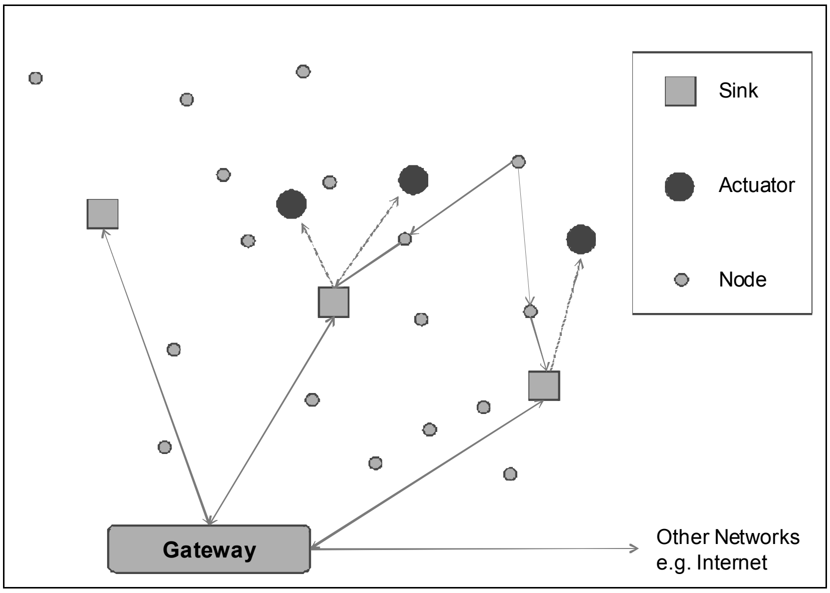
Source: OECD based on Wilson, 2008.

6. *Wireless sensor and actuator networks (WSANs)* are networks of nodes that sense and potentially also control their environment. They communicate the information through wireless links "enabling interaction between people or computers and the surrounding environment" (Verdone *et al.*, 2008). The data gathered by the different nodes is sent to a sink which either uses the data locally, through for example actuators, or which "is connected to other networks (*e.g.* the Internet) through a gateway" (Verdone *et al.*, 2008). Figure 1 illustrates a typical WSAN.[2] Sensor nodes are the simplest devices in the network. As their number is usually larger than the number of actuators or sinks, they have to be cheap. The other devices are more complex because of the functionalities they have to provide (Verdone *et al.*, 2008).

7. A sensor node typically consists of five main parts: one or more sensors gather data from the environment. The central unit in the form of a microprocessor manages the tasks. A transceiver (included

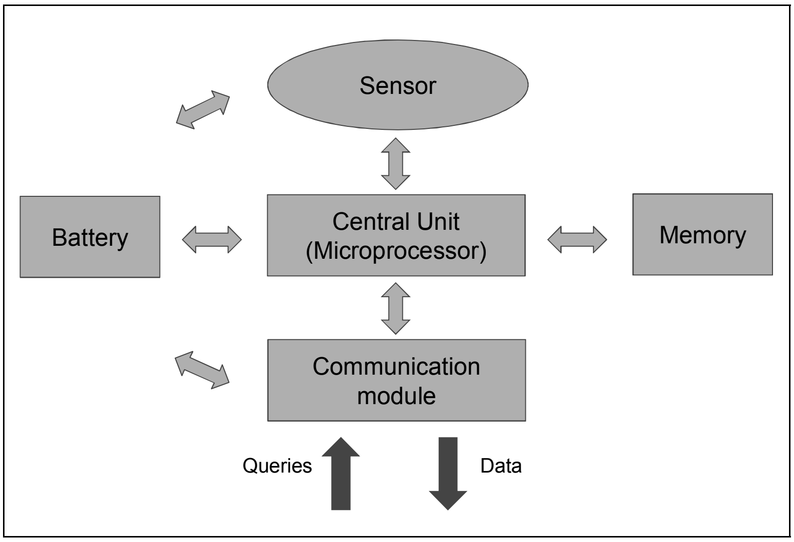
in the communication module in Figure 2) communicates with the environment and a memory is used to store temporary data or data generated during processing. The battery supplies all parts with energy (see Figure 2). Energy efficiency in all parts of the network is crucial, and data processing tasks are often spread over the network, *i.e.* nodes co-operate in transmitting data to the sinks (Verdone *et al.*, 2008). Although most sensors have a traditional battery there is some early stage research on the production of sensors without batteries, using similar technologies to passive RFID chips.

Figure 1. Typical wireless sensor and actuator network



Source: OECD based on Verdone *et al.*, 2008.

Figure 2. Architecture of a sensor node

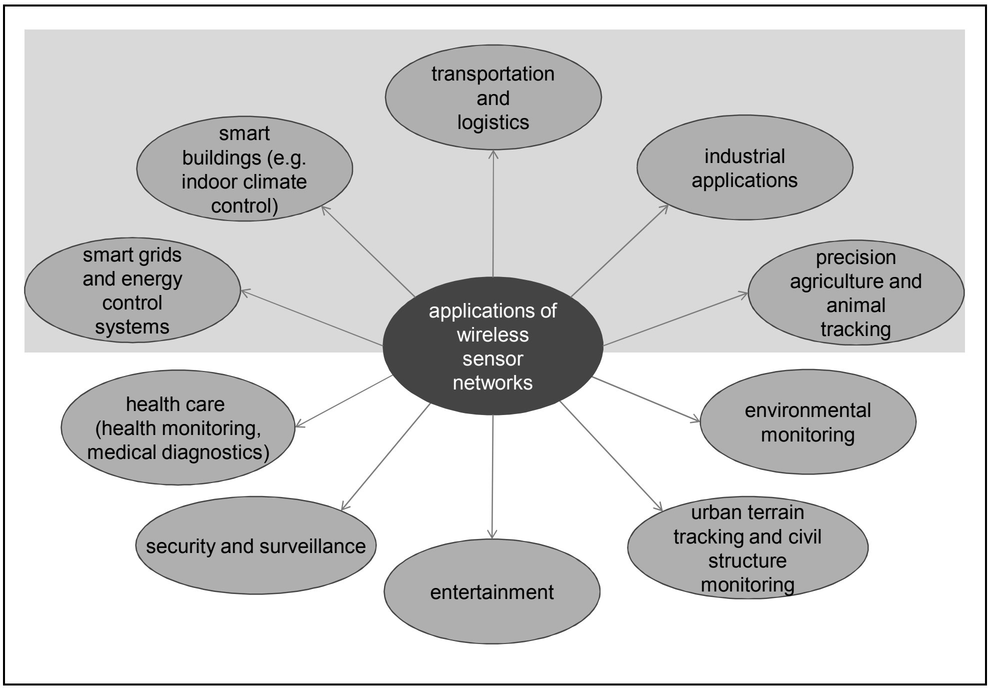


Source: OECD based on Verdone *et al.*, 2008.

Fields of application of wireless sensor networks

8. There are numerous different fields of application of sensor networks. For example, forest fires can be detected by sensor networks, they can be used to monitor the structural integrity of bridges, and to monitor human physiological data (Verdone *et al.*, 2008). Figure 3 shows the most important fields of application. The upper part of the figure 3 shows fields of application that have high potential to tackle environmental challenges. The following sections outline selected applications of wireless sensor networks.

Figure 3. Fields of application of wireless sensor networks



Source: OECD based on Culler *et al.*, 2004, Heppner, 2007, Verdone *et al.,* 2008.

Selected applications and their environmental impact

Smart grids and energy control systems

Introduction, definition and main components

9. Coal power plants are responsible for “nearly 40% of electricity production worldwide”, and electricity generation is thus responsible for a significant share of CO_2 emissions (Atkinson, Castro, 2008). To decrease emissions from the energy supply side, alternative clean technologies can be used to generate electricity or energy can be distributed in a more efficient way.

10. On the generation side, sensor networks enable solar energy to be generated more efficiently. Standalone panels “do not always capture the sun’s power in the most efficient manner” (Atkinson, Castro, 2008). Automated panels managed by sensors track sun rays to ensure that the sun’s power is gathered in a more efficient manner. Such systems can also turn on and off automatically.

11. On the distribution side, energy is distributed in an often inefficient way in traditional grids. At the time when present girds were planned and extended, they had one single mission, namely "to keep the lights on" (DOE, 2008). As a consequence, many systems are centralised and rely on important central power stations making it difficult to integrate distributed energy resources and microgrids (EU, 2006). They most often only support one-way power flow and communication from the utility to consumers. Further, utilities can barely track how energy is consumed across the grid (Atkinson and Castro, 2008) and, have no possibility to provide any pricing incentive to balance power consumption over time. As utilities can only accommodate increases in demand up to a certain level, they are forced to rely on additional peak load power plants to cope with unexpected demand increases (Climate Group, 2008). This is highly expensive and potentially polluting, particularly if plants use fossil fuels.

12. As demand rises and additional power from distributed resources is fed into the grid, important changes must be made. The *smart grid* is an innovation that has the potential to revolutionise the transmission, distribution and conservation of energy. It employs digital technology to improve transparency and to increase reliability as well as efficiency. ICTs and especially sensors and sensor networks play a major role in turning traditional grids into smart grids. However, they are only one group of key components of the smart grid, and the smart grid itself is complex to define (see OECD, 2009a).

13. From a solution perspective, the smart grid is characterised by:

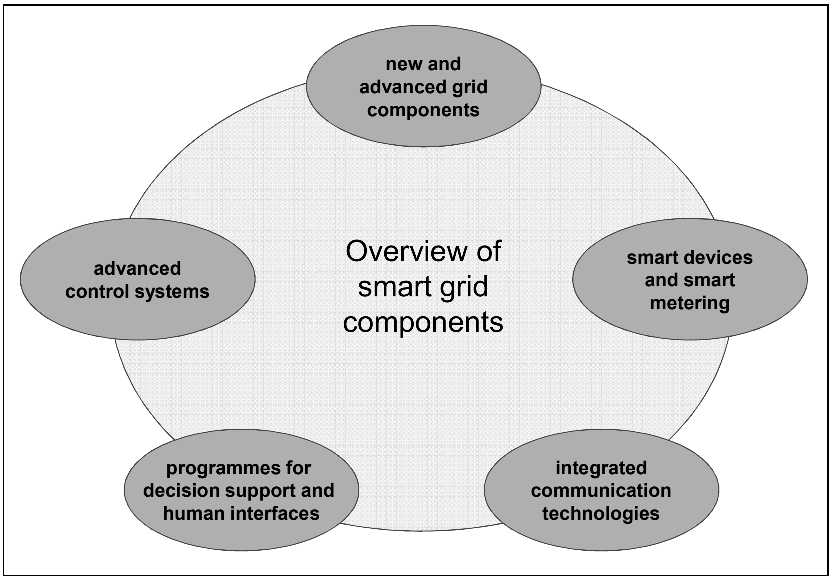
- More efficient energy routing and thus an optimised energy usage, a reduction of the need for excess capacity and increased power quality and security
- Better monitoring and control of energy and grid components
- Improved data capture and thus an improved outage management
- Two-way flow of electricity and real-time information allowing for the incorporation of green energy sources, demand-side management and real-time market transactions
- Highly automated, responsive and self-healing energy network with seamless interfaces.

