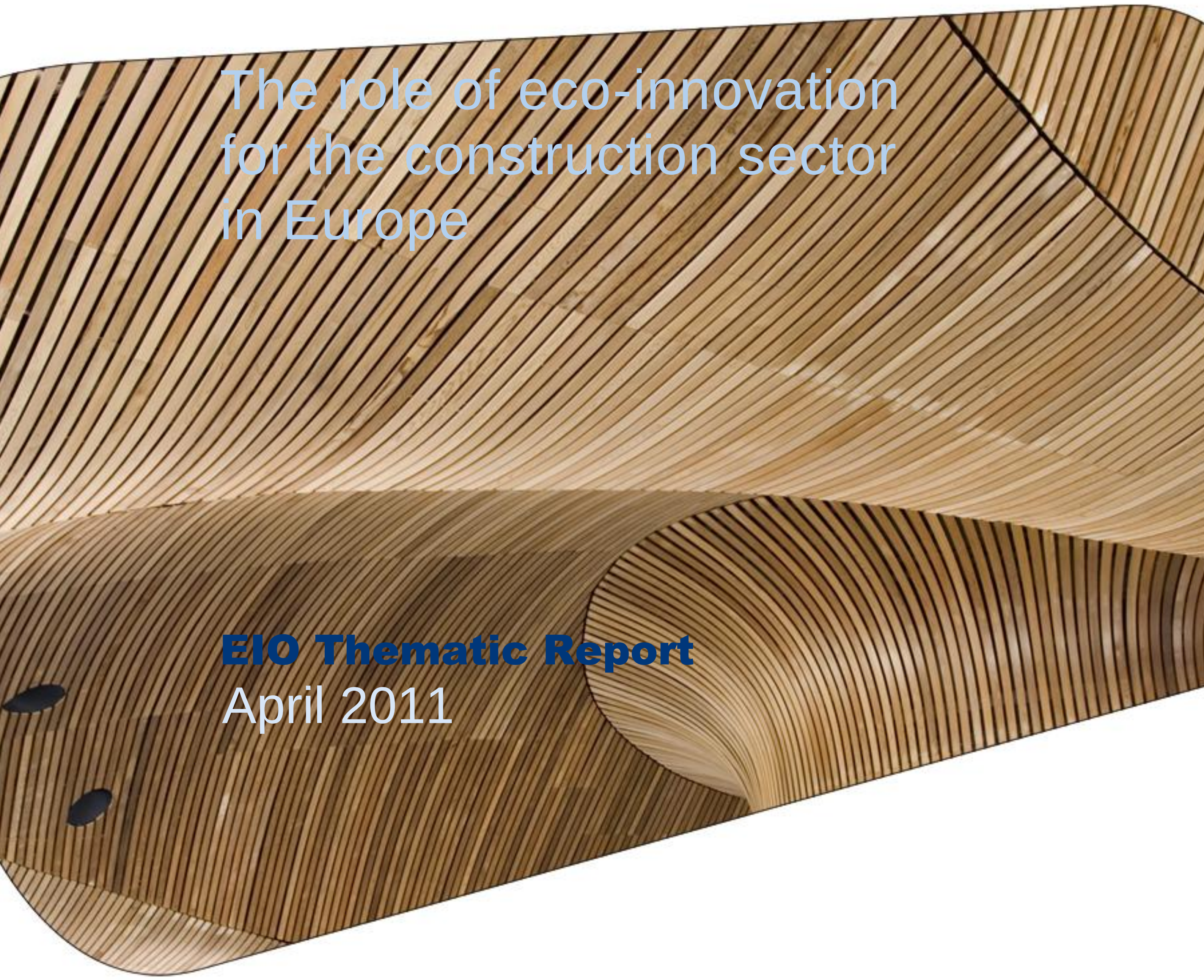
Resource-efficient construction



The role of eco-innovation for the construction sector in Europe

EIO Thematic Report

April 2011

Eco-Innovation Observatory

The Eco-Innovation Observatory functions as a platform for the structured collection and analysis of an extensive range of eco-innovation information, gathered from across the European Union and key economic regions around the globe, providing a much-needed integrated information source on eco-innovation for companies and innovation service providers, as well as providing a solid decision-making basis for policy development.

The Observatory approaches eco-innovation as a persuasive phenomenon present in all economic sectors and therefore relevant for all types of innovation, defining eco-innovation as:

"Eco-innovation is any innovation that reduces the use of natural resources and decreases the release of harmful substances across the whole life-cycle".

To find out more, visit **www.eco-innovation.eu**

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A note to readers
A number of companies are presented as illustrative examples of eco-innovation in this report. The EIO does not endorse these companies and is not an exhaustive source of information on innovation at the company level.

1 | Resource-efficient construction: new horizons for eco-innovation

Housing and construction are basic features of human life and European culture. From the ancient Greeks and Romans to medieval cities and finally to modern architecture, one can hardly imagine any other basic feature that generates comparable passion and attracts the attention of so many people. Yet, construction and housing have come under scrutiny, be it for having been one driver of the worldwide collapse of financial markets or be it for contributing to the greenhouse effect. The following report addresses a new topic: resource-efficient construction.

Resource efficiency basically means using fewer natural resources to achieve the same or improved output; it embodies the concept of achieving "more from less". For construction, it not only means using resources more effectively to build or renovate homes, buildings, and infrastructures, but also refers to reducing the amount of resources needed to operate the built object. It refers to primary materials and energy--including both fossil and renewable resources. While this report will touch on energy efficiency, it will mostly focus on material efficiency, implying a more effective use of concrete, steel, metals, asphalt, insulation, pipes, wires, wood, plastic, and chemical products, to mention some examples.

The construction sector is the largest consumer of raw materials in the EU; construction and demolition activities also account for about 33% of waste generated annually (EEA 2010). Clearly there is an environmental incentive to revamp the resource-intensive and wasteful construction sector: reducing resource use and re-using waste more effectively would significantly reduce the Total Material Requirement (TMR) of European societies. At the same time, there is also an economic incentive as using less material input can substantially lower costs.

However, while 'sustainable construction' is rapidly becoming a buzz word in the European Union, much of the focus so far has been on energy issues. At the European level, legislation (e.g. the Energy Performance of Buildings Directive) and innovation efforts (e.g. the Lead Market Initiative for sustainable construction) related to sustainable construction are largely focused on energy, especially on improving energy efficiency and using more renewable energies. Efforts to this end are undoubtedly important, especially considering that buildings account for the largest share of EU final energy consumption (42%) and produce about 35% of all greenhouse emissions (EU 2007). However, this focus on energy and emissions is too narrow. Restricting the debate just to emissions could mean that innovation efforts just focus on ways to produce energy more "sustainably", missing out on innovation to lower energy demands over the long term. In the same way, focusing only on lowering energy demands may mean that trade-offs with material resources are not taken into account; for example, insulation can lower energy requirements, but what type of insulation offers the best performance (also considering material intensity and recycling options), and what are the alternatives to the conventional construction system? A more comprehensive approach to building and renovation is needed; one that looks at how both energy and materials can be efficiently used, and considers the trade-offs between them. Widening the perspective to resource efficiency would better prepare the construction sector for the challenges of the 21st century and contribute to better attainment of environmental goals.

This report explores how eco-innovation can contribute to resource efficiency in the construction sector. It argues that resource efficiency is the systemic approach needed to frame discussions about sustainable construction because this perspective makes economic, social and environmental sense. Based on survey analysis, it shows that resource-efficiency eco-innovation efforts need to be stepped-up across the EU. Indicative examples of existing innovative practices, processes and products show what types of eco-innovation are relevant to this discussion. While many of these examples focus on buildings and homes, also taking infrastructure into account is vital to the type of comprehensive approach needed for enabling a sustainable construction sector over the long term.

The purpose of the report is not to provide in-depth, detailed analysis of specific processes in the construction sector, but to present the need for thinking about sustainable construction in comprehensive terms. To this end, construction experts from across the EU were asked about their opinions toward the grand challenges and barriers and drivers facing the construction sector today and in the future. Expert judgment reveals that preparing for these grand challenges (climate change, resource constraints, etc.) requires dedicated and well-thought-out innovations today. Moreover, visions of a thriving and resource-efficient construction sector reveal the diversity and magnitude of innovations which could be introduced by companies and implemented by citizens in the transition toward sustainable economies.

Ultimately, resource-efficient eco-innovation is not just about building more efficiently (e.g. by reducing waste), but also about finding new and better ways to achieve the same or even higher functionality—with less resource-intensive materials, new technologies and new approaches to design. And of course, aesthetics remains essential.

2 | Assessing current trends: the relevance for eco-innovation

The construction sector boomed in many European countries at the beginning of this century—as evident by both the market share (up to 20% of GDP) and share of material consumption (70% of DMC) in extreme cases. The recent financial crisis has changed the trend. The question is whether, as things start to turn around, the unsustainable building practices of the past will be repeated, or whether the crisis has marked a turning point for European construction, focused more on renovation and added value.

The following chapter examines the economic and environmental relevance of the construction sector, arguing that a systems perspective is needed to achieve the types of innovations needed for a more stable and long-lasting industry both economically and environmentally. It takes a look at the types and intensity of eco-innovation already occurring in the construction sector—based on an EU-wide survey (Eurobarometer, EC 2011)—and concludes that activities undertaken so far have not been enough to achieve the level of change needed.

2.1 | Economic relevance

Construction is one of the largest markets worldwide. In most European countries it contributes approximately 10% to GDP (Eurostat 2011a). Perhaps one of the most important structural changes of the previous few years is the convergence of the construction output among EU member states. Spain, Portugal and Ireland were performing at around 20% of their GDPs in 2004, but were forced to shrink their construction activity down to average levels due to the recession (Euroconstruct). Construction is of overwhelming importance for employment in most countries; the sector contributes 7.22% to overall employment in the EU (Eurostat 2011a).

2.1.1 | Market size and trends

2009 was the worst year for construction in this decade. Total construction output fell by over 8%, much more than the average economic downturn of 5.65% (Eurostat 2011a). According to the Euroconstruct conference of December 2010, a further shrinkage of -3.3% on average is forecasted for 2010[1]. The difficulties of high public deficits in Ireland, Spain and Portugal impose significant welfare measures, cuts in housing construction and public investments. Moreover, a sluggish domestic demand, the revision of public

[1] *We wish to thank Erich Gluch from the IFO-Institute Munich for useful information on the issue.*

[2] *See EIO's thematic report on water.*

investments, the avoidance of long-term commitments and the reassessment of ongoing public projects led to lower performance in many other countries this year. In the meantime, those performing relatively well (Finland, Germany, Poland, United Kingdom, Sweden, Switzerland) benefit from growing domestic confidence and demand.

However, according to the new country-by-country analysis done by the 19 Euroconstruct members, 2011 will probably become a turn-around year. A slight decline of about -0.1% on average consolidates construction markets on the level of the previous year. After three years of recession, construction market players have had time to adapt to new conditions. Recovery is forecasted to be variable, however, with some countries remaining in a depressed state. Activity is predicted to be significantly stronger in Central and Eastern Europe than in Western Europe.

According to the forecasts, 60% of the residential output will come from renovation activity in 2013 – certainly a key area for this Thematic Report.

Non-residential construction is forecasted to see the slowest recovery; the output in 2013 will hardly reach the level of the early 2000s. Publicly financed health, school construction and renovation might suffer if no action is taken. Small signs of recovery can be discovered in the commercial area. Among the three sub-sectors, civil engineering proved to be the most stable during the crisis years and after. The overweight sub-sector of transport infrastructure will slacken and a shift towards energy and water construction2 will be experienced. The potential threat of public expenditure cuts will likely influence the infrastructure in the Czech Republic, Ireland, Spain and the UK negatively. The previously most severely hit residential construction sub-sector will hardly recover from its poor position - nevertheless a growth of 1.9% in 2011 is expected. In 2013, output of the residential sector is not predicted to reach the performance of 2008.

"These structural changes direct individual countries and construction activity itself towards a more balanced, less vulnerable sector in the European economy. Actually experienced demand and musts in the near-future (efficient energy consumption, upgrading the built environment, housing replacement, new health utilities for the ageing population, lowering CO_2 emission buildings) are expected to force construction to turn into a higher value and higher quality performing sector. This will require new products, new technologies and new skills."

- Anna Gáspár, Senior Advisor of Buildecon and the Hungarian Euroconstruct

Being a vital sector in the European economy, the ten-year-period between 2004 and 2013 will show important structural changes within the construction sector. Most importantly, one will likely witnesses a shift from new construction towards renovation and modernisation, with practically 50% of the total construction output being renovation. This trend – however variable it is across member states – should encourage activities towards resource efficiency.

[2] *See EIO's thematic report on water.*

2.1.2 | Construction and the financial crisis

The financial crisis in 2008 has hit all economies worldwide with unforeseeable consequences. China and other Asian emerging economies have seemed to recover rather quickly and have managed to maintain positive growth rates. Europe, the US and most developing countries are still struggling with secondary effects of the financial crisis, namely with high public deficits.

It is fairly difficult to conclusively determine why all this could happen. Perhaps most instructive is a letter written in July 2009 by leading members of the British Academy to the Queen as a response to her question as to why nobody had noticed that the credit crunch was on its way. It summarizes a „failure of the collective imagination“ of many people, with other words: a lack of integrated system assessment. From today's experience, many warning signals were overlooked: the rise of bubbles in stock markets and housing markets, especially in the US but also in countries such as Ireland, Greece and Spain. After the dot-com bubble burst in 2000, a self-fuelling new bubble occurred in housing markets that was triggered by factors such as excessive speculation, overly optimistic expectations, easy access to credits, and financial instruments hiding the accountability of investors. This cannot be seen as a total surprise: Housing markets show features of long-term consistency and mean reverting, however, short-term prices may massively depart and bubbles have occurred occasionally (Japan in the early nineties, Sweden in the mid nineties). Indeed, the international consequences have been far more severe this time. International macro-economics may have played a role because high liquidity in some emerging economies was seeking investment opportunities on US markets and elsewhere. System dynamics also have been fuelled by bottom-up factors such as rising fuel prices that have led to higher prices for commuting people, a phenomenon that is especially relevant for sub-urban areas. The overshooting of these factors seem to have been one key ingredient for declining economic outputs worldwide after 2008.

Housing, housing finance, risk assessment and monetary policy are thus closely interlinked and interact with the rest of the economy and international markets (see e.g. Tichy 2010). Resource-efficient construction can be seen as a risk-minimizing strategy that gives buildings a higher value while lowering environmental pressure (Lemken 2008, v. Weizsäcker et al. 2009, WBCSD 2010). Indeed, it needs to be encompassed by proper economic policies and a regulation that induces eco-innovation in general.

2.2 | Environmental relevance

The construction sector is associated with a number of environmental impacts. A plethora of workshops, platforms, and literature have emerged recently examining various aspects of sustainable construction. For instance, Chowdhury et al. (2010) focus on materials for road construction, Ding (2007) on assessment tools, Ortiz et al. (2010) on composite walls, among many, many others.

The EIO takes a step back to look at the overarching system. As regards construction, continued expansion of the built-environment not only means the need for land (causing deforestation, covering fertile cropland, diverting water, etc.), but also requires materials and energy, as well as causes emissions. For this reason, the following section focuses more generally on material consumption, argues for a more systems orientated accounting of CO_2 emissions that better reflects the dynamics between old and new buildings, and finally takes a look at the overall trends in the built environment.

