OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

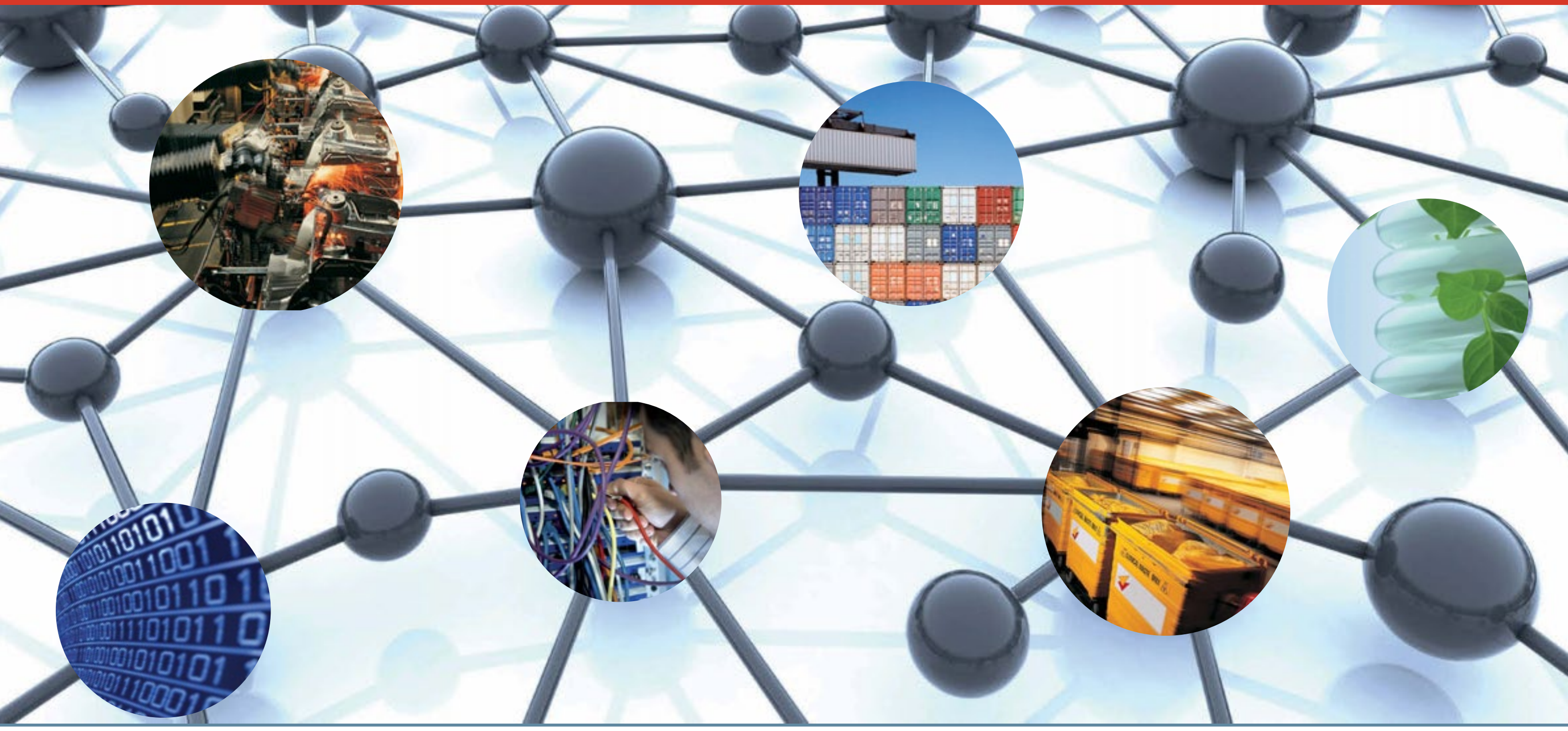
Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org



Emerging Green Technologies
for the Manufacturing Sector

UNIDO
UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Fraunhofer
ISI

Emerging Green Technologies
for the Manufacturing Sector

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna, 2014

Acknowledgements

This report was prepared under the general guidance of Ludovico Alcorta, Director of the Development Policy, Statistics and Research Branch of UNIDO. The contributors to the report are Wolfgang Eichhammer and Rainer Walz, both from the Fraunhofer Institute for Systems and Innovation Research ISI.

Foreword

The manufacturing sector is key to promoting and diffusing technological change, which in turn is a crucial driver of competitiveness and economic growth. Industrial development therefore has great potential to achieve a number of social objectives including high rates of employment, poverty eradication, gender equality, labour standards and better access to education and healthcare. Yet any progress in achieving these social objectives will be short-lived if policymakers and stakeholders do not succeed in ensuring sustainable economic growth and industrial development within an environmentally viable framework.

The task of creating a virtuous cycle of environmentally sustainable and long-term economic growth to eradicate poverty requires the implementation of emerging green technologies that are capable of increasing productivity and growth. These technologies should be at the core of any industrial upgrading effort. They allow for an expansion of the technological capabilities of the manufacturing sector while realizing cleaner production, efficient resource management and reductions in waste and pollution.

This document is one of a series of UNIDO publications designed to provide insights into current and future global trends that will determine the future of manufacturing in developing countries. Its objective is to help policymakers design and implement economic policies to assure continued and sustainable prosperity and to effectively tackle the social, environmental and economic challenges that the world will face in the years to come.

I sincerely hope that this publication will provide useful insights for the reader on emerging green technologies in the manufacturing sector and their contribution to resolving environmental problems while enhancing the competitiveness of developing countries. I invite policymakers, scholars and business leaders to actively participate in the discussion on these pertinent issues and to address the prevailing social and environmental challenges while joining efforts to establish a new long-term and sustainable development agenda.

李勇

LI Yong
Director General, UNIDO


CLINICAL WASTE ONLY
CLINICAL WASTE ONLY
CLINICAL WASTE ONLY

Contents

Executive Summary

Technological change brought about by Emerging Green Technologies (EGTs) is relevant for both developed and developing countries. Emerging green technologies refer to technologies that have either already reached a certain technological maturity but still have comparatively low market shares around the world or technologies that are still in a comparatively early stage of technological maturity, albeit in principle already applicable in daily life.

This report focuses on how EGTs in the manufacturing sector can contribute solutions to environmental problems while enhancing countries' competitiveness. We focus on middle-income countries (MICs) because the phase of development they are in has the highest environmental impact while these countries, on the other hand, have already reached an institutional and organizational level at which they can benefit from the competitive advantages the solutions they develop provide.

We first explore the main drivers of EGTs. Next, we investigate the impacts they trigger in the manufacturing sector in the fields of innovation, especially in MICs. We further provide insights into the impacts of EGTs in the manufacturing sector's productivity.

The analysis shows that the transformation process towards EGTs within the scope of sustainable production and consumption patterns requires changes at four levels:

- Technology level: acquisition of technical skills to include EGTs as part of the production processes; this will require actors in MICs to familiarize themselves with successful concepts for the introduction of EGTs as well as with the competitive advantages technologies provide for companies.
- System perspective: integration of heterogeneous areas of knowledge from the different disciplines involved in the introduction of EGTs; this will require a focus on system-related aspects relevant for the introduction of EGTs.
- Paradigm shift: development of processes accompanying the sustainable transformation of MICs; this will require wider societal debates to make a range of actors aware of the substantial benefits of EGTs.
- System knowledge level: promotion of learning processes that are necessary at all levels to induce transformative innovations; this will require strong involvement of actors in the field of education and training.

Major differences in innovation competence exist, which become evident both in general innovation indicators and in green technology indicators. Countries with higher levels of innovation competence face the challenge of linking existing knowledge with implementation in manufacturing. This implies efforts in networking and improvements in the innovation system. Countries with lower levels of innovation competence have to rely on technology cooperation to a greater extent, especially for process-specific, CCS and industrial power management technologies, as well as capital embodied technology transfer for cross-cutting technologies. Both country types must, however, combine industrial with environmental policy to give the right impetus to manufacturing to place greater emphasis on green energy technologies.

Introduction

This study, carried out by the Fraunhofer Institute for Systems and Innovations Research (Germany), highlights the most significant trends and challenges for emerging green technologies (EGTs) in the manufacturing sector over the next 20 years. In this report, EGTs are defined as a mix of technologies that have already reached a certain technological maturity, but still have comparatively low market shares around the world (for example, solar PV) as well as technologies that are still in a comparatively early stage of technological maturity, although they in principle are already applicable in daily life (for example, electric mobility).

The World Economic Forum's most recent report (WEF, 2013:53) points out the challenges the pressures on the natural environment resulting from economic activity pose: "Pollution has increased, the loss of biodiversity is more and more problematic, while climate change and its unpredictable consequences raise concerns. The world is also facing a progressive scarcity of water, energy, and mineral resources, for which demand continues to climb. Despite some efforts to address these issues, the undesirable environmental consequences of human activity are leading to a less habitable world." The WEF states that "social and environmental sustainability increasingly influence economic policy decisions and can have an impact on economic performance. At the same time, these challenges bring into question whether well-established ideas and models that take a narrow view of economic growth and do not take into account the use of natural resources or social concerns can still provide adequate solutions. The relationships between these challenges need to be better understood and measured in order to inform policies that will set and achieve the desired objectives, and in order to better track progress toward higher levels of sustainable prosperity." (WEF, 2013:69).

Technological change brought about by EGTs is relevant for both developed and developing countries. According to the WEF (2013:69), "so far, economists have devoted most of their efforts to trying to understand the way economic growth impacts the quality of the environment or income distribution within a country and vice versa. However, little is known about how these aspects of sustainability relate to competitiveness and productivity." In the past, EGTs were associated with additional costs and burdens. There is increasing evidence, however, that EGTs offer numerous opportunities to develop new industries, particularly in countries in which industries are still developing. Worldwide demand for EGTs will inevitably increase due to the rising pressures on the environment. Countries will only be able to take full advantage of economic growth if environmental sustainability is ensured. The manufacturing sector in particular has negative impacts on the environment, especially in developing countries, but it is also the sector that can provide solutions to problems relating to sustainability through the development of new business opportunities.

In this report, we focus on how EGTs in the manufacturing sector can provide solutions to environmental problems while enhancing countries' competitiveness. We focus on middle-income countries (MICs) because the phase of development they are in has the highest environmental impact, while they have already, on the other hand, already reached an institutional and organizational level at which they can benefit from the competitive advantages the solutions they develop provide.

We first explore the main drivers of EGTs. Next, we investigate the impact of EGTs in the manufacturing sector in the field of innovation, especially in MICs. We further provide insights into the impact of EGTs on the manufacturing sector's productivity.

This study focuses on energy and climate technologies, but does not consider other (non-climate change-related) pollution reducing technologies (e.g. soil and water pollution) or recycling technologies.

In the field of energy technologies, the report investigates:

- Green technologies for energy-intensive industries, in particular iron/steel, cement, pulp and paper, aluminium and selected chemicals;
- Green technologies for less energy-intensive industries, in particular cross-cutting industrial technologies such as electric motors and smart grid technologies for load management in industry.

In the field of climate change technologies, the report examines:

- CCS technologies for industry;
- Renewable energy sources for the manufacturing sector;
- Specific technologies to reduce industrial gases such as PFs or SF6.

The study focuses primarily on middle-income countries (MICs) for two reasons:

- They have already accumulated a certain amount of absorptive capacity to develop opportunities for EGTs;
- They have the capacity to rapidly catch up with competitors from high-income countries with regard to EGTs.

Chapter 1 addresses the main drivers of EGTs in the manufacturing sector:

- We focus first on energy consumption and greenhouse gas emissions (GHG) and the related problems of availability of energy resources and the greenhouse gas effect as the main drivers of emerging energy and climate technologies.
- In the second section, we discuss long-term changes in sustainable "production and consumption" paradigms, which are increasingly linking the entire product cycles from production to consumption.
- Lastly, we present a selection of sustainable energy and climate technologies which the following chapters focus on.

In **Chapter 2**, we investigate impacts triggered by EGTs in the manufacturing sector in the field of innovation. The data shows that MICs have started building up competences in green technologies. However, there are significant divergences in innovation competences, which show up in both general innovation indicators as well as in green technology specific indicators. We thus arrive at two conclusions: countries with higher levels of competence face the challenge of linking existing knowledge with implementation in manufacturing. This implies efforts in networking and improving the innovation system. On the other hand, countries with lower levels of competence rely to a greater extent on technology cooperation, especially for process-specific, CCS and industrial power management technologies as well as capital embodied technology transfers for cross-cutting technologies. Both country types must, however, combine industrial with environmental policy in order to give the right impetus to manufacturing to place greater emphasis on green energy technologies.

We provide insights into the impacts of EGTs on the manufacturing sector's productivity in **Chapter 3**. The findings in that section support the hypothesis that EGTs, which are process-integrated and sector-specific, increase productivity, and are hence to be considered critical for MICs to assume leadership in certain EGTs.

1. Main drivers of emerging green technologies in the manufacturing sector

This section provides a brief overview of the main drivers of EGTs in the manufacturing sector:

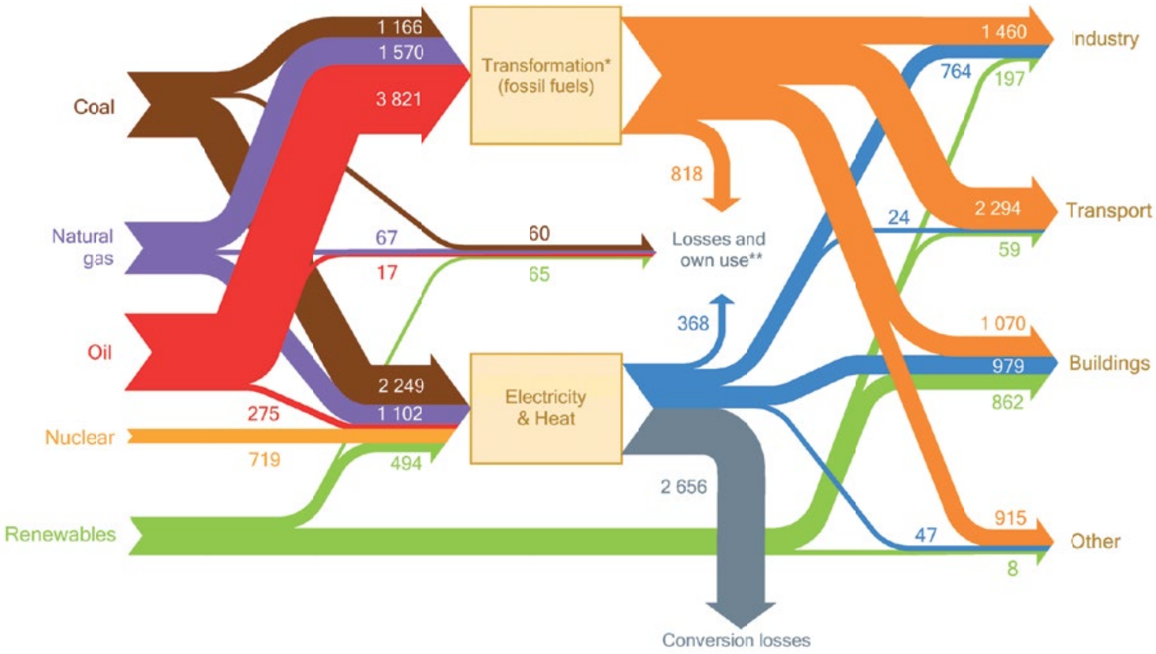
- We focus first on energy consumption and greenhouse gas emissions (GHG) and the related problems of availability of energy resources and greenhouse gas effects as the main drivers of emerging energy and climate technologies, by looking at their past trajectory, present state and expected further development.
- In the second section, we present long-term changes in sustainable "production and consumption" paradigms which are increasingly linking the entire product cycle from production to consumption. The section looks beyond energy and climate technologies which are the major focus of this report, including material efficiency, recycling and reduced impacts on air, soil and water through measures along the producer-consumer chain. There are also considerable opportunities in this paradigm shift for companies to enter new markets through technical innovation.
- Finally, we present a selection of sustainable energy and climate technologies.

Further drivers are inherent in the fact that green technologies are also those that are most beneficial from an economic and sometimes social perspective. Companies might invest in green technologies not because they emit less carbon dioxide, but because they make sense from a business perspective or because they enhance the company's public image (hence, are also beneficial in economic terms). These aspects are discussed in Chapters 4 (innovation impacts of green technologies) and 5 (productivity impacts of EGTs).

1.1 Manufacturing industry: Energy consumption and GHG emissions as major driving forces

Rising energy consumption and GHG emissions are major drivers of the development of EGTs. Industry, transport and construction roughly account for equal shares of energy consumption and GHG emissions of around 30 percent in the projections of the International Energy Agency in the World Outlook 2012 (Figure 1).