14. From a technical components' perspective, the smart grid is a highly complex combination and integration of multiple digital and non-digital technologies and systems. Figure 4 provides an overview of the main component of a smart grid: *i)* new and advanced grid components, *ii)* smart devices and smart metering, *iii)* integrated communication technologies, *iv)* programmes for decision support and human interfaces, *v)* advanced control systems. These individual grids do not need to be centralised, but can be more highly integrated, but despite economic advantages, but there are challenges regarding security if they become too centralised and interconnected.

New and advanced grid components

15. Components include advanced conductors and superconductors, improved electric storage components, new materials, advanced power electronics as well as distributed energy generation. Superconductors are used in multiple devices along the grid such as cables, storage devices, motors and transformers (DOE, 2003), and new high-temperature superconductors allows transmission of large amounts of power over long distances at a lower power loss rate. New kinds of batteries have greater storage capacity and can be employed to support voltage and transient stability (SAIC, 2006). Distributed energy is often generated close to the customer, which improves reliability, can reduce greenhouse gas emissions and expand efficient energy delivery (DOE, 2008). Furthermore, most alternative energy generation technologies close to customers are renewables such as solar panels, wind power stations, small hydro-electric and small hydro-thermals that can also be operated by consumers or small providers.

Figure 4. Main components of a smart grid



Source: OECD based on SAIC, 2006, DOE, 2003, EPRI, 2006.

Smart devices and smart metering

16. *Smart metering* includes sensors used at multiple places along the grid, *e.g.* at transformers and substations or at customers' homes (Shargal and Houseman, 2009b). With full two-way communication and interconnection with utilities' data management systems, smart meters form an Advanced Meter Infrastructure (AMI) enabling remote monitoring and demand-side management, and new business processes such as real-time pricing.

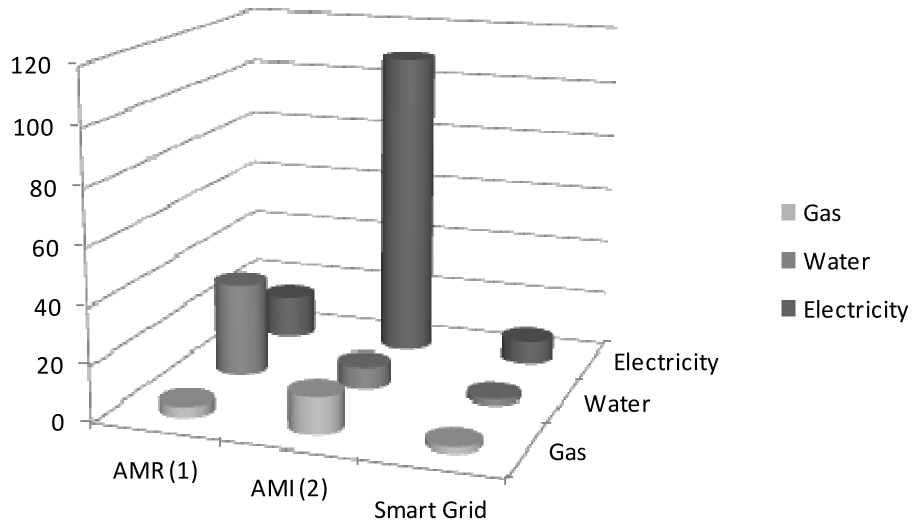
17. Spread over the grid, sensors and sensor networks monitor the functioning and the health of grid devices, monitor temperature, provide outage detection and detect power quality disturbances. Consequently, maintenance staff can maintain the grid just-in-time in the case of disruptions rather than rely on interval-based inspections.

18. Smart meters at customers' homes play a crucial role. They allow for real-time determination and information storage of energy consumption and provide "the possibility to read consumption both locally and remotely" (Siderius and Dijkstra, 2005). Further, they also provide the means to detect fluctuations and power outages, and permit remote limitations on consumption by customers. This results in important cost savings and enables utilities to prevent electricity theft.[3] Smart meters are more than just simple Automatic or Automated Meter Reading (AMR) devices which collect and send metering data to a central database automatically, but do not allow information to be sent back to customers (two-way communication).

19. Electricity providers get a better picture of customers' energy consumption and obtain a precise understanding of energy consumption at different points in time and develop new pricing mechanisms. Energy can be priced according to real-time costs taking peak power loads into account and price signals can be transmitted to home controllers or customers' devices which may then evaluate the information and power accordingly (DOE, 2003). Customers thus become more interactive with suppliers and "benefit from an increased visibility into their energy consumption habits" (IBM, 2007). They are aware of actual power costs rather than obtaining a monthly or even yearly electricity bill. Figure 5 shows the number of initiatives world-wide in 2009 and 2010 focussing on advanced meters. It highlights the concentration of

advanced meter initiatives on Advanced Meter Infrastructure (AMI) for smart electricity metering (109 out of 170 initiatives), well beyond less advanced Automated Meter Reading (AMR) devices.

Figure 5. Number of large-scale advanced meter projects initiated in 2009 and 2010



1) Automatic Meter Reading (AMR)
2) Advanced Meter Infrastructure (AMI)
Source: OECD based on 170 initiatives worldwide focusing on “smart” metering (Engage Consulting, 2010).

Integrated communication technologies

20. Information provided by smart sensors and smart meters needs to be transmitted via a communication backbone. This backbone is characterized by a high-speed and two-way flow of information and diverse technologies in the area of *communication network technologies* are deployed within a smart grid, with WAN and LAN technologies used to reach the customer and those at customer sites (EPRI, 2006). Table 2 presents the main WAN technologies and their strengths and weaknesses for deployment in the smart grid, some of which require high-speed broadband, some of which do not.

21. LAN technologies connect different smart devices at customers’ sites. These technologies can be classified into three main groups: *wireless IEEE standards 802.x*, *wired Ethernet*, as well as *in-building power line communications* (EPRI, 2006).

22. *Wireless IEEE standards* include Wi-Fi (IEEE 802.11), WiMAX[4] (IEEE 802.16), ZigBee (IEEE 802.15.4) and Bluetooth (IEEE 802.15.1). Based on EPRI (2006), Table 3 shows how these standards can be employed for different applications at customers’ sites and summarises their strengths and weaknesses.

23. *Wired Ethernet* is the prevalent LAN technology. Customers’ sites can be connected via Ethernet with WAN or other networks. It is widely used, has wide market support, multiple different products are available and costs are relatively low (EPRI, 2006). However, it is a local area network technology only.

Table 2. Strengths and weaknesses of different WAN technologies

WAN technology		Strengths	Weaknesses
ADSL **(Asymmetric Digital Subscriber Line)**		• high availability • consistent bandwidth regardless of number of users and use in time	• decreasing bandwidth with distance
Cable modem		• high bandwidth • high availability	• inconsistent bandwidth depending on number of users and time of day
FTTH **(Fibre to the Home)**		• scalability • high bandwidth • planned security measures	• relatively high costs • no deployment in rural areas
WiMAX (IEEE 802.16)		• does not require deployment of a costly wired infrastructure	• early stage of deployment, uncertain whether the technology will meet its range targets
Power line communications	**BPL** **(broadband over power line)**	• existing wired infrastructure (particular advantage in rural areas)	• cost of deployment[5] • BPL not suited for particular applications as it is dependent on current on the power line • mostly proprietary
	Narrowband PLC (e.g. IEC 61 334-5 PLC)	• field-proven in Europe • international standards (mostly European)	• cost of deployment • not suited for particular applications as it is dependent on current on the power line
Cellular Services		• high coverage area • potentially low costs	• fast development of new technology (danger of being tied to one provider) • some packet-switched services not very reliable • security concerns • some systems may not transmit unsolicited data
Satellite Services		• universally available, regardless of concrete location	• high costs • low effective bandwidth • additional security measures required • low reliability during bad weather conditions
Paging Systems		• ubiquity • low costs • reliability	• low bandwidth and thus only support of a few applications such as simple emergency alerts

Source: OECD adapted from EPRI, 2006.

24. *In-building power line communications:* The two most common technologies in this area are Home Plug and X10 (EPRI, 2006). Home Plug is a broadband over power line (BPL) system that provides a bit rate of approximately 14 Mbps (The Power Alliance, 2009b). It is suited for applications requiring Quality of Service (QoS) with four different levels of priority. Strengths of the Home Plug network include connectivity to home wiring and QoS features (EPRI, 2006). The main shortcoming is the lack of standards both at the national and international level. The Home Plug Alliance is working with the ZigBee Alliance and EPRI to define a Smart Energy Standard for consumer applications (The Home Plug Alliance, 2009a).

Table 3. Overview of IEEE standards

IEEE standard	Applications	Strengths	Weaknesses
Wi-Fi (IEEE 802.11)	• connecting equipment at customer' site • access between WAN networks and customers' site	• easy deployment • falling costs	• only useful within the customer site • additional security layers required
ZigBee (IEEE 802.15.4)	• drive-by meter reading • user interface at customers' site • connection of sensors and other equipment in a customer LAN	• low power requirements • low implementation cost • good scalability (many devices can be connected) • particularly designed for use in industrial and home automation or security applications	• limited range • relatively low data rates (but probably sufficient) • possibly more secure than other standards
Bluetooth (IEEE 802.15.1)	• drive-by meter reading • user interface at customers' site • connection of sensors and other equipment in a customer LAN	• more mature than ZigBee • many products already available • permits higher data rates than ZigBee	• so far, most equipment does not have Bluetooth implementation • limited maximum number of devices in a network • security vulnerabilities

Source: OECD based on EPRI, 2006.

25. X10 strengths include multiple equipments compatible with X10 and low implementation costs if devices already use power lines (EPRI, 2006). However, it cannot be used as a general purpose LAN. Further, it is a *de facto* standard only and there is no open access to the protocol (EPRI, 2006).

26. Overall, defining a smart grid's communication backbone is paramount for the interoperability of different devices. If not done properly at an early stage, sub-projects "may have to be retrofitted later to accommodate the eventual communication standards, adding greatly to time and expense" (Shargal and Houseman, 2009a). At this stage of development, a compilation of information regarding the success or failure of electricity service providers in their choices for the communication backbone will, for example, help telecommunications regulators to work out what kind of investment in national broadband infrastructures will help achieve the aims of building smart infrastructures.[6]

Programmes for decision support and human interfaces

27. The data volume in smart grids will increase tremendously compared to traditional grids. As Houseman and Shargal (2009) suggest, "a utility with five million customers […] will have more data from their distribution grid than Wal-Mart gets from all of its stores, and Wal-Mart manages the world's largest data warehouse". Challenges include integration and management of the generated data and making the data available to grid operators and managers in a user-friendly manner. Tools and applications include systems based on artificial intelligence and semi-autonomous agent software, visualisation technologies, alerting tools, advanced control and performance review applications (SAIC, 2006) as well as data and simulation applications and geospatial information systems (GIS).