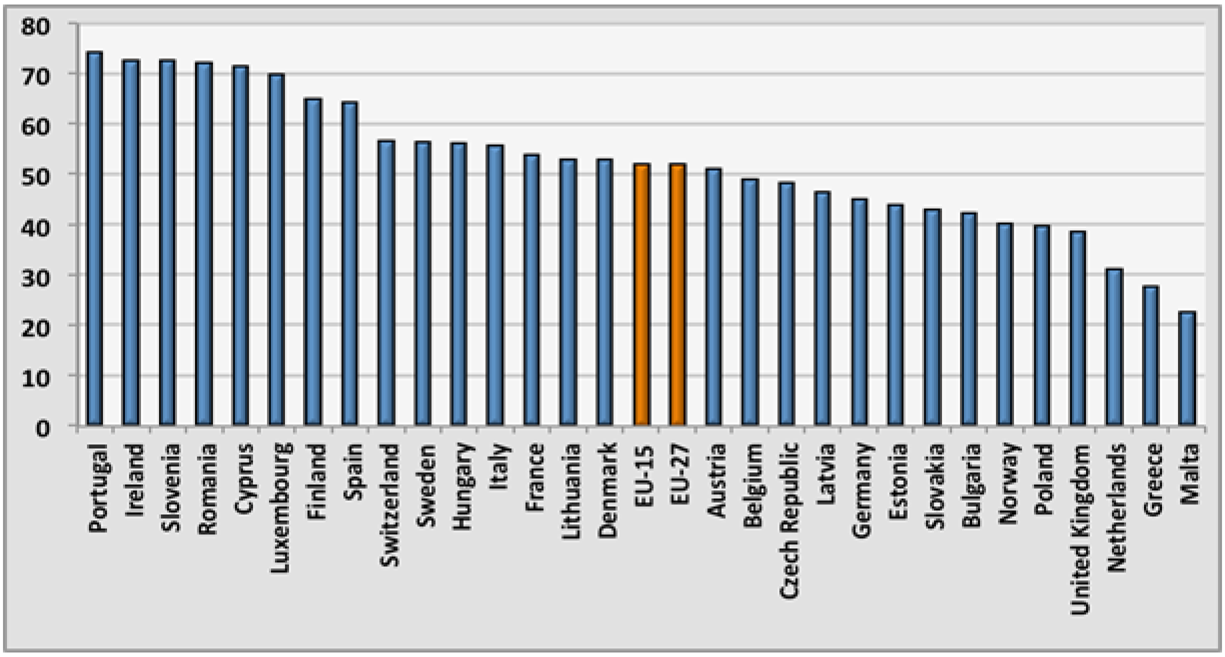
2.2.1 | The material requirements of construction

It is the overconsumption of resources that is contributing to the one of the greatest environmental challenges of the 21st century. While this consumption does not manifest itself as a straightforward and visible problem, like pollution or toxicity, it is contributing to enhanced environmental pressure and problem shifting (for example shifting the negative impacts of production abroad so that they are not seen by consumers in consumption countries). The planet has reached its tipping points for a number of environmental systems, beyond which the fear of overshoot and collapse becomes relevant (see for instance Rockström et al. 2009, EEA 2010, Meadows et al. 2004). As the biggest consumer of resources, the construction sector is critical to this trend, and there is a large potential to reduce material consumption through resource-efficient construction.

The share of minerals of the domestic material consumption (DMC) of the EU-27 is around 52%. While a small proportion of these minerals may not be used in the construction sector, the overwhelming majority are, making it a rough proxy for the material consumption of the construction sector. As evident in Figure 2.1, this share differs widely among European countries. From over 70% for instance in Portugal and Ireland to around 30% in the Netherlands and Greece.

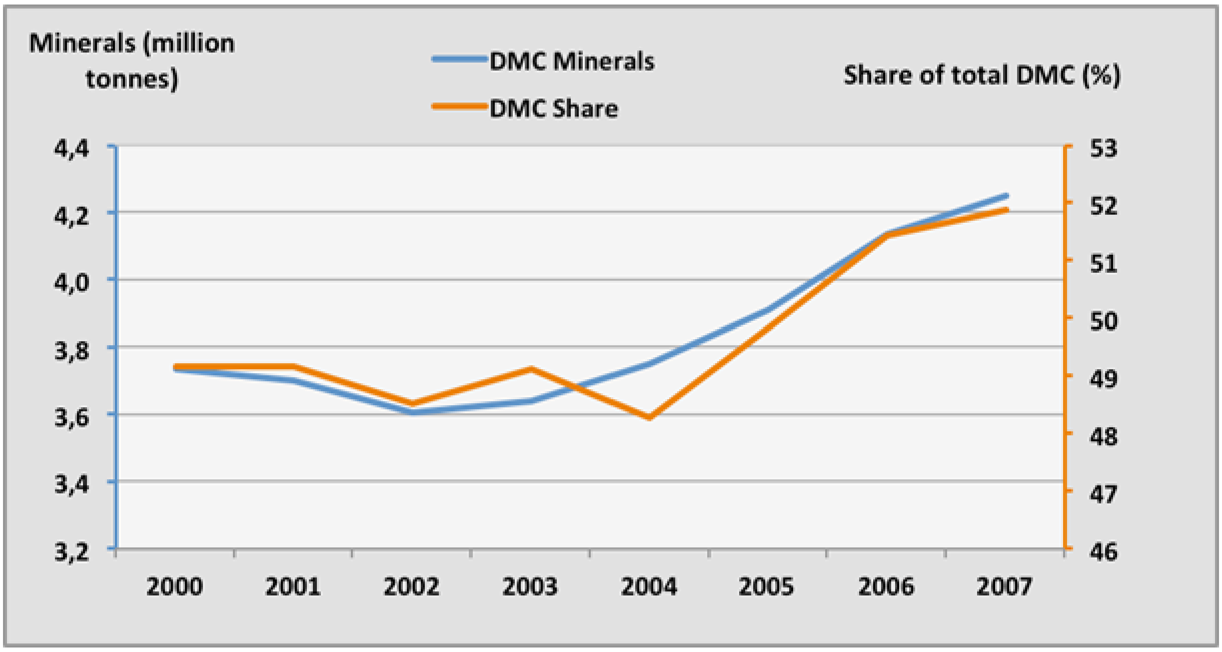
Between 2000 and 2007 this share has risen in the EU-27 (from around 49 to 52% of the DMC; see Figure 2.2). The trends also differ widely among countries. For instance, comparing the years 2000 and 2007, the total amount of minerals consumption has decreased in Italy, Germany, the Netherlands and the United Kingdom, whereas it has increased significantly in Spain (consuming 31% more in 2007 than in 2000), Ireland (consuming 40% more) Greece (consuming 42% more) and Bulgaria, Lithuania, Romania, Estonia and Latvia (all with increases over 50%).

Figure 2.1 | Share of minerals in the Domestic Material Consumption of European countries in 2007



Source: based on data from Eurostat 2010b

Figure 2.2 | Total and share of DMC minerals in the EU, 2000-2007



Source: based on data from Eurostat 2010b

Unfortunately, the data does not yet extend to 2008, and is thus unable to reflect the mineral consumption changes induced by the financial crisis.

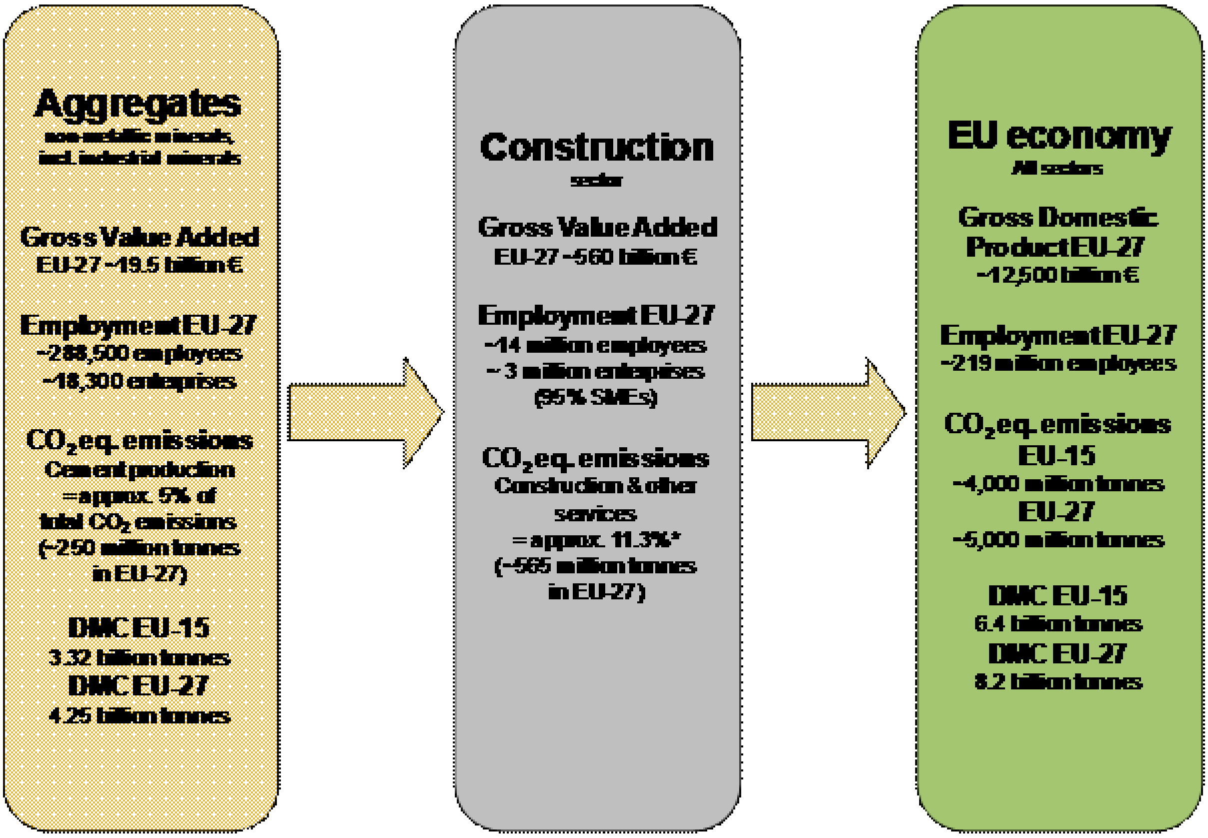
Aggregates are an example of a material intensive construction material. They provide an excellent illustrative example as while they may not contribute to highly visible environmental *problems* (like direct pollution), they do contribute heavily to environmental *pressures.* Aggregates are granular materials, like sand, gravel and crushed rock. They are, for instance, the main ingredient of ready-mixed concrete and comprise the overwhelming majority of construction minerals (see e.g. BGS 2010). In 2009, the total European aggregates demand was around 3 billion tonnes, produced mainly by SMEs on 22,000 sites across Europe (UEPG 2010). The construction of a typical new home uses up to 400 tonnes of aggregates while the construction of 1 km of motorway uses up to 30,000 tonnes (Bleischwitz and Bahn-Walkowiak 2007).

Across the life-cycle, environmental *problems* are present, especially at the extraction phase (land use change for mines and quarries, changed groundwater levels, ect.), but environmental *pressures* are also highly relevant. Primarily, the extraction of aggregates contributes to resource depletion and may be a relevant factor hindering the absolute decoupling of GDP from the DMC (see for instance van der Voet et al. 2005 and Bleischwitz and Bahn-Walkowiak 2007). In their use phase, aggregates are used to make concrete, releasing high amounts of CO_2 (see Box 2.1) and then contribute to the sealing of fertile land to extend the built environment (see section 2.2.3). At the end of their use, aggregates are disposed or recycled. Construction and demolition waste (C & DW) is currently extensive, comprising 33% of waste generated annually in the EU (EEA 2010). Redevelopment and demolition of buildings generates large quantities of materials that can be recycled (Geibler et al. 2010). In 2008, UEPG data show that 216 m tonnes were recycled. This corresponds to just 40% of total available C & DW, but in turn equates to only about 6% of the total European aggregates demand for that year. Aggregate supply predominately comes from primary sources, and demand is expected to increase to meet the growing physical needs of Central and South-Eastern Europe (UEPG 2010).

In a case study for the city of Zurich, Switzerland, it was found that about 80% of deconstruction material is recycled (AWEL 2010). Most of this material is, however, used as an inferior building material. The other 20% is disposed of in landfills. Currently, all types of recycled concretes have slightly worse attributes than concretes made from primary gravel. However, if this is properly accounted for in the planning of a construction project, even recycled concretes can be used in structurally relevant parts of a building. Nevertheless, this would require some rethinking in the building industry. Therefore, the AWEL has created the Swiss information initiative “Kies für Generationen” (gravel for generations; own interpretation). The purpose of this initiative is to spread knowledge on the use of recycled materials and to enhance the information exchange between science and industry (AWEL, 2010).

Altogether, there seems to be a high potential for eco-innovation for finding better ways to recycle aggregates (for instance in urban mining, see 3.2.2) with a view to use it as input in new value adding goods or contributing to new ways of reducing the need for aggregates through substitution or resource-light construction (see section 3.1.2).

Figure 2.3 | Comparison of Various Variables Indicating the Proportions of the EU Economy, the Construction Sector and Aggregates

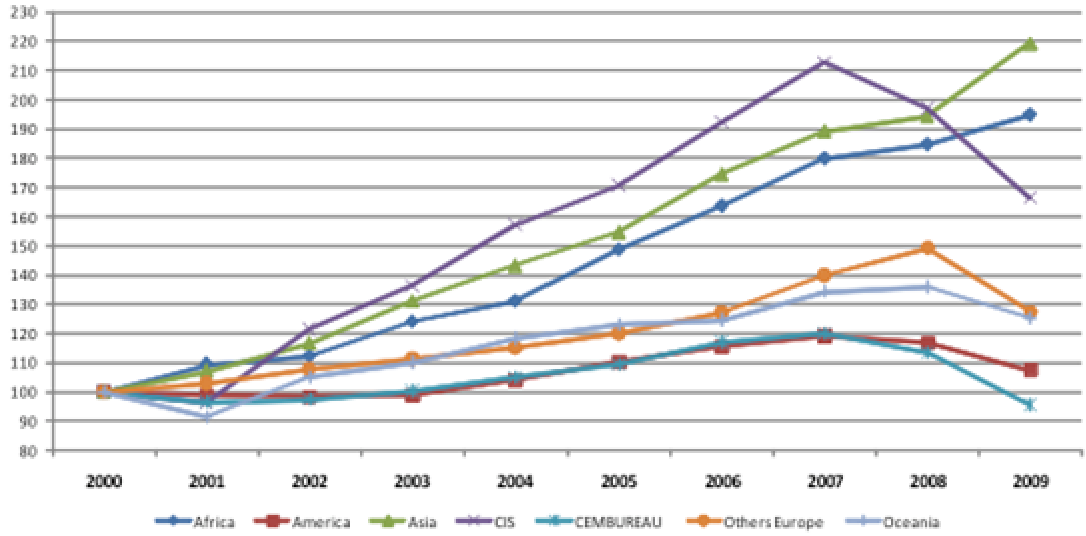


*Sources: Eurostat 2010b, c; 2011b, c; Eurostat and EC 2010 (compiled by Bahn-Walkowiak/Wuppertal Institute 2011); all data for 2007, except * data for 2006*

Box 1 Snapshot of cement production

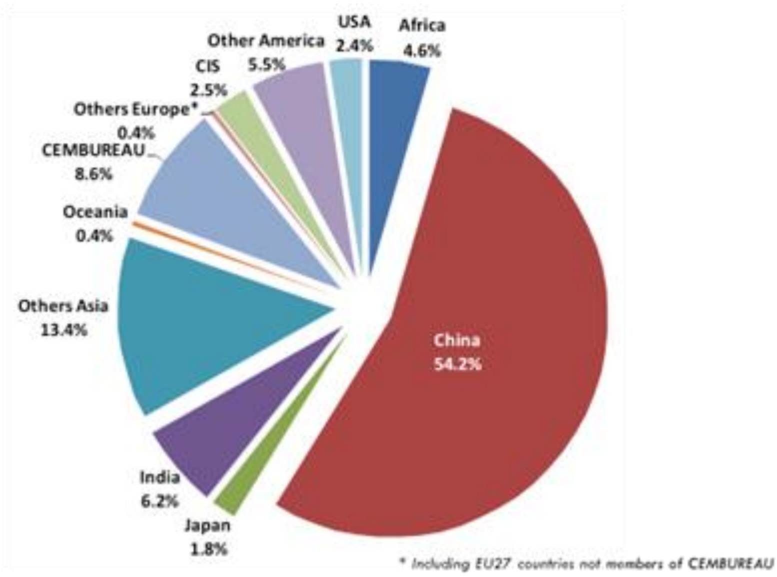
Cement and concrete are the most relevant construction materials today. Their strength and durability make them suitable to both roads and buildings. The global production of cement is approximately 2.5 billion tons per year and it is rapidly increasing. China is the world's largest producer of cement (producing about 54% of world production in 2009) (Cembureau 2010).