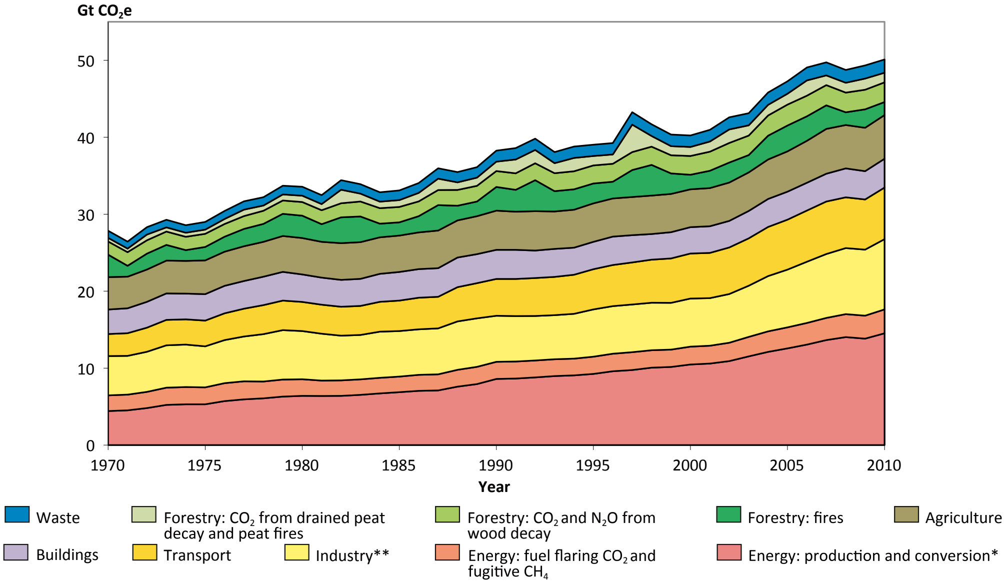
Figure 1: The importance of industry in the global energy system 2010



Source: IEA, 2012

Trends in emissions from industry, including process emissions, are presented in the following figure in the context of overall emissions (Figure 2). The figure shows that industry is still the largest emitter, for example, the transport industry which uses fuels such as coal with higher emission factors.

Figure 2: Trends in global greenhouse gas emissions, 1970-2010 by sector



* Power generation, refineries, coke ovens, etc.

** Including non-combustion CO_2 from limestone use and from non-energy use of fuels and N_2O from chemicals production.

Source: UNEP, 2012

The share of industry in energy remains fairly stable over time, but conceals important divergences between world regions. Table 1 shows the development of the global industrial sector from the perspective of the New Policy Scenario (which takes existing policy commitments into account and assumes that the recently announced measures are being implemented, albeit in a cautious manner).

While the share of industry in OECD countries in total final energy consumption (TFC) will stagnate at levels of around 23 percent between 2010 and 2035, and even below 20 percent in the case of the U.S., the share of industry worldwide will increase from 28 percent to nearly 30 percent according to the New Policy Scenario. In a country like China, the share of industry in total final energy consumption could even exceed 45 percent by 2035.

The IEA Outlook 2013 (IEA, 2013) confirms these trends and even expects a slightly higher increase in worldwide energy consumption, including for industry.

Table 1 Industrial energy consumption in the IEA's New Policy Scenario (2012)

	Energy demand (Mtoe)							Shares (%)		CAAGR (%)
	1990	2010	2015	2020	2025	2030	2035	2010	2035	2010-35
TFC	**6 275**	**8 678**	**9 565**	**10 223**	**10 742**	**11 241**	**11 750**	**100**	**100**	**1.2**
Coal	773	853	970	982	984	983	976	10	8	0.5
Oil	2 593	3 557	3 813	3 984	4 108	4 219	4 336	41	37	0.8
Gas	942	1 329	1 464	1 612	1 740	1 864	1 993	15	17	1.6
Electricity	833	1 537	1 802	2 047	2 255	2 463	2 676	18	23	2.2
Heat	333	278	293	303	305	305	305	3	3	0.4
Bioenergy	795	1 103	1 188	1 250	1 294	1 335	1 373	13	12	0.9
Other renewables	4	22	33	45	57	72	91	0	1	5.9
Industry	**1 809**	**2 421**	**2 790**	**3 035**	**3 203**	**3 355**	**3 497**	**100**	**100**	**1.5**
Transport	**1 568**	**2 377**	**2 596**	**2 778**	**2 935**	**3 093**	**3 272**	**100**	**100**	**1.3**
Buildings	**2 243**	**2 910**	**3 121**	**3 302**	**3 452**	**3 599**	**3 748**	**100**	**100**	**1.0**
Other	**655**	**970**	**1 057**	**1 107**	**1 152**	**1 194**	**1 232**	**100**	**100**	**1.0**

Abreviations: NPS: New Policies Scenario, CAAGR: Compounded Average Annual Growth Rate
Source: IEA, 2012

1.2 Long-term changes in sustainable "production and consumption" paradigms (Production-Consumption 2.0)

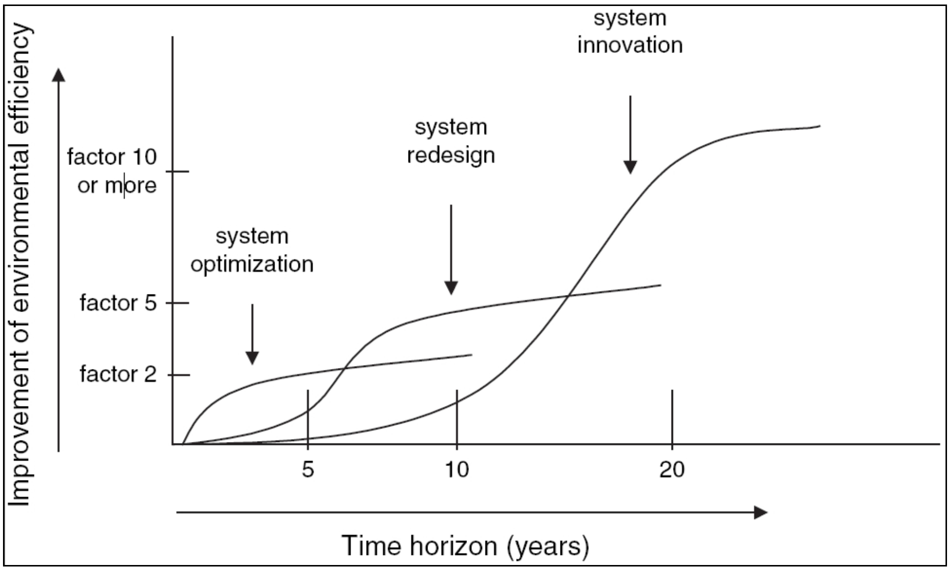
In addition to questions linked to resource availability and climate issues, EGTs are also driven by actors' objective to establish long-term sustainable "production and consumption" paradigms involving new ways of supplying products and services in the face of changing basic global conditions (EU, 2008; EU, 2010). This addresses one of the greatest challenges of the future: preserving the ecosphere, which is vital to human survival. This section also touches upon issues and technologies beyond energy and climate technologies such as technologies and concepts for material and resource efficiency. These issues lie outside the focus of this report but are central to changes in production and consumption concepts. Realizing such an important transformation requires additional research efforts in technology and other aspects such as conceptual developments and changes in paradigms to achieve the profound changes necessary in production and consumption patterns.

Major initiatives have been introduced worldwide to address these challenges, including but not limited to:

- UNEP's Marrakech Process "Towards a Global Framework for Action on Sustainable Consumption and Production (SCP)" (UNEP, 2011). The Marrakech Process, a bottom-up multi-stakeholder process, was launched in 2003. The Process has promoted and implemented projects on sustainable consumption and production (SCP) and provided significant inputs for the elaboration of the 10-Year Framework of Programmes on SCP (10YFP);
- UNEP/ The Wuppertal Institute Collaborating Centre on Sustainable Consumption and Production (CSCP), which continuously monitors these processes;
- The World Business Council for Sustainable Development's (WBCSD) activities focusing on "ecosystems";
- The development of "industrial ecology" (International Society for Industrial Ecology) in the international research community;
- OECD activities in the field of environment (especially indicators and modelling);
- The European Topic Centre on Sustainable Consumption and Production (EEA, 2013).

Establishing sustainable methods of economic activity is a key global challenge, of which energy and climate issues are an important factor, but not the main focus of this study. A drastic reduction in the ecological footprint of human economic activity necessary to preserve the ecosphere can only be achieved through systemic innovations in patterns of material flows (see Figure 3).

Figure 3: Increasing efficiency through system innovation



Source: Tukker and Butter, 2007

This strive for innovations in the patterns of material flows is strongly linked with production and consumption patterns, giving rise to the concept "Production-Consumption2.0" (where 2.0 refers to "new generation"). This concept aims to develop methods that enable the analysis of material flow patterns in production and consumption in an integrated way. Existing sustainability and innovation research concepts are being further developed and applied to future paradigm shifts, such as the development of highly consistent recycling management concepts. This will generate the development of new patterns of materials usage in industry and society, which will address key social needs in a far more sustainable manner. Transformative innovations linking technological and organizational solutions in new ways will enable the development of such new patterns. Rather than focusing on optimizing individual elements in value adding processes, ProductionConsumption2.0 aims for a systemic transformation of the entire structure, a transformation increasingly being called for by actors from politics, research, economy and society to attain the drastic reductions necessary in the ecological "footprint" of human economic activity.

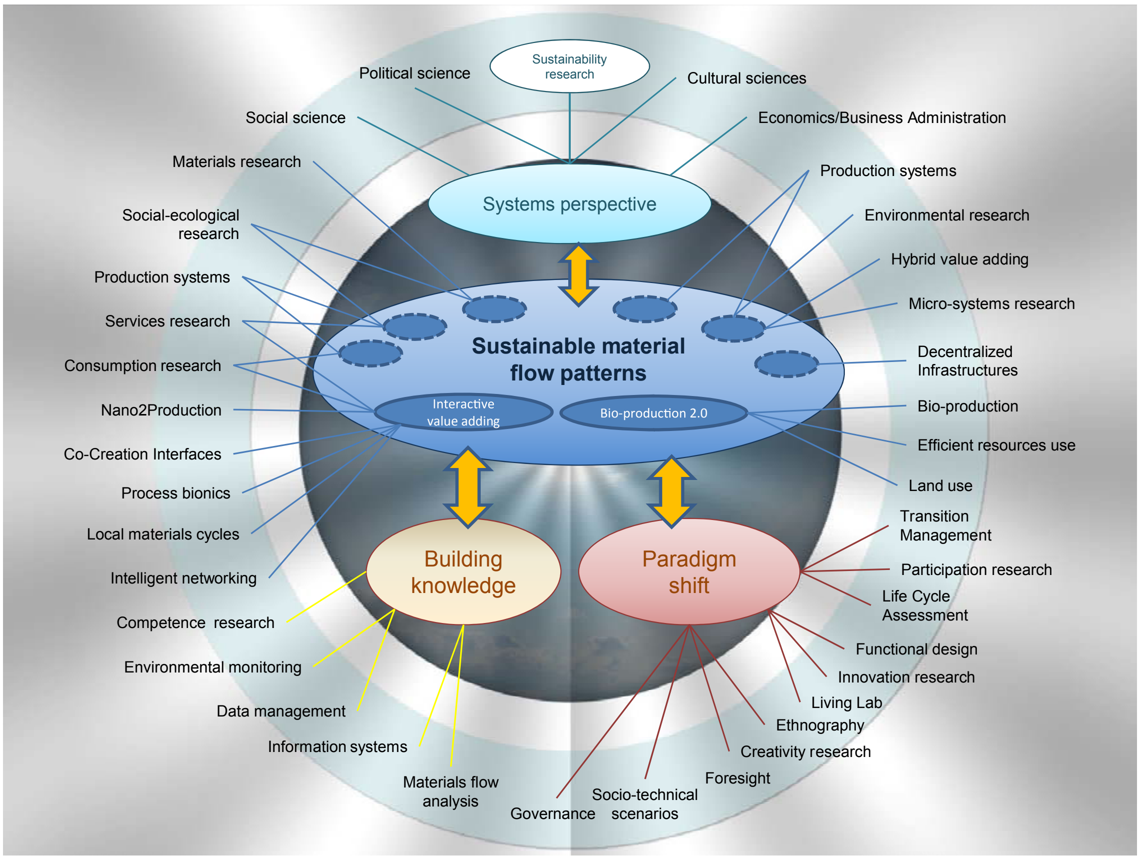
This global trend comprises a number of sub-developments, including general production trends that go beyond aspects relating to sustainable production and consumption, and which are not discussed in this report, such as:

- Efficient use of energy and resources in industrial production, creating material cycles
- Paradigm shift to personalized production, e.g. in generative processes
- Biomass-based, sustainable biotechnical production
- Molecular biological production
- Bio-degenerative materials
- Energy-efficient applied technologies
- Energy-efficient behaviours.

Findings from climate and sustainability research studies indicate that the drastic reduction of the ecological "footprint" required to preserve the ecosphere can only be achieved by fundamentally rearranging the existing patterns of production and consumption. This "impact reduction" can neither be achieved by introducing new environmental and energy technologies, nor by changing consumer behaviour, but only through systemic innovations in materials cycles in industrialized societies. "Transformative innovations" in existing patterns of materials cycles, such as the shift to advanced recycling management concepts or to carbon-neutral economic activities, involve a range of organizational and technical innovations and new ways of linking them.

This transformation process comprises four key elements. Figure 4 clearly demonstrates the close interlinkages between these four key components. A multitude of advanced concepts and methods will be necessary to achieve such a large-scale transformation towards sustainable material flow patterns (centre of Figure 4). Approaches from sustainability research and particularly from "industrial ecology" research on materials cycles must be further developed and linked with technology and social sciences research to arrive at an interdisciplinary systems perspective (top of Figure 4). Methods will also be required to sound out not only the new patterns themselves, but also the paradigm shift (lower right in Figure 4). Anchoring knowledge and skills in the innovation system (lower left in Figure 4) is also an important building block.

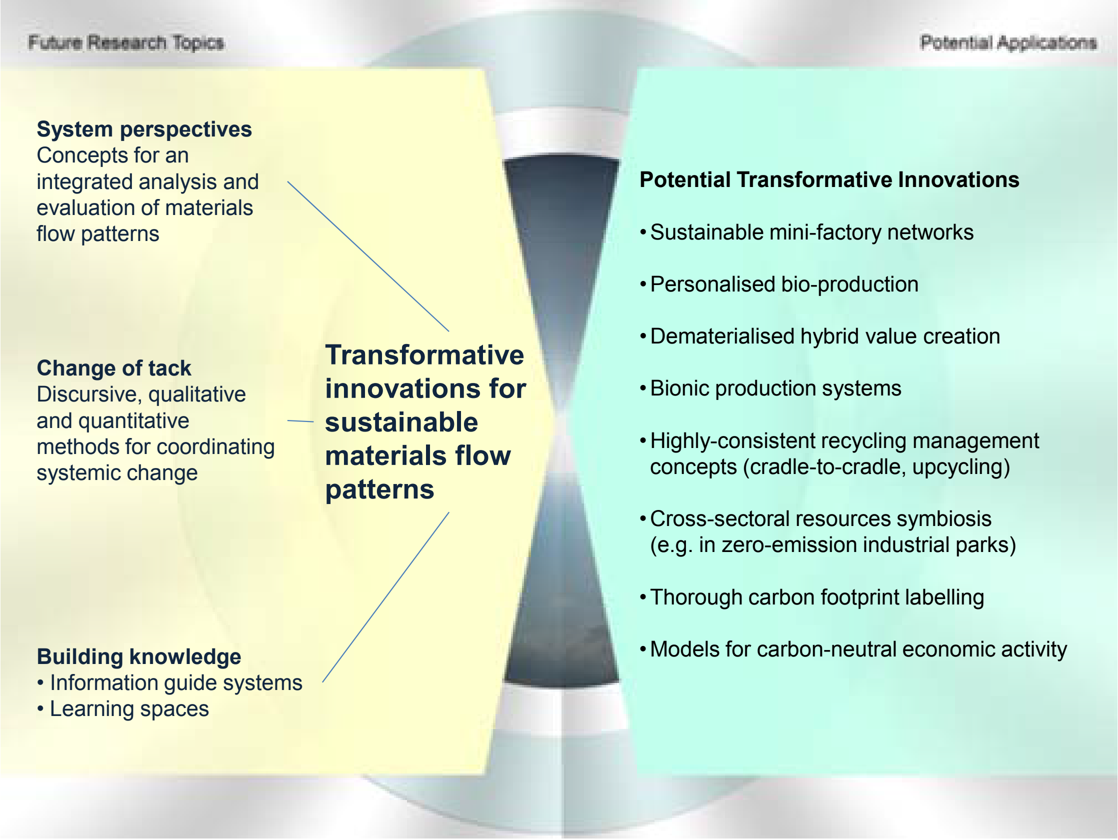
Figure 4: Required systemic innovations in materials cycles in industrialized societies



Source: Fraunhofer, 2009

Some of the innovations that must be introduced during the transformation processes are presented in Figure 5. These are not individual products or technologies, but integrated concepts, including business models, organizational concepts and pathways to transformation.

Figure 5: Research topics and potential applications in Production Consumption 2.0



Source: Fraunhofer, 2009

The main long-term, research-relevant issues with regard to the transformation processes' four key components are outlined below:

Sustainable patterns of materials turnover

This area of research entails trans-disciplinary, systemic research into sustainable production and consumption patterns and possible development paths. Advanced science and technology concepts are systematically combined to sound out sustainable configurations. Significant contributions to this process are expected, in particular from production, services, sustainability and socio-ecological research. Other areas of research such as biotechnology, infrastructure technology, materials, nanotechnology and information and communication technologies will also contribute significantly to the development of sustainable patterns of materials turnovers.

To manage the complexity of overlaps and disparities between different areas of technology research, it seems reasonable to initially focus on areas that have a high level of potential synergies or on production and consumption patterns that will be critical for future materials cycles in industrial societies. These focal areas of technology research would be combined to generate and evaluate integrated development trajectories. The focal areas would be identified step by step, for example, by an interdisciplinary panel of actors.

Examples of possible changes to patterns of materials cycles in materials turnover could be:

- Usage-centred business models (e.g. value for use)
- Hybrid value adding (systematic integration of products and services in service packages)
- Carbon-neutral economic activities (post-carbon economy)
- Green chemistry
- Dematerialized value adding
- Interactive value adding (added value with an extensive contribution from customers/users)
- Bionic process concepts (e.g. cascade models)
- Personalized value-added chains with second generation bio-refineries
- Cross-sectoral recyclable materials symbioses (e.g. zero-emission industrial parks).