Advanced control systems

28. Advanced control systems constitute the last group of the smart grids' key components. They monitor and control essential elements of the smart grid. Computer-based algorithms allow efficient data collection and analysis, provide solutions to human operators and are also able to act autonomously (SAIC, 2006). For example, new substation automation systems have been developed that provide local information and can also be monitored remotely, making information available in the whole grid and thus providing better power management. Faults can be detected much faster than in traditional grids and outage times reduced.

The environmental impact of smart grids

29. Studies quantifying the environmental impacts of smart grids typically only quantify positive impacts. There is a lack of data which quantifies the negative footprint of ICT infrastructure involved in smart grids. In the following section three studies that examine the greenhouse gas abatement potential of smart grids are discussed (for a detailed overview of studies see Annex 6.A1, Table 6.A1.1).

30. The GeSI study (2008) evaluates the opportunity of smart grids by quantifying global positive impacts and presenting a case study for India. Power losses in India accounted for 25% of total power production in 2007 (see Chapter 5, Box 4). Currently, utilities are not able to detect where the losses occur in the traditional grids. ICT platforms with remote control systems, energy accounting and smart meters could have tremendous effects as they would allow utilities to track the sources of losses. Further, India mainly relies on coal-based energy supply to meet increasing demand. Decentralised energy generated by renewable energy sources could be integrated in a smart grid. Smart grids would thus help to address two major needs of Indian energy providers: stemming losses and reducing carbon intensity.

31. For the quantification of positive impacts, the study assesses four levers that have the potential to reduce greenhouse gas (GHG) emissions: *i)* reduced transmission and distribution (T&D) losses, *ii)* integration of renewable energy sources, *iii)* reduced consumption through user information, and iv) demand side management. The study identifies total emission savings of 2.03 $GtCO_2eq$ in 2020 in a "Business as Usual" (BAU)[7] scenario.[8] Assumptions are based on expert interviews. It should be noted that the GeSI estimates of the overall GHG emissions for the year 2020 are based on data published by the IPCC (Intergovernmental Panel on Climate Change)[9] which are higher than IEA estimates for example (see OECD, 2009a for more details).

32. Whereas the GeSI Smart Grid study assesses the positive environmental impact on a global level in 2020, EPRI (2008) focuses on the positive environmental impacts on a national level in the United States for the year 2030. The study evaluates seven levers: *i)* continuous commissioning for commercial buildings, *ii)* reduced line losses, *iii)* enhanced demand response and (peak) load control, *iv)* direct feedback on energy usage, *v)* enhanced measurement and verification capabilities, *vi)* facilitation of integration of renewable resources, and *vii)* facilitation of plug-in hybrid electric vehicle (PHEV) market penetration. PHEV are "hybrid electric vehicles that can be plugged into electrical outlets for recharging" (EPRI, 2008). As PHEV allow for CO_2 emission savings,[10] the study attributes 10-20% of these savings to the smart grid allowing vehicles to be charged over night. However, R&D on PHEV is still at an early stage. As the study evaluates GHG emission savings for a longer time horizon than the GeSI study, the inclusion of PHEV is useful, but the percentage of emission savings from PHEV attributed to smart grids seems potentially overstated.

33. For each lever, the study develops different market penetration ranges and thus obtains evaluations for low and high market penetration. Overall, the EPRI study estimates GHG emissions reductions ranging from 60-211 million metric tons CO_2eq (see Figure 6.A1.1 in Annex 6.A1 for a detailed

overview). GHG emission savings thus vary considerably due to different market penetrations. Furthermore, estimations are partially based on simple assumptions as well as from single cases.

34. The third study discussed in this section assesses both positive and negative impacts of ICTs on environmental sustainability (IPTS, 2004). As opposed to the above studies, it studies an additional lever: the contribution of renewable energy sources to a reduction of CO_2 emissions and especially the impact of ICTs on the share of renewable energy sources. ICTs facilitate the integration of energy from renewable energy sources. According to the authors, the use of ICTs in the smart grid increases the total share of renewable energy sources in the range of 2-7% in 2020. The range is due to best and worst-case values for three different scenarios as shown in Annex 6.A1, Table 6.A1.2. As a consequence, the electricity mix changes which directly affects overall GHG emissions. The authors also argue that ICTs enhance combined heat and power generation which further decreases use of fossil fuel. According to the study, the impact of smart grid ICTs will be 1.5-3.1% of total GHG reductions in 2020.

35. Rebound effects which arise from a higher efficiency in energy supply are included in the IPTS study, which is not the case for the GeSI and EPRI studies. In terms of scenario building, validation measures and the integration of positive and negative effects, the IPTS study is the most sophisticated presented in this section. It is also the only study which integrates rebound effects.

36. Comparing actual GHG emission values is a difficult task as the conception of these studies differs significantly. They assess different smart grid levels on different continents for differing time horizons. Overall, all studies emphasise that fully and properly deployed smart grids could have an important and strong potential to reduce future GHG emissions. The GeSI study, for example, which assesses the environmental impacts of several smart (sensor) applications, attributes the highest potential to smart grids to reduce GHG emissions.

37. However, it may be also necessary to investigate the potential negative environmental impact associated with the deployment of smart grids, for example, the amounts of additional hardware needed to support and improve the electric transmission grid.

38. Because of the potential positive impacts of smart grids, many OECD countries have emphasised the transformation of actual grids into smart grids. For example, the provisions of the U.S. stimulus bill signed in February 2009 include USD 11 billion for "smart grid" investments. Furthermore, some OECD countries (Italy, Norway, Spain, Sweden and the Netherlands) have already issued mandates for smart metering, and the EU Communication on ICTs and the environment (13 March 2009) and EC Recommendation on mobilising information and communications technologies to facilitate the transition to an energy-efficient, low-carbon economy (Commission, 2009) emphasise the role of smart metering.

39. One of the main questions for successful implementation of smart grids will be whether energy suppliers can agree on working together to adopt industry-wide solutions and developing and adopting open standards (Adam, Wintersteller, 2008).

Smart buildings

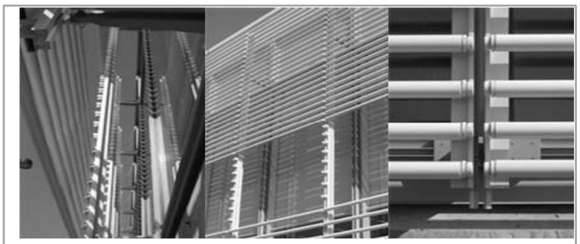
Introduction, definition and main components

40. Smart buildings are a field closely linked to smart grids. They rely on a set of technologies that enhance energy-efficiency and user comfort as well as the monitoring and safety of the buildings. Technologies include new building materials as well as information and communication technologies (ICTs). An example of newly integrated materials is a second façade for glass sky scrapers. The headquarters of the New York Times Company has advanced ICT applications as well as a ceramic

sunscreen consisting of ceramic tubes which reflect daylight and thus prevent the skyscraper from collecting heat (see Box 1).

Box 1: The New York Times Building - a smart building

The headquarters of the New York Times is an example of how different smart building technologies can be combined to reduce energy consumption and to increase user comfort. Overall, the building consumes 30% less energy than traditional office skyscrapers.



Ceramic rods (*Source*: Vorapat Inkarojrit)

Opened in November 2007 and designed by Renzo Piano, the building has a curtain wall which serves as a sunscreen and changes colour during the day. This wall consists of ceramic rods, “a supporting structure for the screen and an insulated window unit” (Hart, 2008).

The building is further equipped with lighting and shading control systems based on ICT technologies. The lighting system ensures that electrical lighting is only used when required. Further day lighting measures include a garden in the centre of the ground floor which is open to the sky as well as a large area skylight. The electrical ballasts in the lighting system are equipped with chips that allow each ballast to be controlled separately. The shading system tracks the position of the sun and relies on a sensor network to automatically actuate the raising and lowering of the shades. Experience had shown that if it were up to employees sitting next to the windows to control the shades, “the shades would likely be down most of the time since occupants” were “often too busy to manage the shades” (LBNL, 2009).

The high-tech HVAC system is equipped with sensors that measure the temperature. It is further able to rely on free air cooling, *i.e.* fresh air on cool mornings is brought into the HVAC system. An automated building system monitors in parallel “the air conditioning, water cooling, heating, fire alarm, and generation systems” (Siemens, 2008). The system relies on a large-scale sensor network composed of different kinds of sensors which deliver real-time information. Consequently, energy can be saved as only as few systems are turned on as needed.

Sources: Hart, 2008, Siemens, 2008, The New York Times Building, 2009, LBNL, 2009.

41. ICTs are used in: *i)* building management systems which monitor heating, lighting and ventilation, *ii)* software packages which automatically switch off devices such as computers and monitors when offices are empty (SMART, 2020) and *iii)* security and access systems. These ICT systems can be both found at household and office level. Furthermore, according to Sharpels *et al*., (1999), first-, second- and third-generation smart building systems can be distinguished.[11] First-generation smart buildings are composed of many stand-alone self-regulating devices which operate independently from each other. Examples include security and HVAC systems. In second-generation smart buildings, systems are connected via specialised networks which allow them to be controlled remotely and “to facilitate some central scheduling or sequencing” (Sharpels *et al.,* 1999), *e.g.* switching off systems when rooms and offices are not occupied. Third-generation smart building systems are capable of learning from the building and adapting their monitoring and controlling functions. This last generation is at an early stage.

42. Sensors and sensor networks are used in multiple smart building applications. These include: *i)* heating, ventilation, and air conditioning systems (HVAC), *ii)* lightning, *iii)* shading, *iv)* air quality and window control, *v)* systems switching off devices, *vi)* metering (see smart grids), *vii)* standard household applications (*e.g.* televisions, washing machines) and *viii)* security and safety (access control).

43. Sensors embedded in HVAC systems, for example, monitor the temperature and the status of parts of the buildings such as open or closed windows. In the field of air quality, new gas sensors, micro electrical-mechanical systems (MEMS), measure the content of CO_2 in rooms. These relatively new types of sensors are made of "silicon chips and an oxidizing layer" (Siemens, 2008c). Overall, different types of sensors for smart buildings include: *i)* temperature sensors and heat detectors, *ii)* light level detectors, *iii)* movement and occupancy sensors, *iv)* smoke and gas detectors, *v)* status sensors (*e.g.* air quality, open windows), and *vi)* glass break sensors (Annex 6.A1, Table 6.A1.3 cross-tabulates applications and typical sensor types used for these applications).

44. According to Siemens (2008c), sensors and sensor networks in smart building systems significantly contribute to energy reduction. They estimate the energy savings due to more precise climate, air quality and occupancy sensors at 30% compared to buildings with traditional automation technology. The following section provide an overview of different impact studies focusing on total smart building and facility management systems and their energy consumption and emissions.