Figure 2.4 | Development of World Cement Production by Region



Source Cembureau 2010 (CSI = Cement Sustainability Initiative) Note: Index: 2000=100

Figure 2.5 | World Cement Production by Region, 2009



Source Cembureau 2010

Most cement that is produced today is Portland cement, a calcium silicate cement, based on the natural raw materials limestone and clay (or marl as a natural mixture of both). The advantages of Portland cement are that it is readily available and uses cheap raw materials, as well as its properties; for instance the high protection level against corrosion of reinforcement steel. Disadvantages include high process temperature (1850°C kiln temperature), energy consumption and large direct CO_2-emissions. The cement industry produces about 5% of anthropogenic CO_2 emissions globally; about 60% stemming from the chemical process and 40% from the burning of fuel required in the process and from indirect emissions (WBCSD 2009).

Different technologies for the production of Portland cement are used today. In general they can be divided between wet and dry processes. Both processes are based on the same raw materials, but the environmental impacts vary, especially the energy consumption. The most efficient production process is the dry process; it uses a rotary kiln and multi stage preheating and is common to Western Europe. Wet process technology has significantly lower efficiency; it is still used especially in Asia and in older plants. An exchange of these older plants with up-to-date technology would lead to a significant reduction in energy consumption and CO_2-emissions. Additional CO_2 reductions could be realized through the substitution of coal with secondary fuels, like used tyres.

Beside optimization strategies for the kiln, significant enhancement has been made in the grounding of cement clinker. Formerly used ball-mills have been partly substituted by more efficient roller-mills. But they still have some disadvantages, especially related to particle size distribution and the water demand of the concrete.

The CO_2-emissions of cement can also be reduced through the use of industrial waste materials like blast furnace slag and fly ashes. Both have comparable properties to Portland cement clinker and especially blast furnace slag is often used, but both must be activated with Portland cement. Therefore, it offers an interesting perspective that needs to be further explored. However in the long run, more radical innovation seems required as their potential for the overall substitution of Portland cement is limited. Other relevant limitations are the availability of blast furnace slag and possible impurities like chromium that can cause cement dermatitis.

Unfortunately all optimization steps (process eco-innovation) do not address the problem that the production of Portland cement requires the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$) and that a relevant CO_2-emission is unavoidable. See section 3.1.1.1 for more information about ongoing product eco-innovation for eco-cement.

Until today only the minor share of concrete and cement is recycled. Most Concrete and cement is disposed in landfill sites where the concrete and cement is an inert substance.

Box 2 The material intensity of roads

Roads not only require large quantities of materials to build, but their maintenance is highly material intensive; indeed, 5 times more materials are needed for road maintenance than for new construction in Germany (MaRess 2011). They are also a huge material stock, potentially interesting as a secondary source of materials for re-use. In a multi-year project (MaRess - Material Efficiency and Resource Conservation) for the German Environment Ministry and the Federal Environment Agency, the material storage and annual material flows for various infrastructure systems in Germany were estimated. Roads were found to be the most material intensive infrastructure system.

The construction of roads in Germany is based on standardized technical regulations. It is thus possible to determine the typical amount of material per km^2 for each type of road, and estimate annual material requirements for new roads based on expansion statistics. While detailed information on maintenance is unavailable, data can be gained using construction waste statistics. However, noise barriers and guardrails cannot be estimated, which could significantly increase material intensity of road networks overall.

Key findings of the project included the fact that despite the fact that Germany's road network is barely growing, huge amounts of mineral resources are required just for maintenance (about 100 million tonnes). Approximately 20 million tonnes are used annually to expand the road network. The project also found that the construction sector uses the majority of recycled construction waste; approximately 50 million tons of recycled construction waste are used in road construction each year in Germany. Therefore, a third of the annual material flows for road construction (about 40-45 million tons) currently make use of recycled materials instead of primary mineral resources. An implication for eco-innovation is, firstly, a need to spread knowledge about high-level recycling practices and, secondly, the need for up-cycling technologies and processes.

2.2.2 | Embodied CO_2 versus operational CO_2

Buildings are responsible for around 30% of all anthropogenic CO_2 emissions globally (Levine et al. 2007). This is more than the transport sector (IPCC 2007).

Until recently, about 80% of the carbon emitted from buildings were associated with *operational* emissions (i.e. the emissions generated through the activities of the building occupier; lighting, heating, cooling, electricity, etc.) and about 20% with *embodied* emissions (i.e. emissions that come about through the construction, maintenance, refurbishment and alteration of a building, including those from the extraction, transport, manufacture and assembly of building materials). Lane (2007) noted a recent shift in the ratio between operational and embodied carbon in the UK; it is now becoming closer to 60:40 for an average building and will probably becoming the dominating factor in the future (Wallbaum et al. 2010; Wallbaum und Heeren 2010). One reason might be because operational emissions are typically measured and regulated (Sturgis and Roberts 2010).

Indeed, targets in the UK, for instance, aim at zero operational emissions for all domestic buildings after 2016 and zero operational emissions for all new non-domestic buildings after 2019 (UK-GBC 2008). However, there is the danger that focusing on reducing operational emissions may unintentionally result in higher embodied emissions. Achieving zero operational emissions may require the use of increasingly carbon-intensive 'solutions'. For instance, in the case of Ropemaker Palace (a 20 storey, 20,000 m^2 office development in London), the operational carbon savings are high (causing it to rank very well on building eco-labeling standards), which are achieved through carbon saving measures such as tilting facades, green roofs, a woodchip boiler, solar water heating, photovoltaic panels, among others. But, over half of the building's CO_2 impacts are attributable to embodied carbon (Sturgis and Roberts 2010). Indeed, in the case of new office buildings, currently some 40–50% of the whole life-cycle carbon costs may be due to embodied carbon emissions. Furthermore, there are differences based on the type of building: a house typically has a ratio of operational to embodied CO_2 emissions of 70:30, whereas a warehouse generally has a ratio 40:60. As such, focusing only on operational emissions may be an inefficient strategy; it may be too narrow of a perspective that misses the other part of the story.

For this reason, Sturgis and Roberts (2010) have developed a method of carbon profiling that analyses operational and embodied carbon emissions at the same time, and on the same unit basis. Annual CO_2 emissions of a given quantity of space are calculated, so that for instance the carbon efficiency of a property can be determined. This would make it possible to make a more informed decision about the choice of refurbishment or demolition and rebuilding. It gives a fuller picture of the carbon performance of existing buildings and new buildings, i.e. when buildings have reached the end of their carbon useful life, and should therefore be considered for replacement and urban mining.

In any case, while aiming to reduce the operational carbon emissions of buildings is a noteworthy target towards increasing sustainability, the larger system trade-offs are also important. Embodied emissions are a good example of the dangers of focusing on a limited systems perspective instead of resource efficiency and the greater systems-wide dynamics and consequences.

2.2.3 | The built environment and net additions to stocks

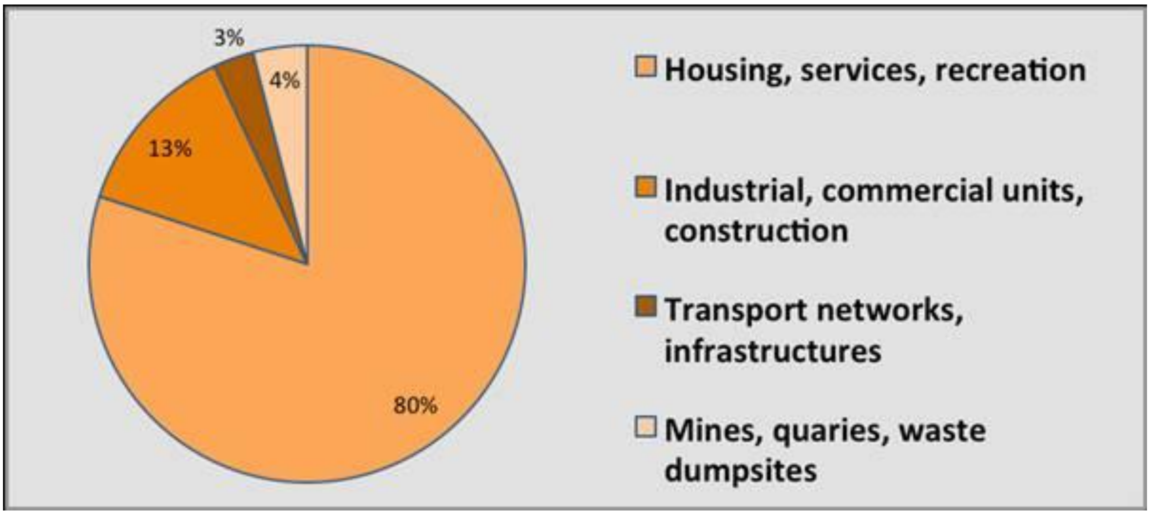
The expansion of the built environment has large environmental impacts that are often overlooked when discussing sustainable construction (focused on improving the process of construction and the efficiency of the end product). Enlarging the context creates a different perspective. While specific measures to improve resource and energy efficiency are indeed needed to improve sustainability, it is also necessary to keep the bigger systems picture in mind to create a long-lasting, overall sustainability.

75% of Europeans live in urban areas (SOER 2010). In per capita terms, the built environment extends about 0.06 (Western Europe) to 0.04 (Eastern Europe) hectares per person. In comparison, about half of the world population live in urban areas (World Bank 2010) and per capita built environment values range from 0.13 ha (in the US) to 0.03 ha (in China, Southeast Asia, and South Asia) (Angel et al. 2005). While the artificial surface (i.e. the built environment, see Figure 2.3) only covers around 4% of Europe's land surface, the artificial area accommodates the majority of Europe's population and hosts the majority of economic activities. This goes hand in hand with a constant exchange of resources and emissions, and results in a number of environmental impacts (e.g. production of waste and emissions, etc).

The built environment is expanding. MFA methodology captures this trend via the category of ‘net addition to stocks’ (OECD 2008). In total, artificial areas increased by around 3.4% (or more than 600,000 hectares) from 2000 to 2006 in Europe (EEA 2010). About 100,000 hectares (or an increase of 0.61% p.a.) of land was covered every year in that period. This was an increase from the annual extension that occurred between 1990 and 2000 (0.57% p.a.). The main reasons for the increase were the extension of housing, services and recreation, and industrial, commercial units and construction (EEA 2010). Overall, expansion is a result of a mix of forces, such as increased transport, land prices, individual housing preferences, cultural traditions and constrains, demographic trends or the application of land use planning policies at both local and regional scales.

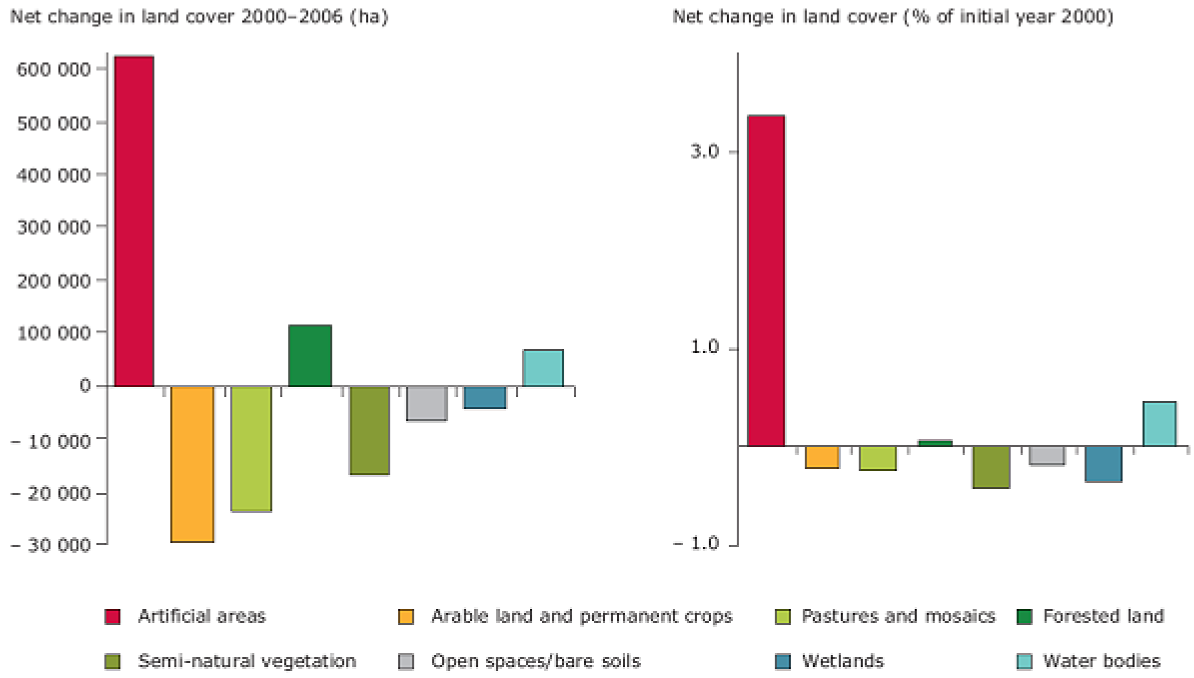
The expansion of built-up land occurs at the cost of other land uses. Figure 2.7 illustrates the net land-cover changes between the years 2000 and 2006. While the biggest gains were made for artificial land, the biggest losses were observed for the categories of cropland and pasture areas. This means that production of crops (food, feed, fuel, materials) must be displaced elsewhere. Indeed, between 1990 and 2000, 49% of urban land was created through decreasing agricultural land (arable land and permanent crops), and 35% through a conversion from pastures and mosaic farmland. 9% came from forests and transitional woodland shrub. Between 2000 and 2006, the majority of expansion still occurred on arable land (47%) and pastures (29%), while the percentage stemming from forests increased by around 5% to 14% (EEA 2010).

Figure 2.6 | Segmentation of artificial surfaces in Europe, 2006 (% of total area)



Source: EEA, 2010

Figure 2.7 | Net land-cover changes 2000-2006 in Europe: total area in hectares (left) and % change from 2000 (right)



Source: EEA, 2010

Without policy reform, Electris et al. (2009) expect the built environment in Western Europe to expand by another 2.2 Mha (or around 8%) and in Eastern Europe by around 2.1 Mha (or around 22%). As an indicative example, Bringezu (2009) calculated that at current rates of expansion it would take 750 years to cover the entire surface area of Germany. Nevertheless, expansion is not a phenomenon that can continue indefinitely. The construction sector will have to adapt to meeting different needs (e.g. renovation, rehabilitation, see also visions below) to remain competitive.

With its high impact on the environment, for example through soil sealing or higher traffic, urban land use and expansion deserve special attention in the assessment of land cover and land use, but also in the context of sustainable construction and the discussion of new buildings versus renovation.

2.3 | Eco-Innovation trends

Eco-innovation is happening in European companies. Based on the Eurobarometer survey[3] this section looks at how companies in the construction sector characterize the amount and types of eco-innovation they are performing. While it is difficult to link results of a survey to the systemic level of change argued for in section 2.2, it is possible to build a picture about what is happening 'on the ground'. Because the survey is specifically about eco-innovation and resource efficiency, we are able to see that the scale of resource-saving eco-innovations undertaken so far is not sufficient. This section begins by examining eco-innovation in general, takes a look at the types of eco-innovation undertaken to reduce material costs, and concludes with the effects on resource efficiency.