Example of changes in sustainable materials flow patterns: Sustainable networks of mini-factories: Miniaturization has been a key research area in the field of production for many years. On the one hand, miniaturization entails the manufacture of increasingly smaller and more highly integrated micro-systems. At the same time, there is an increasing focus on the miniaturization of production units themselves. Mini-factories are conceived less for “tiny products” than for on-site production of individual customized products. Such mini-factories could perhaps even be used by customers themselves (e.g. to produce replacement parts) in the form of 3D printers, for example. The vision of a network of mini-factories as an alternative to centralized mass production, in turn, poses considerable technological and organizational challenges. There is a lack of design concepts for highly individualized distributed production. Suitable customer interfaces in which individual demands are recorded and translated into implementable production instructions will also be necessary. This concept is a response to future challenges that are being identified today and are attributable to changing lifestyles, but also to an increasing need for creative involvement in the production of goods as part of identity formation. This, in turn, implies a new relationship between the production of goods and services. There are calls for more creative services and for a significantly expanded spectrum of services with hybrid business models to accompany products, which will result in products and services being integrated in a new way. However, it remains entirely unclear what a modification to such added value paradigms would mean for ecological sustainability. On the one hand, shorter routes and avoidance of surplus production offer great potential. On the other hand, energy and resource consumption and environmental pollution could increase due to uncontrolled distribution of production. Much would depend on the early course set out for “sustainability”. This trend would also raise many research questions in the area of technology – infrastructure for distributed mini-factories, equipment for semi-virtual co-creation spaces, suitable materials – as well as in the area of services and production concepts. At the same time, knowledge of possible human behaviour patterns offered by environmental psychology or socio-ecological research as well as ethnographic research and cultural sciences,plays a major role. Questions such as what forms of distributed value-adding are conceivable and sustainable can only be answered by introducing new evaluation processes and creative methods. This requires the development of learning spaces for actors. A “living lab” for various co-creation spaces with connected mini-factories might be conceivable, for example. Holistic evaluations of the ecological footprints of the concepts generated are indispensable in this context. Only those processes that entail a significant reduction of pollution will be sustainable in an era characterized by major climate change. The social component of sustainability of an ecologically-intelligent network of mini-factories would also have to be investigated, namely synchronizing the global repositioning of the roles and sites of value-adding elements with the demands for locations of new production jobs for highly-qualified workers.

System perspectives

Sustainable patterns and related transformative innovations cannot be generated with "standard tools". New research methods are required that will allow for the integration of heterogeneous areas of knowledge and strands of research and the identification of possible paradigm shifts. Research on sustainable material flows and turnovers must also be consistently incorporated into comprehensive and globally-oriented concepts of sustainable forms of economic activity. On the other hand, there is a risk that parts of the systems are optimized at the cost of the entire system's sustainability. Holistic evaluation processes will be necessary to estimate the sustainability of possible formations to avoid a one-sided focus and foster a balance between conflicting goals. Hence, qualitative, quantitative and discursive methods to research and assess the systemic transformation of patterns of material flows will need to be developed as part of "system prospects". These will primarily emerge from sustainability research and in particular from "industrial ecology", and will have to be further developed to include other disciplines such as environmental economics, innovation and complexity research and system design.

Examples of methods and concepts of system prospects include:

- Innovation lifecycle analysis, product lifecycle analysis, carbon footprint
- Eco-effectiveness
- Consistency analysis
- Socio-technical scenario-building
- Environmental-economic modelling
- Innovation system dynamic (co-evolution, multi-level concept).

Paradigm shift

The focus here is on investigating ways of moderating the transformation to patterns and paths that have been identified as sustainable. Innovation processes emerge from the interaction of participating actors, i.e. technical, sociological, educational and psychological evaluation and development methods will have to be integrated to understand and engender system change at the interfaces. Potentials from disciplines outside those hitherto focused on in terms of sustainability transformation – such as design, market research, ethnography, cultural sciences, behavioural research, innovation management, governance research, interaction research and creativity research – should also be included. Discursive methods to moderate discourses among actors in the area of transition management could be introduced in this context as well.

Systems knowledge and competence

A systematic expansion in the area of systems knowledge and competence will also be necessary. This, on the one hand, includes developing an information control system in which micro- and macro-economic data to evaluate value-added networks is collected, consolidated and made available to actors in the innovation system. On the other, it entails the establishment of distributed learning spaces for transformative innovation processes of relevant actors in the innovation system. The question is how innovation systems can establish the learning processes that are necessary at all levels to achieve transformative innovations. Research on skills and education will significantly contribute in this regard, and governance tools such as foresight analyses and participative technology assessment, “living labs”, ethnography and ”open innovation” and user innovation approaches will also play an important role. Actors in the innovation system, particularly from companies, educational institutions and social initiatives, will be actively involved.

Such changes are not taking place under generally stable conditions. Many of the relevant global framework conditions of production and consumption are in flux. Developments such as the global repositioning of production and markets, the emergence of a continuously learning society, new demands related to changing lifestyles and values, and new options from technological fields such as information and communication technologies form the background against which successful transformative sustainability innovations will have to evolve. Proactive generation of new forms of materials turnover in industrial societies is being driven, on the one hand, by the pressure of problems in these areas. At the same time, the opening up of countless framework parameters could offer far-reaching opportunities for profound innovations that could drive the leading markets of the future and fulfil social needs in a new quality.

1.3 Sustainable energy and climate technologies

In the previous section, we found that the transformation to sustainable production and consumption patterns is not just about technology - or rather, not mainly about technology - but about changes in paradigms, concepts, institutions and societal organizations. However, the diffusion of already available green technologies into major markets (which does not necessitate technological innovations but innovations in the fields previously discussed), as well as fundamentally new technologies, are also necessary (e.g. CCS in industrial applications). In this section, we focus on the technology component in green technologies and provide information on a variety of relevant energy and climate technologies (for further details, see Annex). We also link this to the broader innovations to be achieved in the transformation process towards sustainable production and consumption patterns.

In the field of energy technologies, we focus on:

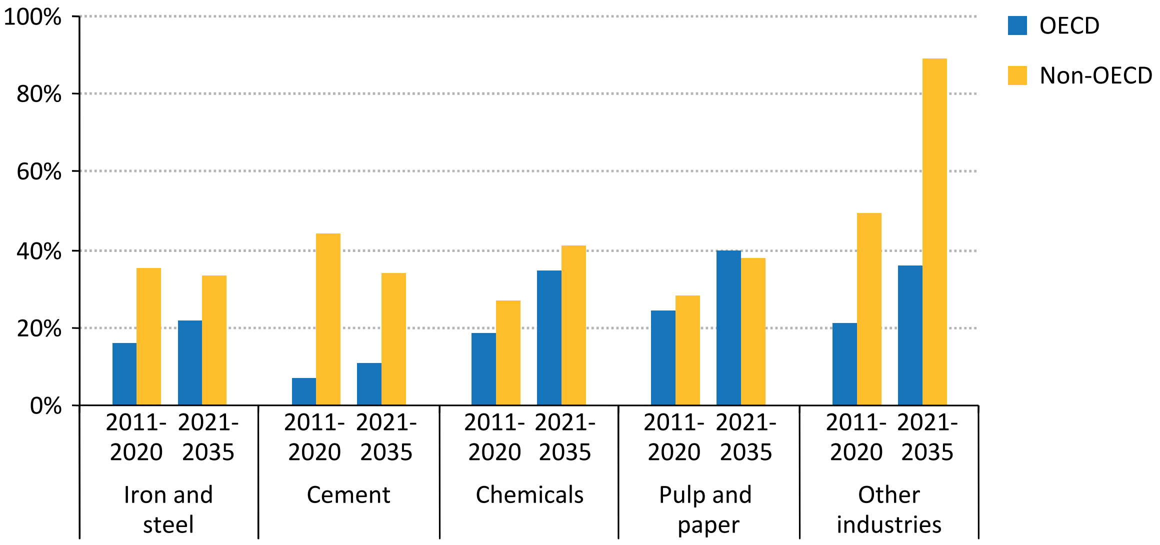
- Green technologies for energy-intensive industries, in particular iron/steel, cement, pulp and paper, aluminium and selected chemicals;
- Green technologies for less energy-intensive industries, in particular cross-cutting industrial technologies such as electric motors and smart grid technologies for load management in industrial companies.

In the field of climate change technologies, we examine:

- CCS technologies for the industrial sector
- Renewable energy sources for the manufacturing sector
- Specific technologies to reduce industrial gases such as PFs or SF6.

It should be noted that most of the cumulative new industry capacity for some of these technologies (in particular, steel, cement and technologies for less energy-intensive industries) will occur in non-OECD countries (see Figure 6), which implies that these countries could possibly also take the lead in technological equipment.

Figure 6: Cumulative new industry capacity as a share of currently installed global capacity in the IEA Efficient World Scenario



Note: Includes replacements of currently existing capacity.

Source: IEA, 2012

In the following sections, we provide a brief overview of the relevant technological developments.

1.3.1. Selected green technologies for energy-intensive industries

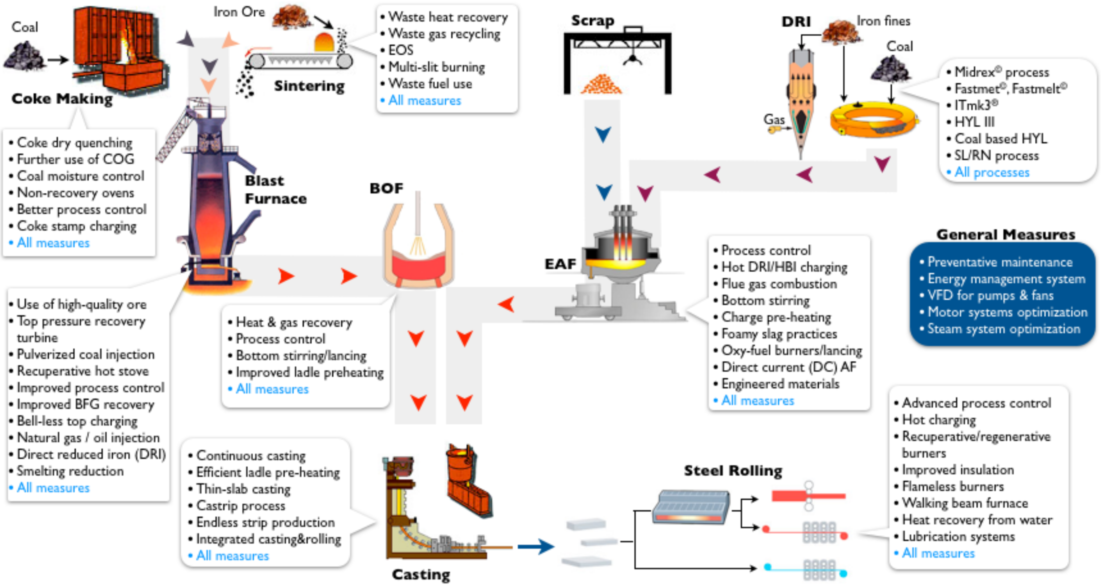
Iron/steel production

Steel production entails several process steps that can be arranged in various combinations depending on the product mix, available raw materials, energy supply and investment capital. The key characteristics of the three main process routes are:

- In the *Blast Furnace* (BF)/*Basic Oxygen Furnace* (BOF) route, pig iron is produced using primarily iron ore (70 percent to 100 percent) and coke in a blast furnace. This is then turned into steel in a basic oxygen furnace. Due to the inclusion of coke-making and sintering operations, this route is highly energy-intensive;
- The *Scrap/Electric Arc Furnace* (EAF) route is mainly based on scrap for the iron input and has a significantly lower energy intensity compared to the BF/BOF route due to the omission of coke- and iron-making processes;
- The *Direct Reduced Iron* (DRI)/EAF route is based on iron ore and often uses scrap for the iron input. The energy intensity of DRI production can be lower than that of the BF route, depending on the size, fuel and ore characteristics.

In recent years, increasing attention has also been paid to smelting reduction, which is emerging as a contender to the blast furnace process.

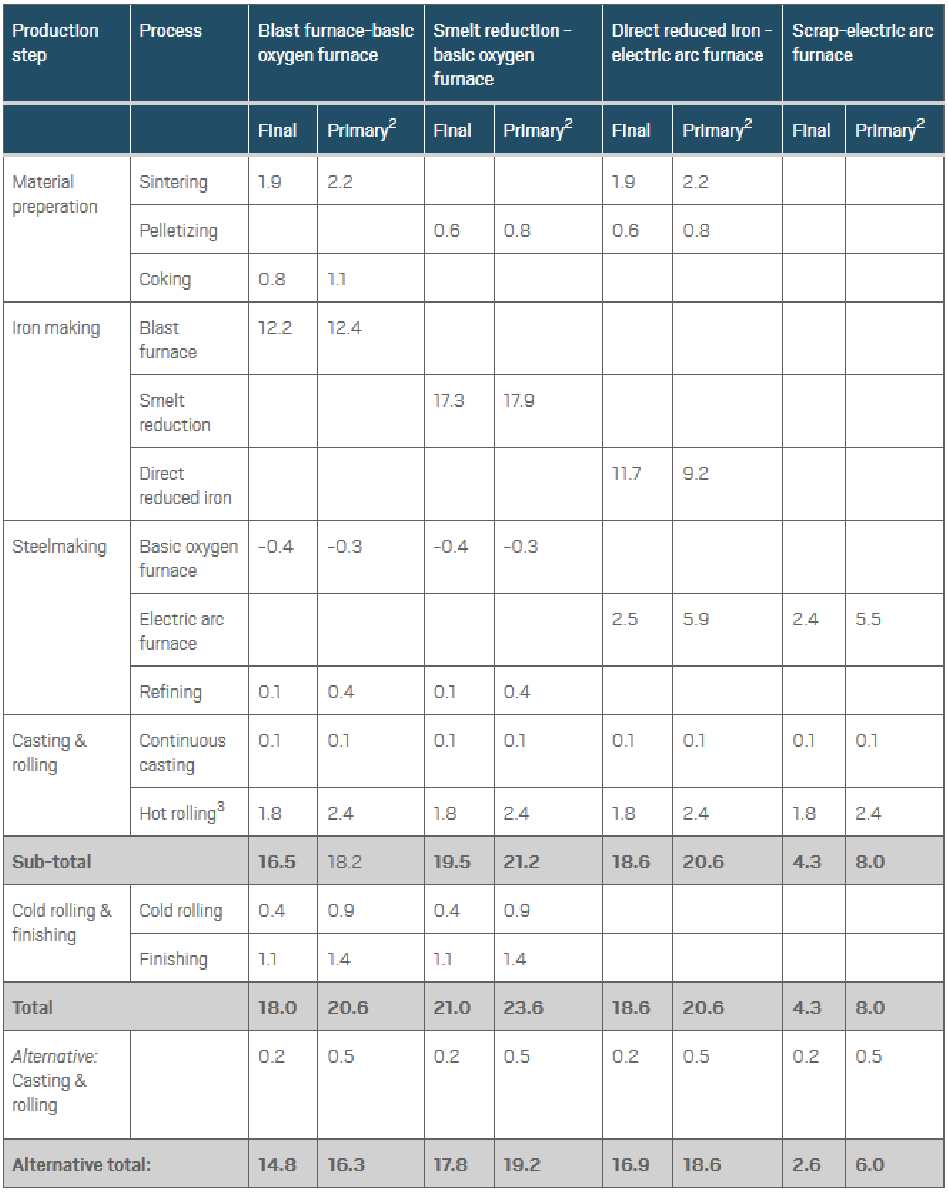
Figure 7: Iron/steel schematic



Source: Industrial Efficiency Technology Database, IIP

The following table presents best practice energy consumption data for different commonly used process routes of iron and steel production. It should be noted that totals for different process routes are highly dependent on feedstock and material flows and can show significant variations between different plants. Therefore, comparing individual plants to the totals listed here may be misleading. For the most energy and GHG efficient technologies, see Annex.