The environmental impact of smart buildings

45. Only a few studies on the environmental impact of smart buildings cover more than single applications and more than one country. In the following studies, GeSI (2008) focuses on positive impacts, whereas the IPTS study (2004) covers both positive and negative impacts.

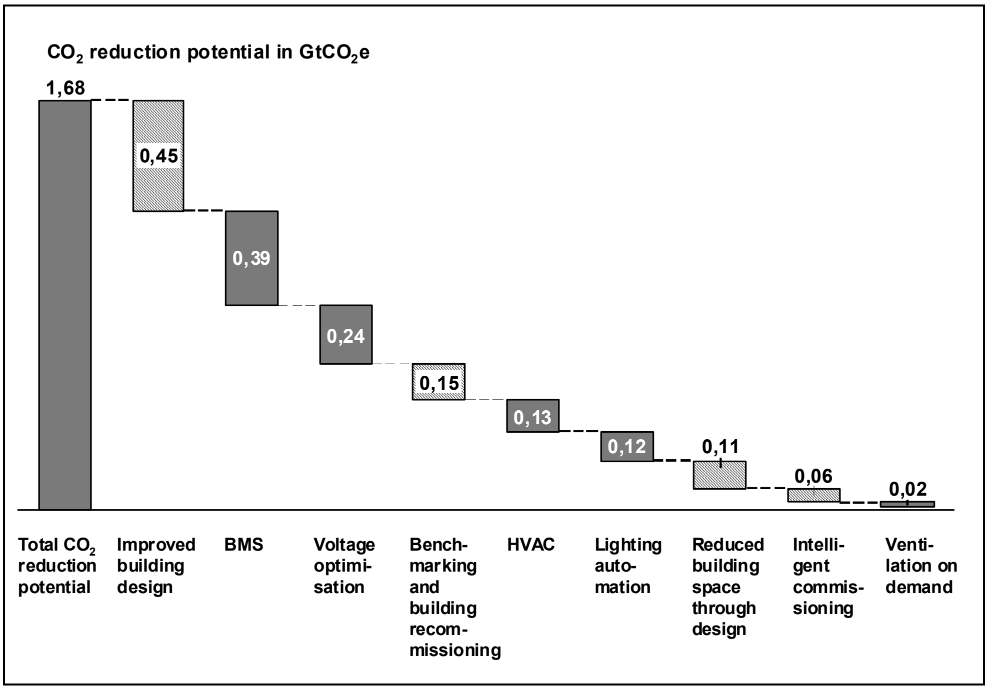
46. According to GeSI estimations (2008), buildings will emit 11.7 $GtCO_2eq$ worldwide in 2020 which equals 22.5% of total emissions. This includes private households, public buildings and offices. The study identifies an abatement potential of 1.68 $GtCO_2eq$ in a BAU scenario. This abatement potential results from levers that can be attributed to sensors and sensor networks and further levers. Figure 6 provides an overview of impacts. Levers including a positive impact of sensors and sensor technology are highlighted in blue solid shading. These levers account for 59.5% of total GHG savings. Most important impact levers include savings due to efficient building management systems and savings resulting from voltage optimisation as well as HVAC systems. Other impacts which cannot directly be attributed to sensors have diagonal lines (for the underlying assumptions, see Annex 6.A1, Table 6.A1.4) Overall, important savings can be obtained by intelligent commissioning of buildings, *i.e.* "ensuring the building's systems are used as specified" (GeSI, 2008). It thus not only depends on the ICT technology and its sophistication but also on a proper use of these systems. As for the smart grid calculations, the GeSI estimates for the year 2020 are mainly based on the global GHG emission data by the IPCC.

47. The IPTS study (2004) covers the environmental impact of smart buildings in the field of facility management where ICT contributes to energy savings. Facility management "targets space heating, water heating, cooling, lighting, cooking and electrical appliances" (IPTS, 2004). With the projected development of ICT, reductions in energy consumption range from 3.5% in the worst case to 7.1% in the best case in 2020. Consequently, ICT in facility management contributes to GHG emissions savings ranging from 3.5% in the worst case to 6.5% in the best case. Overall, an important reduction of energy consumption as well as GHG emissions is observed across all scenarios (for a detailed overview see Annex 6.A1, Table 6.A1.2).

48. Both studies emphasise the pivotal role of governments in attaining significant reductions in both energy consumption and greenhouse gas emissions. They recommend different measures to promote the use of ICTs in smart buildings. These measures include demonstration projects with best practice examples, minimum standards of energy efficiency for existing and new buildings, economic incentives, investments in R&D as well as providing a setting where governments and other stakeholders exchange results on different energy-efficiency measures.

49. To date, several programmes have already been set up to promote increased energy efficiency in buildings such as CASBEE (Japan) or LEED in the United States. Furthermore, the IEA aims at constructing "the world's leading database on efficiency codes and standards for buildings" for comparison purposes (IEA G8 Gleneagles programme, 2008).

Figure 6. Positive environmental impact of smart buildings



Source: GeSI, 2008.

Transport and logistics

Introduction and applications

50. Information and communication technologies (ICTs) and sensor networks in particular have the potential to increase efficiency in freight and passenger transport and to potentially reduce overall transportation. On the one hand, increased use of ICTs can avoid freight and passenger transport through a higher degree of virtualisation, digitisation and teleworking. Digital content is delivered electronically and virtual conferences and teleworking reduce passenger transport. On the other hand, increased use of ICTs can contribute to better management of transport routes and traffic, higher safety, time and cost savings as well as reductions of CO_2 emissions.

51. Sensors and sensor networks play a vital role in increasing transport efficiency. For example, sensor technology contributes to better tracking of goods and vehicles which might result in lower level of inventories and thus energy savings from less inventory infrastructure as well as a reduced need for transportation (Atkinson, Castro, 2008). Furthermore, sensors and sensor networks are pivotal parts of many intelligent transportation systems (ITS).

52. An intelligent transportation system (ITS) can be defined as "the application of advanced and emerging technologies (computers, sensors, control, communications, and electronic devices) in transportation to save lives, time, money, energy and the environment" (ITS Canada, 2009). The ITS can

be categorised into *intelligent infrastructure* and *intelligent vehicles* (RITA, 2009). Figure 7 gives an overview of different ITS applications for both intelligent infrastructure and intelligent vehicles as well as some examples for each application.

53. Many of these applications are based on sensors and sensor networks. In the field of *intelligent infrastructure* sensors in pavements are used to measure the intensity and fluidity of traffic (vehicle count sensors) and to provide information for traffic. These sensors are further able to detect whether, for example, public buses are approaching so that the green phase of traffic lights can be extended, allowing buses to keep their schedules (Veloso, Bento, Câmara Pereira, 2009). They also transmit information to update public transport panels. New sensor applications include intermittent bus lanes (see Box 2). In addition, sensors are used for motorway tolling purposes where they detect vehicle RFID tags and retrieve the required information. Sensors also monitor the state of physical infrastructures such as bridges by detecting "vibrations and displacements" (Veloso, Bento, Câmara Pereira, 2009).

54. *Intelligent vehicles* are equipped with sensors for multiple purposes. Examples include: *i)* Trains in metros, especially driverless systems, use sensors to control the velocity and location of trains as well as stops at metro stations (Veloso, Bento, Câmara Pereira, 2009). *ii)* Buses rely on door sensors to detect whether doors are open. Further applications include environmental sensors on buses and tramways that detect weather conditions, analyse traffic conditions and give alerts via on-board mini-computers (MORYNE FP6 Project, 2008). *iii)* For applications in cars current research projects focus on vehicle-to-vehicle communication based on data gathered by sensors (see for example EU projects such as Coopers and PReVent). These (environmental) sensors collect information on the location of the car, the speed and road and weather conditions. As cars pass each other, they can exchange the summarised information. Based on a detailed description of the environment, cars obtain traffic information and drivers are able to plan their routes more efficiently. In addition, trajectories of vehicles can be predicted resulting in a sophisticated risk assessment and thus increased traffic safety as drivers can be warned of dangerous driving conditions. A further example is a tyre pressure monitoring system which delivers real time tyre pressure information to the driver. Besides improving safety, the system helps to "reduce the amount of emissions released into the atmosphere" (Intelligent Car Initiative, 2008).

Figure 7. Overview of intelligent transportation systems applications

Intelligent Transportation Systems

Intelligent Infrastructure

Arterial and Freeway Management
- Traffic Signal Control, Lane Management
- Surveillance, Enforcement

Crash Prevention and Safety
- Warning Systems
- Pedestrian Safety

Traffic Incident Management
- Surveillance, Detection
- Response, Clearance

Emergency Management
- Hazardous Material Management
- Emergency Medical Services

Electronic Payment and Pricing
- Toll Collection
- Multi-Use Payment

Roadway Operations
- Asset Management
- Work Zone Management

Transit Management
- Operations and Fleet Management
- Transportation Demand Management

- **Traveller Information**
- Pre-trip and En-Route Information
- Tourism and Events

Road Weather Information
- Surveillance and Prediction
- Traffic Control

Information Management
- Information Warehousing Services
- Archived Data Management

Commercial Vehicle Operations
- Carrier Operations, Fleet Management
- Credentials Administration

Intermodal Freight
- Freight and Asset Tracking
- International Border Crossing

Intelligent Vehicles

Collision Avoidance
- Obstacle Detection
- Collision-Avoidance Sensor Technologies

Driver Assistance
- Navigation, Route Guidance
- On-Board Monitoring

Collision Notification
- Advanced Automated Collision Notification
- In-Vehicle Crash Sensors

Source: OECD based on RITA, 2009 and Alberta Transportation, 2009.

Box 2. Intermittent bus lanes

To allow a better flow and speed of public transport, many cities rely on special lanes for buses, taxis and emergency vehicles. However, this system can be further optimised as, at times, the lane is empty and could instead be used for general traffic, especially in heavy traffic situations. The idea of the optimised solution is to normally open the bus lane for general traffic and to reserve it only when public transport is approaching and when the general traffic is slower than the normal speed of public transport.

Researchers in Portugal have developed a wireless sensor network system which has been tested in Lisbon. Installed lights in the tarmac separate the bus lane from other lanes and are only turned on when a bus is approaching. The presence of public transport in the bus lane is detected by sensors in the ground and can be supported by additional information such as data from public transport fleet management systems. This information is processed by a control station installed near traffic lights. In recent systems, the in-pavement components are wirelessly connected to each other and to the control station to reduce installation costs. Each module is battery powered and the batteries are charged by pavement-embedded solar panels (see Silva Girão *et al.,* 2006). Communication is assured via RF transmitters and receivers. Overall, the results of trials in Lisbon are encouraging as the bus speed could be increased and the negative impact on the general traffic flow was low. The researchers have recently also worked on upgrades of the system such as the detection of intrusion of private transport in the bus lane when the lane is reserved for public transport, and the incorporation of cameras for law enforcement.

