INSTITUT
Veolia Environnement

S.A.P.I.EN.S VOLUME 3 ISSUE 2 2010

Surveys

Redesigning Urban Infrastructures for a Low-Emission Future An Overview of Urban Low-Carbon Technologies

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Abstract

Preventing the worst consequences of climate change would require that GHG emissions be reduced to levels near zero by the middle of the century. To respond to such a daunting challenge, we need to rethink and redesign the currently highly energy-dependent infrastructures of industrial societies and particularly the urban infrastructures to become low- or even zero-carbon cities. Sustainable urban infrastructures need technology. In this paper focused on Western European Cities, we discuss a wide set of technologies in the fields of building, energy and transport infrastructures that can significantly contribute to a reduction of energy and/or GHG emissions and are already available or are in the pipeline. Based on the review of a recent study for the city of Munich, we then present how a mix of these technologies could reduce CO_2-emissions by up to 90% for the metropolis of 1.3 million inhabitants and that this strategy could be economically attractive despite a high initial investment.

All of the residential buildings of a city like Munich could be entirely redesigned for €200 per inhabitant annually, which is about one third of an average annual natural gas bill.

Keywords: Low carbon infrastructures, low carbon technologies, energy efficiency, renewable energies, urban infrastructure planning, Munich.

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Published: 20 October 2010.
Edited by: Gaëll Mainguy – This paper has been reviewed by Chris Kennedy and another anonymous referee

1. INTRODUCTION

Our cities are facing a huge transformation challenge. Today almost all large cities around the globe rely heavily on highly energy-intensive urban infra-structures. According to IEA (2008) by 2030 cities will consume about 73 per cent of the world's energy and producea comparable share of the world's greenhouse gas emissions. To prevent the worst consequences of climate change would require that GHG emissions be reduced to levels near zero by the middle of the century (Rockström *et al.* 2009, IPCC 2009, 2007, WBGU 2009). This means that urban infrastructures have to be converted to systems that consume less energy and produce almost no emissions by the middle of the century – or, in short, transformed to low carbon urban infrastructures.

To achieve this transformation, cities need political will and guidance. Many cities around the globe already have set ambitious GHG mitigation targets (Lechtenböhmer 2009b). Cities also need broad participation by all stakeholders, as well as societal and technical innovation (Dröge 2010). Here we focus on the latter. Sustainable urban infrastructures need technology. In the following pages we survey the most relevant fields of urban infrastructure of Western European cities for currently available or future low carbon technologies (LCTs) that offer the potential for a significant reduction in energy demand and/or GHG emissions.

Our survey shows the availability of LCTs, their economic prospects and their infrastructural prerequisites for three main fields of transformation of urban infrastructures:

- Technologies for energy efficiency in buildings regarding a) their heat demand and supply as well as b) the electricity demand of the appliances and the equipment used in buildings.
- Technologies for reducing the energy demand of goods and passenger transport in the city.
- Technologies for the adaptation of the energy supply infrastructure to low energy demand and to a renewable or low carbon supply.

Particular technologies, however, that apply to energy intensive production and industries or such technologies that generally do not occur on a municipal level, such as central power plants, have not been considered in this paper or in the case study for Munich. The latter is reviewed here as an example of the use of the LCT matrix.

2. METHODOLOGY OF TECHNOLOGY SELECTION AND REPRESENTATION

To achieve the overall goal of a GHG emission reduction of 80 percent or even more in large cities by 2050, it is necessary to reduce energy use and emissions in every field to an absolute minimum. Embracing this principle for each of the technology areas that are relevant in cities, we surveyed and selected technologies that can be regarded as capable of significantly reducing energy use and/or GHG emissions to a very low level or that are necessary as parts of a low energy or low emissions system (e.g. enabling the use of other necessary technologies). To establish the list of the LCTs, we undertook a literature review, including internet resources, plus a survey of experts, primarily from different business areas of Siemens. Technologies such as those that are related to the central electricity generation and distribution system were not taken into account here as they are typically located outside the urban infrastructures.

After collecting and selecting relevant technologies, we grouped them by market segment and categorised them according to the potential width and depth of their energy and GHG mitigation potential, their availability and costs, etc. as given in Tables 1 to 4. The categorisations and the estimates used to complete the information in Tables 1 to 4, which mainly reflect the current situation in Western European cities, have been checked further during two workshops in the spring and summer 2008 with technology experts from Wuppertal Institute and Siemens.

As a first step, the **mitigation potential** of each LCT was estimated in order to provide a scale of the potential relevance of all LCTs within a low emission strategy. For the purpose of our estimate, we defined the mitigation potential as the product of the depth and width of an LCT. By **depth**, we characterise the relative order of magnitude of the energy or emission reduction that can be achieved in comparison to a standard or reference technology. In one particular case, a passive house, the energy saving would be around 80 per cent of the energy of a conventional, new building.

In order to provide an ordinal ranking of the technologies, we define four groups of technologies according to their relative mitigation potential (depths). The first group delivers net/zero savings vs. standard technology (–/0). Such technologies are taken into account only when they are needed as enabling technologies for others with higher potentials. The second group of technologies delivers moderate savings (up to 33% vs. standard technology) (+). The third group delivers 33 to 66% savings (++). The fourth group offers high savings of between 66 and 100% vs. standard technology (+++).

The second dimension of the potential is its **width**. This is the size of the potential in regard to the applicability of the LCT in the respective market or technology segment. We discriminate between niche & low width technologies that cover less than 33% of the respective segment (+), medium width technologies that can be applied to between 33 and 66% of the segment (++) and high width technologies that potentially cover more than 66% of the segment (+++).