Table 2: World best practice final and primary energy intensity values for iron and steel (values in GJ/metric ton of steel)



Production step	Process	Blast furnace-basic oxygen furnace		Smelt reduction – basic oxygen furnace		Direct reduced iron – electric arc furnace		Scrap-electric arc furnace	
		Final	Primary[2]	Final	Primary[2]	Final	Primary[2]	Final	Primary[2]
Material preperation	Sintering	1.9	2.2			1.9	2.2		
	Pelletizing			0.6	0.8	0.6	0.8		
	Coking	0.8	1.1						
Iron making	Blast furnace	12.2	12.4						
	Smelt reduction			17.3	17.9				
	Direct reduced iron					11.7	9.2		
Steelmaking	Basic oxygen furnace	-0.4	-0.3	-0.4	-0.3				
	Electric arc furnace					2.5	5.9	2.4	5.5
	Refining	0.1	0.4	0.1	0.4				
Casting & rolling	Continuous casting	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Hot rolling[3]	1.8	2.4	1.8	2.4	1.8	2.4	1.8	2.4
Sub-total		**16.5**	18.2	**19.5**	**21.2**	**18.6**	**20.6**	**4.3**	**8.0**
Cold rolling & finishing	Cold rolling	0.4	0.9	0.4	0.9				
	Finishing	1.1	1.4	1.1	1.4				
Total		**18.0**	**20.6**	**21.0**	**23.6**	**18.6**	**20.6**	**4.3**	**8.0**
Alternative: Casting & rolling		0.2	0.5	0.2	0.5	0.2	0.5	0.2	0.5
Alternative total:		**14.8**	**16.3**	**17.8**	**19.2**	**16.9**	**18.6**	**2.6**	**6.0**

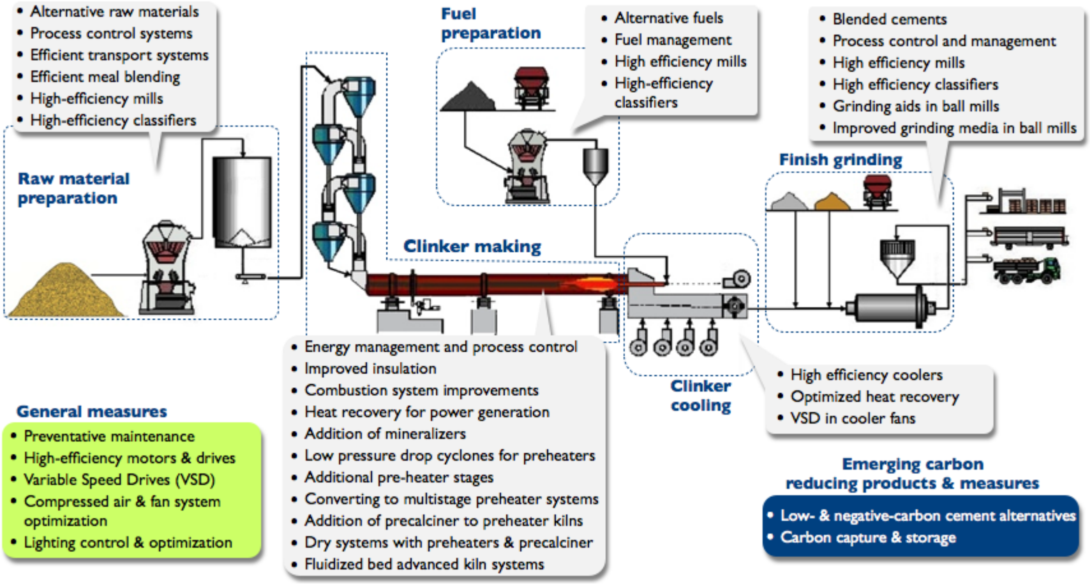
Source: Industrial Efficiency Technology Database, IIP

Cement production

Dry, semi-dry, semi-wet and wet processes are the four main process routes used in the production of cement. Dry processes are considerably more energy efficient but the choice of technology usually depends on the availability of raw materials. Due to the widespread availability of dry materials, a considerable share of their production in developed countries is converted into dry processes. Dry processes are also the main choice of new plants or for plants seeking to expand or upgrade. The energy-intensive wet process is still being used in some countries (and represents a considerable share of production in the CIS, Australia and New Zealand), but at the same time is being phased out in many countries.

Most of the cement industry's energy use and CO_2 emissions are linked to the production of clinker, the main component of cement produced by sintering limestone and clay. The electricity needed to crush and grind raw materials, the fuel required and the finished products have a high energy demand. Proven technological options with the potential to achieve considerable reductions in both energy use and CO_2 emissions can be categorized into a) the use of energy-efficient technologies; b) the use of alternative raw materials and fuels, and c) the reduction of the clinker content of cement through increased use of other blends. Other options are also emerging in the form of alternative cementitious materials and carbon capture and storage.

Figure 8: Cement schematic



Source: Industrial Efficiency Technology Database, IIP

The following table presents best practice energy consumption data for different commonly used process routes for cement. It should be noted here as well that totals for different process routes are highly dependent on feedstock and material flows and may show significant variations between different plants. Therefore, comparing individual plants to the totals listed here may be misleading. For the most energy and GHG efficient technologies, see Annex.

It should furthermore be noted that new cement-making processes have been developed, such as the CELITEMENT process and other similar processes that aim to reduce both energetic emissions (by lowering process heat used) and process emissions (by using a different chemical process). These processes aim to achieve much higher shares of emission reductions in the range of up to 50 percent compared with current levels. The main problem is ensuring that these processes actually work for large volumes (at present, they are being tested for charges of several 100 kg up to several 1000 t in subsequent stages), and to obtain quality certificates for the cement being used for buildings, since the standard testing procedures are inadequate. However, such ambitious and profound process changes cannot be expected to have substantial impacts before 2025. The first who master these processes will gain considerable co-benefits in terms of inputs saved, as well as improvements in productivity.

Table 3: International benchmarks for thermal energy consumption in clinker-making with different technologies

Production Process	Energy Consumption (GJ/t Clinker)	
	Min	Max
Dry, multistage cyclone pre-heater and pre-calciner kilns	2.85	3.0
Dry process rotary kilns with cyclone pre-heaters	3.1	4.2
Semi-dry/semi-wet processes (Lepol kiln)	3.3	4.5
Dry process long kilns		5.0
Wet process long kilns	5.0	6.0
Shaft kilns (up to 100 t/d capacity)	3.1	4.2

Source: Industrial Efficiency Technology Database, IIP

Table 4: World best practice final energy intensity values for Portland cement

Process	Energy carrier	Product unit	kWh/t product	GJ/t prduct	kWh/t clinker	GJ/t clinker	kWh/t cement	GJ/t cement
Raw materials preparation	Electricity	t raw meal	12.05	0.04	21.3	0.08	20.3	0.07
Solid fuels preparation	Electricity	t coal	10	0.04	0.97		0.92	
Clinker making	Fuel	t clinker				2.85		2.71
	Electricity	t clinker			22.5	0.08	21.4	0.08
Additives preparation	Fuel	t additive						
	Electricity	t additive						
Finish grinding								
325 cement	Electricity	t cement					16	0.06
425 cement	Electricity	t cement					17.3	0.06
525 cement	Electricity	t cement					19.2	0.07
625 cement	Electricity	t cement					19.8	0.07
Total								
325 cement							**59**	**2.92**
425 cement							**60**	**2.92**
525 cement							**62**	**2.93**
625 cement							**62**	**2.93**

Assumptions: The ratio of "t of raw materials per t of clinker" is 1.77; the ratio of "t of coal per ton of clinker" is 0.97; the clinker to cement ratio in Portland cement is 0.95; additives to the cement ratio in Portland cement is 0.05.
Source: Industrial Efficiency Technology Database, IIP

Paper production

The processes used to produce pulp and to dry paper are the major energy consumers in the industry. The main production facilities are either pulp mills or integrated paper and pulp mills. Integrated mills are more energy efficient.
Kraft pulping is the most widely used chemical pulping process. It produces high-quality fibres for higher paper grades. However, kraft pulping requires large amounts of heat energy and has a low fibre yield. Kraft mills can meet most or all of their energy needs from by-products (i.e. black liquor) and may even be net exporters of energy. Similarly, sulphite pulping, which is used for speciality papers, is characterized by high energy consumption, but can self-generate a large part of a mill's energy needs from by-products.

Mechanical pulping produces weaker fibres but has a high yield, and thus has a lower final energy demand. Higher energy efficiency is enabled by applications such as thermo-mechanical pulping, where heat is recovered at different grades. However, since electricity is the main form of energy being used, this technology may have a high primary energy demand and CO_2 emissions.

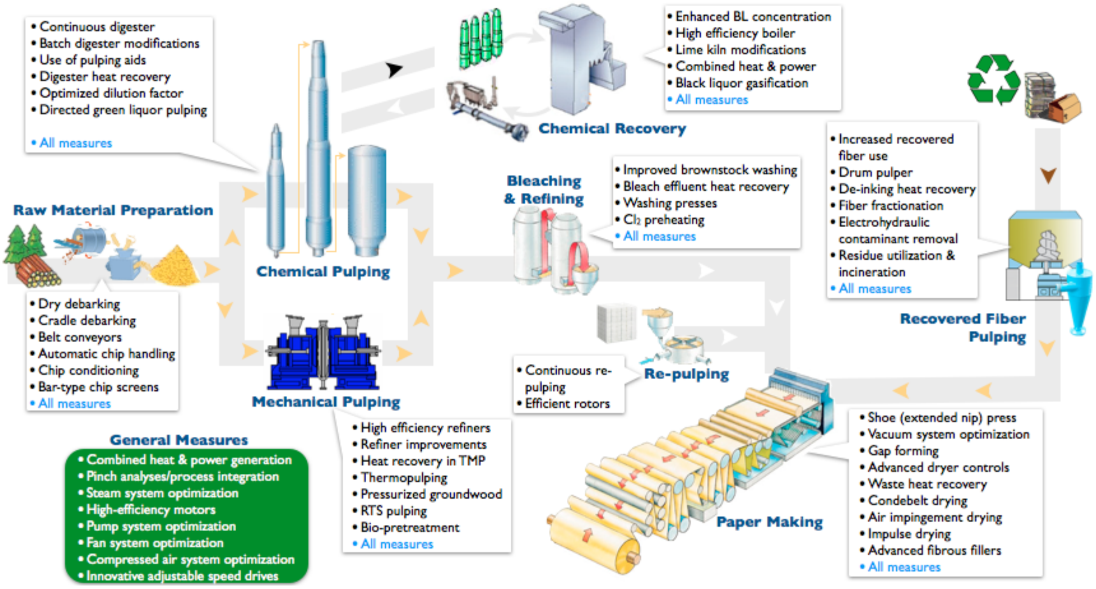
Pulp production from recovered fibres requires substantially less energy compared to virgin pulp (the BAT values for recovered fibre are 0.7-3 GJ/t compared to around 14.3 GJ/t for kraft pulping). It is a promising option in terms of reducing energy consumption and CO_2 emissions, with estimates projected to be as high as 35 percent. However, the availability of recovered paper is sometimes limited and resolving this issue will require modifications to other parts of the paper production lifecycle.

The amount of energy used by paper machines generally depends on pulp quality and paper grade, and can vary considerably. Integrated mills can achieve higher energy efficiency by eliminating intermediate pulp drying and using better processes.

Applications of combined heat and power (CHP) can significantly enhance the energy efficiency of the pulp and paper industry. The industry's CHP potential is estimated to range between 0.3-0.6 EJ/year. Typically, the introduction of CHP can result in fuel savings of about 10 percent to 20 percent and energy savings of around 30 percent compared to traditional technologies.

The IEA asserts that black-liquor gasification and bio-refinery concepts, advanced paper-drying techniques, increased paper recycling and carbon capture and storage will play a key role in reducing energy consumption and GHG emissions in the industry.

Figure 9: Paper schematic



Source: Industrial Efficiency Technology Database, IIP

The following table presents best practice energy consumption data for various commonly used process routes for paper.

A typical mill usually produces several types of pulp or paper and uses various wood species and different mixes of fibre raw material. Although the energy consumption of different product types can be determined, total annual consumption usually fluctuates depending on the distribution of production. There are also differences in the types of production and the sub-processes involved. Collectively, these factors pose a challenge for benchmarking different plants. Furthermore, the impact of different energy efficiency measures on product quality (e.g. tensile strength, freeness, opacity) poses an additional challenge.

Useful benchmarking is often possible for mills working with certain types of pulp and paper, using the same types of production and comparable sub-processes. The tables below present best practice values for both stand-alone and integrated pulp and paper mills.

For the most energy and GHG efficient technologies, see Annex.

Table 5: World best practice final and primary energy intensity values for stand-alone pulp mills / stand-alone paper mills/ integrated pulp and paper mills

Raw Material	Product	Process	Fuel Use for Steam (GJ/ADt)	Steam Exported (GJ/ADt)	Electricity Use (kWh/ADt)		Electricity Produced (kWh/ADt)		Total (GJ/ADt)	
					Final	Primary*	Final	Primary*	Final	Primary*
Non-wood	Market Pulp	Pulping	10.5	-4.2	400	1212			7.7	10.7
Wood	Market Pulp	Kraft	11.2		640	1939	-655	-1985	11.1	11
		Sulfite	16		700	2121			18.5	23.6
		Thermo-mechanical		-1.3	2190	6636			6.6	22.6
Paper	Recovered Pulp		0.3		330	1000			1.5	3.9

Raw Material	Product	Process	Fuel Use for Steam (GJ/ADt)	Electricity Use (kWh/ADt)		Total (GJ/ADt)	
				Final	Primary*	Final	Primary*
Pulp	Uncoated fine (wood free)	Paper machine	6.7	640	1939	9.0	13.7
	Coated fine (wood free)	Paper machine	7.5	810	2455	10.4	16.3
	Newsprint	Paper machine	5.1	570	1727	7.2	11.3
	Board	Paper machine	6.7	800	2424	9.6	15.4
	Kraftliner	Paper machine	5.9	535	1621	7.8	11.7
	Tissue	Paper machine	6.9	1000	3030	10.5	17.8

Raw Material	Product	Process	Fuel Use for Steam (GJ/ADt)		Electricity Use (kWh/ADt)		Total (GJ/ADt)	
			Final	Primary*	Final	Primary*	Final	Primary*
Wood	Bleached uncoated fine	Kraft	14	14	1200	3636	18.3	27.1
	Kraftliner (unbleached) and bag paper	Kraft	14	14	1000	3030	17.6	24.9
	Bleached coated fine	Sulfite	17	14	1500	3030	22.4	24.9
	Bleached uncoated fine	Sulfite	18	17	1200	4545	22.3	33.4
	Newsprint	TMP	-1.3	18	2200	3636	6.6	31.1
	Magazine paper	TMP	-0.3	-1.3	2100	6667	7.3	22.7
	Board	50% TMP	3.5	-0.3	2300	6364	11.8	22.6
	Board (no de-inking)		8	3.5	900	6970	11.2	28.6
	Newsprint (de-inked)		4	8	1000	2727	7.6	17.8
	Tissue (de-inked)		7	4	1200	3030	11.3	14.9

ADt = Air dried metric ton.

*: Primary energy assumes electricity generation, transmission and distribution losses of 67 percent.

Source: Industrial Efficiency Technology Database, IIP

1.3.2. Selected green technologies for less energy-intensive industries

Electric motors convert electrical into mechanical power and are often part of a motor-driven system. In industrial applications, electric motor-driven systems are used for pumping, compressed air, fans, conveyance and other forms of mechanical handling and processing. Although electrical motors and their controls are typically the parts that require the most electricity in a motor-driven system, their impact on the overall efficiency of the system is often limited. This is attributable to the fact that the other system components, such as pumps, fans, valves, pipes, ducts and end-users, affect both the amount of mechanical power required by the entire system and the loss that occurs during the delivery of this power, which collectively have a much more significant impact on overall energy consumption. Consequently, adopting a system approach is crucial to optimize the energy efficiency of motor-driven systems. The level of efficiency of a given system depends on both the extent to which advanced solutions are used and the system's overall design. In most cases, improving the efficiency of a motor-driven system involves the following:

- Use of energy efficient motors
- Selecting the core components – e.g. pumps, fans, compressors, transmissions, variable speed drives – with the right type and size and high efficiency
- Optimization of the design and the entire system's operation.

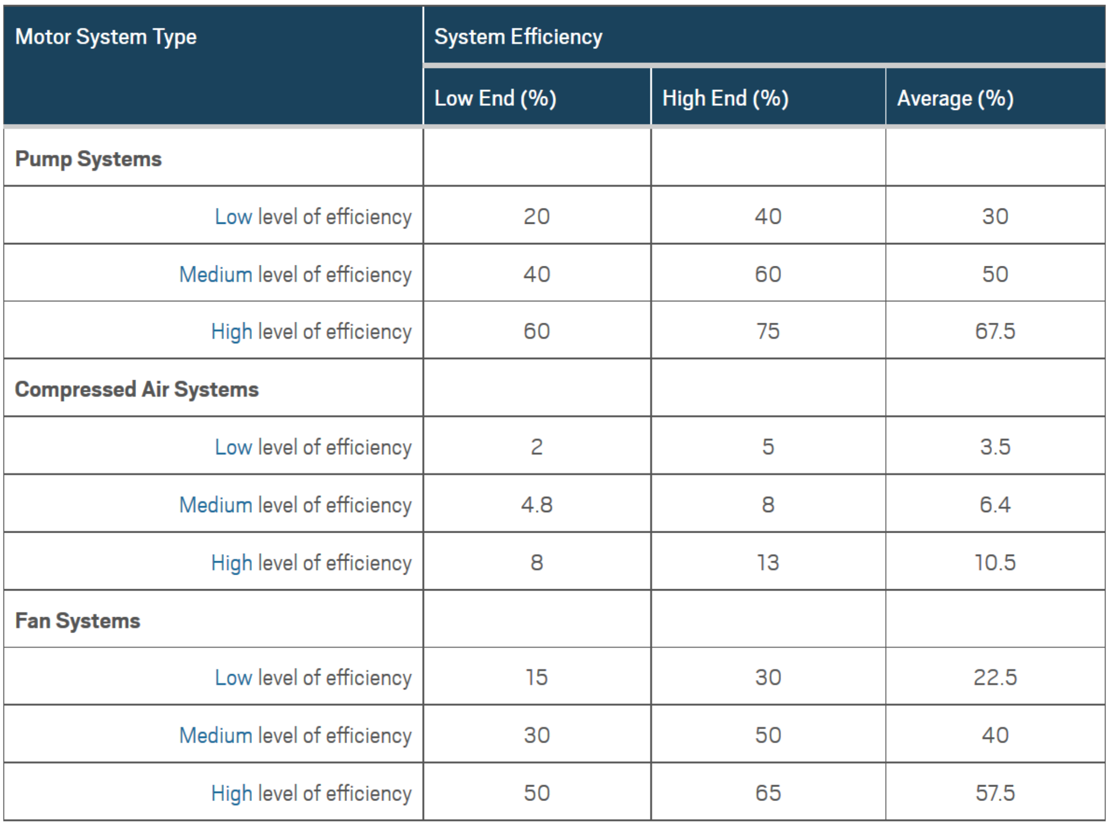
Figure 10: Motor systems schematic

Source: Industrial Efficiency Technology Database, IIP

The following table presents best practice energy consumption data for various commonly used process routes for motor systems. Assessing an electric motor's performance and improvement potential is relatively straightforward when using well-established efficiency classes. Typically, energy efficiency can be improved between 4 percent and 5 percent by using the best available motor. Benchmarking entire motor-driven systems, on the other hand, is more complex due to the fact that efficiency is significantly influenced by the wide range of system components and operational practices. Some generic benchmarks for different efficiency classes are provided below.