Sources: Viegas and Lu, 2005, Silva Girão *et al.,* 2006.

55. Overall, ITS systems make public and private transport more efficient, and potentially cheaper which may increase transport volumes (rebound effect) and the environmental impact might thus be negative. Results of studies analysing the environmental impact of smart transportation are mixed due to this effect, in contrast to other fields of application. In the following the results from GeSI (2008) and IPTS study (2004) are presented (see Annex 6.A1, Table 6.A1.1 for a description of the studies).[12]

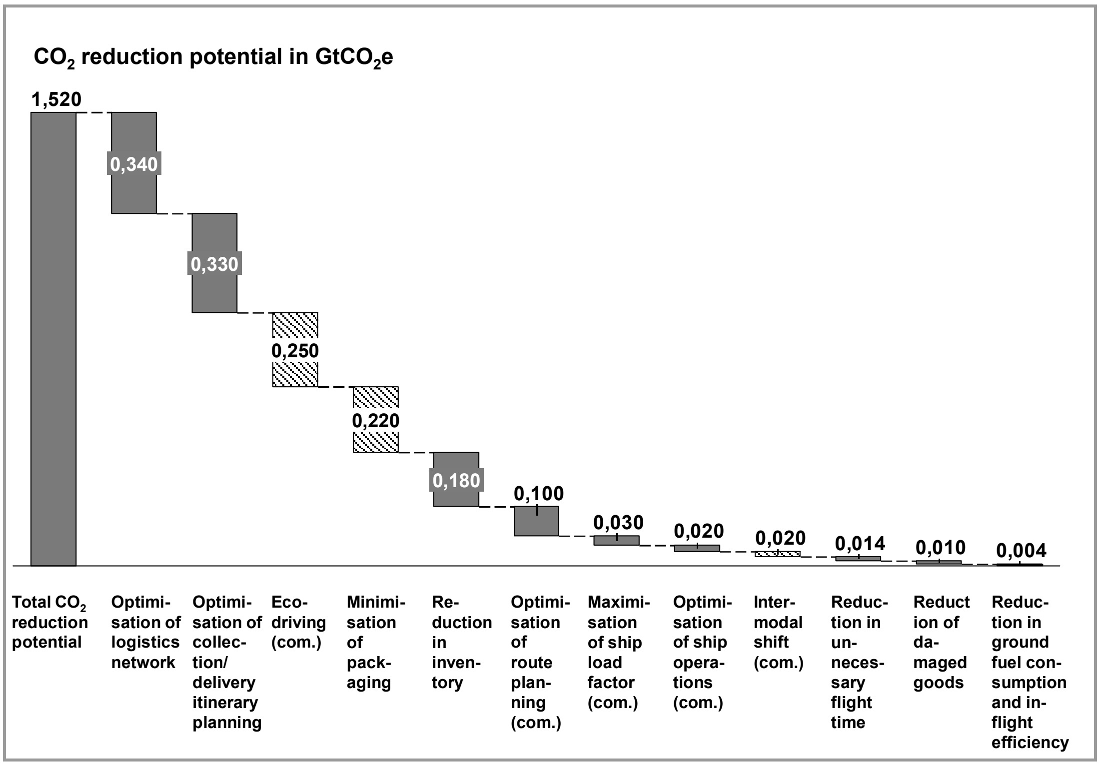
The environmental impact of smart transportation

56. The GeSI study (2008) estimates an abatement potential of 1.52 $GtCO_2eq$ worldwide in the field of smart transport (see Figure 8). Levers that can be attributed to sensors and sensor networks and further levers constitute the overall abatement potential. Levers that can include a positive impact of sensors and sensor networks are marked in blue solid shading in Figure 8, other levers have diagonal lines. The most important levers include the optimisation of logistic networks and optimised collection and delivery planning. Overall, the calculations are based on ambitious assumptions as they assume reductions of over 20%, furthermore, the study does not cover rebound effects (see Annex 6.A1, Table 6.A1.5 for details).

57. The IPTS study (2004) assesses the impact of ITS on passenger and freight transport.[13] In contrast to the GeSI study, the authors find a significant increase of both passenger and freight transport volume across all scenarios with a low data uncertainty and a negative impact of ICTs in the field of ITS. This results in an increase of GHG emissions due to the use of ICT in transportation across all scenarios and best and worst case situations. With the projected development of ICTs compared to a situation without this projected development, an increase in GHG emissions ranges from 1.9% in the best case and 2.7% in the worst case scenario (see Annex 6.A1, Table 6.A1.2 for detailed results).

58. ITS render transport faster, more efficient and flexible and, as a consequence, cheaper, “leading to a full rebound effect” (IPTS 2004). The demand for transportation increases and creates more transport leading to higher consumption of energy and to growing greenhouse gas emissions. According to the authors “higher transport efficiency is the key ICT effect increasing freight transport in 2020. This increase is in the range of 12% to 28%” (IPTS, 2004) for freight transport and of 5-7% for passenger transport. Although the increasing impact of ITS with the projected development of ICTs is significantly higher for scenario B, the absolute freight transport volume is the lowest one in this scenario as environmental costs are already internalised (see the fourth IPTS interim report (Hilty *et al.*, 2004)).

Figure 8. Positive environmental impact of smart logistics



Source: GeSI, 2008.

59. In the field of passenger transport, the increased time efficiency of passenger transport implies that a higher passenger transport volume can be attained in the same time which raises traffic performance. However, "ICT can slow the growth of private car passenger transport, avoiding 10-19% of future car traffic, despite the fact that it stimulates the growth of total passenger transport" (IPTS, 2004) due to better time utilisation. This effect is supposed to increase the use of public transport in the modal split as ICTs can contribute to a more effective use of travel time to work. Public transport thus becomes more attractive which can promote a shift from private cars to public transport. However, this effect also "relaxes the time budget and therefore enables more traffic" (IPTS, 2004).

60. In the field of freight transport, the full rebound effect which results from cheaper transport shows that freight transport is "highly sensitive to fuel prices". Raising fuel prices and thus internalising environmental costs could thus reduce demand significantly.

61. Overall, this overview of the GeSI and the IPTS studies shows mixed results of the impact of intelligent transport systems due to rebound effects. These effects also highlight that governments can have a crucial role in the field of smart transportation. As the IPTS study shows, increased efficiency of transportation should be paralleled with demand-side management. Internalisation of environmental effects by raising energy and fuel prices or the inclusion of transportation in emission trading could reduce demand for transport and thus reduce GHG emissions (IPTS, 2004). Furthermore, governments can make use of ITS in public transport to render it more attractive and promote a modal shift from private cars to public transport. Further measures also include better services such as real-time time-table information and optimised route planning.

Industrial applications

Introduction and applications

62. The industry sector is an important emitter of greenhouse gas emissions. According to GeSi (2008), it was responsible for 23% of total emissions in 2002 and used nearly half of all global electricity. Sensors and especially sensor networks are used in multiple ways in industrial applications. They enable real-time data sharing on industrial processes, on the "health state" of equipment and the control of operating resources to increase industrial efficiency, productivity and reduce energy usage and emissions.

63. As the variety of different sensor applications is immense across industry sectors,[14] this section describes three examples of industrial fields of application of sensors for: *i)* process control, *ii)* control of (physical) properties during the production process, and *iii)* equipment management and control.

64. In the field of process control, sensor and sensor networks deliver real-time data on the production process and are able to detect *in situ* variations in the process. Control can thus be moved from the finished product after the completed production run to the production process itself (DOE, 2007). Faults can be minimised reducing the percentage of deficient and reprocessed goods. Furthermore, a continuous monitoring of processes allows for efficient use of energy during production processes. An application example in this field is an online laser-ultrasonic thickness gauge which measures the thickness of steel tube walls under harsh conditions in mills. During production, it ensures that "tube walls are uniform and reduces the need to remove excess material from the walls of the tubes". Consequently, product consistency can be improved and material saved while "reducing the time and energy used during production" (DOE, 2004).

65. In the field of the control of physical properties during production processes, sensors and sensor networks measure different properties and the amount of available resources during production. This allows that resources are employed in an efficient and precise manner resulting in energy savings and the reduction of pollutants. Examples are sensors measuring the temperature and composition of combustion gases and sensors measuring the concentration of hydrogen gas (DOE, 2007).

66. In the third field, equipment management and control, sensors monitor the "health of machines" and their usage. Sensors installed on different machines measure physical properties such as temperature, pressure, humidity or vibrations (Verdone, 2008). The sensor nodes are able to communicate between each other and send data to the network where the data is processed. When critical values are achieved, the system immediately sends signals making predictive maintenance possible. This intelligent maintenance monitors the functionality of parts and ensures that they are replaced based on a degradation assessment rather than on replacement rules. Sensors also control motors during usage. Motors running at full capacity regardless of load can be inefficient and waste energy (GeSi, 2008). Sensors allow the motor to adjust the power usage according to the required output. Wireless networks linking different sensors make machine-to-machine communication possible and have the potential to increase energy efficiency in whole factories.

67. As the examples have shown, many specific and niche sensor applications are used in factories. Consequently, interoperability of different systems becomes a crucial issue to connect different sensor systems and to maximise efficiency and energy savings. Some standards have already been launched such as the interface IEEE 1451 group of standards which aims at enabling plug-and-play of different sensors and sensor networks (Chong, Kumar, 2003).

The environmental impact of smart motor systems

68. There is so far little information on the overall environmental impact of sensors and sensor networks across different fields of industrial applications. GeSi (2008) assessed the impact of one major

industrial field of application: smart motor systems. The study focuses on positive impacts (for a description of the study, see Annex 6.A1, Table 6.A1.1). In the following, the results of this analysis are discussed to give an example of the environmental impact of smart industrial applications.

69. According to GeSi (2008) motor systems account for 65% of total energy use by industry. Smart motors which adjust power consumption to outputs can have an important role in reducing this demand. The authors of the study estimate a worldwide abatement potential of 970 $MtCO_2eq$ in a BAU scenario. This is due to an optimisation of motors' speed (abatement potential of 680 $MtCO_2eq$) and to ICT-driven automation in key industrial processes (abatement potential of 290 $MtCO_2eq$). Overall, the authors assume a penetration rate of motor system optimisation technology of 60% which is relatively high compared to the assumed penetration rate of process optimisation technology of 33%.[15]

70. The example highlights that sensor technology has an important impact on energy and greenhouse gas emission savings for industrial automation and control. Savings are especially high when different sensors and sensor networks communicate with each other. Besides the use of sensor technology, sound process planning, for example with process optimisation tools, plays an important role. Various initiatives have been created such as Motor Decision Matters,[16] and Work Energy Smart[17] which focus on technology and process planning and improvement.