As it clearly influences the introduction strategy, we qualitatively describe in a separate column of the tables whether and which **system changes** need to be introduced to make use of an LCT.

Finally, the product of depth and width of the mitigation potential of a certain LCT, as given in Tables 1 to 4, indicates its overall reduction potential compared to the standard technologies in that segment. However, the share of the total potential depends on the specific situation in every city and on more detailed scenario analyses (e.g. Lechtenböhmer et al. 2009a).

Further to the potential, we characterise the LCTs according to their **life cycle costs**. Such a characterisation is, however, somewhat difficult for a time span of 40 to 50 years. Innovation will lead to significant changes in the costs of LCTs and the costs of fossil fuels and the external costs of the energy system will greatly change during the decades to come. Therefore, the economic aspects of the LCTs should be seen from a dynamic perspective. We reflect this with two estimates, one for the current status and one for the future, when the respective LCT is expected to have reached a certain status of maturity. We also provide the estimated date when the technology will have reached this mature status.

Given the long time frame of this overview, we cannot provide exact costs. Thus, we do not provide hard quantitative estimates like those given in the marginal abatement cost curves (MACs) that were developed by McKinsey[1], E.ON (2006) or others. These MACs are typically calculated for timeframes that end in 2020 or 2030 (by McKinsey) at the latest. For a timeframe that ends in 2050, the uncertainties regarding future costs of LCTs, as well as the costs of fossil energy supply, are too great to permit such quantifications (Fleiter *et al.* 2009).

Instead, we group technologies into three main categories for their comparative life cycle costs vs. standard technologies. Technologies in the first category lead to increased life cycle costs vs. a standard technology. We regard this as significant if the estimated increase is at least one third (and up to two thirds). The second category of technologies has or promises life cycle costs that are approximately (+-33%) equivalent to standard technologies. Finally, the third category consists of technologies that provide life cycle costs that are significantly (more than a third) lower than those of standard technologies.

For the total life cycle costs, the investment typically is a very important factor, however as many technologies discussed here substitute energy for capital, the expected development of future energy prices is even more decisive. With potentially high future fossil energy prices, the life cycle costs of the LCTs are often lower than those of standard technologies. For our survey, we assumed an annual real increase in the price of electricity of 1% per year from a current level of 20 ct/kWh to 32 ct/kWh in 2050, and for fuels in a range from 1.5 to 2.5% (i.e., from 8 ct/kWh to a level of 16 to 26 ct/kWh[2]). We do not explicitly take external costs, as well as CO_2-prices, into account. However, it can be assumed that LCTs by definition have lower external costs and particularly lower CO_2 costs.

Finally we provide **examples of pilot projects** where the LCTs mentioned already have been realised and provide a rough sketch of the status of each LCT, whether it is already in the market, available in the form of first pilot applications or in the research pipeline with further R&D necessary.

When combining the LCTs into concepts and scenarios for actual cities or regions, further systemic aspects, such as overlaps, potential rebound effects and synergies, must be taken into account. These considerations are not subjects of this paper. Instead, we review the results of another study in which the LCTs discussed here have been used to formulate a low-carbon scenario for the city of Munich (Lechtenböhmer 2009 a,b; see Figure 1).

3. OVERVIEW OF TECHNOLOGIES FOR LOW-EMISSION URBAN INFRASTRUCTURES

The following paragraphs give an overview of the LCT survey that was conducted and provide a first interpretation of the results.

3.1 LOW-CARBON BUILDING INFRASTRUCTURES

In the field of heat demand and supply for buildings, a number of LCTs are available with very high depth. These are LCTs that have the potential to reduce energy demand and emissions to a very low level. On the heat demand side, these are new construction concepts for new buildings, as well as for the refurbishment of existing ones. They constitute the backbone of a low energy and low emission strategy in this field, but are flanked by a number of other LCTs, some of which are single technologies that might be capable of further improving the technical properties of insulation, for example. Depending on their development status, these technologies will still need higher investment than standard building concepts. However, all solutions in this field promise to achieve equal or even lower life cycle costs in the future than the standard.

The heat supply technology must be adapted to the low remaining demand. Here technologies range from adapted heat grids, new micro-CHP and heating and cooling technologies over solar systems to new developments of heat storage technologies, which could be used to balance the seasonal divergence of heat supply and demand. A larger bundle of partly alternative solutions is presently available or in advanced levels of R&D. These vary in depth of impact and most are limited to parts of the heating market. Their technologies must be adapted to the respective situation on a very local scale. Almost all supply side options have higher investment needs than standard technology. However, for most options, this will be balanced by later energy cost savings. The overall picture, however, is less positive than for the heat demand side technologies.

1 McKinsey (2009). Climate Change Special Initiative, http://www.mckinsey.com/clientservice/ccsi/Costcurves.asp (lists several McKinsey MAC studies)
2 These numbers are without inflation (real values in Euro 2008) and have been derived by Lechtenböhmer *et al.* (2009b) from recent long-term scenario studies for Germany (BMU 2008).