For the most energy and GHG efficient technologies, see Annex.

Table 6 Typical system efficiencies for electric motor-driven systems



Motor System Type	System Efficiency		
	Low End (%)	High End (%)	Average (%)
Pump Systems			
Low level of efficiency	20	40	30
Medium level of efficiency	40	60	50
High level of efficiency	60	75	67.5
Compressed Air Systems			
Low level of efficiency	2	5	3.5
Medium level of efficiency	4.8	8	6.4
High level of efficiency	8	13	10.5
Fan Systems			
Low level of efficiency	15	30	22.5
Medium level of efficiency	30	50	40
High level of efficiency	50	65	57.5

Source: Industrial Efficiency Technology Database, IIP

Energy efficiency options in electric motor systems in developing countries are analysed in more detail in Fleiter and Eichhammer (2012).

1.3.3 Selected emerging green technologies: Carbon capture and storage (CCS) and renewables

Carbon capture and storage CCS

This section focuses on carbon capture and storage in major industrial applications, primarily in the context of removing CO_2 from fossil fuel uses. However, in stringent climate mitigation scenarios, CCS could be required in post-fossil contexts coupled with biomass-based energy generation to achieve negative emissions.

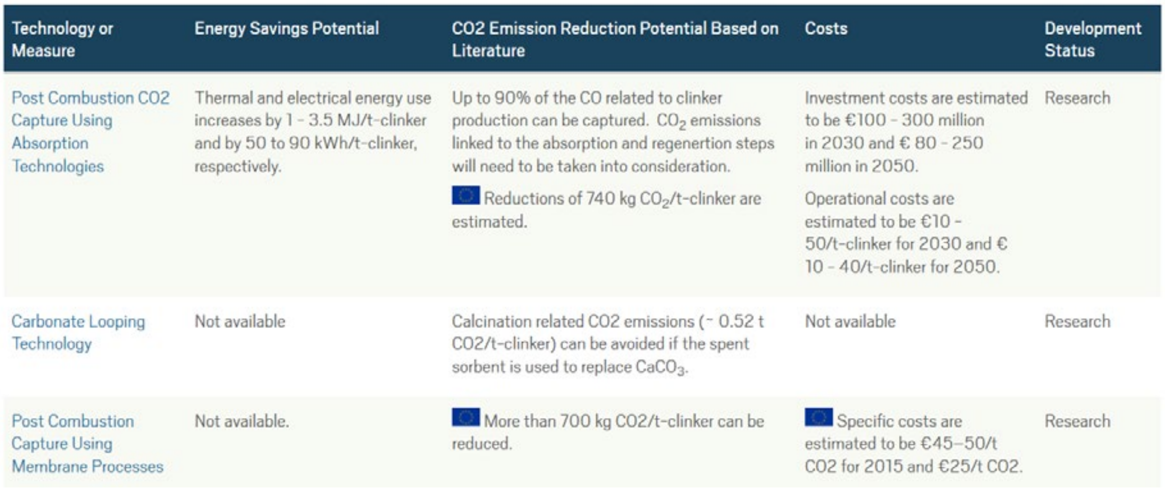
The use of carbon capture and storage technology is a necessary precondition for the continued use of fossil fuel-based reducing agents in steel production. This process is based on capturing carbon dioxide (CO_2) from large point sources and storing it in such a way that it does not enter the atmosphere. It can also be used to describe the scrubbing of CO_2 from ambient air as a geo-engineering technique. This emerging technology could be based on various capture and storage options, some of which could be adapted to the context of energy-intensive processes, such as steelmaking, cement or paper, while others still require further research. This process consumes considerable amounts of energy.

It is estimated that the overall potential of emissions reduction in the iron/steel industry by using CCS ranges between 0.5 Gt to 1.5 Gt of CO_2/yr. CCS for blast furnaces costs around US\$40/t CO_2-US\$50/t CO_2. CCS for direct reduced iron can cost less than US\$25/t CO_2. CCS is not expected to make any substantial contributions in the industries discussed in this report before 2030. The most extensive research in this context is currently being carried out by the ULCOS project of the European Union and the European Steel Platform. The objective is to achieve reductions in emissions of 50 percent.

CCS for the cement industry involves capturing the CO_2 arising from the combustion of fuels and from the treatment of raw materials and storing it away from the atmosphere for very long periods of time. This technology is emerging as the favoured approach for CO_2 abatement.

In principle, three basic technologies are known for capturing CO_2: pre-combustion capture, oxyfuel combustion and post-combustion capture. For the cement industry, oxyfuel combustion and post-combustion capture are considered alternative approaches. Many of the carbon capture applications are currently in demonstration or research phases. The transport and storage of compressed CO_2 are available techniques, but are currently limited to specific applications. Experiences on a larger scale are not yet available. It should be noted that CCS costs are high, and the adoption of this technology in industry is highly dependent on policy intervention.

Table 7 CCS options for cement-making



Technology or Measure	Energy Savings Potential	CO2 Emission Reduction Potential Based on Literature	Costs	Development Status
Post Combustion CO2 Capture Using Absorption Technologies	Thermal and electrical energy use increases by 1 - 3.5 MJ/t-clinker and by 50 to 90 kWh/t-clinker, respectively.	Up to 90% of the CO related to clinker production can be captured. CO_2 emissions linked to the absorption and regenertion steps will need to be taken into consideration. 🇪🇺 Reductions of 740 kg CO_2/t-clinker are estimated.	Investment costs are estimated to be €100 - 300 million in 2030 and € 80 - 250 million in 2050. Operational costs are estimated to be €10 - 50/t-clinker for 2030 and € 10 - 40/t-clinker for 2050.	Research
Carbonate Looping Technology	Not available	Calcination related CO2 emissions (~ 0.52 t CO2/t-clinker) can be avoided if the spent sorbent is used to replace $CaCO_3$.	Not available	Research
Post Combustion Capture Using Membrane Processes	Not available.	🇪🇺 More than 700 kg CO2/t-clinker can be reduced.	🇪🇺 Specific costs are estimated to be €45–50/t CO2 for 2015 and €25/t CO2.	Research

Source: Industrial Efficiency Technology Database, IIP

A detailed technology roadmap for CCS applications in industry was prepared by IEA/UNIDO (2011). With regard to industrial applications of CCS, the roadmap states: "Whereas the power sector can take advantage of alternatives to fossil fuels, in several industries deep emission reductions can only be achieved through CCS […] For developing countries, CCS could be part of a low-carbon industrial development strategy. If CCS can be implemented through the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) or other new global climate mechanisms, the cost barrier could be partly overcome. It is likely that if CCS moves forward under the CDM, the first projects will be in industry."

Renewables and smart grids

Renewables and smart grid options are a short-term solution for industrial manufacturing and imply a substantial reorganization of process management. However, such options are far from being mainstream in industrial applications and require substantial innovations in the organization of industrial processes. This implies:

- Use of wind or PV as sources of electricity. For example, the Lafarge company makes use of such alternative sources in Morocco to cope with high electricity prices and to ensure a stable supply of electricity
- Small concentrated solar power units (solar dishes of a size of 20-30 kW and more when modules are combined) can be used to provide process heat for industrial processes (medium temperature range)
- Performant solar collectors or absorber units could be used for low temperature heat or cooling ranges for both buildings and processes
- Use of industrial heat pumps
- Use of (sustainable) sources of biomass
- Biowaste could be used for selected processes
- Biogenic material may replace selected raw materials which are presently derived from oil-based chemistry.

A report published by the Imperial College London (Bazilian et al., 2011) investigates leapfrogging in the field of electricity grids. The report argues “that these Smart Grid advances may enable sub-Saharan African countries to leapfrog elements of traditional power systems in terms of both technology and regulation. This could accelerate national and regional electrification timeframes, improving service delivery, minimizing costs and reducing environmental impact.” The report also introduces “the notion of Just Grids to reflect the need for power systems to contribute towards equitable and inclusive global, economic and social development. While Smart Grids may provide an efficient mechanism to address the massive electricity infrastructure building requirements, Just Grids will help guarantee access to modern energy services without marginalizing the poor.“

2. Impacts of emerging green technologies for the manufacturing sector on innovation

2.1 Green technologies as drivers of innovation

Several developments have taken place in green technologies over the last two decades. There are pronounced differences in the role innovation plays within the different strategies (see Figure 11).

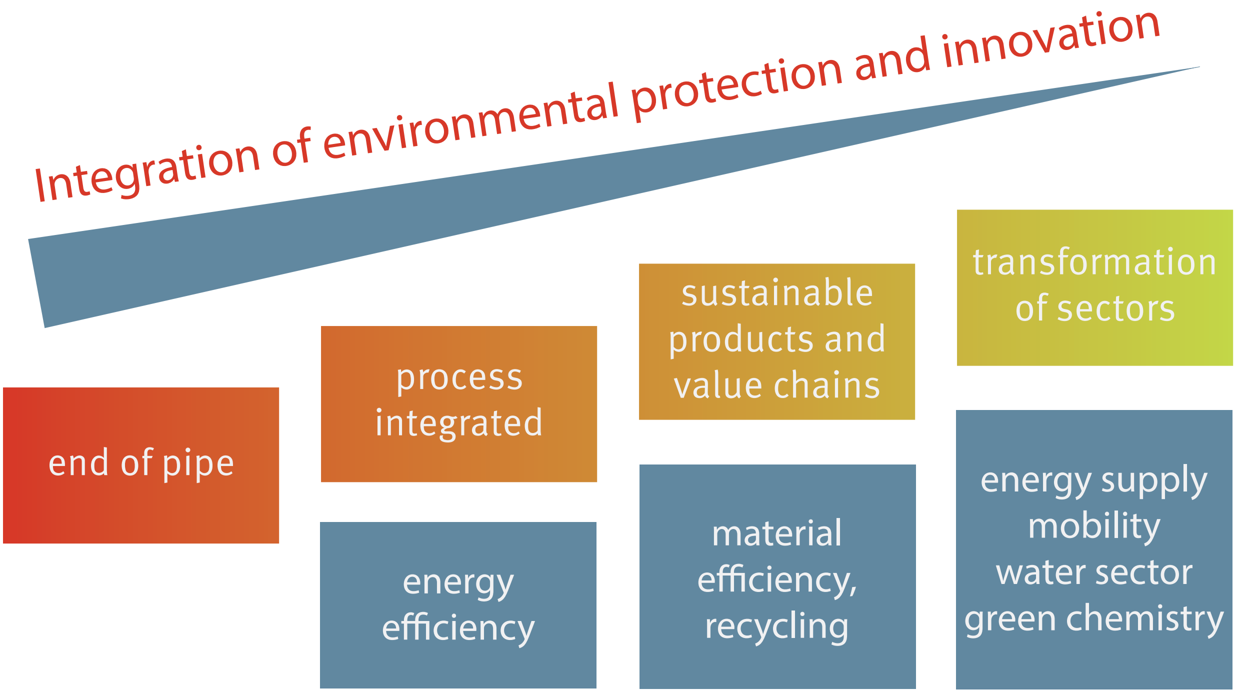
Initially, end-of-pipe solutions were used. These do not modify the production process, but are add-on technologies. Thus, production's core business was not affected by them, and key innovation tasks included the reduction of both costs and emissions. The reduction of pollutants such as CO_2 can be attributed to this strategy.

In a second stage, more process-integrated strategies were employed, such as more energy efficient processes that reduce energy use and related emissions. These strategies have to be integrated into the core process of production, that is, aspects such as the quality of production and changes in economic productivity become relevant. On the one hand, this raises the complexity of these innovations. On the other, there are economic rewards in addition to the environmental benefits, because the innovations can also lower the costs of production inputs and contribute to the modernization of production capital. The shift from traditional processes to entirely new processes, e.g. in steel-making or more energy efficient electrical motors, is one example.

A third environmental strategy emphasizes the closing of materials cycles and the integration of product policy and product use. These strategies address problems such as product design without the use of toxic materials or the growing demand for scarce but precious resources. They are also associated with new assessment tools such as life-cycle-assessment. These strategies add yet another layer of innovation complexity to environmental problems, because they require coordination along the value chain, from the production and processing of raw materials to the manufacture of products to the re-use of products or the recycling of materials. Furthermore, new products often also require new business models which in turn implies changes within firms. These strategies also open up new economic opportunities, as new products are a prerequisite for the development of new markets. To sum up, companies' environmental and innovation strategies are turning into the same side of the coin.

The enormous task of attaining sustainability has increased awareness that a transformation of entire industries is necessary. In the field of energy, water, transportation and chemistry, in particular, there is a need to shift the resource base and to encourage substantial structural changes in the manufacturing sector, e.g. towards a carbon-free economy. This not only requires substantial innovations within firms, but an extensive co-evolution of technologies with nearby institutions, standardization and regulations on the system of education and skills development. That is, the complexity of innovation also encompasses the meso-economic level.

Figure 11: Innovation dimension of environmental technologies



Source: Fraunhofer ISI

To sum up, environmental strategies are becoming increasingly complex with regard to innovation. This has important implications for green technologies in manufacturing:

- Green technologies for energy-intensive and for less energy-intensive industries, in particular cross-cutting industrial technologies which are energy efficient technologies;
- CCS technologies have characteristics that are very similar to end-of-pipe technologies;
- Renewable energy sources for the manufacturing sector do not modify the process itself, but might contribute to a cheaper and more secure supply of power necessary for operating processes.

There is widespread consensus on the importance of innovations for reducing environmental pressure and for fostering economic development. How innovations emerge is therefore of particular relevance. Innovations are the first application of a solution, either technical, organizational or even institutional. They can be incremental, i.e. existing solutions are improved or entirely new solutions are developed. Innovations that lead to an improvement of the environment are referred to as eco-innovations. Thus, the purpose of developing innovations must not necessarily be environmental, but must lead to a reduction of the environmental burden, regardless of the reason why the innovations were developed. The term *sustainability technologies* is used in this context as well in order to highlight the economic dimension of eco-innovations with regard to integration into the production process, new processes or even the transformation of sectors.

The innovation process is not linear, but entails many feedback loops between invention, technology development and diffusion. The need for producer-user interactions and learning in the market makes early diffusion of technologies crucial.

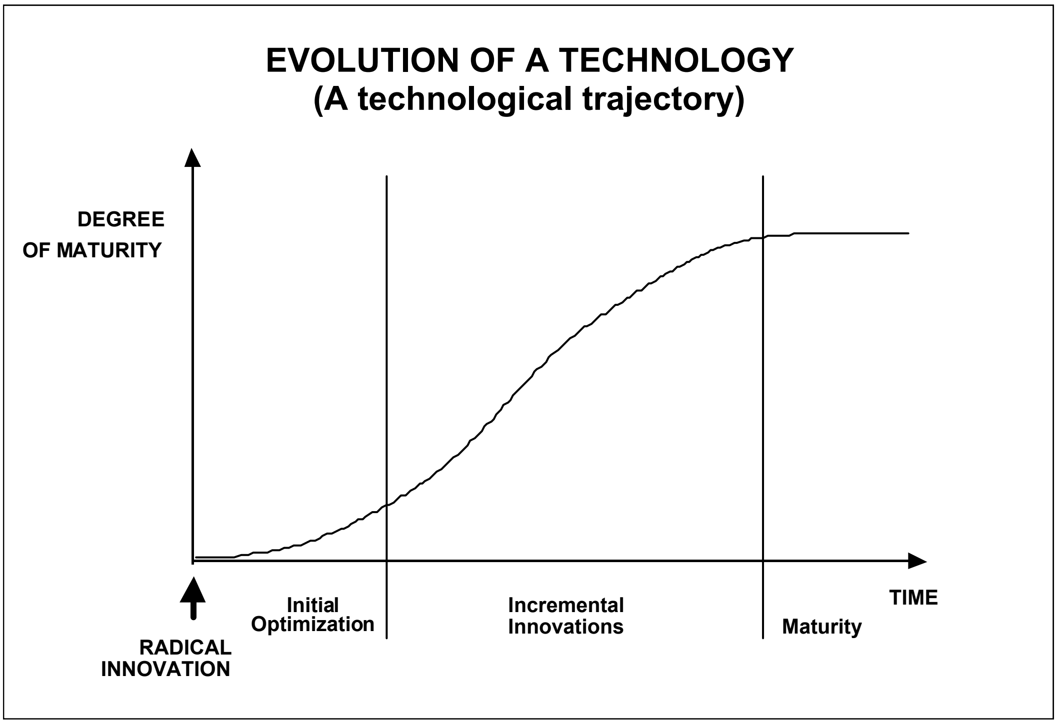
Innovations are triggered by supply (push) factors, that is, by the development of new ideas and concepts of technology. However, demand (pull) factors also play an important role, i.e. demands for new solutions and the functions new technologies offer have to be met to be effective. Another important aspect is the difference between innovations along a technological trajectory, and innovations that involve a radical change from one technological paradigm to another (Dosi, 1982). A radical innovation arises from a new technological paradigm. The different designs of competing technologies ensure diversity. Selection processes take place and eventually a dominant design emerges. Learning effects and economies of scale drive costs down, leading to additional diffusion which in turn enables further incremental innovations along the existing technological trajectory.