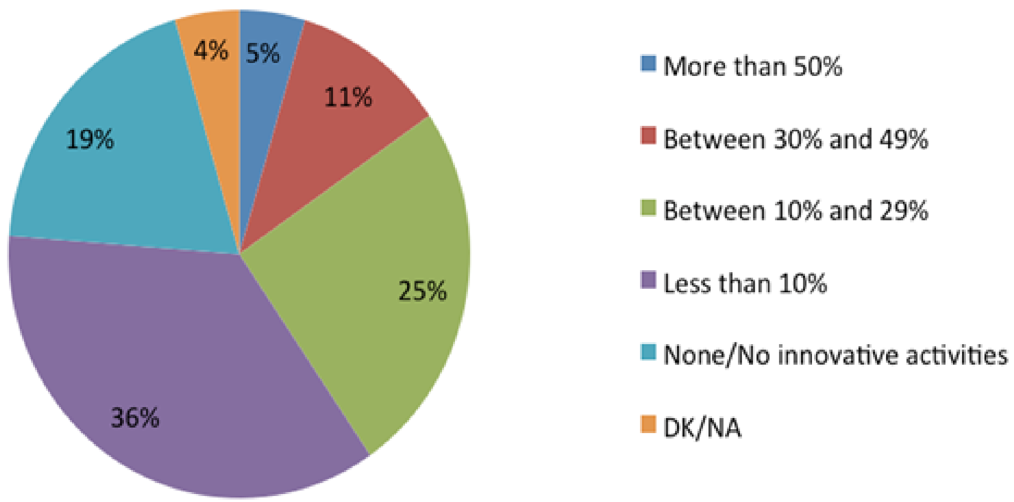
Eco-innovation in general

From the construction sector, around 1,526 companies across the EU were surveyed by Eurobarometer. The overwhelming amount of these companies (87%) were SMEs with between 10 and 49 employees. Around half of the companies had an annual turnover of less than 2 million Euros, with only 1.8% reporting Figures over 59 million Euros.

While the majority of companies in the construction sector have made some kind of investment into innovation in the past 5 years, the share of those investments that were related to eco-innovation is relatively small. More than a third of companies responded that eco-innovation made up less than 10% of their innovation investments (Figure 2.8). Only 5% of companies reported that more than 50% of their innovation investments were eco-innovative. This is lower than relative shares in other sectors; for instance, around 10% of companies in the water and agriculture sectors reported that more than 50% of their innovation investments were eco-innovative. All in all, it can be seen that the majority of innovation investments are, not yet, focused on eco-innovation.

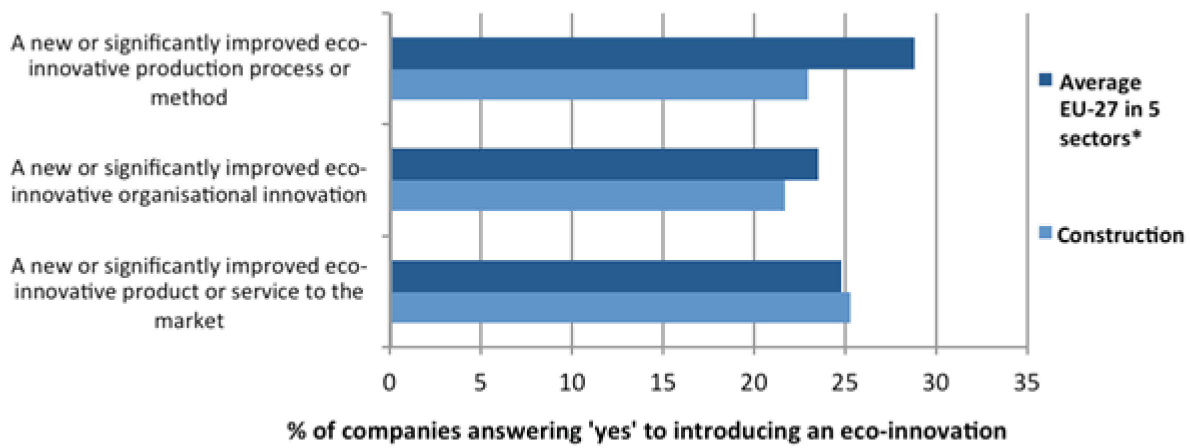
[3] *The Flash Eurobarometer survey on "Attitudes of European entrepreneurs towards eco-innovation" was a telephone survey carried out in early 2011. A total of 5,222 SMEs from across the EU-27 were asked about their attitudes and expectations towards the development and uptake of eco-innovation as a response to rising prices of resource and resource scarcity. Companies stemmed from 5 sectors: 1) Agriculture, forestry and fishing 2) Water supply; sewerage; waste management and remediation activities 3) Manufacturing 4) Food and beverage services and 5) Construction (EC 2011).*

Figure 2.8 | Share of eco-innovation related investments in the construction sector over the last 5 years



Source: Eurobarometer 2011 (EC 2011); Question: Over the last 5 years, what share of innovation investments in your company were related to eco-innovation, i.e. implementing new or substantially improved solutions resulting in more efficient use in material, energy and water.

Figure 2.9 | Introduction of eco-innovation in the past 2 years



*Source: Eurobarometer 2011 (EC 2011); Question: During the past 24 months have you introduced the following eco-innovation? * Agriculture, Water, Manufacturing, Food services and Construction.*

The same holds true when looking at the types of eco-innovation occurring in the construction sector. Roughly a quarter of all construction companies have introduced a new or significantly improved eco-innovative product or service in the past 2 years (Figure 2.9). This is the most popular type of eco-innovation in the construction sector, whereas process eco-innovation is the most popular type across all five sectors surveyed. This may indicate something about the structure of the construction sector. Nearly 31% of companies in manufacturing and 40% of companies in agriculture and fishing have implemented process eco-innovations, compared to 23% of companies in construction. One reason may be the greater levels of industrialized production seen in manufacturing and agriculture, which lead to the opportunity for more process eco-innovation in these sectors. Greater levels of industrialization may be an opportunity for construction to expand its innovative activities (see also section 3.2.1). Other reasons might be that (a) companies implemented process innovation in the years before and now believe to operate at the technology frontier, (b) there is lower pressure for production-integrated environmental management from customers downstream, or (c) demand exists for new eco-innovative products.

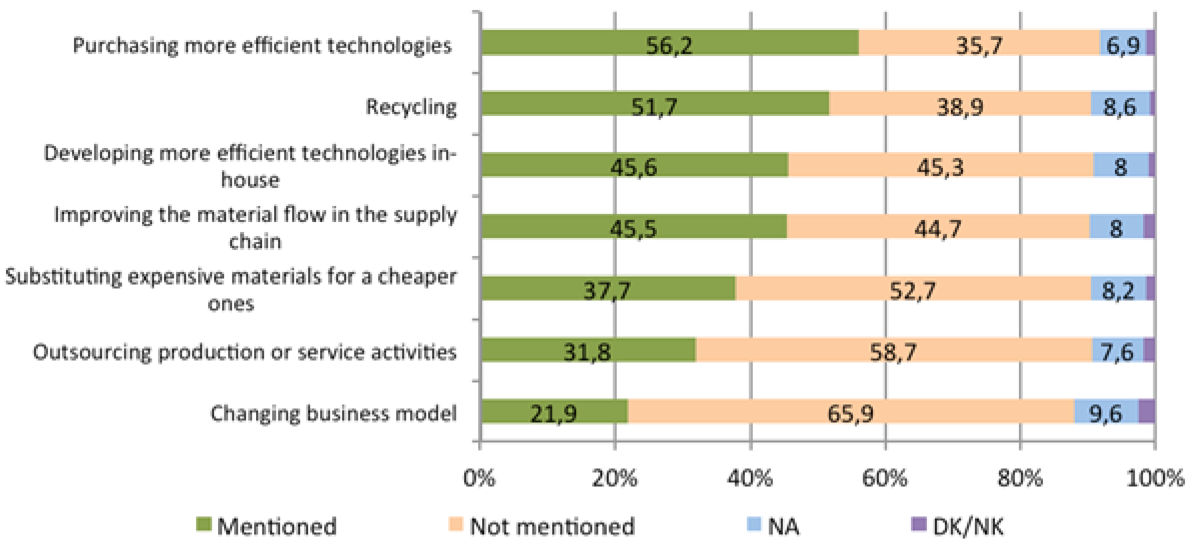
Reducing material costs through eco-innovation

Rising material costs are expected to be a driver of eco-innovation in the future. Indeed, according to Eurobarometer, 86% of companies had introduced at least one change in the past 5 years to reduce material costs.

As the sector with the largest material requirements, material costs are relevant to the construction sector. Indeed, around 73% of companies have experienced increasing material costs over the last 5 years (increases were dramatic for 21% of companies) and 89% expect material cost increases in the coming 5 to 10 years. One can thus expect increasing efforts towards reducing material costs in the coming years.

The types of change currently being implemented to reduce material costs reveal a lot about the more specific types of eco-innovation happening in the sector.

Figure 2.10 | Type of changes implemented to reduce material costs in the past 5 years



Source: Eurobarometer 2011 (EC 2011); Question: Have you implemented any changes to reduce material costs in the past 5 years?

Purchasing more efficient technologies was by far the most common strategy in the construction sector (undertaken by 56.2% of companies; see Figure 2.9). This is in keeping with the general trend across all sectors surveyed. However, the construction sector has seen lower amounts of activities in all other categories, indicating that other sectors have been more active in perusing strategies to reduce material costs. One reason for this could be that in the construction sector, materials and labour are sometimes purchased separately, so that there is no incentive for companies active in building to dramatically reduce costs (see Chapter 4). The areas where construction is particularly lagging behind are in the amount of responses for developing more efficient technologies in-house (about 46% of companies in construction compared to 53% of companies surveyed on average) and changing the business model (around 22% of companies in construction compared to 27% of companies surveyed on average). This seems to indicate a relative lack of innovation capacities that should be addressed.

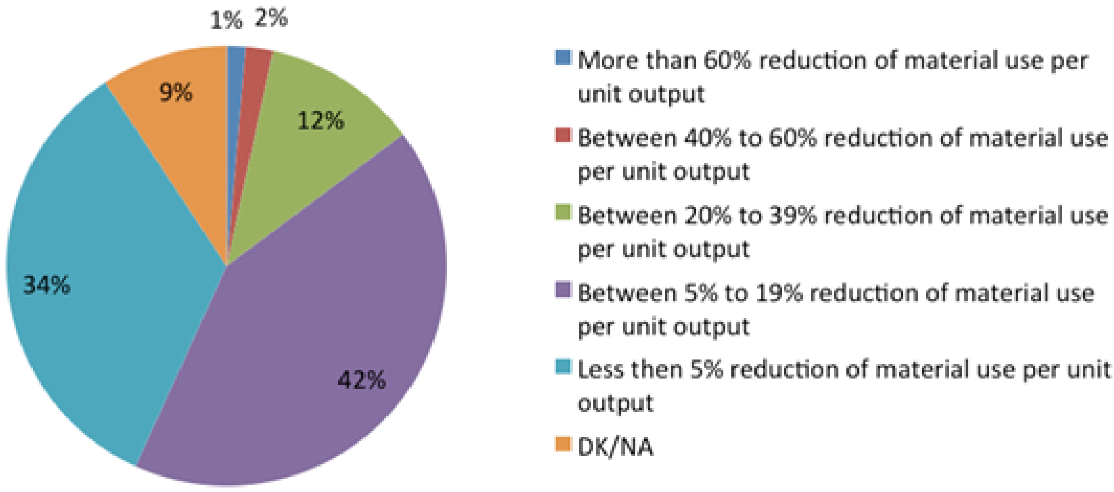
Effects of eco-innovation

Despite efforts to reduce material costs, remarkable material savings have only been achieved by a small number of companies. Around 3% of the companies which implemented eco-innovation in the last two years declared that efforts led to a more than 40% reduction of material use per unit output (Figure 2.10). Around 42% of eco-innovators reported between 5 and 19% resource-efficiency improvements and around 34% of eco-innovators declared a 5%, or less, reduction of material use per unit output. This indicates that the majority of companies eco-innovating are implementing incremental innovations. If these innovations continue on a year-by-year basis, such efforts may result in substantial changes in the efficiency of resource-use over time. If these innovations describe “one-off” measures, it indicates that only a minimal number of companies are achieving resource-efficiency eco-innovations at the intensity needed to initiate the kinds of systemic change argued for in Chapter 2.2 and presented in the visions (Chapter 5).

In comparison with other parts of the economy, the construction sector is slightly behind all sectors in terms of ‘Factor 2’ eco-innovations (corresponding to 50% improvements in resource productivity; see the EIO Annual Report).

Results suggest that overall innovation efforts at the company level have not yet been focused on improving resource efficiency. An up-scaling of not only the number of companies being active in this field, but also the amount and the intensity of eco-innovation occurring in the construction sector towards reducing material use is needed.

Figure 2.11 | Resource efficiency gains due to eco-innovation in the construction sector



Source: Eurobarometer 2011 (EC 2011); Question: How would you describe the relevance of innovation you have introduced in the past 24 months in terms of resource efficiency?

3 | Eco-innovation in practice

This section provides examples of leading edge technologies and good practices that are currently used to improve the resource efficiency of the built environment. These include eco-innovations which may already be in wide practice in some EU countries, but have not yet gained popularity in others, or practices that while common in specific segments of the sector, have not yet reached full market diffusion. While a number of highly innovative building technologies may exist, we concentrate here on more indicative examples, exemplifying why the resource efficiency perspective is important to the construction sector.

The EIO has proposed a new typology for characterizing eco-innovation. This moves beyond the product / process classifications common to innovation science and the perception of ‘eco’ as only relevant to clean-tech technologies and renewable energies. Instead, it focuses on what the innovation does; *Material-flow innovation* captures innovations across the material value chains of products and processes that lower the material intensity of use while increasing service intensity and well-being. This includes:

- developing new materials (with better environmental performance)
- substituting resource-intensive materials and products (with new materials, functionally new products or functionally new services)
- establishing whole life-cycle processes of resource efficiency (e.g. by enforcing sustainable extraction and production, optimising transportation logistics, enhancing re-use and recycling, and increasing the lifetime and durability of products)
- transforming infrastructures towards a steady-state stocks society (e.g. by improving road and building maintenance; developing resource-light buildings and infrastructures (such as wastewater systems); establishing a solarised technosphere; and slowing down urban sprawl).

All of these facets are highly relevant to the construction sector. All of them will be necessary to manage the transition of the highly resource-intensive construction sector into an efficient user (and re-user) of materials. Chapter 3 provides examples of these factors; eco-cement is a new material; the building envelope can enhance functionality and substitute environmentally-intensive materials; industrialized construction may be able to improve material efficiency; urban mining can optimize the re-use of materials to steer development towards a steady-stocks society. But clearly *much* more innovation is needed to achieve sustainability, balancing environmental and socio-economic goals. Trade-offs and synergies will have to be considered more comprehensively in the future; meaning that instead of just developing one new material to replace one other material, innovators will have to think about how one component could substitute multiple functionalities while serving customer needs in different regions. Innovative technologies, but also an innovative re-structuring with ensuing participatory governance processes will be needed to re-make the sector to meet the needs of sustainable societies.

3.1 | Reducing the resource intensity of construction materials

Substituting resource-intensive materials with 'eco-materials' is one strategy to improve resource efficiency in the construction sector. Resource-light construction is a more comprehensive approach that regards the building as a single functional unit, rather than separate components, and tries to optimize functionality of the entire system. Moreover, the functionality of the individual components is a part of this concept, and finding how functionality can be achieved, or even improved, with less material input is the pinnacle of material-flow innovation.

3.1.1 | Eco-materials

Eco-materials are less resource-intensive and less polluting than alternative ones. This includes gains made in the production process and the substitution of resource-intensive raw materials. However, the line between what constitutes 'eco' and 'not eco' is not black and white; one material may even fulfill the criteria for both under different circumstances. For instance, wood may be the more environmentally sound choice for building a family home compared to concrete, if the timber comes from a sustainably managed forest nearby. But if the demand for timber to build houses were to exceed the supply of timber, promoting only wood frame houses would probably lead to a rebound effect (which means that at a certain scale, consequences are negative; i.e. in this case, deforestation).