Table 1: Low carbon heat demand and supply technologies

Technology/ System solution/ supply of services	**Potential relevance**			**Economic aspects c)**		**Example**
	Necessary system transformation	Depth a)	Width b)	Life cycle costs today d)	Life cycle costs maturity e)	
1. Heat/ building						
1.1 Building concepts						
a) New buildings						
Passive house design for residential and commercial buildings	Dimensioning of energy supply infrastructures	+++	++	→	↘ 2020	Available[1]
Plus energy house renewable heat and power self supply + net power/ heat surplus	Change from 100% demand to a mix of supply and demand	+++	(++)	→	↘ 2025	Pilot projects[2]
b) building stock						
Innovative concepts of rehabilitation (passive house standard for rehabilitation in renovation activities)	Quality assurance and increased investment in refurbishment of buildings	+++	+++	→	↘ 2025	Pilot projects[3]
1.2 Individual techniques for innovative buildings						
New materials and technologies for thermal insulation / new technology for improving the outer surface of a building (e.g. vacuum insulation and windows)	No system change, but a significantly higher level of quality and quality assurance is necessary	++	+++	↗	→ 2020	pilot projects[4]
Phase change materials (PCM) in insulation materials / passive cooling	New concept, easy integration in conventional renovation or new buildings	++	++	↗	→ 2020	First applications available[5]
Utilisation of daylight	Change in planning principles (new buildings)	++	+	→	↘ 2020	Pilot projects: new building for the German Federal Environment Agency in Dessau[6]
1.3/4.2 Heating and cooling supply network						
Small district heating grids						
a) Conventional b) "cold systems" (with decentralised heat pump) particularly relevant for very low energy building developments; offers the option to better introduce renewable energies, can be fed by low temperature waste heat sources	Alternative to single heating systems, can be taken into account with new development plans; existing structures: introduction of a new heat supply grid can be difficult depending on local situation.	++ to +++	++	→ →	→2015 →2025	a) Available b) Pilot projects: heat supply concepts Simmern[7] Nordkirchen[8]
Micro combined heat and power (CHP) (other CHP see "4. energy infrastructure)	No system change, but decentralised grid connection and central control (smart grid) necessary	++	++	↗	→ 2020	Market introduction[9]
Solar collectors for producing heat (heating installation/ hot water supply /process heat)	(Building) central heating system needed, new developments: orientation & roof shape can be optimised	++	++	→	→ 2015	Available
Heat pumps						
a) Electrical b) Gas-heat pumps (mainly for small applications)	Space for / availability of heat sources	+	+++	→ →	→ 2010 → 2020	a) Available b) Market introduction[10])

Geothermal heat supply (e.g., in combination with on-site heating / heat pumps/ CHP ect.)	No (if heat grid available)	+++	+ to ++	→	→ 2025	Available (further R&D necessary)
Innovative cooling (building, plants, data processing center) (tall > 12 kW / small < 12 kW)	Higher space needs for machines and for heat source	+++	++	see below	see below	Available (further cost degression necessary)
a) **Free** cooling by overnight ventilation, ground water etc.	See above	+++	++	↘	↘ 2015	Available[11]
b) **Trigeneration** (district heating/ CHP waste heat) use of waste heat for industry via absorption/adsorption	See above	+++	++	→	→ 2020	Available (further cost degression necessary)
c) Solar cooling via absorption/adsorption	See above	+++	++	↗	→ 2025	Available (further R&D necessary)
Coupling of heating and cooling demand (commercial/ industrial): simultaneous supply of cooling (e.g., cooling room) and heating (e.g., hot water, swimming complex)	Integrated planning necessary	++ to +++	+	↘	↘ 2020	Available[12]
Big capacity, low cost heat storages						
a) Decentralised (latent heat storage)	Coupling with decentral heat grids	++	++	↗	→ 2025	Pilot projects (further R&D and cost degression necessary)[13]
b) Central for seasonal storage of CHP heat or solar heat (e.g., aquifer)	Coupling with decentral heat grids	++	++ to +++	↗	→ 2025	Pilot projects (further R&D and cost degression necessary): Solar colony Ackermannbogen/ Munich[14]) Aquifer storage Chemnitz[15]) and Berlin[16]) Especially Aquifer Thermal Energy Storage (ATES) yet available in some countries (e.g. Netherlands)[17])

Legend:
a) Order of magnitude of energy/emission reduction vs. standard (business as usual) technology; b) Market size, saving potential with regards to the respective segment; c) Investment / costs relative to standard technology; d) life cycle costs of current technology vs. standard technology at moderate real energy price increase; e) life cycle costs at status of maturity of the technology vs. standard and expected date of maturity
Potential relevance (savings of CO_2 or energy by technology):
Depth: – / 0 = net/zero savings vs. standard technology; + = small (up to 33% savings vs. standard technology); ++ = medium (33 to 66% savings); +++ = high (66 up to 100% savings)
Width: + low (niche & low width technology, covers less than 33% of the segment); ++ medium (covers 33 to 66% of the segment); +++ high (covers 66 to 100% of the segment)
Economic aspects
↗ / ↑ = life cycle costs higher than standard technology by more than 33% / 66% (macroeconomic perspective, no external costs of costs of climate change taken into account);
→ = life cycle costs equivalent standard (+- 33%); ↘ / ↓ = life cycle costs lower than standard technology by more than 33% / 66%