Precision agriculture and animal tracking

71. Sensors and sensor networks are important components of precision agriculture aimed at "maximum production efficiency with minimum environmental impact" (Taylor and Whelan, 2005). Land over-exploitation, one of the major concerns of intensive agriculture, leads to soil compaction, erosion, salinity and declining water quality (Wark *et al*., 2007). Sensors and sensor networks can play a critical role in measuring and monitoring soil health and water quality from pre- to post-production. In the field of animal tracking, the movement of herds, the health of animals and the state of the pasture can be controlled via sensor networks. So far, trials and field experiments are under way, but widespread applications are at an early stage. This section briefly describes applications of sensor networks in precision agriculture and animal production. Environmental impacts are presented qualitatively due to the early application stage.

72. In precision agriculture, sensor networks can be used for: *i)* plant/crop monitoring, *ii)* soil monitoring, *iii)* climate monitoring and *iv)* insect-disease-weed monitoring. For plant/crop monitoring, wireless sensors have been developed to gather, for example, data on leaf temperature, chlorophyll content and plant water status, to help farmers detect problems at an early stage and implement real-time solutions. Plant and crop cultivation can be improved with better knowledge of soil fertility, water availability and compaction. Further, sensor nodes which communicate with radio or mobile network weather stations can provide climate and micro-climate data and sensors registering the temperature and relative humidity detect conditions under which disease infestation is likely to occur (see Box 3).

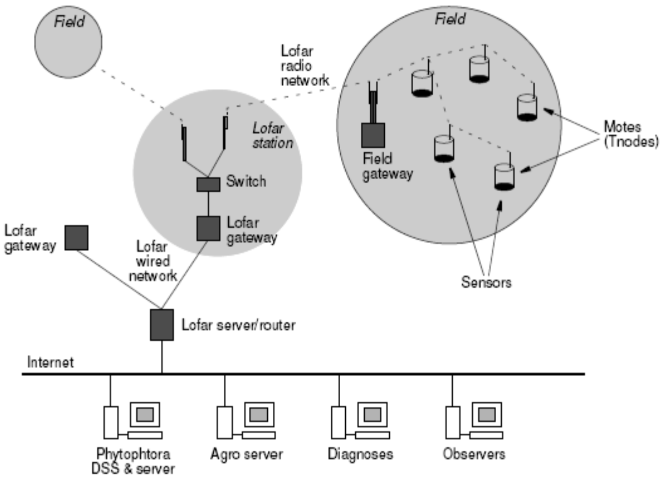
73. The health of pastures can also be evaluated through high-resolution remote sensing tools. Healthy pastures usually "have a consistent cover of evenly dispersed perennial vegetation" (Ludwig *et al.*, 2008). Remotely sensed satellite maps depict the location of persistent vegetation cover. Based on these maps and information on the three dimensional shape of the landscape, Australian scientists calculate leakiness values and their changes over time. As a result, conditions of pastures can be measured and problematic areas detected (Ludwig *et al.*, 2008).

74. Wireless sensors are further used for precision irrigation, and systems developed for remotely controlled automatic irrigation. Sensors assume, for example, the tasks of irrigation control and irrigation scheduling using sensed data together with additional information, *e.g.* weather data (Evans and Bergman,

2003). Finally, sensors are used to assist in precision fertilisation. Based on sensor data, decision support systems calculate the "optimal quantity and spread pattern for a fertilizer" (Wang *et al.*, 2006).

Box 3. Monitoring crop micro-climates

The LOFAR (Low Frequency Array) Agro Project measured the micro-climate in a potato field to provide information on how to combat the fungal disease phytophtora which depends on climatological conditions in the field.



150 sensor nodes which measure both temperature and relative humidity were deployed (see figure). Additional sensors were deployed to monitor soil humidity. A weather station "registering the luminosity, air pressure, precipitation, wind strength and direction" completed the setup.

Sensor nodes sent the gathered data via a wireless connection every 10 minutes to field gateways which sent it to an ordinary PC for data logging (the Lofar gateway in the figure). The data was further transmitted to other servers for data analysis via a wired Internet connection. A decision support system mapped the temperature distribution together with other information. Based on this information, farmers can take different actions and vary the amount of fertilizer and pesticide used.

Source: Baggio, 2005. Note that most such projects have not been scaled-up.

75. Wireless sensors are further used for precision irrigation, and systems developed for remotely controlled automatic irrigation. Sensors assume, for example, the tasks of irrigation control and irrigation scheduling using sensed data together with additional information, *e.g.* weather data (Evans and Bergman, 2003). Finally, sensors are used to assist in precision fertilisation. Based on sensor data, decision support systems calculate the "optimal quantity and spread pattern for a fertilizer" (Wang *et al.*, 2006).

76. Wireless sensor networks also contribute to better understanding of cattle grazing habits, herd behaviour and their interaction with the surrounding environment (Wark *et al*., 2007). Such information helps famers to understand the state of the pasture and optimise resource use. To test sensor applications for cattle management, sensor nodes were attached to cattle collars. Cattle collars pinged each other "with each ping containing an animal's GPS position and time of each ping transmission" (Wark *et al.,* 2007). Based on the positioning data of each node and inertial information, individual and herd behaviour could be modelled and more general models developed. As a result, farmers can more optimally manage environmental resources and plan grazing areas to prevent overgrazing and erosion. Recent work focuses on the integration of sensor networks and radio frequency technology (RFID) as a significant number of cattle are equipped with RFID tags to record for example cattle characteristics and food information.

The environmental impact of precision agriculture and animal tracking

77. Through the monitoring of the soil, climate and plants, a precise irrigation rate can be determined which may lead to a *reduced consumption of water*. Usually, fields are irrigated with uniform amounts of water. However, the variability in a field requires different amounts for different areas due to the combination of different crops and soil types (USDA, 2007).

78. Various projects have been conducted to measure the extent of water savings. Damas *et al.*, (2001), for example, tested an automated irrigation system for a 1 500 ha area in Spain, with water savings of 30-60%. According to the USDA, another study found water savings of 5.7 million gallons on 279 acres in 2002 (USDA, 2007). One study by King *et al.* (2006) showed no significant water savings for a variable rate irrigation system. However, the spatial variability in available water holding capacity (AWHC) of the soil was considered the main determinant influencing crop yield and the basis for a site-specific irrigation management (SSIM) system. The authors acknowledge that the "... results from this study and others collectively suggest that AWHC may not be the best or only parameter to consider in delineating irrigation management zones. A systems approach to SSIM will likely be required that takes into account all known factors affecting yield ... " (King *et al.,* 2006). Overall, the majority of studies showed a reduced consumption of water, but that deployment should be based on a thorough analysis of the area being irrigated and a comprehensive consideration of different factors which affect site-specific irrigation. Sensors and sensor networks can significantly contribute to this analysis by providing the required data.

79. Further important benefits of precision agriculture are *reductions of fertilisers and pesticides*. Applications of the latter affect surface and groundwater quality, the quality of crops, soil properties and non-target species. Through monitoring the soil, the micro-climate and crops, it is possible to apply only the fertilisers and the pesticides crops need. Rates can be varied in real-time within fields based on different field and plant properties. Additionally, applications can be more precisely controlled in environmentally sensitive areas (USDA, 2007). Finally, a more targeted application of pesticides can reduce problems of pesticides resistances.

80. In the field of animal tracking, farmers are able to manage grazing areas based on information on herd behaviour. As a consequence, *overgrazing of pastures as well as land erosion can be avoided.* Limited pasture resources can thus be effectively managed.

81. Overall, sensors and sensor networks significantly contribute to a more sustainable use of natural resources. However, development of sensors and sensor networks for precision agriculture is in an early stage and sensor applications tend to be expensive. To date, farmers only take economic benefits into consideration when deciding on whether they should rely on precision agriculture (USDA, 2007). Governments can help farmers to recognise the environmental dimension by illustrating the economic benefits of improved soil and pasture quality and reduced applications of fertilisers and pesticides. Further, precision agriculture can be encouraged through technical assistance and conservation programmes.

Conclusion

82. This chapter surveys sensor and sensor network applications and their impact on the environment. Studies show that the technology has a high potential to contribute to reductions of green house gas emissions across various applications. Sensor applications in smart power grids, smart buildings and smart industrial process control significantly contribute to more efficient use of resources and the reduction of greenhouse gas emissions and other sources of pollution.

83. Nevertheless, whereas studies clearly estimate an overall strong positive effect in smart grids, smart buildings, smart industrial applications and precision agriculture and farming, results for smart transportation are mixed due to rebound effects. Intelligent transport systems make transport more efficient, faster and cheaper. As a consequence, demand for transportation and consumption of resources both increase with potentially negative overall consequences.

84. Government policies and initiatives are crucial in fostering positive environmental effects of the use of sensors and sensor networks and are an essential part of strategies to radically improve environmental performance (OECD, 2009b). However, due to rebound effects, increased efficiency

associated with the use of sensor technology should be paralleled with demand-side management to internalise environmental costs, for example by raising CO_2-intensive energy and fuel prices. In the field of smart buildings and smart grids, minimum standards of energy efficiency can be a major factor in reducing electricity use and mitigating climate change.

85. In general, many promising applications are still at an early stage of development. Joint R&D programmes as well as demonstration and implementation projects can promote the use of sensor technology and contribute to industry-wide solutions and the development of open standards. Finally, the use of ICTs and especially sensor technology may be relatively expensive, for example in agriculture and farming. Governments can encourage the use of ICTs and sensor technology through conservation programmes and by accentuating the environmental dimension of ICTs in agriculture and farming.

NOTES

---

[1] The work on sensors and sensor networks is part of OECD work on ICTs and environmental challenges (see OECD, 2009a, 2009b, 2009c, 2009d). It is also a direct follow-up to the June 2008 *Seoul Declaration for the Future of the Internet Economy* which invited the OECD and stakeholders to explore the role of information and communication technologies (ICTs) and the Internet in addressing environmental challenges. The work has resulted in an OECD Council Recommendation (OECD, 2010).

[2] Wireless networks have several advantages over wired networks: lower installation and maintenance costs, easier replacement and upgrading, higher flexibility and (more recently developed) wireless networks have the capability to simply configure themselves into effective communication networks (see DOE, 2002).

[3] Note that customer power inputs into the power system require a separate inverter module and input meter.

[4] WiMAX can be both grouped to LAN and WAN technologies. It is discussed further below under WAN.

[5] Costs are dependent on the technical infrastructure: *e.g.* the signal must bypass the final transformer from the utility to customers' site. In the United States, bypassing the final transformer is much more expensive than in Europe as only a small number of customers are connected to one final transformer (EPRI, 2006).

[6] See also DSTI/ICCP/CISP(2009)2/FINAL for broadband investments in smart grids.

[7] Business as usual (BAU) scenario: baseline scenario that examines the "consequences of continuing current trends in population, economy, technology and human behaviour" (EEA, 2009).

[8] Greenhouse gas emissions are commonly expressed in carbon dioxide equivalent (CO2eq) emissions. Different greenhouse gases vary in their global warming potential (GWP) and CO2eq emissions represent the sum of individual gas emissions multiplied by their respective GWP.

[9] IPCC, 2007.

[10] The extent of the savings depends on the carbon-intensity of overall generated electricity.