3.1.1.1 | Eco-cement

Cements are a broad group of materials that harden with a hydration reaction. The widely used Portland cement emits high amounts CO_2 and requires high amounts of energy in its production (see Box 2.1). A number of comparable cements are lower in CO_2-emissions and on-going research is focused on the development of cement that has comparable properties to Portland cement but that can be produced with less CO_2-emissions and energy consumption.

A feasible way to reduce both is the more intensive use of industrial waste materials like slag and natural hydraulic-setting minerals like pozzolan. The big advantage of these materials is that they do not contain carbonates, as such they do not have to be calcinated. The disadvantage is that they need to be activated, either by adding Portland cement or by producing so-called geopolymers or alumino silicate-cements. For the latter, long-term experience is missing and the availability of raw materials is limited. At the same time, no carbonates are used and a reduction in energy consumption up to 85% is possible (Weizsäcker 2009).

Another possibility is the use of other raw materials and the development of new processes. An interesting option is a cement with reduced calcium content. Such a technology, called Celitcement, is under examination at a pilot plant in Germany, but as it is still based on carbonates, it releases some CO_2-emissions in production. There are a number of technologies available or under development to reduce the environmental burdens, especially the CO_2-emission of cement[4]. While some of these materials seem to

[4] *See e.g. Ecocem Ltd. and Novacem Ltd.*

have comparable strength to Portland cement, only limited information concerning other relevant properties, like long-term protection of steel against corrosion, porosity and frost resistance, is available. New processes and other raw materials are options to reduce the CO_2-emissions of cement and concrete, but one of the biggest challenges is the recycling of hardened cement paste from concrete. As the cement paste is a hydrate, it is not carbonated and therefore can be calcined without any CO_2-emissions from the cement paste. However, until now there is no process available that enables this potential. It is a relevant area for future eco-innovation.

3.1.1.2 | Building with wood

Building with wood to increase the sustainability of buildings in all life-cycle phases has increased over the last decade. Examples include the Swiss Expo 2000 pavilion or recent multi-storage buildings like the Rhomberg Lifecycle Tower (see Box 3.1) or the Kerbl nursing home in Berlin-Lichtenberg (Kristof et al. 2008). There are several possible contributions to the field of sustainability when building with wood, but these strongly depend on the circumstances. Only wood from sustainable sources that does not contribute to undesired deforestation will have a positive effect on GHG emissions (see Kristof et al. 2006) even though its processing may still be more energy efficient than that of cement or steel (see e.g. APA 2005). Additionally, cascading use of wood is crucial for the sustainability potential of wood, i.e. using wood as a material before using it to generate energy (for instance, using wood in construction and then burning it at the end of its life cycle) (Bienge 2010). To this end, eco-innovation of new materials, such as ‘liquid wood’ may be critical[5].

Box 3 Rhomberg’s “Life-Cycle Tower”: a multi-storey tower based on wood

As a reaction to rising scarcities of many materials and the need to increase resource efficiency in the construction sector, Rhomberg Bau, a construction firm based in Austria, invented a building system based on wood for multi story buildings. A special hybrid construction makes it possible to lift a wood-based building up to 30 storeys and to construct the building in a very short period of time. The used materials as well as the operation help to reduce carbon emissions in comparison to an ordinary concrete building. Wood is one of the oldest building materials and is well known for creating a comfortable living environment. Rhomberg Bau is using it as the main material for eco-innovative construction, not only because it is renewable but also because it can be used in a modular design, which helps to reduce the working time on-site. The life-cycle tower is going to be realised for the first time through a pilot office building in 2011.

5 ‘Arboform’ combines the properties of natural wood with the processing capabilities of thermoplastic materials. With it, the SME TECNARO GmbH won the European inventor award 2010 in the SMEs/research category.

For more information see Rhombergbau (http://www.rhombergbau.at/en/start_page/allgemein_informationen/skills/construction/lifecycle_tower.html) and the EIO Online repository

3.1.1.3 | Building with straw-based materials and clay

Recently, there has been a noticeable return to traditional construction materials in the building sector. Wood is known as one of the oldest construction materials (see above), but also straw was used in the first buildings human's erected. Straw is characterized by a high insulation capacity and it creates a comfortable indoor climate. Moreover, it is particularly well suited to regions of Europe where it can be grown regionally, making it a cheap, local resource which can be handled easily.

As proof of the feasibility and advantages of building a house based on straw, the so-called "S-House" was erected as a two storey demonstration building in Austria. The objective of the S-House was to realise an example of Factor 10 construction: a building that uses 10% of the resources and energy of conventional construction. At the same time, it has high energy saving standards, meets with high ecological criteria and achieves high user comfort.

The walls of the S-House consist of clay plastered straw bales with a wooden frame; it additionally has a green roof and utilizes passive house windows.

Straw-based construction is a small, but fast-growing field within the area of eco-innovative construction. It may offer a viable alternative to burning straw for heat and power generation. In 1995, only 40 straw-based buildings existed in Europe, mainly in the UK, Norway and France. This number had grown to 400 by 2001 and further since then (Wimmer et al., 2005). In Austria and many other countries, small companies are specialising in straw-based construction of mainly residential buildings and small office buildings.

For more information see: The S-House (http://www.s-house.at) and Clay Works (http://www.wupperinst.org/en/publications/entwd/index.html?beitrag_id=1186&bid=234)

3.1.2 | Resource-light construction

One of the biggest challenges of the 21st Century is probably the sensible use of limited resources. This requires a change in construction. From aerospace and automotive engineering we know that a higher weight automatically means more energy burdens. Thus, technologies and materials are needed that make a building lighter, less resource and energy consuming. However, resource-light construction must be understood beyond the simple description of using light weight materials or minimizing material use. Resource-light construction refers directly to the appropriated use of construction materials and building techniques, providing the most efficient response to specific needs in a built object. Again, the methodology of material flow analysis and the calculation of material intensities offer useful tools. Basically there are three principles of lightweight construction:

- Lightweight materials have high strength and stiffness in relation to their weight;
- Lightweight structures have optimal load transfer mechanisms for a structure, e.g. the
- avoidance of bending stresses;

Lightweight system design combines various functions in a single component (Wiedemann, 1989).

Resource-light construction aims to identify the best material for each specific application. This process goes beyond the built object and accounts for the local conditions, the user's behaviors and the economy, thus having an integrated view on the real needs. It is important to clarify that a solution can only be considered as life-cycle wide "eco" under specific conditions; a building considered as 'resource-light' or sustainable in one location may be unsustainable in another.

This concept is based on the idea that each material has its best place of application. Consequently, the selection of an eco-material should not only be based on its environmental performance, but also on its mechanical properties, lifespan and maintenance requirements, as well as human and eco-toxicities.

But the concept of resource-light construction goes even further and relates to the service unit and its functionality. From this perspective, the material choice is made based on the functions that a certain product will provide to the building and its users. Therefore, the selection is based on the unit, assessing the performance of the constructive elements as a group. To exemplify this concept, let us examine an example of a typical service unit, a wall. Walls are composed of a series of layers that provide the unit with different characteristics; for example aesthetics, thermal and acoustic insulation, and load bearing. In order to obtain an eco-beneficial service unit, a seemingly sound idea is to provide it with a good layer of insulation material. But, while this might provide a 'solution' to one problem (improving energy efficiency), it increases the material use in the unit (and therefore worsens material efficiency). Therefore, this may not be the best option with respect to resource efficiency overall. A better alternative could be the selection of a special building block with high levels of thermal and acoustic insulation, which would reduce the resource use of the unit. With such a building block, the load bearing capacity of the unit will be fulfilled, and the outer layers of insulation can be significantly reduced or eliminated, thus reducing the resources needed to provide the service of the unit while achieving the same function (load bearing, thermal and acoustic insulation).

Light resource construction needs a deeper understanding of the built object, the local conditions around it, and a detailed material selection process. Light resource construction is achieved when the characteristics and interactions of all construction materials maximize the performance of the building as a whole, while reducing energy and material flows, carbon emissions as well as other harmful emissions to humans and/or the environment.

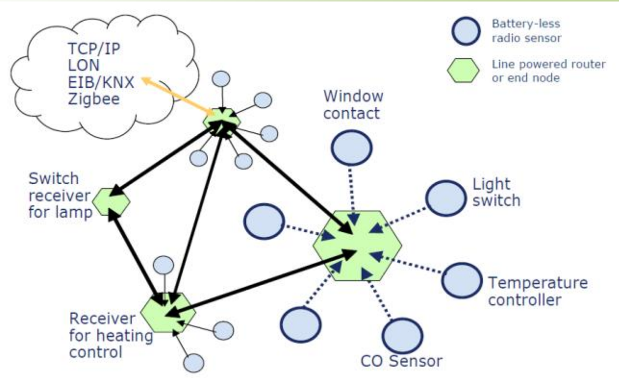
See also Box 3.4 for an illustrative example of resource-light construction.

3.1.3 | Rethinking functionality

Inventions that achieve greater functionality with less environmental burden are at the core of eco-innovation. There are numerous examples of such innovations that have opened completely new markets and changed the way we interact with technology and society. In the construction sector, such innovations can range from radical to incremental.

Building automation is an example of a compilation of new technologies that enable development of 'intelligent green buildings'. This means buildings that optimize cost efficiency, energy use and comfort. These buildings have automated control systems that at the most basic level regulate temperature, for instance by closing and opening shutters. A number of eco-innovative technologies are incorporated into the design of such buildings. One example is light switches that utilize wireless radio technology. While this may appear to be a rather simple example, using radio technology reduces the need for copper cables (see box 3.2).

Box 4 'No batteries, no wires'



Business Case:

The company EnOcean advertises that switches and sensors linked through radio technology save about 30% of the installation cables required, and estimate that with average construction trends in Germany, replacing all switches could amount to 10,000 tons of copper savings per year.

Their wireless building technologies also take advantage of energy harvesting techniques; these collect energy from sources like motion, solar energy and slight temperature differences. Thereby eliminating not only wires, but also batteries. Without wires building space can be much more flexibly designed and re-modeled.

See EnOcean for more information; www.enocean.com.

3.2 | Using and re-using resources more effectively

Improving resource efficiency is also about using resources more effectively across the life-cycle. This requires a careful examination of what the life-time of the existing building stock is and whether it makes more sense to renovate or build new. Approximately 2/3 of the material used during the construction and use phases can be saved by converting an existing building (Lemken 2008). Further potential for resource savings can be made by optimizing building processes to require less resources (for instance through industrialized construction) and better optimizing re-use by developing procedures for secondary sourcing of construction materials, such as urban mining.

3.2.1 | Industrialized construction

Unlike manufacturing, construction is one of the few industries which has not been converted to an industrialized style of fabrication and production. Whereas automobiles and consumer products are typically produced in a factory (often with increasing levels of resource efficiency), homes are regularly still hand-built. General consensus exists over the potential for considerable resource-savings with a greater level of industrialization in the construction sector (Bock and Linner 2010; van Egmond and Scheublin 2005; Landin and Kaempe 2007).

Industrialised building has been defined by the International Council for Research and Innovation in Building and Construction as "a building technology where modern systematized methods of design, production planning and control as well as mechanised and automated manufacture are applied" (as cited in van Egmond and Scheublin 2005). It does not necessarily equate to mass production, but rather to the application of accumulated knowledge and technologies in construction processes that become increasingly mechanized, rationalized, systematized, standardized, automatized and flexible (Van Egmond and Scheublin 2005).

The question is, why has change in the construction sector been slower than in other sectors, such as the automobile industry. The answer probably lies in the different drivers for innovation, diffusion and application in the different sectors (Van Egmond and Scheublin 2005). The traditional construction process involves a number of different actors participating at different stages of construction, leading to poor levels of cooperation and lost opportunities for innovation and resource-savings. It is also characterized by the presence of many small and medium sized companies (Landin and Kaempe 2007), perhaps lacking the economies of scale needed to innovate towards industrialization. Additionally, much of the knowledge in the construction sector is tacit and experience-based, making knowledge diffusion more problematic. Moreover, the tendency towards conservatism in the construction industry may slow down both acceptance and the application of eco-innovations. For instance, acceptance of prefabrication remains mixed today, despite the multitude of ecological and economic benefits it can provide (Van Egmond and Scheublin 2005).

Industrialized structures and technologies in construction could help to enhance resource productivity, reduce waste, improve safety and working conditions, support supply with affordable housing and enable continuous deconstruction, reuse and recycling (Bock and Linner 2010). Mah (2007) found that on average between 0.7 and 1.4 tonnes of material waste is generated during the construction of a single-family stick-frame house in Canada, largely dependent on the experience of the tradesman. In contrast, a pre-fabricated, modular component is produced in a factory with a high-level of precision and the opportunity to better minimize and re-use wastes (Olearczyk et al. 2009). It therefore reduces costs and construction times, and production is not subject to weather conditions. A big advantage is that prefabrication enables easier reparation, rebuilding and rearranging of the building (Landin and Kaempe 2007). On the other hand, prefabrication requires a greater level of planning and coordination (Van Egmond and Scheublin 2005).

Trends differ in Europe. For instance, around the middle of the 1990s only around 15% of apartment houses in Sweden were produced industrially, whereas in both Finland and Denmark around 70% were produced industrially (Fernstoem and Kaempe 1998 as cited in Landin and Kaempe 2007). Currently, the percentage of construction work involving prefabricated parts is just as high in Sweden as in Denmark (Landin and Kaempe 2007). In other parts of the world, such as Canada and Japan, prefabrication is also becoming more popular. For instance, in Japan prefabricated houses can both be bought and traded-in. Following the principles of pulling and lean production, the Company Sekisui Heim produces customized housing products. In their prefabrication factories waste is both reduced through on-demand order of compatible elements and fastidiously collected and sorted to be fed into a connected recycled system. The houses can also be easily deconstructed; first, joints between steel frame units are eased and then the house is transported to a special dismantling factory unit by unit. There, the steel frame units are inspected, refurbished, and equipped for the desires of a customer who has chosen to buy a re-used house. A web-platform is used to match people who want to sell their modular house for reuse and people willing to buy reused house modules for further customization (Sekisui Heim (2011) as cited in Bock and Linner (2010)). With a growing number of customers willing to purchase a 'used house', there is a good opportunity to develop a highly efficient component circulation, reverse logistics and remanufacturing system (Bock and Linner 2010).

It is key that prefabricated construction does not carry the stigma of monotonous and dreary mass production (Landin and Kaempe 2007), especially as there is a growing demand for creativity and individuality today (Piller 2006). One strategy for delivering user adapted or even personalized products is customization; it can be aimed at enhanced efficiency while creating user-centered innovations. In the future, the extension of classic ICT by advances in robotics and intelligence may even create more efficient customization structures. Considering regional, cultural and climatic differences and preferences, one strategy for prefabrication could be locally-based factories integrated into a distributed and flexible factory network (Kirchner et al. 2004), similar to the automobile industry (see Bock and Linner (2010) for more information).

All in all, innovation in the construction industry has mostly been incremental, and it has taken place in various areas: materials, engineering, transport and equipment, ICT, computers, robotics and management. First elements of industrialization were seen in the mechanization of parts of the on-site construction process and the prefabrication of building components. However, because this industrialization has lagged behind the manufacturing industry, the recent progress made has been characterized by van Egmond and Scheublin (2005), for instance, as a convergence of technologies and knowledge from different areas and disciplines; a combination of innovative solutions based on accumulated technological and knowledge advances have been adopted in attempts to move from largely craft-based construction to a systematic construction process where resources are utilised efficiently. In the future, established industrialized processes could lead to sequential process innovation with quite radically improved performance over time – as has been seen in other industrialized sectors – in the areas of flexibility, deconstruction and remanufacturing. New organizational structures, process technologies, ICT systems, and knowledge based logistics are key enablers of a necessary system innovation in the construction sector (Bock and Linner 2010); from economic growth to resource efficient construction and sustainable economic development.