The innovation process is embedded in the production of knowledge and socioeconomic developments and institutions. Thus, innovation follows certain paths, which may lead to path dependencies and obstacles towards new technological solutions. At the same time, innovations are not only a purely technological process. They require organizational adaptations as well as the co-evolution of institutions that support the further development of technologies. This co-evolution is crucial for the debate on globalization and innovation:

- The dynamics of innovation are not linear: the need for co-evolution represents a barrier to new technological paradigms and increases path dependency. Once a new trajectory has been set, co-evolution will increase the innovation dynamics along the trajectory.
- Globalization is also seen as a process in which the sourcing of new solutions and the accumulation of knowledge becomes more global. However, it is more difficult to transfer institutions and system linkages than single technologies that embody technological change.
- The need for organizational and institutional co-evolution underlines the different facets of globalization. Economic development is functionally interlinked with institutional changes, which adds to the social dimension of globalization.

The innovation process takes place in different phases. In the early phase of an emerging radical innovation, the selection process for the dominant design plays an important role, as does the availability of diverse solutions to select from. In subsequent phases, market formation and feedback from users and producers assume increasing importance, and the co-evolution of technologies and institutions fosters further incremental innovations.

Figure 12: Evolution of a Technology (technology trajectory from radical innovation to maturity)



Source: Perez (2004) citing Nelson and Winter / G. Dosi

2.2 Innovation dynamics for green technologies are relevant in manufacturing

Competences in green development and leapfrogging in MICs are becoming increasingly urgent from a global perspective. The integration of these innovations in the development process of MICs requires knowledge accumulation. The concepts Social or Absorptive Capacity (Abramovitz, 1986; Cohen and Levinthal, 1990) and technological capabilities (Lall, 1992; Bell and Pavitt, 1993) have become widely known since the end of the 1980s. Recent research results (e.g. Fagerberg and Godinho, 2005; Nelson, 2007; Malerba and Nelson, 2008) and of empirical studies on developing capabilities, especially in the context of Asian countries (Lall, 1998; Lee and Lim, 2001; Lee, 2005; Lee and Lim, 2005; Rasiah, 2008) have emphasized the importance of absorptive capacity and competence building.

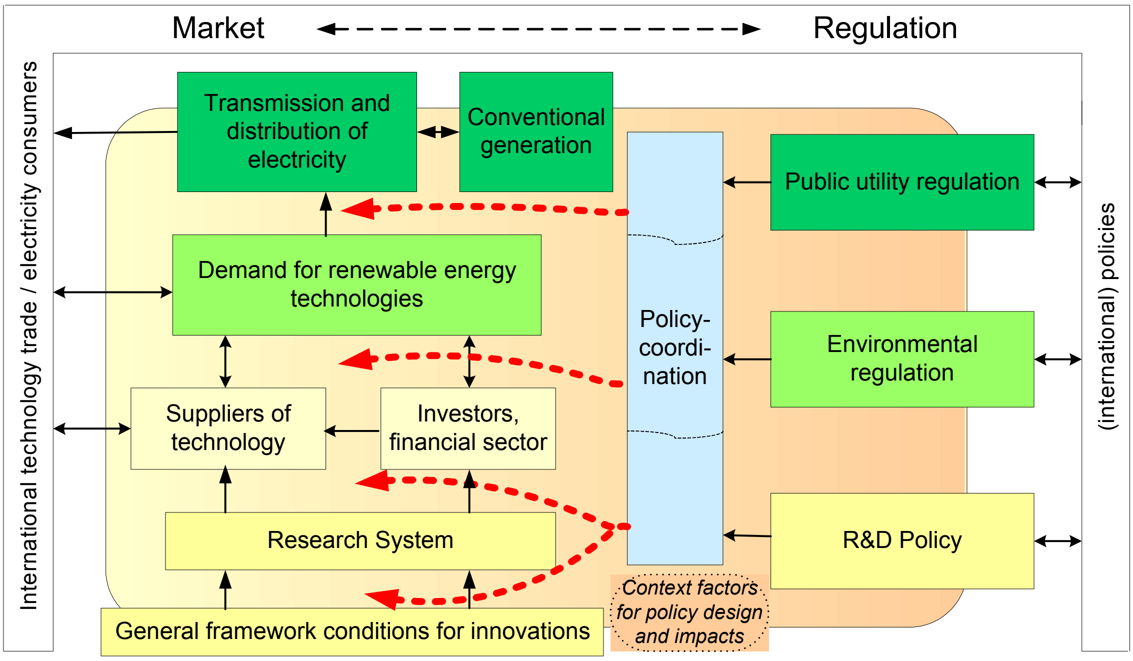
This has to be considered in light of the fact that technological innovation is not a linear process but consists of complex interactions. In the 1990s, the heuristic approach of systems of innovation gained wide acceptance. In addition to the demand and technology factors, this approach clearly underlines the manifold aspects of intra-firm determinants of innovation, the characteristics of innovation as an interactive approach, the role of institutions in shaping activities, the importance of the home (lead) market as a base for competitiveness on the international markets and the regulatory framework. The key notion of the systems of innovation approach is that these factors influence each other, highlighting the importance of feedback mechanisms. Experiences with this framework have resulted in conclusions about the conditions that shape innovation processes. The following factors are particularly important:

- Innovation is not a linear process, but consists of many feedback loops from invention to technology development and diffusion.
- Innovation is embedded in the production of knowledge and socioeconomic development and institutions, which may lead to path dependency.
- Producer-user interaction and learning in the market makes early diffusion crucial.
- There is a need for a diversity of solutions, on the one hand, and selection of a dominant design, on the other.
- The stability of the framework conditions in general enhances innovation processes.
- Communication between actors on various levels is essential to disseminate knowledge and gain new insights.

In contrast to traditional thinking, policies that push the diffusion of technology are an important prerequisite for new technological solutions. Furthermore, the lock-in effects, which create path dependency, are also linked to the diffusion of traditional technologies. This highlights the role of the demand side. The demand for EGTs is dependent on regulation (triple regulatory challenge). Thus, the role of demand regulation emerges as a key factor for the analysis of the relation between regulation and innovation.

Figure 13 presents an example of such a system of innovation and the results of a delineation of the most important actors for the case of renewable energy.

Figure 13: System of innovation in the case of wind energy



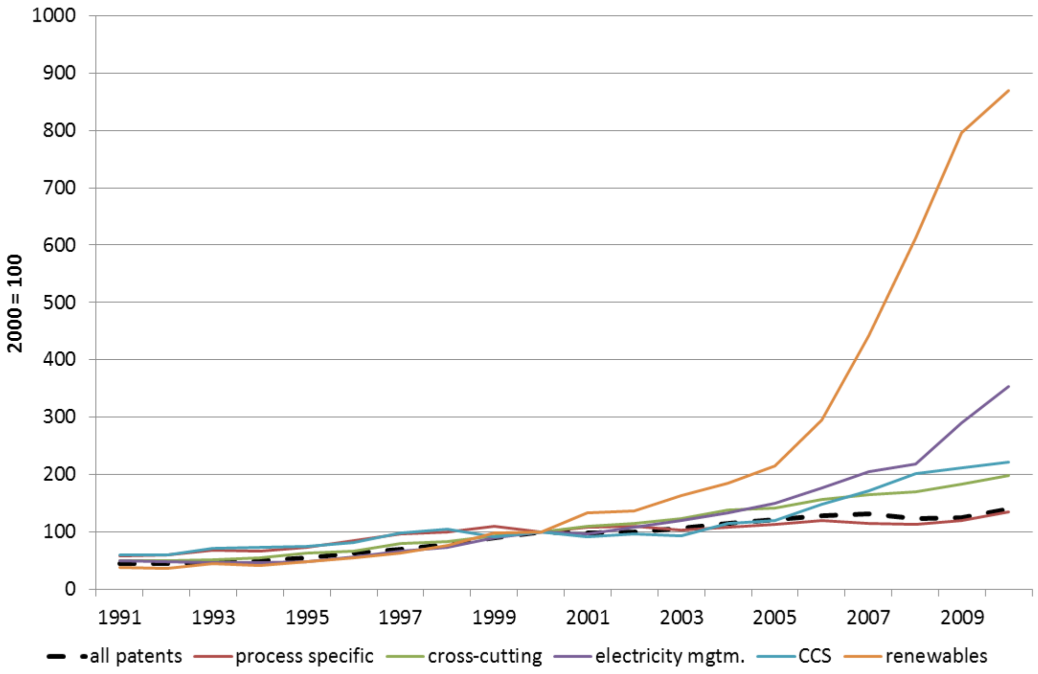
Source: Walz et al., 2008

First, demand for a renewable energy technology arises, which depends on its diffusion. Second, there are suppliers of renewable energy technologies. These are companies that have similar structures to other companies within the given investment sectors. Third, there are investors in renewable energy technologies and financial institutions supplying capital. Fourth, the electricity produced by the renewable energy must be transmitted and distributed to the customers. Hence, access to the grid is crucial for the renewable electricity. Electric utilities play a key role in this regard. They are in charge of the transmission and distribution of electricity. On the other hand, electricity from the renewable energy substitutes electricity supplied from other conventional power plants. That is, electric utilities are competitors. Figure 1 also highlights the leading role of the triple regulatory challenge in the system. Aside from its direct influence on the relevant actors, which is transmitted through interactions between these actors, the triple regulatory challenge also entails indirect effects. Moreover, many context-specific "soft" factors influence the design of policies and impact the system of innovation.

The debate on the changing nature of learning and knowledge acquisition is intensifying. One aspect to consider is the tendency that acquired technological and production capabilities are increasingly diverging (Bell and Pavitt, 1993). Another aspect is the effect of globalization on the mechanisms of knowledge dissemination. Archibugi and Pietrobelli (2003) assert that importing technology has little impact on learning per se, and call for policies to advance cooperation strategies towards technological partnering. Nelson (2007) highlights the changing legal environment and the fact that the scientific and technological communities have moved much closer together. All these factors lead to the conclusion that domestic innovation competences are increasingly becoming a prerequisite for the successful absorption of green technologies in MICs. The absorption of modern technologies and the development of abilities to further advance them and their international marketing are closely interwoven (Nelson, 2007).

The necessary competences also depend on the technologies' characteristics. Green technologies in manufacturing are, in general, medium/high technologies. Studying the results of foresight processes reveals a fairly high innovation potential which is attributed to these green innovations. A comparison of patent developments of green technologies with all patents indicates high innovation dynamics (Figure 14).

Figure 14: Patent dynamics for green technologies (2000 = 100)



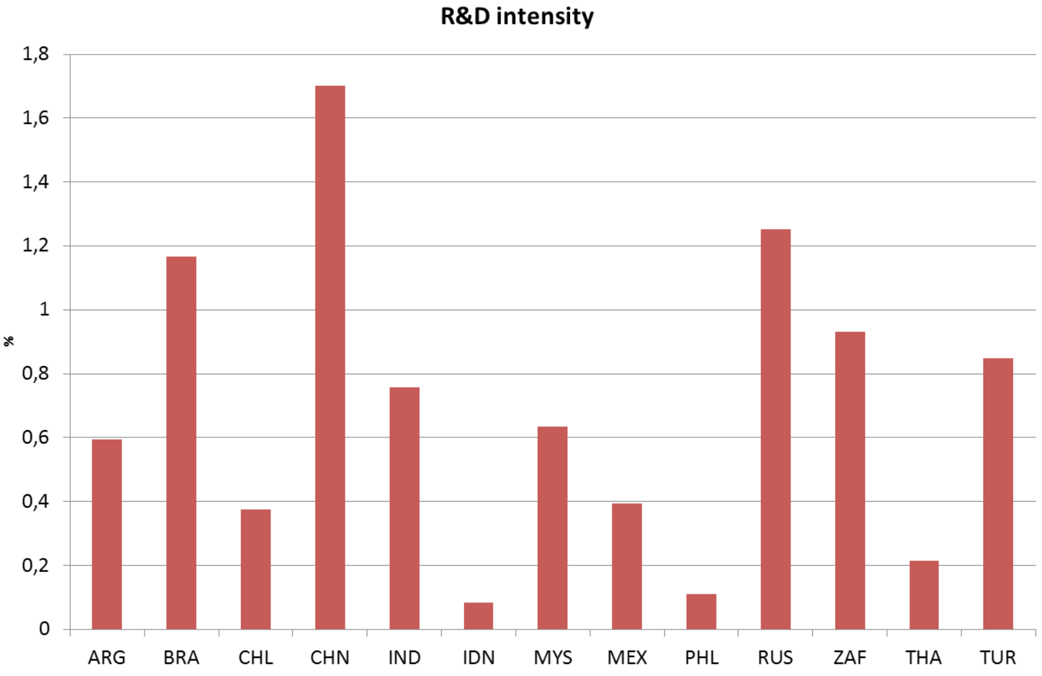
The figure reveals that renewable technologies (index at 875 in 2010 compared to 2000) and technologies for industrial electricity management (such as smart grids or cogeneration, index at 350 in 2010 compared to 2000) have very strong dynamics. Cross-cutting industrial energy efficiency technologies and CCS have also demonstrated much stronger innovation dynamics than the average of all technologies (index for all technologies at 130 compared to 2000). It can thus be concluded that these green technologies, by and large, require substantial technological capabilities.

In this section, innovation indicators for selected MICs are presented. The selection of countries depended on data availability. General innovation indicators that characterize the innovation environment for technologies on an aggregate level, hence also for emerging green technologies, are presented.

2.2.1 General innovation indicators

The quantitative data on innovation capacity provide a first indication of the general conditions for innovation. Expenditure on research and development (R&D) is one of the most widely used measures of innovation inputs. R&D intensity (R&D expenditure as a percentage of GDP) is used as an indicator of an economy's relative degree of investment in generating new knowledge. Several countries have adopted "targets" for this indicator to help focus policy decisions and public funding. Figure 15 shows that the national R&D intensity differs substantially for the MICs covered. It ranges from very low numbers to figures that are significantly higher and come close to some OECD countries. China, for example, has increased its R&D expenditure in recent years. Although the R&D intensity of different technologies and sectors can vary considerably and countries may focus on different industries and technologies, the aggregate figure of R&D intensity is frequently used to characterize the general R&D environment in an economy which is also relevant for EGTs. Countries with a generally higher R&D intensity seem to also be those countries that are able to incorporate emerging green technologies in their portfolio (e.g. Brazil, China, India, South Africa, Turkey). The Russian Federation, for example, has a high R&D intensity but a weak focus on EGTs, whereas Chile's general R&D activity is relatively low but has begun focusing on EGTs. This reveals that the general R&D framework is indeed relevant but that it is not the only explanation for a good absorptive capacity for EGTs. The OECD's average absorptive capacity for emerging green technologies in 2009 was 2.3 percent, the EU-27's was 1.9 percent, the USA's was 2.8 percent and Japan's was 3.3 percent.

Figure 15: R&D intensity 2009 for selected MICs (R&D spending in relation to GDP)



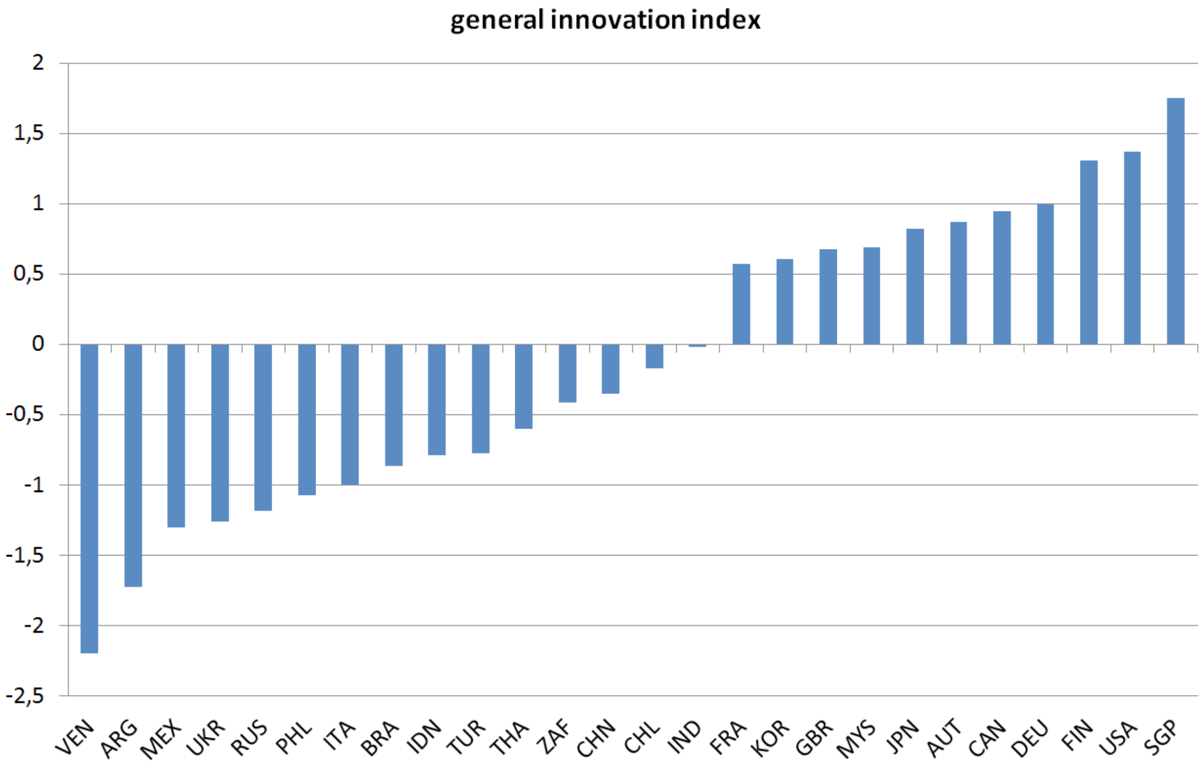
Abreviations: ARG Argentina, BRA Brazil, CHL Chile, CHN China, IND India, IDN Indonesia, MYS Malaysia, MEX Mexico, PHL Philippines, RUS Russian Federation, ZAF South Africa, THA Thailand, TUR Turkey

Source: World Bank (http://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?display=default)

A second approach to analyse the general framework conditions for EGTs uses the survey data of the World Economic Forum (WEF) (2008), which, in turn, is based on expert opinions. To obtain an innovation system index, Peuckert (2011) classifies the indicators into different categories, namely human resources, technological absorption, innovation capacity and innovation friendliness of regulations. For this index, 56 countries were included consisting of OECD countries as well as other high income countries and some MICs for which the indicator values were available. The index values were normalized in a way that a value of zero indicates that a country's general innovation capabilities are estimated to be the average of all 56 countries included in the survey.