Sources:
1) http://www.passivehouse.com/, Archived at http://www.webcitation.org/5rqrtc5G8 on August 9th, 2010; 2) www.plusenergiehaus.de, Archived at http://www.webcitation.org/5rquSUPpw on August 9th, 2010; 3) www.passivhausprojekte.de, Archived at http://www.webcitation.org/5rquNFZMs on August 9th, 2010; 4) www.vip-bau.de, Archived at http://www.webcitation.org/5rqubYnpt on August 9th, 2010; 5) www.glassx.ch, Archived at http://www.webcitation.org/5rquhdMjj on August 9th, 2010 / www.micronal.de, Archived at http://www.webcitation.org/5rqunzHjG on August 9th, 2010; 6) www.enob.info/en/research-areas/enbau, Archived at http://www.webcitation.org/5rqu4vHxv on August 9th, 2010; 7) www.siekmann-ingenieure.de/www/pdf/referenzen/energie/01_KalteNahwaerme-Rinderberg.pdf, Archived at http://www.webcitation.org/5rquvuT8J on August 9th, 2010; 8) ifeu / WI 2008 ; 9) www.stromerzeugende-heizung.de/download/geraeteuebersicht.pdf, Archived at http://www.webcitation.org/5rqvEAo8t on August 9th, 2010; 10) www.transferstelle.info, Archived at http://www.webcitation.org/5rqvgvads on August 9th, 2010 / www.igwp.de, Archived at http://www.webcitation.org/5rqwONi1C on August 9th, 2010; 11) « München : Pilotprojekt « Fernkälte » in Betrieb », Strom Magazin, May 19th, 2004, URL : http://www.strom-magazin.de/strommarkt/muenchen-pilotprojekt-fernkaelte-in-betrieb_11549.html, Archived at http://www.webcitation.org/5rr0Ugthw on August 9th, 2010; 12) www.robur.com, Archived at http://www.webcitation.org/5rqwku59w on August 9th, 2010; 13) http://hybrid-storage.de, Archived at http://www.webcitation.org/5rqwu3qCn on August 9th, 2010 / www.alfredschneider.de/prod06.htm / www.powertank.de, Archived at http://www.webcitation.org/5rqxF4QD0 on August 9th, 2010; 14) www.muenchen.de/Rathaus/rgu/wohnen_bauen/energie/best_practice/209577/index.html, Archived at http://www.webcitation.org/5rr0ac5oF on August 9th, 2010; 15) BINE (2007); 16) BINE (2003); 17) Snijders, A. (2008)

Table 2: High efficiency electric equipment and appliances

Technology/ System solution/ supply of services	Necessary system transformation	Potential relevance		Economic aspects c)		Example
		Depth a)	Width b)	Life cycle costs today d)	Life cycle costs maturity e)	
2.1 power, equipment and appliances						
Cooling and freezing devices for households (improved insulation, efficient compressors)[1]	–	++	++	↘	↘ 2009	Available on the market
Cooling and freezing devices for commerce (improved insulation, efficient compressors, CO_2 as cooling medium)[2]	–	++	++	↘	↓ 2015	Some first appliances available on the market
Dishwasher (warm water connection)[3]	Connection to warm water hot water produced nearby	+	+	↘	↘ 2009	Available on the market
Washing machine[3]	Connection to warm water hot water produced nearby	++	+	↘	↘ 2009	Available on the market
Cooking (substitution of electricity through gas)	Gas connection[f]	++	++	↘	↘ 2009	Available on the market
Laundry dryer (heat pump dryer and gas laundry dryer)[1]	Possibly gas connection[f]	++	+++	→	↘ 2010	Available on the market
Lighting (LED, sensors for daylight, presence annunciator)[4]	–	+++	+++	↘	↓ 2009 (sensors) – 2015 (LED)	Sensors are available on the market, first LED – lights are on the market but will be improved in the future
Reduction of stand-by losses[5]	–	+++	+++	↓	↓ 2009	Available on the market
Pumps in heating systems and in industry (EC technologies)[6]	–	+++	+++	↘	↓ 2015	Available on the market
Hot water boiler (substitution of electricity through gas via heating of water in a central heating system[4]	Gas connection, domestic hot water storage tank and hot water pipe necessary	++	++	→	→ 2009	Available on the market
Ventilators, air conditioning, climate (EC technologies)[7]	–	++	+++	↘	↘ 2009	Available on the market
Compressed air (efficient compressors, reduction of leakages)[8]	–	++	+++	↓	↓ 2009	Available on the market
2.2 Strategies for the future concerning power, equipment and constructions						
Lighting: organic light emitting diode[9]	–	+++	++	↘	↓ 2020	First applications on the market (mobile phone displays), but still under development
Cooling/freezing: solar cooling (see under 1. heating/ building)	–					
Washing: washing with ultrasound or cold water[10]	–	++	+++	↘	↘	Ultrasound washing machine is on the market in Japan, but unclear if suitable for the European market, washing agents for cold washing are on the European market, but their future market success is still unclear
IT infrastructure: data processing centres[5])		+	+++	↘	↘	Already on the market, unclear, if data processing centres will become standard for everybody
2.3 street lighting (q.v. "4. Energy infrastructure						

Explanations:

a) Order of magnitude of energy/emission reduction vs. standard (business as usual) technology; b) Market size, saving potential with regards to the respective segment; c) Investment / costs relative to standard technology; d) life cycle costs of current technology vs. standard technology at moderate real energy price increase; e) life cycle costs at status of maturity of the technology vs. standard and expected date of maturity f) substitution of electricity by natural gas results in GHG emission reductions only when and until fossil generated electricity is substituted. This may not be the case in cities with almost non-fossil electritiy supply. However, it is important to note that such discussions should not be based on average carbon contents of electricity but rather reflect the marginal production that would be substituted.