3.2.2 | Urban mining

Urban mining emphasizes the extraction of obsolete resources situated in buildings, infrastructure and landfills. Over time, massive amounts of material resources have been extracted for buildings and infrastructure development. The resulting accumulation - so-called urban stocks - could be important resource reservoirs in the future. In the case of particular metals, for example copper or precious metals, stocks in the built environment are already of comparable size to "virgin" reserves (Gerst and Graedel 2008). Explorative research shows that there is a huge potential for urban mining activities in the future (for instance see also for Germany: Golding 2009; Trend-Research 2009; Rettenberger 2010; Lucas 2010).

The question is how to overcome barriers to maximize this potential? The challenges of urban mining can be summarized as *attraction* and *extraction*; namely, gaining access to a sufficient quantity of items for recycling, and developing an efficient means of extracting the materials contained in them. The main problem with attraction is that the numerous opportunities for replacing traditional mining processes with urban mining techniques are not organized in a systematic manner. The reasons for this lack are manifold:

- *Lack of information*: In the past only a few municipalities systematically registered the different uses of materials in the building sector. To get detailed commodity data additional studies are needed, in particular about the location and life-cycle of construction materials.

- *Market demand*: In the past commodity prices underwent great variations. This volatility on prices makes investments in new urban mining technologies difficult to calculate and to assess its risk. On the other hand, expected scarcity for some special metals could be a driver for more development in this area.

- *Landfill tariffs and costs:* Landfill tariffs and costs for recovery are strongly connected. As long as tariffs are lower than costs, there is no incentive for urban mining.

As regards extraction, the success of any urban mining strategy depends greatly on achieving economies of scale. Because of the high investment costs, a refiner has to be able to amass sufficient quantities of material to make processing efficient, cost effective and sustainable. The processing of urban material in so-called integrated smelters is one approach; where waste materials are also used as a fuel for further processing and manufacturing. For example scrap metal recycling has many major benefits for the environment. It helps cut GHG emissions, saves energy and protects the depletion of natural resources. Significantly less energy is required to produce steel or copper products from recycled scrap metal than from virgin ore.

If developed and implemented properly, urban mining will result in a wide range of positive economic impacts on the national scale. Companies in the waste business, for instance, could adapt their strengths to create a new business model, applying their skills, financial resources and technologies to focus upon these emergent mining opportunities. The local and regional 'exploring' in urban areas should be combined with a global redistribution network; creating an extensive client base in multiple sectors, new logistical know-how, and a wide range of experience in recycled construction materials trading. Ultimately, it could expand the skills set and workforce across the entire value chain; from exploration and extraction to transportation and recycling/refining, and finally to marketing, selling and re-use. For example, smelter operators could become involved in finding new ways of identifying the potentials.

To bring urban mining into practice a selective demolition process (which greatly assists separate collection by separating materials at source) is very desirable; it would lead to establishing recycling standards for buildings. Although local planners and regulators should take into account the availability of recycling and disposing facilities when encouraging or requiring selective demolition, they should also recognise that the two issues are interrelated. On the one hand, they should not overwhelm local facilities by requiring them to deal with more materials than they can bring into secondary markets. Moreover, incentives to the construction sector are needed to expand their capacities and interest for using secondary materials. There is a need to better understand these dynamics to enable informed policy guidance.

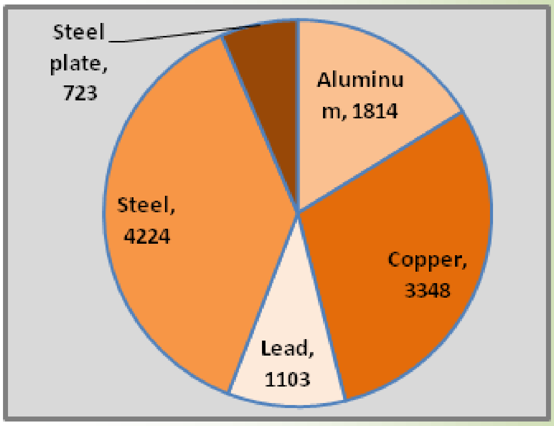
Urban mining also involves encouraging people to recycle their out-of-date electronic gadgets and other obsolete products. Old electronic devices such as cell phones and computers contain precious metals such as gold, silver, iridium and a range of other valuable materials that can be recaptured for reuse.

In summary, the main challenges for urban mining are:

- Designing houses and infrastructures for recycling within a strategy of resource efficiency
- Collecting data of material use (net addition to stocks) systematically, including the establishment of urban resource cadastres in Europe
- Developing processes to collect, separate and treat valuable materials efficiently
- Separating hazardous materials effectively and delivering them to appropriate final disposal centers
- Creating standards and developing guidelines for logistics, deconstruction, treatment, exploitation, and marketing for reused-products.

Box 5 Examples of urban mining potential

Figure 3.1 | Material stand in German electricity grid in 1,000 t



The first step towards an effective urban mining strategy is to collect data on all the material stocks contained in the built environment (infrastructures and buildings), in all EU countries. The second would be developing a strategy to obtain and utilize these 'forgotten resources' in the most efficient way. Figure 3.1 demonstrates the extensive stocks present in the German electricity grid; it is indicative of the type of information that is needed across the EU.

Source: MaRess Teilprojekt 2.3

Aluminum is one example of a material that may be relevant for enhanced urban mining activities. Aluminum use in construction has rapidly increased since the 1950s; nearly 30 million tons have been used for construction purposes in Europe since then. It is a corrosion-resistant, lightweight and structurally strong material with a life-cycle in buildings of about 30 to 50 years. Bottom-up-studies show that infrastructure and buildings contain nearly 60% of the total in-use stock, and transportation vehicles nearly 40% (Recalde et al. 2008). Aluminum stored in such products is therefore in effect 'warehoused' for future use. For instance, around 485,000 tons of aluminum are used for construction purposes in Germany, with an end-of-life collection ratio for construction of around 85% (Radlbeck 2005). The energy required to produce recycled ingot from scrap is only about 5% of that required to produce primary aluminum. Mining secondary aluminum could become an more attractive market in the future.

Box 6 The recyclable building

The recyclable building is a concept just coming into trend that could make the urban mining of the future much easier. It means that the end-of-life deconstruction of the building is already taken into account in the design or it. For instance, the four-storey R128 house created by German architect and engineer Werner Sobek is an excellent example. It was designed so that all components are completely recyclable. The building also requires zero-energy (meaning it generates all the energy it needs) and produces zero CO_2 emissions. This is part of the 'Triple Zero' concept of Werner Sobek's. It also illustrates resource-light construction, and the types of innovative design needed to develop resource-efficient buildings. It can mean 'thinking outside the box' about building materials. For instance, the protective envelope for Station Z, a commemorative site on the grounds of the former concentration camp in Sachsenhausen, Germany consists of a free-span, steel-frame structure covered with a total of 500 kilograms of textile. It is stabilized by simple air pressure, regulated by a small pump, and was built in such a way that later everything can be easily dismantled and removed (Sobek 2010).

For more information see R128, Triple Zero, Station Z.

R128 by Werner Sobek

Photograph by Roland Halbe, Stuttgart Germany

3.3 | Building smarter to 'save' energy

Energy efficiency is also a part of resource efficiency (lowering the requirement of fossil fuels for instance). The question is, how can buildings be built or remodelled in such a way that they require less energy?

There are several examples of how smart buildings and building design adds to energy and resource efficiency. In the following, the three examples of resource-efficient cladding, remote energy saving tuning services, and green roofs will be presented, as well as a discussion of 'low exergy'.

3.3.1 | Resource efficient cladding

The operation of buildings can be very energy-intensive, with buildings accounting for about 42% of EU final energy consumption (EU 2007). Cladding and roofs have a significant influence on this energy consumption. By means of modern technologies the consumption of final energy may be cut by 80% (Wuppertal Institute 2009).

Cladding is the gateway between the building interior and exterior: It determines the inside temperature through insulation. Here, the challenge is to insulate cladding and the roof to the best degree possible without increasing material consumption drastically. Otherwise, an improved insulation might increase energy efficiency while decreasing life-cycle wide resource efficiency (see 3.1.1). Future building materials and cladding systems will therefore combine different technologies, which could also improve quality of life as well. For instance, modern glazing and thermal insulation systems protect against cold and warm temperature and against sound. They convert solar irradiation into thermal energy and store it while regulating daylight and fresh air supply. Adaptive claddings are able to transmit or absorb solar irradiation depending on interior conditions. Vacuum insulated panels offer improved insulation while reducing required space. Phase-Change-Materials (PCM) reduce daily hot spots and emit the stored thermal energy at night.

StoSolar solar element (cladding) made of translucent capillary plate with transparent glass plaster

Source: Fachverband transparente Wärmedämmung 2010

The usage of highly insulating and transparent wall panels cuts energy consumption for heating, air conditioning and lighting. Furthermore, reduced layer thickness and savings in construction building materials lower the resource consumption of construction activities. For instance, vacuum insulated panels reduce the layer thickness by a factor of 5 to 10 compared to conventional solutions (Wuppertal Institute 2009). The improved insulation decreases energy consumption (and thus cuts CO_2 emissions).

3.3.2 | Remote Energy Saving Tuning Service

In order to reduce the energy consumption of buildings it is not only necessary to optimize insulation and heating systems, but also the cooling system. The energy consumption of air conditioning systems has a share of about 40% of total energy consumption of buildings in Japan (Daikin Industries 2010).

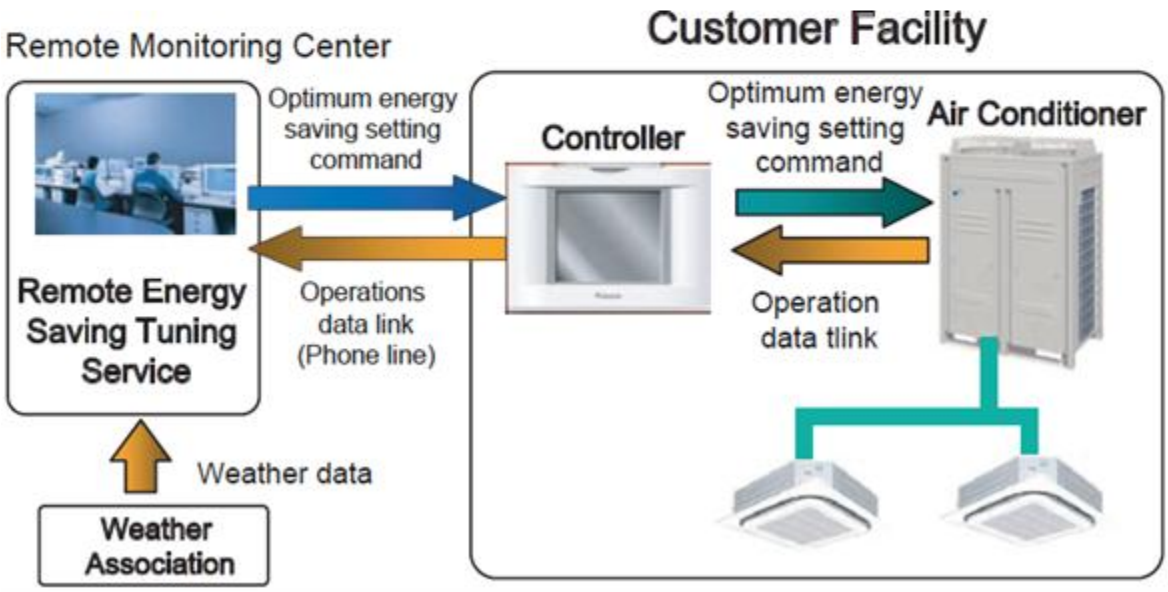
The energy consumption of air conditioning systems is highly dependent on user behaviour. In order to optimize user behaviour, the Japan based company Daikin Industries has developed a remote energy tuning service. Besides offering and coordinating maintenance services, it integrates a remote distance tuning. The Remote Monitoring Centre collects performance data of the connected air conditioning systems and optimizes their calibration in terms of energy efficiency. The main goal is to cut energy consumption while ensuring maximum convenience for the users by adapting the system to their needs. The service combines data on the building the system is installed in, past and present operational performance of the connected and similar systems and on local weather (and weather forecasts). As a result, the system reduces the likelihood of impaired comfort levels by the air conditioner when compared to ordinary on-and-off control systems.

An increase in the efficiency of the air conditioning system is achieved in three ways:

1. Keeping the consumption of electrical energy under an adjusted maximum value.
2. Avoiding over-cooling or over-heating.
3. Automatic control of the air conditioning based on building-specific factors of influence (e.g. purpose of the building, number of employees)

First tests and calculations assessing the service have revealed that it may cut energy consumption for air conditioning by about 20 % (Daikin Industries 2010).

Figure 3.2 | Overview of the energy saving system



Source: Daikin Industries (2010).

3.3.3 | Green roofs

Green roofs offer great resource-efficiency potentials – and most people like their aesthetics. They are essentially roofs covered with plants and protected against roots and water by membranes. Since plants are biodegradable and the membrane is often made from recyclable plastics, end-of-life costs (economic and ecological) are typically lower. Furthermore, roof planting reduces the need for heating and air conditioning by reducing the thermal gradient between the building interior and roof, and thus cuts energy consumption.

Green roofs can be divided into two categories: intensive and extensive. *Intensive* green roofs are roof gardens and preferentially have a recreational purpose only. Similar to ground level gardens they need intensive care and often require artificial irrigation. *Extensive* green roofs are covered with herbs, grasses, mosses and drought tolerant succulents; they need minimal maintenance and irrigation (Blackdown Horticultural Consultants Limited 2006).

Extensive green roofs (and sometimes intensive ones as well) serve many purposes from both the building perspective and in providing ecological, economic and even psychological benefits. Green roofs offer both insulation in winter and cooling in summer. In summer, they prevent solar irradiation from being absorbed by roof surfaces. Instead, green roofs convert solar energy into photosynthesis activity and evapotranspiration. In winter, they not only insulate through added mass and materials, but also induce heat through biological activity, as well as serving as wind protection by creating a thicker boundary layer through an increased roughness length. The insulation effect however depends on the amount of water absorbed by the substrate and plant layers.

Due to protection against ultraviolet radiation and huge temperature fluctuations (which cause membrane roofs to deteriorate), green roofs have an estimated durability of 40 years, compared to 15-25 years for membrane roofs. Other benefits are improved rainwater management and a reduction of air pollution (see FBB 2010 and Blackdown Horticultural Consultants Limited 2006 for more information).

In Germany, about 12 % of all roofs are green roofs. The green roof industry has been assessed to be growing by 10-15 % per year (Michigan State University 2010).

Green roof

Source: Optigrün, FBB 2010

3.3.4 | Low Energy: Energy quality matters

Buildings play a significant role in the generation of anthropogenic CO_2 emissions (see 2.2.2). Besides the reduction of fossil-based operational energy, for instance through more ambitious insulation, another approach that is becoming more and more popular is called low energy (see e.g. the Annex 49 project). In short and applied to the urban fabric, the energy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. When the surroundings are the reservoir, energy is the potential of a system to cause a change as it achieves equilibrium with its environment. Energy sources are usually solar radiation, tidal forces, and geothermal heat. Ground source heat and geothermal energy have huge potential in the building sector, and there are many new methods of capturing passive solar energy as heat, as well as passive wind energy for more efficient ventilation (Meggers, F. 2010).

Especially for the building stock, e.g. in historical city centres of many European cities with listed buildings as well as for office buildings where internal heat gains can be used, the insulation of the facades do not offer an adequate response to the above mentioned environmental challenges and social-cultural goals. Eliminating fossil fuel-based energy will be an important step toward zero emission buildings. The appropriate and locally adapted mixture of energy efficiency as well as low energy measurements carries an interesting potential for more resource-efficiency in construction.