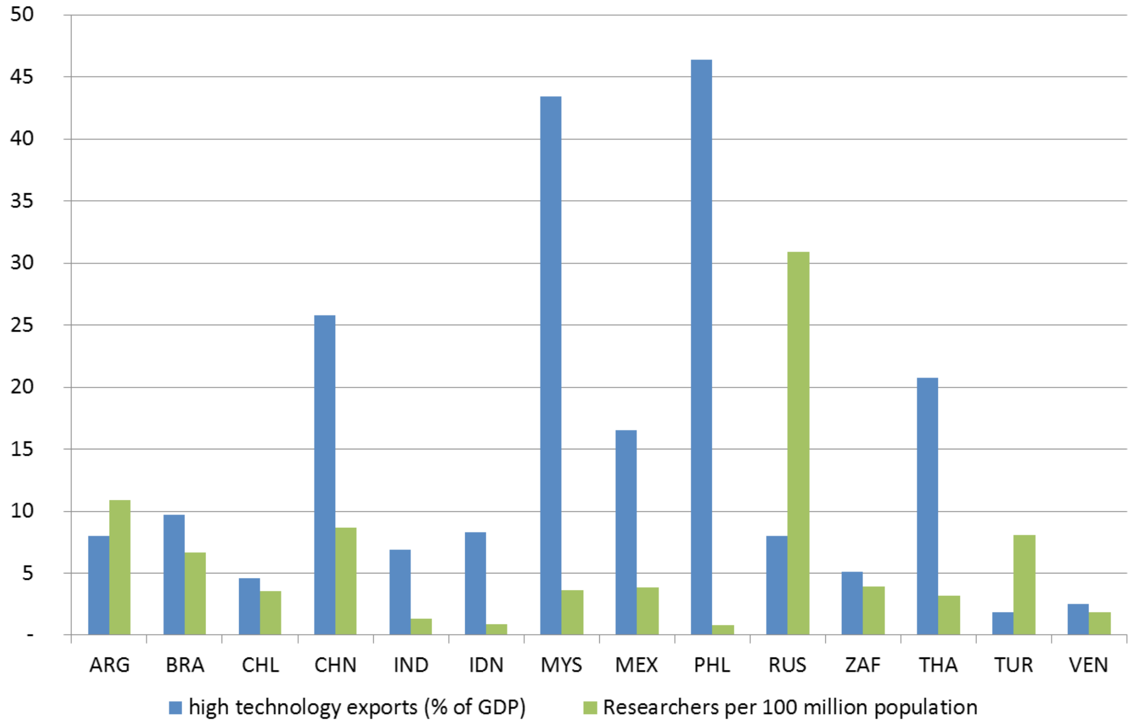
According to the survey's results, Singapore, Taiwan, the Republic of Korea, Malaysia, India and Chile are classified as those countries with the best framework conditions among the MICs analysed. Comparing the results on the basis of both approaches, differences become apparent, e.g. between Malaysia and China. Thus, a careful interpretation is necessary taking the results of both methods into account. The results also show that some MICs, including Malaysia, India and Chile, have increased their innovation capability. Other indicators such as researchers per capita or share of high-tech exports indicate that various MICs are developing their capabilities further.

Figure 16: Results based on survey data from WEF and IMD on the general innovation conditions in MICs



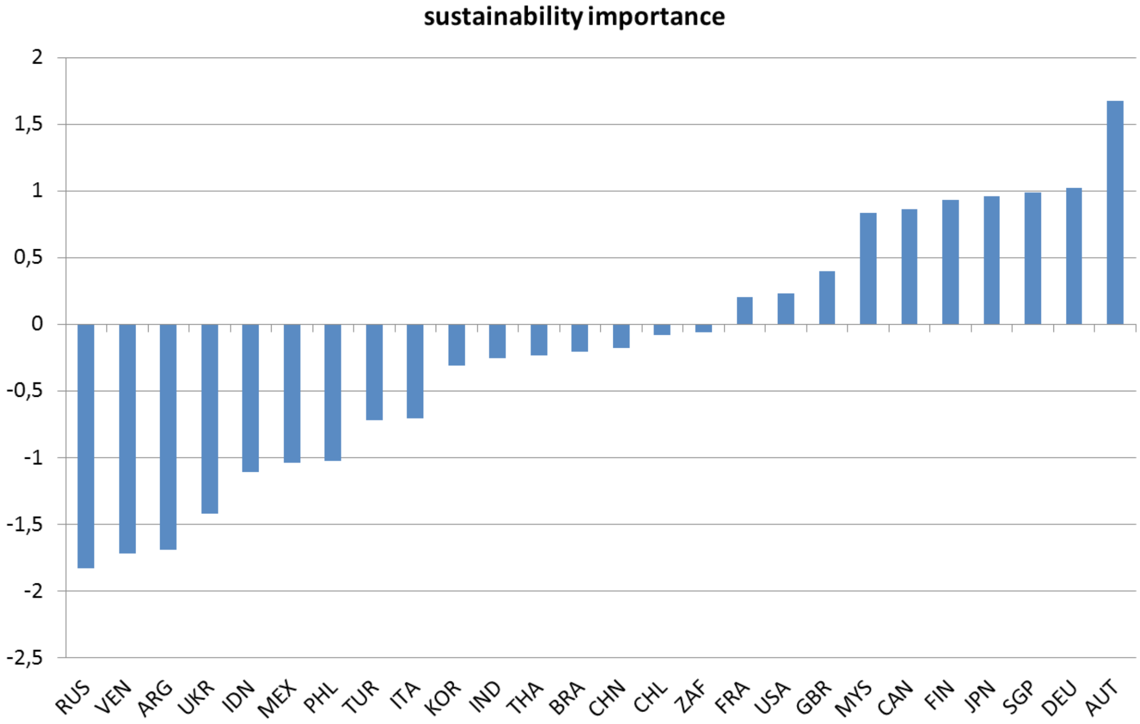
Source: Data from Peukert, 2011 and 2013

Figure 17: Exports of high-tech products in % of GDP and share of researchers per 100 million population in selected MICs



Source: Data from Peukert, 2011

Figure 18: Results based on survey data from the World Economic Forum (WEF) and IMD on the general innovation conditions in MICs



Source: Data from Peukert, 2011

The WEF survey includes questions that refer to the significance of sustainability. This data can be used to create a sustainability index. A high value in this index indicates that society expects manufacturing to address sustainability issues. According to the survey's results, sustainability issues are gaining ground in MICs. There is generally a fairly high complementary between general innovation capability and sustainability concern.

2.2.2 Green technology competences

To analyse green technology competences in MICs, a detailed patent analysis was performed for 15 countries: Argentina, Brazil, Chile, China, India, Indonesia, Malaysia, Mexico, Philippines, the Russian Federation, South Africa, Thailand, Turkey and Venezuela.

The accumulated number of worldwide patents for sustainability technologies of the selected MICs was around 6 percent. There is some variation among the green technologies analysed, however, it is fairly insignificant. There has been a considerable increase in the share of green technologies over the last ten years. Thus, an accumulation of competence is also evident in green technologies. However, the data on specialization indicates that MICs do not place a higher than average emphasis on technologies. Indeed, the development of the Relative Patent Share (RPA), which had been positive in the mid-1990s, indicates that the selected MICs have improved their competences in other areas faster than in green energy technologies relevant for manufacturing.

Table 8 Patent shares and relative patent share (RPA) for 15 MICs

	All energy and climate technologies	Process-specific	Cross-cutting	Industrial electricity managmt.	Renew-ables	CCS
Patent share of selected MICs						
1995-99	2.1%	2.0%	2.4%	1.4%	1.5%	1.9%
2005-09	6.0%	5.1%	6.6%	5.5%	5.8%	5.4%
Relative patent share (RPA) of selected MICs						
1995-99	25.6	23.8	35.9	-14.1	-11.5	16.4
2005-09	-4.0	-14.5	4.3	-14.6	-8.4	-11.1

The following 15 MICs were selected for the analysis: Argentina, Brazil, Chile, China, India, Indonesia, Malaysia, Mexico, Philippines, the Russian Federation, South Africa, Thailand, Turkey and Venezuela

Among the MICs, it is especially Brazil, China, India, the Russian Federation, South Africa, Malaysia and Turkey for which the build-up of competences already shows up in patenting. With the exception of China and India, these countries are heavily specializing on green technologies.

Table 9: Patent shares and relative patent share (RPA) of MICs with advanced competences in green technologies

	BR	CN	IN	RU	ZA	MY	TR
Patent Share	0.4%	2.6%	0.4%	0.9%	0.5%	0.2%	0.3%
Relative Patent Share RPA	33	-37	-56	53	69	48	34

The data shows that MICs have started building up competences in green technologies. However, there are significant differences in innovation competences, which are evident in both general innovation as well as in green technology indicators. Thus, two conclusions can be drawn: countries with a higher degree of competence face the challenge of linking existing knowledge with application in manufacturing. This implies efforts in networking and improving the innovation system. Countries with a lower degree of competence must rely to a greater extent on technology cooperation, especially for process-specific, CCS and industrial power management technologies and capital embodied technology transfers for cross-cutting technologies. It is important for both country groups to integrate industrial and environmental policy in order to give manufacturing the right signals to place greater emphasis on green energy technologies.

3. Productivity impacts of emerging green technologies on the manufacturing sector

This section provides insights into the impacts of EGTs on the manufacturing sector's productivity.

Technological change is often linked to investments. A national economy's production capabilities increase over time due to growth and the renewal of capital stock. However, environmental innovation investments can crowd out other productive investments. Under the assumption of a constant total investment volume, the following two cases are conceivable:

- In the first case, it is assumed that environmental technologies do not show any productive impact. Thus, the increase in productivity is lower compared to the development in which all investments are used for productive technologies ("technological crowding out").
- In the second case, it is assumed that environmental innovations also have a productive character. This effect occurs, for example, if the environmental technologies represent new efficient production technologies that replace older production technologies burdened with higher emissions and lower productivity. The crowding out of investments with productive effects derived under the ceteris paribus condition of a constant investment volume is then alleviated, or, in an extreme case, does not occur at all.

The hypothesis of a non-productive effect of investments in environmental protection is probably valid for end-of-pipe solutions which are added on to the production systems and tended to dominate environmental protection in the 1970s and 80s in OECD countries. It seems plausible that investments which directly affect production (production-integrated environmental protection), and which have become more important over time, have more productivity-increasing effects than end-of-pipe systems.

The assumption of a constant investment volume can be abandoned if an increase in the investment volume is assumed. Accordingly, if environmental investments have a productive character, this is tantamount to a "technological crowding in" and an increased modernization of the national economy. This induces additional investments in new, more productive systems with lower emissions (Xepapadeas and de Zeeuw, 1999).

Thus, to sum up, the overall effects of eco-innovations on productivity depend on both the direct character of the given eco-innovations and the effects on the volume of investments. Depending on the combinations between these two effects, a continuum from crowding out to crowding in of different investments becomes possible (Table 10).

Table 10: Overall productive impacts of eco-innovations

	No or low productive character of environmental innovation	Productive character of environmental innovation equals "normal" investment
No change in macroeconomic investment volume	Crowding out of productive investment	No effect on macroeconomic productivity
Increase in macroeconomic investment volume	Impact depends on which effect is dominating	Increase in macroeconomic productivity

Source: Fraunhofer ISI

3.1 Add-on versus integrated EGTs

In order to estimate the technology-specific productivity effects of emission-reducing technologies in a bottom-up approach, we use a technology set similar to the one identified for the IIP database. Most of these technologies reduce specific energy demand and, hence, energy-related GHG emissions. In some instances, they reduce GHG emissions through energy substitution (e.g. through natural gas). In other cases, the share of recycled energy-intensive materials is increased. Only the additional effects of such technologies relative to "autonomous technological progress" are of interest. The year 2020 was selected as a time horizon. Considering the reinvestment cycles for technologies, this horizon appears long enough for the implementation of the given reduction potentials to be realistic, at least to some degree. We only consider technologies that are already being applied or that have already been specified and tested in pilot plants or in research laboratories. Hence, mainly diffusion effects are depicted. However, since technological progress beyond the status quo and entirely new technological solutions are not considered, this approach tends to underestimate both the emissions reduction potential and the policy-induced technological progress of energy-intensive processes.

The technologies have been derived from several projects (Fleiter et al., 2013; Wietschel et al., 2010; Eichhammer et al., 2009) based on different criteria, among others:

- Large share in energy consumption and CO_2 emissions of the concerned industrial branches
- Large impact of the savings of the technologies investigated
- Availability for a comparatively rapid diffusion
- Cost efficiency in application

These criteria were evaluated on the basis of expert interviews and modelling exercises.

Table 11: List of the most important technologies of climate protection in industry: process-specific technologies

Technology	Sector	Integration in main process	Importance
Impulse drying	Pulp/Paper	i	+++
Refining at increased rotational speed	Pulp/Paper	i	+++
Increasing use of recycled paper	Pulp/Paper	a	+++
Optimization of sinter process	Iron/Steel	i	+++
Injection of coal/plastics	Iron/Steel	i	++++
Enhanced efficiency of blast furnaces	Iron/Steel	i	++
Waste heat recovery from slag	Iron/Steel	a	+
Converter gas recovery	Iron/Steel	i	+++
Increased steel production in EAFs	Iron/Steel	i	++++
Optimization of EAF	Iron/Steel	i	++++
Hot charging of slabs in mills	Iron/Steel	i	++++
Gas phase process for polyolefin prod.	Chemical	i	+++
Process optimization ammonia	Chemical	i	++++
Optimizing methanol production	Chemical	i	++++
Installation of gas turbines in steam crackers	Chemical	a	++++
Optimizing olefin production	Chemical	i	++++
Chlorine prod. via membrane process	Chemical	i	++++
Membrane reactors	Chemical, Food	i	+++
Improved Hall-Herault electrolysis	Non-Ferrous	i	++++
Alum. scrap recycling with less salt	Non-Ferrous	i	+++
QSL lead production process	Non-Ferrous	i	+++
Regenerative burners	Non-Ferrous	i	++++
Insulation of bottle cleaning	Food	a	++
Infusion mash process	Food	i	++
Biogas from organic waste	Food	a	+++
2-stage cristallization	Food, Chemical	i	++
Permeable radiation walls	Glass, Steel	i	+
Optimized glass furnaces	Glass	i	+

Increased use of cullets	Glass	a	+
Batch preheating	Glass	a	++
Minimization of leak air	Minerals, Glass	i	+
Reducing wall heat losses	Minerals	a	++
Improving clinker coolers	Minerals	i	++
High pressure grinding rolls	Minerals	i	++
Mechanical conveyance of materials	Minerals	a	+
New furnace technology	Minerals	i	+++
Improved control of fuel flow	Minerals	i	+
Fast firing	Minerals	i	++
Tunnel drier	Minerals	i	++
Saving kiln furniture	Minerals	i	+
New brick-making technology	Minerals	i	+

i = integrated; a = additive; + = low; ++ = medium; +++ = high; ++++ = very high;

Table 12: List of the most important technologies of climate protection in industry: cross-cutting technologies

Technology	Integration in main process	Importance
Chokes	a	+
Three band lamps	a	+
Compressed-air production	a	+++
Low emission burners in steam generation	i	++
Combustion with oxygen (instead of air)	i	+++
Absorption refrigeration	i	+
Vapour compression	i	+
Utilization of waste heat	a	+++
Heat integration supported by Pinch analysis	i	++
Membrane processes	i	+++
Evaporative drier	i	+++
Measurement and control in combustion systems	a	++
Process control engineering	a	+++
Cogeneration	a	++++
Discrete electric motors	a	++++
Motors integrated in production technology	i	++++
Reduction of space heat demand (insulation)	a	++++

i = integrated; a = additive; + = low; ++ = medium; +++ = high; ++++ = very high;

It cannot be assumed that all the technologies identified above have the same effect on productivity. Indeed, it can be argued that different types of technologies will lead to different effects: in order to improve productivity, the production process has to be modernized. Thus, it can be assumed that technologies that are an essential part of the core production process itself (process-integrated technologies) are more likely to have an effect on productivity than technologies that are added to the production process (add-on technologies). Furthermore, it can be argued that technologies that are tailored to the needs of a specific process (sector-specific technologies) are more likely to take into account the various opportunities for productivity improvements within that process compared to technologies that were developed for all different kinds of applications, regardless of the specific circumstances (cross-cutting technologies). Thus, the classification of technologies can provide first insights into the likely effects on productivity: if sector-specific, process-integrated technologies are prevalent, positive effects are more likely to occur.

However, even though it has been argued in the past that progress in energy technology will more likely result in industry-specific, integrated technologies, this claim has not yet been empirically validated. An analysis of the most important EGTs reveals whether these technologies are both industry-specific and process-integrated. Therefore, the technologies identified in Table 11 and Table 12 are classified according to:

- Area of application (industry-specific or cross-cutting technology)
- Integration into the industrial core process (integrated or additive processes), and
- Economic importance of the technology within the framework of all technologies considered (very high, high, medium, low).

Among the emission-reducing technologies identified, there are 41 industry-specific technologies (e.g. hot charging of slabs in mills or chlorine production via membrane process) and 17 cross-cutting technologies, such as more efficient lighting. These findings support the hypothesis that industry-specific technologies prevail among the most important energy efficient technologies (Table 13).