Potential relevance (savings of CO_2 or energy by technology):

Depth: – / 0 = net/zero savings vs. standard technology; + = small (up to 33% savings vs. standard technology); ++ = medium (33 to 66% savings); +++ = high (66 up to 100% savings)

Width: + low (niche & low width technology, covers less than 33% of the segment); ++ medium (covers 33 to 66% of the segment); +++ high (covers 66 to 100% of the segment)

Economic aspects

↗ / ↑ = life cycle costs higher than standard technology by more than 33% / 66% (macroeconomic perspective, no external costs of climate change taken into account); → = life cycle costs equivalent standard (+- 33%); ↘ / ↓ = life cycle costs lower than standard technology by more than 33% / 66%

Sources:

1) Euro-Topten. 2009; www.topten.info, Archived at http://www.webcitation.org/5rr2Aqcin on August 9th, 2010; 2) ProCool 2007; 3) Bätig 2005; 4) E.ON 2006; 5) Centre for Energy Policy 2003; 6) Energy+ Pumps 2008, www.energypluspumps.eu, Archived at http://www.webcitation.org/5rr2cCjqG on August 9th, 2010; 7) Radgen 2002; 8) Radgen 2000; 9) Lichtnews 2009. www.lichtnews.de/wp/index.php/2009/05/durchbruch-rekord-oleds-stechen-leuchtstoffrohren-aus, Archived at http://www.webcitation.org/5rr35DfMG on August 9th, 2010; 10) Sanyo 2001 and Ariel 2009: www.rolf-keppler.de/ultraschall.htm, Archived at http://www.webcitation.org/5rr3ErDti on August 9th, 2010, and www.ariel.de/kalt-ist-heiss/index.html, Archived at http://www.webcitation.org/5rr3LSsNV on August 9th, 2010

3.2 HIGH EFFICIENCY ELECTRIC EQUIPMENT AND APPLIANCES

Electricity use in equipment, appliances and machines is a major use of energy and a key source of GHG emissions. As the GHGs are not emitted at the point of use, but at the point of electricity generation, this field is directly linked to the topic of electricity supply (see table 2).

There are two groups of LCTs among electric appliances. The first group consists of improved appliances, almost all of which are already available on the market. Their savings depth ranges from small to large and, as most are available at competitive prices, they lead to reduced life cycle costs for the respective energy service. For other LCTs, like LED-lighting and advanced cooling technologies, there is still some R&D or market transformation necessary. However, it is to be expected that these efficient appliances will soon become more mainstream and that their costs will also equal the market average.

The second group of LCTs comprises appliances that are still mainly in the research pipeline, but promise an even higher depth of efficiency gain for several applications of electric energy. They range from new lighting technologies that use organic LEDs to completely different technologies for washing and for greening IT. All of these offer very high electricity savings, but are still under development or have just entered the market. This leads to a still unclear picture of their cost, although it can be assumed that these LCTs will be introduced at competitive investment costs in the future and will enable significant life cycle cost savings for the energy services they provide.

The changes in appliances assumed here for both groups do not need significant systems transformations, except for the substitution of electricity by centrally-heated hot water or natural gas heating for washing, dish washing, cooking and drying appliances. For these, minor adaptations of in-house installation are needed (e.g. connection to the sanitary hot water supply or to the gas grid). However, there will be major system changes anyway (e.g. with office, IT and home entertainment systems) and possibly with a number of other appliances as well. These are taken into account here, but are simplified to the parts of those systems that will consume the bulk of energy – which will be, like today, mainly the central server and user interfaces, such as monitors, printers etc.

3.3 LOW-CARBON TRANSPORT TECHNOLOGIES

In the transport sector two main LCT fields—low emission vehicle technology and transport infrastructure technology—can be seen as relevant for a low emission development.

Vehicle technologies that are often in the focus of the debate can be grouped in:

- LCTs optimising current vehicles (e.g. by weight reduction, improvements of conventional engines and energy recovery). All of these offer a low to medium emission reduction depth, but wide coverage. They can be complemented by increasing shares of bio fuels, which add to the depth of available GHG emission reductions. These LCTs are available or will come onto the markets over the next couple of years. They add somewhat to vehicle costs, but should be repaid by fuel savings.
- The other group of LCTs. This implies new drive trains that are fuelled by natural gas, electricity or hydrogen. Here, deeper emission cuts seem to be possible. They, however, depend also on the level of indirect emissions of the electricity or hydrogen (i.e. on the way these secondary energy carriers are produced).

While the first group of LCTs does not need significant system transformations, the switch to alternative energy carriers for transport does and significant differences remain between natural gas, electricity and hydrogen: infrastructures for natural gas already exist, those for electricity seem to be available at reasonably low efforts while the ones for hydrogen are still missing, are probably expensive and could suffer from a chicken and egg problem. From the cost side, new drive trains will probably come with higher investment—at least for the next decade. Also, their overall life cycle costs tend to be higher than those of standard vehicles, depending on the respective energy price development. In the long run, we estimate that alternative drive trains with natural gas or electricity will be available at costs that are comparable to those of standard cars. Hydrogen cars, on the other hand, might remain more expensive overall. However, highly efficient conventional drives offer the potential of delivering even lower costs than the standard vehicle.