4 | Grand challenges and barriers and drivers of eco-innovation

The EIO has had undertaken an on-line Delphi survey among construction experts in various European countries from mid-December 2010 until mid-February 2011. The first round of the Delphi received 128 responses. The analysis of this chapter will be largely based on the results of this survey.[6]

4.1 | Grand challenges and resource-efficient construction

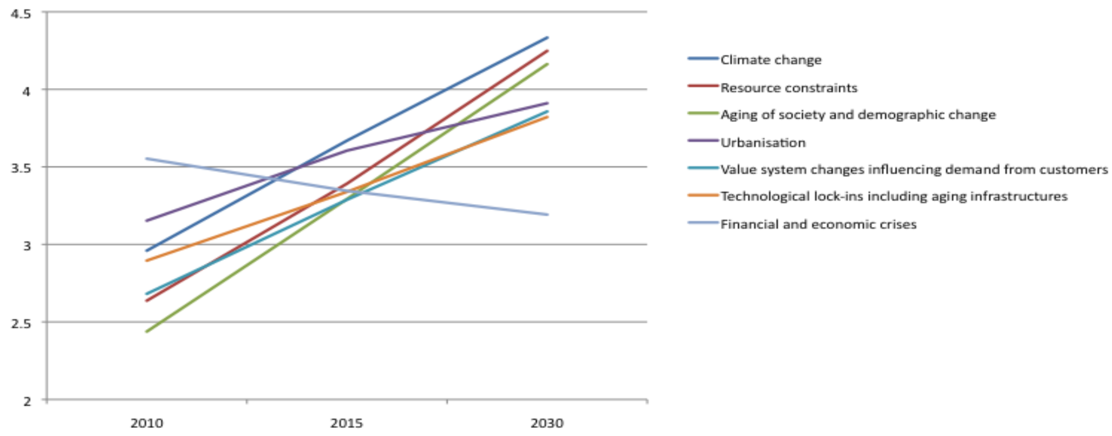
According to the experts surveyed, the financial and economic crises currently have the strongest impact on the construction sector by far. This result does not come as a surprise, especially given that the consequences of the recent financial crisis are still suffered across the European and global economies. Urbanisation, climate change and technological lock-ins (including aging infrastructures) followed in terms of the strength of the impact. The least relevant challenge today was seen to be the aging of society and demographic changes, as well as resource constraints.

Experts foresee substantial changes in the challenges that will have the greatest impacts on construction in the future. The relevance of all challenges is thought to grow, with the exception of the financial and economic crises. According to the experts, 20 years from now the impact of climate change, resource constraints and an aging society will exert the strongest influence on the construction sector.

While these results represent expert opinions and must, therefore, not be taken as strong prognoses, they are representative of the kind of forward-looking thinking needed in innovation efforts, as well as policy guidance, today.

[6] *In the last quarter of 2011, the EIO will also produce a foresight report on sustainable construction based on two rounds of Delphi surveys, scenario development, impact analysis and roadmapping.*

Figure 4.1 | Impact of grand challenges on the resource efficient construction



Source: EIO Delphi survey (2011); horizontal axis based on the average ranking of responses (scale: 1 to 5 where 5 is the highest impact)

4.2 | Drivers and Barriers of resource-efficient construction

The potential for eco-innovation seems enormous. However, innovation processes are shaped by numerous drivers and barriers that determine their outcomes, notably their implementation on the market. Some drivers and barriers are pervasive to any innovation processes – such as financing and information deficits. Others are genuine to or more important for eco-innovation. Rennings (2000) refers to a ‚double externality' for eco-innovation: competitors may take advantage of non-internalization of negative externalities while at the same time the innovation is faced with the positive externality of delivering a socially desired outcome with comparatively low private benefits.

The EIO analyses determinants of eco-innovation in five groups:

- Economic and financial factors (e.g. market position, access to capital, cost factors)
- Technical and technological factors (e.g. access to and ability to develop technical and technological solutions, infrastructure, technological lock-ins)
- Environmental factors (e.g. access to and need of material and natural resources)
- Socio-cultural factors
- Human resources and knowledge base
- Organisational and management capacity

- Social capital (ability to collaborate and to take collective action)
- Cultural capital (including attitudes towards change, risk)
- Regulatory and policy framework (including legal system and ownership, standards and norms, intellectual property rights, public policy) (EIO 2010).

In the Delphi survey, experts were asked about drivers and barriers in each of these categories (Figure 4.2). As regards drivers, results reveal that the strongest drivers of eco-innovation according to the experts surveyed are a good skills base and strong collaboration between research, experts and business. Additionally, the regulatory and policy framework are seen as having growing importance, especially concerning ambitious regulations and standards as well as government subsidies and incentive based programmes. Market drivers are among the relatively weakest determinants of eco-innovation in the construction sector: the prices of building materials and the competition for innovative building components are not currently considered strong incentives to eco-innovate. The relevance of both drivers is expected to slightly grow in the future.

The most significant barriers of eco-innovation in the construction sectors were also seen by experts to be related to socio-economic factors, especially to deficiencies in the knowledge base (e.g. lack of knowledge of planners and technicians) and social factors (e.g. risk averse attitudes in the construction sector and the lack of awareness of home owners). While a lack of demand for eco-innovative buildings (user-investor dilemma) were considered critical today, this was considered to have decreasing importance as a barrier in the future. Indeed, user demand is expected to grow as driver over the next 20 years.

This chapter explores the five groups of eco-innovation determinants in more detail.

Figure 4.2 | Drivers and barriers according to the EIO Delphi survey Drivers

	Drivers	2010	2015	2030
Economic and financial factors	Competition for innovative building components	2,9	↗	↗↗
	High price of building materials (as an incentive to search for substitutes)	2,8	↗	↗↗
Technological factors	Innovative technology development	**3,2**	↗	↗↗
	High research and development activity in the construction sector	**3,2**	↗	↗↗
Environmental factors	Scarcity of materials for energy and resource-efficient technologies	2,6	↗	↗↗
	Favourable geographical location (e.g. stable temperatures, ground composition)	2,4	↗	↗
Socio-cultural factors	Building planners skilled in sustainable construction (architects, engineers, etc.)	**3,5**	↗	↗
	Strong collaboration between research, experts and business in the sector	**3,4**	↗	↗
	High level of awareness of building/home owners	**3,3**	↗	↗↗
	Handworkers skilled in sustainable construction (electricians, plumbers, etc.)	**3,3**	↗	↗
	High level of acceptance of building/home users	**3,3**	↗	↗↗
Regulatory and policy framework	Ambitious building regulations and standards	**3,4**	↗	↗↗
	Subsidies and programmes for sustainable construction	**3,4**	↗	↗
	Green public procurement	3,0	↗	↗↗
	Construction materials tax	2,5	↗	↗

	Barriers	2010	2015	2030
Economic and financial factors	Building materials are too cheap	2,6	↗	↗
	Building materials are too expensive	2,9	↗	↗
	Limited access to venture capital & other sources of finance for innovative projects	**3,2**	↘	↘
	Price of materials for innovative technologies is too high	**3,7**	↘	↘↘
	Lack of competition for innovative building components	**3,3**	↘	↘
	Limited demand for eco-innovative buildings (user-investor dilemma)	**3,9**	↘	↘↘↘
	Refurbishing too expensive	**3,8**	↘	↘↘
Technological factors	Lack of innovative technology development	**3,3**	↘	↘↘
	Technological lock-ins (e.g. old energy infrastructures)	**3,7**	↘	↘↘
	Low research and development activity in the construction sector	**3,8**	↘	↘↘
Environmental factors	Scarcity of materials for energy and resource-efficient technologies	2,5	↗	↗↗
	Unfavourable geographical location (e.g. limited sunlight, extreme temperatures)	2,6	↗	↗
Socio-cultural factors	Weak collaboration between research, experts and business in the sector	**3,8**	↘	↘↘
	Lack of knowledge/training of handworkers (electricians, plumbers etc.)	**4,0**	↘	↘↘
	Lack of knowledge/training of building planners (architects, engineers etc.)	**4,0**	↘	↘↘
	Lack of awareness of building/home owners	**3,9**	↘↘	↘↘↘
	Lack of acceptance of building/home users	**3,7**	↘	↘↘
	Risk averse attitudes in the construction sector	**3,9**	↘	↘↘
Regulatory and policy framework	Lack of subsidies and programmes for sustainable construction	**3,5**	↘	↘↘
	Unambitious regulations and standards	**3,6**	↘	↘↘
	Monitoring and certification underdeveloped	**3,7**	↘	↘↘

Source: EIO Delphi survey (2011); average results of 128 responses; results in bold are above 3; Legend: experts rated all factors from 1 to 5 where 5 was the highest importance. The symbols indicate:

↗ or ↘ lower / higher importance by less than 0.5 compared to the 2010 rating; ↗↗ or ↘↘ lower / higher importance by more than 0.5 and less than 1.0 compared to the 2010 rating; ↗↗↗ or ↘↘↘ lower OR higher importance by more than 1.0 point compared to the 2010 rating.

Economic and financial factors

- Prices determine economic decision-making, but often in an imperfect way. Ideally, prices not only need to tell the 'ecological truth', but also need to capture other unwanted and indirect effects. Examples may include:
- Building materials are relatively cheap, environmentally sound materials too expensive;
- Refurbishing is too expensive because it is labour-intensive and requires specific skills;
- Secondary materials / re-used construction materials are usually not competitive and faced with high volatility;
- Scarcity of materials for energy and resource-efficient technologies; here, one needs to take into account the volatility of raw material prices that make rational expectations for future prices more difficult;
- Lack of financial incentive to invest specifically in eco-innovations. This may be due to a lack of investment support, tax advantages, public support, etc.

According to the survey results, prices for building materials are not considered strong incentives to innovate or to search for more environmentally friendly substitutes. The relevance of price is expected to grow in the construction sector in the future, perhaps indicating that experts expect price to more fully reflect the 'ecological truth' in 2030.

Competition for innovative building components was also not seen as a very relevant driver of eco-innovation activities today. This may reflect a 'first mover' trap in the current structure of the construction sector. Typically, companies have an incentive to continually enhance their processes and products and thereby gain price or quality advantages over their competitors. However, there are also risks associated with the expenses for research and development ('sunk costs') as market success is uncertain. Companies, therefore, have an incentive to be the 'first mover' only with appropriate patent protection and expectations about future demand; given real uncertainties, it is often rational for companies to wait and see in order to benefit as the 'second mover' from the pioneer's efforts in market development. This may especially be the case in the construction sector due to it rather traditional nature; lack of consumer acceptance and awareness are ranked as high barriers.

Indeed, the lack of demand for eco-innovative buildings (user-investor dilemma) was seen as one of the strongest current barriers to eco-innovation in the sector. This may be enhanced by split incentives between building owners and building users to invest in, for instance, energy-efficiency technologies with a long payback period (Schartinger 2010). Experts foresee that the situation regarding demand will improve in time; the relevance of this barrier is expected to decrease substantially in 2015 and 2030.

Technological factors

Path dependencies and market power favour incremental innovations and hinder investments in radical innovations and in system innovations (e.g. solarized infrastructures, low fossil carbon neighborhoods, etc.). Quite often, the capabilities may be lacking, for example, through managerial deficits, lack of technological understanding, learning ability or absorptive capacity to make use of externally generated and new technology.

Hence, eco-innovation is not exclusively about enhanced research and technology supply, but also about the development of competencies, about an active capability enhancement and about the creation of lead markets. Urban areas with lighthouses – see the upswing of Bilbao (Spain) after the Guggenheim Museum was erected – offer rich potential that is often not fully exploited. The following barriers in this category seem relevant:

- Technological lock-ins (e.g. prevailing energy infrastructures),
- Low research and development activity in the construction sector,
- Risk averse attitudes in the construction sector,
- Lack of competition for innovative building components,
- Lack of willingness of public administrations to develop innovative infrastructure and housing development concepts.

According to the Delphi survey, technological factors are currently among determinants of average significance. In the next five and further twenty years the drivers ‘high research and development activity in the construction sector’ and ‘innovative technology development’ are estimated to keep increasing in their relevancy. In contrast, all the barriers related to technology in the EIO survey were anticipated on average to diminish in their relevancy. Technological lock-ins were estimated to be slightly above the average significance at present and to have a mild decrease of relevancy during the next twenty years.

Environmental factors

While environmental related drivers and barriers to eco-innovation may be numerous, only two issues were brought under the attention of experts in the first round of the Delphi survey: namely, the ‘scarcity of materials for energy and resource-efficient technologies’ and ‘(un)favourable geographical location’’. In relation to the current situation, the experts regarded both issues (as a driver and a barrier) as among the weakest determinants of eco-innovation.

According to the results of the survey, experts estimated that the impacts of the grand challenge ‘resource constraints’ would strongly increase in the next two decades. Following the same logic, the relevance of the ‘scarcity of materials for energy and resource-efficient technologies’ was on average estimated to gain increased relevance both as a driver and a barrier to eco-innovation. However, experts positively estimated 'scarcity of materials' as more relevant as a driver than a barrier. It could thus be interpreted that experts expect the grand challenge of 'resource constraints' to create opportunities for eco-innovations during the next twenty years.

As regards 'geographical location', experts on average considered its relevancy now to be slightly below the medium. Only mild alteration towards increased relevancy of 'favourable geographical location' (e.g. stable temperatures, ground composition) was estimated to occur.

Socio-cultural factors

A good skills base and the strong collaboration between research, experts and business in the construction sector are among the strongest of all drivers of eco-innovation in the sector.

On the other hand, the determinants related to information deficits, i.e. the deficiencies of the knowledge base and social and cultural capital issues were considered by far to be the most critical eco-innovation barriers. Information deficits can be regarded as parts of human life and all economic activities. However misallocations of resources can occur due to frequently asymmetrically distributed information, for example, if users or other relevant decision-makers know less about resource efficiency than producers or experts. Quite often, knowledge does exist, but can be seen as dispersed among too many people who are unable to get connected. This leads to a market barrier for improvements (Feige et al. 2011).

According to the experts surveyed by the Delphi survey, four out of five of the most relevant barriers of eco-innovation relate to information deficits and socio-cultural factors. In particular, the lack of knowledge and training of building planners (architects, engineers, etc.) and of hand-workers and technicians were rated as the most significant among all barriers in the survey. A number of new trainings will be needed across Europe to close the skills gap and meet future skills requirements in the construction sector (Schartinger 2010). Other highly ranked barriers considered as important factors hampering eco-innovation in this category included risk-averse attitudes, low research and development activity in the construction sector (see also results from the Eurobarometer survey in this report) and weak collaboration between research, experts and business.

Regulatory and policy framework

Needless to say, policy has a role to play in overcoming barriers and enabling the full commercialisation of green innovations, especially regarding the barriers resulting from system failures. Indeed, policy inconsistencies, lack of coordination and related failures should be recognized and removed. Government can work to remove barriers to full participation by the public and private sectors and other stakeholders in the development of innovative solutions to social problems and thus help to develop a shared vision and make policies more effective in meeting social goals. Relevant barriers are as follows:

- Lack of subsidies and programmes for sustainable construction (much exists on CO_2 reduction though),

- Unambitious regulations and standards,
- Monitoring and certification underdeveloped,
- Lack of a ‚champion' who is willing to lead and shows his/her face if resistance against large-scale transitions occurs,
- General lack of visions, capabilities and accountability, combined with existing intransparencies.

Experts considered ambitious regulations and standards along with government subsidies and programmes to be relevant eco-innovation drivers. Significantly, the importance of regulations and green public procurement is expected to grow over the next 20 years. The experts surveyed do not believe that a construction materials tax will become a strong driver in the future – be it because they believe it is ineffective or because they do not expect it to come into force – but its relevancy is expected to increase somewhat. There is substantial debate on this topic, however, and the opinions of experts surveyed by the Delphi may not reflect scientific examination about the potential impacts of such a tax (see for instance EEA 2008).

Unambitious regulations as well as underdeveloped monitoring and certification systems are currently considered strong barriers; these factors represent serious information deficits. The experts, however, believe that the importance of these barriers will decrease in time.

All in all, the Delphi survey revealed that in general, experts expect drivers to be intensified and barriers to decrease in their relevancy, with the exception of environmental factors, in the future. It must be remembered that this examination is based on a survey, and as such results should be used with caution. Nevertheless, if these general trends prove to be true, it may indicate opening doors for eco-innovation as hindrances are removed and drivers intensified over the coming decades.