[11] The authors use the term "intelligent buildings". In this chapter, smart buildings and intelligent buildings are treated as synonyms.

[12] The section on the impact of smart logistics does not cover the impacts of dematerialisation and virtualisation as sensor and sensor networks play a minor role in these fields.

[13] The IPTS study also analyses teleshopping, telework, virtual meeting and virtual goods on passenger and freight transport. This is not discussed as sensor and sensor networks have a minor impact in these fields.

[14] For an introduction to applications related to sustainable manufacturing see DSTI/IND(2008)16/REV1.

[15] For the assumptions for the calculation of the abatement potential, see Annex 6.A1, Table 6.A1.6.

[16] www.motorsmatter.org/index.html.

[17] www.energysmart.com.au/wes/displayPage.asp?flash=-1.

REFERENCES

Adam, R. and W. Wintersteller (2008), *From Distribution to Contribution. Commercialising the Smart Grid*, Booz & Company, Munich.

Alberta Transportation (2009), "Intelligent Transportation Systems", www.transportation.alberta.ca/606.htm.

Atkinson, R. and D. Castro (2008), *Digital Quality of Life – Understanding the Personal & Social Benefits of the Information Technology Revolution*, October, The Information Technology and Innovation Foundation, Washington DC.

Baggio, L. (2005), "Wireless sensor networks in precision agriculture", *REALWSN 2005 proceedings,* www.sics.se/realwsn05/papers/baggio05wireless.pdf.

Chong, Chee-Yee and Srikanta P. Kumar (2003), "Sensor Networks: Evolution, Opportunities, and Challenges", *Proceedings of the IEEE*, 91, 8, 1247-1256.

Climate Group, and GeSI (2008), *SMART 2020: Enabling the Low Carbon Economy in the Information Age*, www.theclimategroup.org/assets/resources/publications/Smart2020Report.pdf.

Commission of the European Communities (2009), Commission Recommendation of 9.10.2009 on mobilising Information and Communications Technologies to facilitate the transition to an energy-efficient, low-carbon economy, C(2009) 7604 final.

Culler, D., D. Estrin and M. Srivastava (2004), "Overview of Sensor Networks", *Computer*, August 2004, IEEE Computer Society, Washington, DC, pp. 40-49.

Damas, M., A. M. Prados, F. Gómez and G. Olivares (2001), "HidroBus® system: Fieldbus for Integrated Management of Extensive Areas of Irrigated Land", *Microprocessors and Microsystems*, 25, 177-184.

Department of Energy, United States (DOE, 2007), *Energy Technology Solutions – Public-Private Partnerships Transforming Industry*, Washington, DC.

Department of Energy, United States (DOE, 2004), *Industrial Technologies Program - On-Line Laser-UltrasonicMeasurement System*, Washington, DC.

Department of Energy, United States (DOE, 2003), *Grid 2030 – A Vision for Electricity's Second 100 Years*, Washington, DC.

Department of Energy, United States (DOE, 2003), *The Smart Grid: An Introduction*, Washington, DC.

Department of Energy, United States (DOE, 2002), *Industrial Wireless Technology for the 21st century*, Washington, DC.

Electric Power Research Institute (EPRI, 2005), *IntelliGrid^{SM} – Smart Power for the 21st century*, www.epri-intelligrid.com/intelligrid/docs/Intelligrid_6_16_05.pdf.

Electric Power Research Institute (EPRI, 2006), *IntelliGrid^{SM} Consumer Portal Telecommunications Assessment and Specification, Technical Report*, Palo Alto, CA.

Electric Power Research Institute (EPRI, 2008), *The Green Grid - Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid, Technical Update*, Palo Alto, CA.

Erdmann, L. (2009), *Development of a Framework and Overview Paper on ICTs and Environment*, OECD, working paper.

European Commission (EC, 2006), *European SmartGrids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future*, Brussels.

European Environment Agency (EEA) (2009), "Environmental Terminology and Discovery Service (ETDS) – Business-As-Usual Scenario", http://glossary.eea.europa.eu/terminology/concept_html?term=business-as-usual%20scenario.

Engage Consulting (2010), Smart Metering Project Map, maps.google.com/maps/ms?ie=UTF8&oe=UTF8&msa=0&msid=115519311058367534348.0000011362ac6d7d21187

Evans, R. and J. Bergman (2003), "Relationships Between Cropping Sequences and Irrigation Frequency under Self-Propelled Irrigation Systems in the Northern Great Plains, *USDA Annual Report*.

Franz, O., M. Wissner, F. Büllingen, Ch. Gries, C. Cremer, M. Klobasa, F. Sensfuß, S. Kimpeler, E. Baier, T. Lindner, H. Schäffler, W. Roth and M. Thoma (2006), *Potenziale der Informations- und Kommunikations-Technologien zur Optimierung der Energieversorgung und des Energieverbrauchs (eEnergy)*, Bad Honnef.

Green, K. (2007), "A Wireless Sensor City", MIT Technology Review, 13 April, MIT, Cambridge, MA.

Group on Earth Observations (GEO) (2008), Geo Members, www.earthobservations.org/ag_members.shtml.

Healthy Aims (2008), EU Framework VI project, *www.healthyaims.org*.

Heppner, A. (2007), Sensornetzwerke - Beispiele aus der Praxis, in: *Sensornetzwerke. Konzepte, Technologien und Anwendungen*, Theel, O., University of Oldenburg, Oldenburg.

Home Plug Alliance (2009a), "EPRI Collaborates with ZigBee and HomePlug to Define Smart Energy Standard for Consumer Applications", www.homeplug.org/news/pr/view?item_key=48cbecfda7c48fea53ea088758dd6cfefe4101b1.

Home Plug Alliance (2009b), "HomePlug Standard Brings Networking to the Home", www.commsdesign.com/main/2000/12/0012feat5.htm.

IEA (2008), G8 Gleneagles programme, Hokkaido Summit, www.iea.org/g8/index.asp#effi.

IBM (2007), *Advanced Meter Management from IBM lights way for utility companies: Innovation that matters*, Armonk, NY.

Institute for Prospective Technological Studies (IPTS, 2004) - European Commission Joint Research Centre, *The Future Impact of ICTs on Environmental Sustainability*, Seville.

Intelligent Car Initiative (2008), Tyre Pressure Monitoring System (TPMS), European Commission, http://ec.europa.eu/information_society/activities/intelligentcar/technologies/tech_19/index_en.htm.

Intelligent Transportation Systems Society (ITS Canada, 2009), "About Intelligent Transportation Systems (ITS)", www.itscanada.ca/english/aboutits.htm.

Intergovernmental Panel on Climate change (IPCC, 2007), *Climate Change 2007: Synthesis Report*, Valencia.

King, B. A., J. C. Stark and R.W. Wall (2006), "Comparison of Site-Specific and Conventional Uniform Irrigation Management for Potatoes", *Applied Engineering in Agriculture*, 22 (5), 677-688.

Ludwig, J., F. Henderson and M. Filmer (2008), "Leakiness Index to Aid Land Management", *Farming Ahead*, 194, 50-53.

Miller, J. (2008), "The Smart Grid – How Do We Get There?" *Smart Grid News*, 26 June.

MORYNE (2008), MORYNE Project, www.fp6-moryne.org.

OECD (2009a), "Smart sensor networks: Technologies and applications for green growth", DSTI/ICCP/IE(2009)4/FINAL, Directorate for Science, Technology and Industry, OECD, Paris.

OECD (2009b), "Towards Green ICT Strategies - Assessing Policies and Programmes on ICT and the Environment", DSTI/ICCP/IE(2008)3/FINAL, Directorate for Science, Technology and Industry, OECD, Paris.

OECD (2009c), "Measuring the Relationship Between ICT and the Environment", DSTI/ICCP/IE(2008)4/FINAL, Directorate for Science, Technology and Industry, OECD, Paris.

OECD (2009d), "Network Developments in Support of Innovation and User Needs", DSTI/ICCP/CISP(2009)2/FINAL, Directorate for Science, Technology and Industry, OECD, Paris.

OECD (2010), *Recommendation of the Council on Information and Communication Technologies and the Environment*, C(2010)61, 8 April.

ON World (2007), *WSN for Smart Buildings - A Market Dynamics Report*, ON World, San Diego.

Research and Innovative Technology Administration, U.S. Department of Transportation (RITA, 2009), "Intelligent Transportation Systems – Applications Overview", www.itsoverview.its.dot.gov/.

Science Applications International Corporation (SAIC, 2006), *San Diego Smart Grid Study Final Report*, San Diego.

Shargal, M. and D. Houseman (2009a), "Why Your Smart Grid Must Start with Communications", *Smart Grid News*, 24 February.

Shargal, M. and D. Houseman (2009b), "The Big Picture of Your Coming Smart Grid", *Smart Grid News*, 5 March.

Siderius, H. and A. Dijkstra (2006), Smart Metering for Households: Costs and Benefits for the Netherlands, http://mail.mtprog.com/CD_Layout/Day_2_22.06.06/0900-1045/ID57_Siderius_final.pdf.

Siemens (2008), Sustainable Buildings – Smart Meters: Stabilizing the Grid, http://w1.siemens.com/innovation/en/publikationen/publications_pof/pof_fall_2008/gebaeude/zaehler.htm.

Silva Girão, P., F. Algeria, J. M. Viegas, B. Lu and J. Vieira (2006), "Wireless System for Traffic Control and Law Enforcement", *IEEE International Conference on Industrial Technology*, 15-17 December, 1768-1770.

Taylor, J. and B. Whelan (2005), *A General Introduction to Precision Agriculture*, www.usyd.edu.au/agric/acpa/pag.htm.

United States Department of Agriculture (USDA, 2007), "Precision Agriculture: NRCS Support for Emerging Technologies", *Agronomy Technical Note No. 1*, Greensboro, North Carolina.

Veloso, M., C. Bento and F. Câmara Pereira (2009), "Multi-Sensor Data Fusion on Intelligent Transport Systems", *MIT Portugal Transportation Systems Working Paper Series*, ITS-CM-09-02, March.

Verdone, R., D. Dardari, G. Mazzini and A. Conti (2008), *Wireless Sensor and Actuator Networks*, Academic Press/Elsevier, London.

Viegas, J. and B. Lu (2001), "Widening the Scope for Bus Priority with Intermittent Bus Lanes", *Transportation Planning and Technology*, 24, 87-110.

Wang, N., N. Zhang and M. Wang (2006), "Wireless Sensors in Agriculture and Food Industry: Recent Development and Future Perspective", *Computers and Electronics in Agriculture*, 50, 1-14.

Wark, T., P. Corke, P. Sikka, L. Klingbeil, Y. Guo, Ch. Crossman, Ph. Valencia, D. Swain and G. Bishop-Hurley (2007), "Transforming Agriculture through Pervasive Wireless Networks", *Pervasive Computing*, April-June, 50-57.

Wilson, J. (2008), *Sensor Technology Handbook*, Newnes/Elsevier, Oxford.