Table 3: Low carbon transport technologies

Technology/ System solution/ supply of services	Necessary system transformation	Potential relevance		Economic aspects c)		Example
		Depth: a)	Width: b)	Life cycle costs today d)	Life cycle costs maturity e)	
3. Transportation						
3.1 Vehicle technology						
Natural gas[1]	Filling infrastructure necessary	+ to ++	+++	↗	→	Several bus and car models
Improvement of efficiency combustion engine[2]	–	+ to ++	++	↗	↘	Available
Biogenic fuel (biogas, bio methane)	–	+++	++	↗	→	Available
Renewable hydrogen and fuel cell[3]	Hydrogen grid and filling infrastructure necessary	+++	+++	↑	↗	Concept cars (e.g., Daimler)
Mild hybrid[4])	–	+++	+++	→	→	Toyota Prius
Plug-in technology (complete hybrid)[4]	Plug in stations necessary, with high shares: load management, possibly grid strengthening	++ to +++	++	↗	→	Concept cars (e.g. Chevrolet Volt)
Battery operated electric vehicles (REG power)[4]	Plug in stations necessary, with high shares: load management, possibly grid strengthening	+++	++ to +++	↗	→	Small batch model (Tesla Roaster)
Weight reduction through lightweight construction[2]	Adaptation of automobile production to new concepts	++	++	→	→	Available on the market
Downsizing of drive trains[2]	–	++	++	→	→	Available on the market
Busses with energy recovery[5]	–	++	+ to ++	→	→	Solaris Urbino 18, Hybrid busses in London
Regenerative breaking of trains[6]		++	+++	→	→	Budapest tramway, several subway models
3.2 Transportation infrastructure						
3.2.1 Communication, information						
Integration of sub-systems (intermodal) for a recording of the present traffic situation	–	+	+	→	→	R&D
Smarter choices - (personalised travelling plans, information according to a user profile)[7]	–	+	+	→	→	Perth (Australia)
Forecast of "total trip costs" including travel time, level of service, user fee etc.[8]	–	0 to ++	++	→	→	Mobil Check of Deutsche Bahn
Travelling time prediction (unimodal, multi-modal)	–	0 to +	0 to +	→	→	Pilot tests
3.2.2 Optimising of inter modality (see also 3.2.1)						
Improvement of City logistics	–	+	++	→	→	
Physical intermodal interface (e.g. Parking/ Bike and Ride)	–	++	+	→	→	Available
Integrated (micro)payment solution for public transport, parking etc.[9]	–	++	+	→	→	Octopus smart card in Hong Kong

3.2.3 Control system						
Traffic management "on trip": floating car/ people/mobile data; vehicle infrastructure Interchange (bidirectional)[10])	New communication infrastructures necessary	+	0 to +	↗	→	Pilot tests
Forecast of traffic situation and transportation demand and traffic light control according to demand[11])	–	0 to +	+	→	→	Available, Munster, Germany
3.2.4 Improved service quality of non-motorized transport						
Improvement of individual comfort of public transport system: assurance of connection, quality management, e-payment, e-booking, trip booking change management	–	++	++	→	→	Available (e.g., VerkehrsverbundRhein -Ruhr, Germany)
Optimisation of traffic flow in the public transport system: prioritisation, adaptive control[11])	–	+	+ to ++	→	→	Prioritisation of buses in Valby (Copenhagen, Denmark)
Improvement of physical infrastructure of the public transport system and non-motorised individual transport[12])	–	+++	++	→ ↘	→ ↘	Copenhagen, Groningen
3.2.5 Demand side management						
Financial incentives for recruitment of new customers in the public transport system[13])	–	+	+	↗	↗	Seattle: bus trips within the city centre free of charge
Fiscal instruments in the motorised individual transport system: city road charge/ congestion pricing, restricted access, demand driven parking charge[14])	–	++ to ++	+ to ++	→	→	City road charging schemes in, London
Avoidance of traffic through organisational measurements (e.g., e-work)	–	+	+	↘	↘	Available

Explanations:
a) Order of magnitude of energy/emission reduction vs. standard (business as usual) technology; b) Market size, saving potential with regards to the respective segment; c) Investment / costs relative to standard technology; d) life cycle costs of current technology vs. standard technology at moderate real energy price increase; e) life cycle costs at status of maturity of the technology vs. standard and expected date of maturity

Potential relevance (savings of CO_2 or energy by technology):
Depth: – / 0 = net/zero savings vs. standard technology; + = small (up to 33% savings vs. standard technology); ++ = medium (33 to 66% savings); +++ = high (66 up to 100% savings)
Width: + low (niche & low width technology, covers less than 33% of the segment); ++ medium (covers 33 to 66% of the segment); +++ high (covers 66 to 100% of the segment)
Economic aspects
↗ / ↑ = life cycle costs higher than standard technology by more than 33% / 66% (macroeconomic perspective, no external costs of costs of climate change taken into account); → = life cycle costs equivalent standard (+- 33%); ↘ / ↓ = life cycle costs lower than standard technology by more than 33% / 66%

Sources:
1) concawe/EUCAR/JRC (2007); 2) Schallaböck *et al.* (2006); 3) Joest *et al.* (2009); 4) Wietschel/Dallinger (2008); 5) VDV (2009); 6) Siemens (n.d.). Metro-Systeme und Straßenbahnen: http://w1.siemens.com/responsibility/de/umwelt/portfolio/mobilitaet.htm, Archived at http://www.webcitation.org/5rr3x6XYK on August 9th, 2010 ;7) Department for Transport (2004); 8) ifeu (2008); 9) www.octopus.com.hk, Archived at http://www.webcitation.org/5rr4Cld2F on August 9th, 2010; 10) Aktiv (2008); 11) Siemens (2008); 12) Fietsberaad (2006); 13) http://transit.metrokc.gov/tops/bus/ridefree.html; 14) Transport for London (2008)

Transport infrastructure LCTs can improve transport by avoiding congestion, by optimising the flexible use of different transport modes and by improving the service quality of public transport. All of these technologies can be seen as important enabling technologies that can be grouped together to create more sustainable low emission urban transport systems. They individually have a rather small or medium depth and width of impact. However, apart from e-work, all of them have positive life cycle costs that, in general, add little to the overall costs of transport, but from an overall point of view can well be capable of reducing the total costs of transport systems.