Table 13: Number of climate protection technologies in the individual categories

	"integrated"	"add-on"	total
Industry-specific technology	32	9	41
Cross-cutting technology	8	9	17
Total	40	18	58

The predominance of technologies that are integrated into the core process is particularly striking within the class of industry-specific technologies where almost four times as many integrated technologies are applied compared to add-on technologies (32 versus 9). By contrast, this ratio is about one (9 versus 8) among cross-cutting technologies. Overall, more than half of the identified technologies (32 out of 58) are both integrated and industry-specific technologies. For some technologies, a precise distinction between process-integrated and add-on technologies is difficult, and these figures confirm the predominant role of process-integrated technologies.

In summary, the classification of technologies shows that both industry-specific and process-integrated technologies are prevailing. Thus, it is likely that EGTs will have positive effects on productivity.

3.2 Productivity impacts of individual technology types

In this section, we empirically analyse whether EGTs, particularly if they are process-integrated and industry-specific, indeed increase productivity. For this purpose, a first assessment is made about which impact the identified technologies might have on total factor productivity, that is, on output, capital, labour and other resources. Again, a bottom-up approach is used since the new technologies considered will mainly be used in the future and statistical information on these impacts could therefore not be derived. We analyse whether there is a significant difference in productivity between the additional investments for energy efficient technologies in the tax scenario compared to the reference scenario. Total productivity is assumed to increase if the energy efficient technology increases or improves the quality of the output or if, due to technology substitution, an augmentation of the production factors capital, labour or other resources is to be expected.

The estimation of productivity effects was conducted as follows: for each of the 58 EGTs identified, the components used to define total factor productivity were broken down so they could be measured technologically. For example:

- The impacts of the EGT on the amount of output and product quality,
- Impacts on the lifespan of the plants, idle times, process control, flexibility of use, etc.; if, for example, idle times of the production process are reduced by the EGT, the productivity of capital is increased,
- Changes in the necessary work involved (including maintenance, etc.), qualification requirements,
- Changes regarding intermediate products required or raw and auxiliary materials, impacts on the use of other environmental resources (water consumption, emissions to the atmosphere, waste, sewage) in the production process.

The estimates derived here are to be interpreted as additional effects (secondary benefits or costs). All 58 technologies were evaluated with regard to productivity components and classified on a scale with the following grades:

- (clearly) higher/better,
- approximately the same, or
- (clearly) lower/worse

than the reference technology.

The main results of this analysis are summarized in Table 14.

Table 14: Influence of energy efficient technologies on productivity

Influence on productivity	Output	Capital	Labour	Other resources
All technologies				
Increasing	48 %	24 %	21 %	95 %
Approx. the same	52 %	71 %	72 %	5 %
Decreasing	0 %	5 %	7%	0 %
Industry-specific technologies				
Increasing	54 %	22 %	24 %	95 %
Approx. the same	46 %	73 %	71 %	5 %
Decreasing	0 %	5 %	5 %	0 %
Cross-cutting technologies				
Increasing	35 %	29 %	12 %	94 %
Approx. the same	65 %	65 %	76 %	6 %
Decreasing	0 %	6 %	12 %	0 %
Integrated technologies				
Increasing	58 %	28 %	28 %	95 %
Approx. the same	43 %	65 %	70 %	5 %
Decreasing	0 %	8 %	3 %	0 %
Add-on technologies				
Increasing	28 %	17 %	6 %	94 %
Approx. the same	72 %	83 %	78 %	6 %
Decreasing	0%	0%	17 %	0 %
Integrated industry-specific technologies				
Increasing	63 %	25 %	31 %	97 %
Approx. the same	38 %	69 %	66 %	3 %
Decreasing	0 %	6 %	3 %	0 %

The figures in the upper part of the table demonstrate that nearly half the emission-reducing technologies (48 percent) are expected to increase output. The experts believe that more than 20 percent of all technologies contribute towards increasing capital and labour productivity. Almost all technologies (95 per cent) are expected to also improve resource productivity (in addition to energy conservation effects). In the majority of cases, these savings result from the reduction of conventional air emissions (which reduces the use of the environmental resource clean air), and in some cases from additional savings in raw and auxiliary materials. Thus, while specific investments in energy efficient technologies are in general higher, they not only reduce energy consumption and costs, but at the same time also raise the quality of the technologies and tend to increase the productivity of capital, labour and other resources.

The figures in the last part of the table show that the integrated sector-specific technologies have a greater than average effect on productivity. Other distinctions between the different types of technology are shown in the other rows of the table. Combining the findings for all types of technologies, the following conclusions can be made:

- Industry-specific technologies have a greater impact on output and labour than cross-cutting technologies.
- Output, capital and labour are positively affected to a higher extent by integrated technologies than by add-on technologies; with regard to impact on labour, the number of productivity-reducing add-on technologies actually exceeds those that increase productivity, as they often require additional labour for operation and maintenance.
- On average, the positive influence on output is more pronounced among all technology types than the influence on capital and labour.

To sum up, the findings in this section clearly support the hypothesis that EGTs that are process-integrated and industry-specific increase productivity in two cases out of three.

References

Abramovitz, M. (1986). Catching up, Forging Ahead and Falling Behind. Journal of Economic History XLVI/2, June 1986, p385.

Archibugia, D. and Pietrobelli, C. (2003). The globalisation of technology and its implications for developing countries. Windows of opportunity or further burden? Technological Forecasting & Social Change, 70 (2003) 861–883.

Bazilian, M., Welsch, M., Divan, D., Elzinga, D., Strbac, G., Howells, M., Jones, L., Keane, A., Gielen, D., Murthy Balijepalli, V.S.K, Brew-Hammond, A. and Yumkella, K. Smart and Just Grids: Opportunities for sub-Saharan Africa. Imperial College London, 2011.
http://owe.unu-mc.org/3442/Bazilian-et-al_Smart-and-Just-Grid_Feb11.pdf

Bell, M. and Pavitt, K. (1993). Technological Accumulation and Industrial Growth: Contrasts between developed and developing countries, Industrial and Corporate Change, 2 (2), 157-209.

Cohen, W.M. and D.A. Levinthal (1990). Absorptive Capacity: A New Perspective on Learning and Innovation. Administrative Sciences Quarterly 35, 569-596.

Dosi, G. (1982). Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change, Research Policy, 11(3), 147-162.

EEA (2013): Environmental pressures from European consumption and production — A study in integrated environmental and economic analysis, Technical report No 2/2013, European Environment Agency, Copenhagen, 2013.

Eichhammer, W.; Fleiter, T.; Schlomann, B.; Faberi, S.; Fioretto, M.; Piccioni, N.; Lechtenböhmer, S.; Schüring, A. and Resch, G. (2009). Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries: Final Report for the European Commission Directorate-General Energy and Transport. Fraunhofer ISI, Karlsruhe, 2009.
http://ec.europa.eu/energy/efficiency/studies/doc/2009_03_15_esd_efficiency_potentials_final_report.pdf

EU (2008). Communication from the European Commission on the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan, COM(2008) 397 final, Brussels, 16.7.2008.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52008DC0397:EN:NOT

EU (2010). Making sustainable consumption and production a reality, A guide for business and policy makers to Life Cycle Thinking and Assessment, European Union, Brussels, 2010.
http://ec.europa.eu/environment/pubs/pdf/sustainable.pdf

Fagerberg, J. and Godinho, M. (2005). Innovation and Catching-up. In: Fagerberg, J.; Mowery, D.; Nelson, R.(ed.). The Oxford Handbook of Innovation. Oxford: Oxford University Press.

Fleiter, T. and Eichhammer, W. (2012). Energy efficiency in electric motor systems: Technology, saving potentials and policy options for developing countries. Working Paper 11/2011. United Nations Industrial Development Organization UNIDO, Vienna 2012 http://www.unido.org/fileadmin/user_media/Publications/Research_and_statistics/Branch_publications/Research_and_Policy/Files/Working_Papers/2011/WP112011%20Energy%20Efficiency%20in%20Electric%20Motor%20Systems.pdf.

Fleiter, T.; Schlomann, B.; Eichhammer, W. (Ed.) (2013): Energieverbrauch und CO_2-Emissionen industrieller Prozesstechniken - Einsparpotenziale, Hemmnisse und Instrumente. Stuttgart: Fraunhofer Verlag. http://www.verlag.fraunhofer.de/bookshop/buch/Energieverbrauch-und-CO2-Emissionen-industrieller-Prozesstechnologien-Einsparpotenziale-Hemmnisse-und-Instrumente/239044 (in German).

Fraunhofer (2009). Foresight process – new future fields. Study on behalf of the German Federal Ministry of Education and Research. Fraunhofer ISI/Fraunhofer IAO, Karlsruhe 2009.

IEA/Unido (2011). Technology Roadmap Carbon Capture and Storage in Industrial Applications. OECD/International Energy Agency IEA and United Nations Industrial Development Organization UNIDO. Paris 2011.

IEA (2012). *World Energy Outlook 2012*. International Energy Agency OECD/IEA, Paris 2012.

IEA (2013). *World Energy Outlook 2013*. International Energy Agency OECD/IEA, Paris 2013.

Lall, S. (1992). Technological Capabilities and Industrialization, World Development, 20, 165-86.

Lall, S. (1998). Technological capabilities in emerging Asia. Oxford Development Studies 26, 213-243.

Lee, K. and Lim, C. (2001). Technological regimes, catching up, and leapfrogging: findings from the Korean industries. Research Policy 30, 459-483.

Lee, K. and Lim, C. (2005). Emerging digital technology as a window of opportunity and technological leapfrogging: catch up in digital TV by Korean firms. International Journal of Technology Management 29, 40-63.

Malerba, F. and Nelson, R.R. (2008). Catching up: in different sectoral systems, Globelics Working Paper Series No. 08-01.

Nelson, R.R. (2007). The changing institutional requirements for technological and institutional catch up. International Journal of Technological Learning. Innovation and Development 1, 4-12.

Perez, C. (2004). Technological Revolutions, Paradigm Shifts and Socio-Institutional Change. In: Reinert, E. (ed). Globalization, Economic Development and Inequality: An alternative Perspective, Edward Elgar, Cheltenham, UK • Northampton, MA, USA, 2004, pp. 217-242.

Peuckert, J. (2011). Measuring capabilities of emerging countries for catching-up through sustainability. Int. J. Technology and Globalisation 5 (3/4), pp. 190-211.

Peuckert, J. (2013). Developing Systems of Environmental Innovation in Emerging Economies. Challenging the Environmental Kuznets Curve. Dissertation. http://opus4.kobv.de/opus4-tuberlin/frontdoor/index/index/docId/3690

Rasiah, R. (2008). Conclusions and implications: The role of multinationals in technological capa-bility building and localization in Asia. Asia Pacific Business Review 14, 165-169.

Tukker, A.; Butter, M. (2007). Governance of sustainable transitions: about the 4(0) ways to change the world. Journal of Cleaner Production 15 (2007), p. 94-103.

UNEP (2011). Paving the Way for Sustainable Consumption and Production. The Marrakech Process Progress Report. United Nations Environment Programme, 2011. http://www.unep.fr/scp/marrakech/ and http://www.unep.fr/scp/marrakech/pdf/Marrakech%20Process%20Progress%20Report%20FINAL.pdf

UNEP (2012). *The Emissions Gap Report 2012. A UNEP Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi 2012.

Walz, R.; Schleich, J. and Ragwitz, M. (2008). How regulation influences innovation: an indicator based approach for the case of renewable energy technologies. Paper presented in the VI Globelics Conference at Mexico City, September 22-24 2008, Fraunhofer Working Paper, Karlsruhe 2008.

WEF (2008). The Global Competitiveness Report 2008-2009: Full data edition. World Economic Forum, Geneva, 2008.

Wietschel, M., Arens, M., Dötsch, Chr., Herkel, S. Krewitt, W., Markewitz, P., Möst, D. and Scheufen, M. (2010). Energietechnologien 2050 - Schwerpunkte für Forschung und Entwicklung. Technologienbericht. ISI-Schriftenreihe Innovationspotenziale. Hrsg.: Fraunhofer ISI, Karlsruhe, 2010 (in German). http://www.verlag.fraunhofer.de/bookshop/artikel.jsp?v=233344 and http://www.energietechnologien2050.de/wDefault_4/index.php

World Bank: Science & Technology data: Research and development expenditure (% of GDP). http://data.worldbank.org/topic/science-and-technology (interrogated November 2013). Xepapadeas, A. and de Zeeuw, A. (1999). Environmental Policy and Competitiveness: The Porter Hypothesis and the Composition of Capital. Journal of Environmental Economics and Management, Elsevier, vol. 37(2), 165-182.

Annex: Important Emerging Green Technologies (EGTs) for process-specific and cross-cutting industrial technologies

Iron/Steel production

Important energy saving and GHG reduction measures are listed in the following table.

Coke Dry Quenching	BOF Bottom Stirring	Coke Stabilization Quenching
Coal Moisture Control	BOF Heat and Gas Recovery	Improved Ladle Preheating
Non-Recovery Coke Ovens	Emissions Optimized Sintering	Thin Slab Casting - Near Net Shape Casting
Pulverized Coal Injection	Waste Heat Recovery in Sinter Plant	Variable Frequency Drives on Ventilation Fans
Natural Gas Injection	Additional Use of Coke Oven Gas	Direct Rolling (Integrated Casting and Rolling)
Top Pressure Recovery Turbines	Hot DRI/HBI Charging to EAF	Endless Strip Production (ESP)
Increased Blast Furnace Top Pressure (> 0.5 Bar Gauge)	Post Combustion of EAF Flue Gas	Hisarna
Improved Recovery of Blast Furnace Gas	Direct Current (DC) Arc Furnace	Variable Speed Drives on Flue Gas Control, Pumps and Fans
Blast Furnace Process Control	Optimal Charge Calculation in EAF	Strip Casting – Castrip® Process
Plastic Waste Injection	Foamy Slag Practices	Software Tools to Boost Steam System Efficiency
Heat Recuperation from Hot Blast Stoves	Scrap Preheating	Coke Stabilization Quenching

For a wider list of technologies & measures and details, please follow the link under the source provided.

Source: http://www.ietd.iipnetwork.org/content/iron-and-steel

Cement production

Important energy saving and GHG reduction measures are listed in the following table.

Dry Kilns with Multistage Pre-heaters and Pre-calcination	Waste Oil and Oil Sludge as Fuel	Cement grinding with Horomill
Conversion of Long Dry Kilns to Preheater/Precalciner Kilns	Used Tyre Gasification	Emerging Grinding Technologies
Addition of Pre-Calcination to Kilns with Preheaters	Use of EAF slag - CemStar®	High Efficiency Fans for Preheaters
Process Control and Optimization in Clinker Making	Limestone Portland Cement	Variable Speed Drive and High-Efficiency Fans for Dust Collection
Waste Heat Recovery for Power Generation	Carbide Slag as Raw Material	Efficient kiln drives
Replacing Vertical Shaft Kilns	Cement with Pozzolana	High-Pressure Roller Press
Kiln Shell Heat Loss Reduction	Gravity Type Blending Silos	Geopolymer Cements
Combustion System Improvements	Bucket Elevators for Kiln Feed	Preventive Maintenance
Proper Sealing and Seal Replacement	High-Efficiency Roller Mills	Variable Frequency Drive for Clinker Cooler Fans
Low Pressure Drop Cyclones for Suspension Preheaters	High-efficiency Separator/ Classifier for Coal Grinding	High efficiency motors & drives
Conversion to Reciprocating Grate Coolers	Vertical Roller Mills for Finish Grinding	Variable Speed Drives
Revolving disc clinker cooler	High pressure roller press as pre-grinding to ball mill	Improved Burnability Using Mineralizers
Optimizing Fuel Properties		Cement grinding with Horomill
Refuse Derived Fuel (RDF) Co-processing		Emerging Grinding Technologies

Post-Combustion CO_2 Capture Using Absorption Technologies or Membrane Processes will be mentioned under CCS

For a wider list of technologies & measures and details, please follow the link under the source provided.

Source: http://www.ietd.iipnetwork.org/content/cement

Paper production

Important energy saving and GHG reduction measures are listed in the following table.

Combined Heat and Power (CHP) Generation	Continuous Digester	Optimization of Water Removal in Press Section
Increased Use of Recycled Pulp	Batch Digester Modifications	Waste Heat Recovery from Paper Drying
Advanced Thermo Mechanical Pulping (ATMP)	Digester Blow/Flash Heat Recovery	Condebelt Drying
RTS Pulping	Black Liquor Solids Concentration	Using Drum Pulpers
Improvements in Chemi-Thermomechanical Pulping (CTMP)	High Temperature Odor-Free Recovery Boiler	Dry Debarking
Low Consistency Refining (LCR)	Black Liquor Gasification	Replacing Pneumatic Conveyors with Belt Conveyors
Heat Recovery in Thermo-mechanical Pulping	Optimization of Water Removal in Forming	

For a wider list of technologies & measures and details, please follow the link under the source provided.

Source: http://www.ietd.iipnetwork.org/content/paper

Motor systems

Important energy saving and GHG reduction measures are listed in the following table.

High-Efficiency Motors	High Efficiency Motors in Pump Systems	Pressure Profile Optimization - System Controls
Installing Zero-Loss Condenser Drains	Predictive Maintenance Programme	
Variable Speed Drives for Pump Systems	Variable Frequency Drives	

For a wider list of technologies and measures and details, please follow the link under the source provided.

Source: http://www.ietd.iipnetwork.org/content/motor-systems

Printed in Austria
V.1-100-October 2014

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna International Centre · P.O. Box 300 9 · 1400 Vienna · Austria
Tel.: (+43-1) 26026-0 · E-mail: info@unido.org
www.unido.org