ANNEX 6.A1

Table 6.A1.1. Comparison of the GeSI, EPRI and IPTS studies

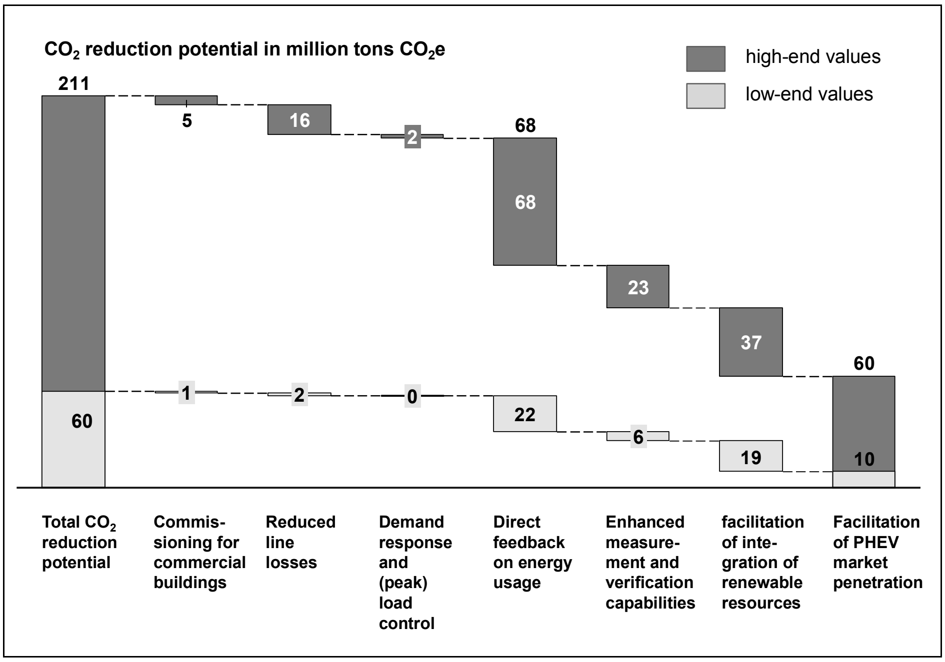
	GeSI (2008)	EPRI (2008)	IPTS (2004)
Title	Smart 2020: Enabling the Low Carbon Economy in the Information Age	The Green Grid Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid	The Future Impact of ICTs on Environmental Sustainability
Time horizon	2020	2030	2020
Geographical coverage	World	US	Europe
Considered smart grid levers for the Reduction of GHG emissions	• Reduced transmission and distribution (T&D) losses • Integration of renewable energy sources • Reduced consumption through user information • Demand side management	• Continuous commissioning for commercial buildings • Reduced line losses • Enhanced demand response and (peak) load control • Direct feedback on energy usage • Enhanced measurement and verification capabilities • Facilitation of integration of renewable resources • Facilitation of plug-in hybrid electric vehicle (PHEV) market penetration	• Renewable energy sources
Considered impacts	• Positive impacts • Negative footprint: no consideration on the smart grid level (overall ICT level)	• Positive impacts • No consideration of negative footprints	• Positive impacts • Negative impact considered but not on the smart grid level
Rebound effects	• Only discussed in a qualitative way	• Only discussed in a qualitative way	• Quantification of the rebound effect
Methodology	• Expert interviews • Literature review: publicly available studies, academic literature • Information provided by partner companies • Case studies • Quantitative analysis (models based on the McKinsey cost curve and emission factors)	• Calculations draw on data from single cases • Simple assumption are made to calculate impacts	• Screening and scoping • Literature analysis • Interviews • Policy-integrated scenarios • Modelling • Validation workshops • Reviews and policy recommendations

Table 6.A1.1. Comparison of the GeSI, EPRI and IPTS studies (cont'd)

	GeSI (2008)	EPRI (2008)	IPTS (2004)
Scenario	BAU (Business as usual)	No concrete scenarios (only ranges of savings which depend on different market penetration rates)	Three scenarios: • Technology • Government First Stakeholder democracy
Plausibility	• Use of GHG emission data from IPCC (2007) with higher GHG emission prospects than prospects provided by the IEA • Possible overestimation of the positive impacts due to some assumptions • Overall, use of good data	• Possible overestimation of some effects due to some assumptions • Partially very simple assumptions and calculations	• Consideration of various effects (*e.g.* rebound effects) • Most holistic approach • Only report with validation methods
Stakeholders	• Involvement of industry stakeholders • Commissioned by GeSI (ICT industry association)	• EPRI: research institute of the power industry	• Research institutes, scientific report • Involvement of scientific and industry stakeholders

Source: Erdmann, 2009.

Figure 6.A1.1. Positive environmental impact of smart grids



Source: Adapted from EPRI 2008.

Table 6.A1.2. Impact calculations of the IPTS study for different fields of application

	Scenario A			Scenario B			Scenario C		
Scenario description									
Technology regulation	Incentives for innovation			Government intervention			Stakeholder approach		
Attitudes to ICT	Moderate, conservative			Receptive			Highly receptive		
ICT in business	High level of cooperation			High level of competition			Between A and B		
Attitudes to the environment	Moderate/controversial			High awareness and interest			High awareness and interest		
Impacts of ICTs in smart grids for different scenarios									
	worst	mean	best	worst	mean	best	worst	mean	best
Renewable energy sources share in electricity	1.9 %	2.9 %	4.2 %	1.9 %	2.9 %	4.5 %	3.0 %	4.6 %	6.7 %
Total GHG emissions	-1.5 %	-1.9 %	- 2.8 %	-1.5 %	-2.1 %	-3.1 %	-1.6 %	-2.3 %	-3.0 %
Impacts of ICTs in facility management for different scenarios									
	worst	mean	best	worst	mean	best	worst	mean	best
Total energy consumption	-3.5 %	-4.3 %	-5.2 %	-4.2 %	-5.4 %	-7.1 %	-3.5 %	-4.4 %	-5.8 %
Total GHG emissions	-3.5 %	-4.6 %	-5.8%	-4.2 %	-5.4 %	-7.1 %	-3.6 %	-4.7 %	- 6.5 %
Impacts of Intelligent Transportation Systems (ITS) for different scenarios									
	worst	mean	best	worst	mean	best	worst	mean	best
Freight transport tkm	13.3 %	13.4 %	13.5 %	27.3 %	27.8 %	28.2 %	12.4 %	12.5 %	12.6 %
Passenger transport pkm	5.5 %	5.3 %	5.2 %	6.1 %	6.1 %	6.1 %	5.6 %	5.7 %	5.7 %
Total energy consumption	1.9 %	2.1 %	1.9 %	2.6 %	2.8 %	2.5 %	1.9 %	2.0 %	1.9 %
Total GHG emissions	1.9 %	2.0 %	1.9 %	2.6 %	2.7 %	2.6 %	1.9 %	2.0 %	2.0 %

Note: Freight transport volume is measured in tons x kilometres. Passenger transport volume is measured in number of passengers x kilometres.

Source: Erdmann, 2009.

Table 6.A1.3. Cross-tabulated smart building applications and sensors

	HVAC	Lighting	Shading	Air quality and window control	Systems switching off devices	Standard HH appli-cations	Security and safety
Temperature and heat detectors	■						■
Light level detectors		■	■				
Movement and occupancy sensors	■	■	■	■	■	■	■
Smoke and gas detectors				■		■	■
Status sensors		■	■	■	■	■	■
Glass break sensors						■	■

Source: OECD.

Table 6.A1.4. Assumptions underlying the calculations of positive impacts of smart buildings

Lever	Assumptions for the calculations
Improved building design	40% reduction in retail buildings and 30% in others Implementation: 60% new buildings, 15% of retrofits (except 0% for residential)
BMS	12% less in residential and retail buildings, 7% in warehouse and 36% in office and other emissions Implementation: 40% new offices and retail, 25% retrofits; 33% all other new and 10% of retrofits
Voltage optimisation	10% reduction in heating/cooling and appliance consumption Implementation: 80% new buildings, 30% commercial retrofits and 20% residential retrofit
HVAC	13% reduction in HVAC consumption (except warehouses) Implementation: 40% for new retail and offices, 33% for remaining new, 25% for all retrofits
Benchmarking and building recommissioning	35% reduction in current commercial building heating/cooling emissions Implementation: 25% of new builds and 50% of retrofits
Lighting automation	16% reduction in lighting Implementation: 40% for new retail and offices, 33% for remaining new, 50% for commercial retrofits and 25% for residential retrofits
Reduces building space through design	25% reduction in retail and warehouse space Implementation: 60% of new buildings and 20% of retrofits
Intelligent commissioning	15% reduction in commercial building (except warehouses) heating/cooling emissions Implementation: 60% of new builds
Ventilation on demand	4% reduction in heating/cooling emissions in commercial buildings except warehouses Implementation: 60% of new builds and 25% of retrofits

Source: OECD, based on GeSI, 2008.

Table 6.A1.5. Assumptions underlying calculations of positive impacts in the field of smart transport

Lever	Assumptions for the calculations
Optimisation of logistics network	14% reduction in road transport 1% reduction in other modes of transport
Intermodal shift	1% reduction in road transport owing to shift towards rail- and waterborne transport
Reduction in inventory	24% reduction in inventory levels 100% of warehouses and 25% of retail are assumed to be used for storage
Optimisation of collection/delivery itinerary planning	14% reduction in road transportation
Optimisation of truck route planning	5% reduction in carbon intensity of road transport owing to avoidance of congestion
Eco-driving	12% reduction in carbon intensity owing to improved driving style
In-flight fuel efficiency	1% reduction in fuel consumption achievable for 80% of t-km flown
Reduction in ground-fuel consumption	32% reductions in ground fuel consumption achievable for 80% of flights Impact calculated for average European fleet
Reduction in unnecessary flight time (comm.)	1% reduction in fuel consumption achievable for 80% of t-km flown 32% reduction in ground fuel consumption achievable for 80% of flights
Reduction in unnecessary flight time	3% reduction in flight time achievable for 80% of flights
Maximisation of ship load factor	4% reduction in marine transport owing to improved utilisation of ships
Optimisation of ship operations	3% increase in fuel efficiency, *e.g.* by adjusting ballasts and optimising speed
Minimisation of packaging	5% reduction in packaging material, leading to a 5% reduction in all transports and in storage
Reduction of damaged goods	0.2 % reduction in damaged goods achievable through better tracking (*e.g.* RFID) and conditions monitoring (*e.g.* bio-sensors)

Source: GeSI, 2008.

Table 6.A1.6. Assumptions underlying the calculations of positive impacts of smart motor systems

Lever	Assumptions for the calculations
Optimisation of variable speed of motor systems	30% increase in efficiency of industrial motor systems through optimisation 60% penetration of motor system optimisation technology
ICT-driven automation in key industrial processes	15% decrease in total electricity consumption 33% penetration of process optimisation technology

Source: GeSI, 2008.