3.4 LOW CARBON ENERGY INFRASTRUCTURE

Energy infrastructure obtains a multiple function in the context of low emission, urban infrastructures. First, it must be adapted to the minimised energy flows of the demand systems, such as buildings and transport. Second, it must be adapted to new, partly decentralised, renewable and low emission energy sources. Third, new energy carriers might be introduced for example in the transport sector that will need the introduction of the respective infrastructures.

Table 4: Energy infrastructure technologies

Technology/ System solution/ supply of services	Necessary system transformation	Potential relevance		Economic aspects c)		Example
		Depth a)	Width b)	Life cycle costs today d)	Life cycle costs maturity e)	
4. Energy infrastructure						
4.1 Power						
4.1.1 Generation						
Combined heat and power cycle (q.v. local heat) with gas and steam plant/ steam turbine, gas turbine/ CHP unit/ stirling/ steam motor/ fuel cell/ ORC	Expansion of heat supply grids	+ to +++	+ to +++	↗	→	Available
a) Large/ central CHP systems (district heating and CHP unit > 2 MW)	Expansion of heat supply grids	+++	++	↗	↗ 2010 ↗ 2025	Available / pilot projects e.g. for "low-ex-concepts"
b) Small/ decentralised CHP systems (local heat and entity supply < 2 MW)	Micro heat grids (can be integrated with new dev.)	++	++	↗	→ 2020	Available
c) micro CHP systems (entity supply ← 10 kW)	Integration into the grid, decentralised controls and/or virtual power plant needed	++	+++	↗	→ 2020	Market introduction[1]
d) Industrial CHP systems (usually > 100 kW)	–	+++	+++	→	→ 2010	Available
Photovoltaics						
a) Grid connected PV roof top construction	With high market shares: adaptation of local grids necessary, potentially decentralised storage (smart grid)	+ to ++	+ to ++	↗	→ 2020	Available; some mil. units in operation[2]
b) Grid connected building and entity integrated PV		+ to ++	+ to ++	↗	→ 2030	Available, e.g., 5MWp in Bürstadt and 3.9 in Muggensturm[3]
c) Grid connected PV free space construction		++ to ++	+ to ++	↗	→ <2020	Available; e.g., 40 MW thin film solarparc in Waldpolenz[4]
d) PV insular system	(DC appliances)	+++	+	↘	↘ <2020	Available; some 40 MW off grid installed[2]
Geothermal power generation (ORC or Kalina processes)	Decentralised heat grids advantageous	+++	+	↗	→ 2020	Pilot plants: ORC plant in Soultz-sous-Forêts[5a] Kalina plant in Unterhaching[5b]
Wind power						
Small wind power stations ("urban turbines" with 1-10 kW for e.g. roof tops)	(smart grid)	++	++	↗	↗ 2025	Available / pilot projects[6]
single wind power plant with a usual size (standard)	(smart grid)	+++	++	→	→ 2020	Available
Hydropower						
Small hydro power stations	–	+++	+	→	→ 2020	Available (R&D needed)
Sewage water power plant	–	++	+	↗	↗ 2020	Pilot projects (Aachen)
Biomass						
Co-combustion of biomass (in coal fired power plants)	–	++	++	↗	↗ 2020	Available
Biogas CHP	Biomethane in gas grid and / or heat grid necessary	+++	++	↗	↗ 2020	Available

4.1.2 Grids and regulations						
Virtual power or hybrid power plant (renewables)	Smart grid as enabler; introduction of ITC-Technology	+ to ++	++ to +++	↗	→ 2030	Pilot projects; see[7]
Electronic "smart" meters	Introduction of ITC-Technology	0 to +	+	↗	→ 2020	Market Introduction; see[8/9]
Smart grids	Smart meter; introduction of ITC-Technology; load management; energy storage	+ to ++	+ to ++	↗	→ 2030	Pilot projects; see[10]
More efficient distribution transformers	–	++ to +++	+ to ++	↘	↘ 2020	Available; see[11]
Gas insulated lines (GIL):	–	++	0 to +	↑	↑ –	Available; e.g. PALEXPO Genf[12]
Supra conductive cables (HTSC)	Cooling necessary; grid adaptation	++ to +++	+	↗	↗ –	Pilot projects
Vehicle to the grid (V2G) utilisation of vehicle batteries for balancing power & RE-integration	Loading stations and smart grid	0 to ++	+ to ++	↗	↗ 2050	Concepts available; R&D needed; see [13]
Power storage technologies for balancing power & RE-integration	(Smart grid)	+	+ to ++	↗	↗ 2040	Available; R&D needed
4.2 Other energy infrastructure	(Heat see table 1)					
Natural gas fuel filling infrastructure	Filling stations (biogas feed-in)	0 to +	+	↗	→ 2020	Available; >800 stations in Germany;[14]
Natural gas decompression turbine (for the transition of natural gas high pressure grids to low pressure grids)	–	++	+	↘	↘ 2015	Available[15]
Biogas feed-in/ import from surrounding areas	Biogas conditioning, adaptation of gas network operation (rules)	+ to +++	+	↗	↗ 2020	Available / pilot projects
Hydrogen supply infrastructure	Development of hydrogen consumers (to be synchronised with supply infrastructure)	0 to ++	+ to ++	↗	↗ 2040	Available / pilot projects
HVDC transmission line for RES imports	Adaptation of supranational and national electricity grids	0 to +	+	→	→ 2030	HVDC lines available (RE import conceptual)