5 | Visions of a resource-efficient construction sector

From a resource perspective, it is the throughput of materials that has to slow down in order to enable a sustainable and long-lasting prosperity. Because the construction sector is such a major driver of current material throughput (extraction to disposal) there are a number of 'visions' to improve it. We will focus on two: the steady-stocks society and the solarized technosphere[7], and how they relate to construction. Both reach beyond just improving the resource efficiency of material flows to depict a structural shift in the industrial metabolism; we will explore how this could transform the construction sector into a truly resource-efficient industry. These visions roughly sketch concepts that we feel are necessary to make the transition to a 'sustainable society', but they are by no means scenarios of what we expect or roadmaps of what we think should happen. They are ideas. As the saying goes; every good innovation starts with an idea. In putting these concepts on paper we hope to spark debate about ideas for the future, perhaps trigging eco-innovations in ways that have not yet been thought of. They are a starting point, which we hope to accompany and further develop in the context of the Eco-Innovation Observatory[8].

To present our ideas we take the perspective of a citizen of the future (living around 2100), reflecting back on how the transition towards sustainability was achieved.

5.1 | The transition to a steady-stocks society

As a result of the flagship initiative 'resource-efficient Europe', and the accompanying initiatives to achieve it, as well as rising material costs, businesses implemented a number of innovations to improve resource efficiency in the 2nd decade of the 21st century. In the housing sector this represented a shift towards greater levels of industrialized construction with better potential to optimize material use. At building construction sites, waste quickly became a thing of the past as materials became too expensive to waste carelessly. But, the net physical stock of buildings and infrastructure continued to expand and the industrial metabolism was still based on the linear flow of resource extraction, consumption and disposal.

While resource efficiency reduced the size of these flows, the system still relied on a resource supply and absorption capacity greater than the earth could supply. This was also a result of the spectacular growth of 'transition' and 'developing' countries as they reached living standards closer to those of 'industrialized' countries in the second and third decades of the 21st century. At the same time, in the European Union

[7] The visions presented here are mostly based on the visions presented in Bringezu (2009), available here, which are described in the EIO Annual Report.

[8] The EIO invites your feedback and comments to the visions presented here under: www.eco-innovation.eu

population growth continued to slow down and even decline in many member states (Eurostat 2008). In Western European countries particularly, the built environment was already extensive. Entrepreneurs and politicians both recognized the potential in the existing stock of, increasingly empty, buildings. Instead of continuing policy structures that favored new dwellings, frameworks shifted to favor renovation and refurbishment, for example through policies like a construction materials tax. As urbanization continued, entrepreneurs recognized that the building stock not only held value for refurbishment, but that the materials contained in the building stock of 'aging cities' also had value. Efforts to regain this material increased, and urban mining became a buzz word across the European Union.

To aid urban mining efforts, governments set up monitoring mechanisms to keep track of which materials were contained in the building stock. Geological services were supplemented by resource management departments, which established inventories of material stocks, facilitated knowledge transfer between real estate agencies, architects and construction engineers as well as universities, the recycling industry and others. They provided information on the technological options and regional potentials for acquiring recycled material for the (re-)construction of buildings and infrastructure. Buildings and infrastructures received a compulsory *resource inventory,* which listed the amount and types of materials it contained, as well as the information necessary for their recovery. The information was saved on a chip incorporated in the building, with the possibility for up-dates, e.g. in case of repair or renovation, with relevant construction items being equipped with RFID[9] pads. An inventory to identify all site and building components also became important for the real estate business, as the value of the buildings increased with the amount of recyclable materials. Incidents where copper cables were buried and forgotten became stories of the past.

As urban mining efforts intensified, architects and building planners started designing new and renovated buildings and sites in a way that would ease this end-of life recovery process. Growing concerns for resource use coupled with waste reduction mandates led to increased recalling of construction and demolition debris. To facilitate this practice, the processes of dismantling a building or site shifted from demolition to deconstruction. Engineers further developed old materials (like cement, see section 3.1.1) and innovative new building materials (like panels) so that they could be easily re-used and recycled. This trend extended not only to the building exterior, but also to interior building elements (like carpet, facets, fixtures). As re-use increased, the concept of maintenance, guarantee and responsibility changed. Companies realized that if they designed their products in such a way to enable easy re-use, it also made sense to be the ones doing that re-using. In this way they could create a closed-loop system of supply. As a result, logistic departments expanded and branched out--reverse logistics became common practice.

Construction minerals continued to enter Europe's industrial metabolism, but to a much lesser extent than at the beginning of the century. As the rate of the building stock matured and the lifetime of a large portion of existing building stock came to an end around the 2030s, the market was flooded with scrap metals. This marked a fundamental shift of entire economies toward sourcing secondary minerals rather than primary ones, because they were both cheaper and closer.

The building industry changed with the times; it evolved to shift its primary activities toward renovation and refurbishment, and – to a growing extent – deconstruction of old and reconstruction of new buildings at the

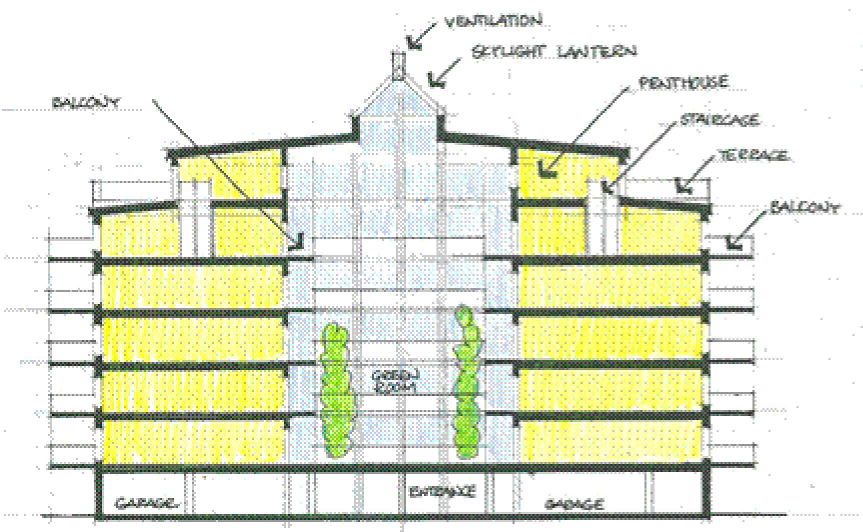
[9] *RFID stands for Radio Frequency Identification Device*

same location. Engineers and craftsmen became experts in renovation and the search for resource efficient potentials (e.g. through insulation, more exact planning, or inspection to avoid damages due to lacking repair), and brick-layers and builders were trained to handle both traditional and modern materials in a resource saving manner. Dematerialization was also achieved with a greater focus on resource-light buildings, focused on designing functional buildings that operated as a system in and of themselves. Building automation jointly with smart grid technologies on the neighbourhood or even city level helped to better regulate and control buildings so that they used minimal energy for maximum comfort. New materials aided this shift. Nanotechnology enabled innovation in building materials, for instance replacing heavy concrete with carbon columns.

The public also began to approach building functionality differently. As it became clear that increasing the building stock meant encroaching on valuable agricultural, forestry and nature areas, people started intensifying the use of existing buildings through multi-functionality. Along with societal change and collective action towards sustainable consumption, shared space became common, with buildings performing different services during the day and at night. The way people approached living space also changed, with a number of people content to live in a more compact way, sharing for instance common space, such as gardens, and utilities, like washing machines.

As the building stock was undergoing radical systemic changes, so were the transport and infrastructure networks. High costs of road maintenance triggered innovation for less resource consuming patterns of maintenance and repair, aimed at a higher durability and appropriate modes of exchange between the system components. The construction of new roads, especially in member states with extensive road systems, slowed down as transport policies shifted away from expansion of highways to the optimization of existing infrastructures. In some member states, new roads could only be built when the constriction or deconstruction of roads at other places was undertaken.

Figure 5.1 | Example of sustainable urban living from Anders Nyquist, Swedish Architect



Source: Anders Nyquist Arkitektkontor AB. The Nydala Project Umea, 32 apartments built based on a social, ecological, technical and economic vision. See EcoCycleDesign for more information.

The overall extension of water supply and sewage systems also approached a steady-stock phase. First, during renovation in the 2020s and 2030s the systems were diversified to adapt to low, medium and high density conditions. In this way, the resource-efficiency of water supply and wastewater management increased dramatically. For instance, in less populated regions, central sewage systems were increasingly substituted or supplemented by semi-central and decentralized systems. The high costs of renovation led to the development of more material and energy efficient ways for construction, operation, maintenance, renovation and deconstruction of utility systems. And, the re-use of nutrients such as phosphorus became a big business.

This also marked a shift in the logic of utility services, from conventional supply-driven logic of building up network capacity to meet constantly rising demand to a demand-orientated management of facilities and services. Innovation cities were created where green building design was integrated into the surrounding urban infrastructure. First trials to this end occurred already in the beginning of the century, and revealed new approaches towards participation of different stakeholders and communities related to urban planning. Thus, the innovation processes not only had its roots in specific technological visions, but also in the different ways people wanted to live. Therefore, issues of resource management combined with other societal forces shaped urban development in innovation cities. New models of urban development demonstrated how the interaction between the physical and technical side of service provision and the socio-cultural dimensions of resource consumption could powerfully shape the context for environmental innovation.

At the beginning of the century, the net addition to stock (NAS) amounted to about 10 t/cap in Europe. It represented the mass of additional buildings and infrastructure, and thus, the physical expansion in the material stock of the technosphere. Before the middle of the century this growth phase was superseded by a 'maturity phase' in Europe, characterized by a dynamic, steady-state flow equilibrium between input and output. Eventually, NAS approached values around zero around the turn of the 22nd century. This does not mean a fixed input and output of specific materials, but an overall balanced system. The construction industry has remained a dynamic industry, having adapted to the changed system by fulfilling customer's desires with renovation and refurbishment, increasingly sourcing recycled materials from urban mining, and employing ever-increasing resource-light innovations in (re)construction.

5.2 | The solarized technosphere

At the turn of the century, the prospect of replacing fossil fuels with biofuels was extremely popular. It didn't take long to realize that this was not the most effective strategy for Europe. That was because in 2010 average solar technology could already transform about 10 to 20% of sunlight into energy. Highly efficient crops could utilize no more than 6%. Instead, research and innovation activities worked to find a way to better mimic natural systems, by using sunlight to produce both energy and materials. Both had big implications for the construction sector.

Left: building integrated PV fasade (location: Ferdinand Braun Institute, Berlin, Germany).

Top Right: Roof-integrated PV system (location: the French Alps) (Sulfurcell Solartechnik GmbH: www.sulfurcell.com

Bottom Right: Building integrated Photovoltaics (location: SCHOTT Solar headquarters, Mainz, Germany) (SCHOTT Solar GmbH 2008).

As the century progressed, innovations in solar technologies also increased. By 2050, innovation had made it possible to achieve around 60% PV efficiency on average. In the construction sector, greater technology integration became more and more common—especially building-integrated photovoltaics (BIPV). This meant that the absorption, transformation, and transport of solar energy could be better integrated into the "skin" of the technosphere[10]. Instead of plugging special equipment on top of roofs and in front of facades, the photovoltaic elements could be integrated directly into the surface of buildings, sparing materials and costs. First steps had already been realized at the beginning of the century in the form of photovoltaic tiles and photovoltaic curtain walls. Thin layer technology further allowed window panels to function as solar panels[11]. The more technology integration proceeded, and functions such as solar radiation control (absorption, transformation or reflection), insulation, humidity control and static functions became compounded, the higher the degree of resource efficiency which could be achieved.

The ‘solarized technosphere’ became a reality. It meant that buildings were capable of producing their own energy. Roads were sometimes lined with photovoltaic elements, further reducing the need to use arable land for energy production. In the first half of the century, solar energy was mostly used for heat and

[10] Lightfoot and Green (2002) estimated that only the world roofs could supply 15 EJ solar electricity per year (with 5 EJ in OECD countries)

[11] See for instance ongoing activities at Oxford Photovoltaics Ltd., among many others.

electricity. However, activities using sunlight to produce hydrogen from industrial by-products, water (hydrolysis) and other sustainable sources also increased. While hydrogen and derived hydrocarbons could be used as a fuel, scientists started to increase efforts towards developing 'industrial photosynthesis'. They used recycled carbon—from carbon capture and re-use—, hydrogen (and hydrogenated compounds), and sunlight to mimic the biochemical process of photosynthesis. This is an innovation that, when it became mainstream (around the turn of the 22nd Century), revolutionized the industrial metabolism toward a photoautotrophic system. It also eased land use pressures as food continued to be produced naturally, but biomaterials began to be synthesized industrially.

However, the development of the solarised technosphere has also come at its costs. At the turn of the century, photovoltaic cells required a large amount of energy, especially to produce pure silicon or its substitutes. For instance, one kilowatt-hour of electricity from ground mounted PV-systems required 0.28 kg of abiotic primary materials at that time[12] (Graebig 2007). There were also trade-offs with regard to the quality of resources. For PV cells, often a combination of cadmium and tellurium or a combination of arsenic and gallium were used. These are hazardous substances which not only need safe handling during production, but also require a safe waste disposal. Throughout the century, innovation made gains in reducing material-intensity and finding less hazardous alternatives.

Altogether, the construction industry will have played a major role in transforming the industrial metabolism of the 20th century into the sustainable metabolism of the 21st century, both by adjusting to the demands of a steady-stocks society and integrating power supply in a multi-functional way, but also in a number of ways not mentioned here. And indeed, eco-innovation in construction remains a well-spring of new aesthetics and well-being.

[12] *Which was still significantly less than the material intensity of the German electricity mix of 4.7 kg/kWh$_{el}$*

6 | Main findings and key messages

1. There is a substantial potential to eco-innovate in the construction sector; good practice examples from across the EU display the wide range of eco-innovation happening in different countries—these activities can be enhanced and ramped up throughout the EU. Visions set out an ambitious pathway for construction in the future, but also reveal that the opportunities are both plentiful and within reach.

2. Different types of eco-innovation are happening in the EU, but the focus on incremental and product eco-innovation needs to be enhanced with greater levels of process and systemic change. While most of the eco-innovation so far has focused on products, process innovation is possible, especially through increased levels of industrialized construction. More radical innovation is happening in the form of urban mining, but efforts to this end should be intensified.

3. Experts see the impact of the financial and economic crises as the biggest challenge facing the construction sector today. In 20 years, however, the impacts of climate change, resource constraints and changed demographics are expected to have the strongest impact on the sector.

Box 7 Critical actions

To aid and enable greater levels of resource-efficient eco-innovation in the construction sector the following actions are considered critical:

- Recycling of construction materials: create a database to help facilitate recycling activities, develop better norms and standards, and better disseminate best practices and routines. The database should include information about the material composition of the built environment to enable better material re-use, recycling, and refining.

- Markets for eco-materials: step up research and development activities, as well as deployment strategies on eco-materials; make sure that innovative start-ups and SMEs have access to finance for such strategies; at the same time ensure that policies do not lead to problem shifting or a level of use which cannot be supported by sustainable supply.

- Stakeholder dialogues and strategic roadmaps: engage experts, stakeholders and policy makers in a discussion about visions for the construction sector. These visions should form the basis for policy guidance.

- Social learning: Step up public education about the sustainable refurbishment of buildings, e.g. by assessing local experiences and establishing networks at the European level.

4. According to the Delphi survey, the most significant determinants of eco-innovation today are related to socio-cultural factors, in particular regarding the knowledge base and skills training of both handworkers and building planners. As the skills base grows, the effect of this factor is expected to become more important as a driver and less important as a barrier. In contrast, resource scarcity is expected to become a very critical barrier for both energy and material-efficient technology in the future, whereas it is not considered very important today. Resource scarcity shall also increasingly act as an incentive to search for substitutes to develop new technologies and techniques in the future. The regulatory and policy framework is expected to grow in importance as a driver of resource-efficient construction.

5. All in all, a more comprehensive approach to building and renovation is needed; one that looks at how both energy and materials can be efficiently used, and considers the trade-offs between them. This involves a candid discussion about the benefits of renovation versus building new, and the political frameworks which favour one over the other. This discussion should happen today, to set the tone for role of the construction sector tomorrow.

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