Explanations:
a) Order of magnitude of energy/emission reduction vs. standard (business as usual) technology; b) Market size, saving potential with regards to the respective segment; c) Investment / costs relative to standard technology; d) life cycle costs of current technology vs. standard technology at moderate real energy price increase; e) life cycle costs at status of maturity of the technology vs. standard and expected date of maturity

Potential relevance (savings of CO_2 or energy by technology):

Depth: – / 0 = net/zero savings vs. standard technology; + = small (up to 33% savings vs. standard technology); ++ = medium (33 to 66% savings); +++ = high (66 up to 100% savings)

Width: + low (niche & low width technology, covers less than 33% of the segment); ++ medium (covers 33 to 66% of the segment); +++ high (covers 66 to 100% of the segment)

Economic aspects

↗ / ↑ = life cycle costs higher than standard technology by more than 33% / 66% (macroeconomic perspective, no external costs of costs of climate change taken into account); → = life cycle costs equivalent standard (+- 33%); ↘ / ↓ = life cycle costs lower than standard technology by more than 33% / 66%

Abbreviations: ITC= Information- & Telecommunication;

Sources:

Source for determining date of economic maturity for renewable energy technologies (PV, biogas, geothermal, wind): BMU 2008 / own estimates.

1) www.stromerzeugende-heizung.de/download/geraeteuebersicht.pdf, Archived at http://www.webcitation.org/5rr4mDyPK on August 9th, 2010 2) BSW (2009). Daten und Infos zur deutschen Solarbranche, www.solarwirtschaft.de, Archived at http://www.webcitation.org/5rr4uZdOa on August 9th, 2010; 3) Solarserver (2007). Building integrated Photovoltaics (BIPV): Solar electric power systems conquer large roofs and façades; www.solarserver.de/solarmagazin/solar-report_0607_e.html, Archived at http://www.webcitation.org/5rr5VBIMb on August 9th, 2010 4) Solarserver (2008). Solarstrom: Juwi baut weltgrößtes PV-Kraftwerk mit 40 Megawatt Leistung, http://www.solarserver.de/news/news-6485.html, Archived at http://www.webcitation.org/5rr5et4SA on August 9th, 2010 5a) BINE 2009 5b) BINE 2009 6) www.wind-energie.de/de/themen/kleinwindanlagen, Archived at http://www.webcitation.org/5rr5jQxLe on August 9th, 2010 7) BMWI 2009, E-Energy Modellregionen; http://www.e-energie.info/, Archived at http://www.webcitation.org/5rr5pu63B on August 9th, 2010; 8) RWE; 9): EnBW (n.d) EnBW starts mass production of intelligent electricity meters; http://www.metering.com/node/13704, Archived at http://www.webcitation.org/5rr5uixuk on August 9th, 2010; 10) BMWI 2009, E-Energy: "Smart Grids - Made in Germany"; http://www.e-energie.info/, Archived at http://www.webcitation.org/5rr673PhL on August 9th, 2010; 11) SEEDT (n.d.): Project Summary ; http://seedt.ntua.gr, Archived at http://www.webcitation.org/5rr6BZwtF on August 9th, 2010; 12) Siemens/Poehler (2002). Gasisolierte Übertragungsleitungen (GIL) für unterirdischen Energietransport; www.life-needs-power.de/2002/, Archived at http://www.webcitation.org/5rr6GWJro on August 9th, 2010; 13) UDEL (2009). Vehicle to Grid Technology - University of Delaware http://www.udel.edu/V2G/, Archived at http://www.webcitation.org/5rr6M0Vu8 on August 9th, 2010; 14) www.erdgasfahrzeuge.de, Archived at http://www.webcitation.org/5rr6PP6ks on August 9th, 2010 15) www.rmg.com/produkte/turboexpander.html, Archived at http://www.webcitation.org/5rr6ntMV5 on 9th, 2010

This is most pronounced for the power infrastructure. Here there are a number of new urban power sources, which range from diverse CHP technologies to several renewable electricity generation options. Together with the changes on the demand side, the grid must be adapted to become "smart" to be able to much better balance diverse, and possibly bidirectional, flows of electric energy in the grid.

Central public and industrial CHP systems still offer large opportunities for GHG emission mitigation in urban areas. This is amended by decentralised small and micro CHP systems. Apart from the efficiency gains that the combined electricity and heat generation offers, these systems provide the option to ease a conversion to a renewable energy supply at a later point in time as they can be converted to biomass firing much more easily than to single heating systems. However, this strategy may be limited by the availability of sustainable biomasses for energetic use. Detrimental to most CHP solutions is their necessity to develop or expand heat grids, which are often quite investment-intensive. Overall, this leads to a tendency to increase costs when CHP technologies are used. However, this depends heavily on future price developments and local situations.

Several technologies for renewable electricity generation add to the LCT options for energy infrastructures. In urban contexts, these are mainly photovoltaic systems plus—depending on local potential—small hydro and wind power, as well as the use of biomass (in CHP plants) and geothermal energy, if available. In industrialised metropolises that have existing supply structures, these renewable generation technologies are typically characterised by higher investments than standard technologies. These greater investments will not always be fully recovered by further, significant cost reductions for these technologies. Again, this can lead to increasing life cycle costs for electricity generation, depending on future fossil energy prices.

LCT solutions to modify the electricity grid, like a "smart grid" and decentralised electricity storage technologies, are important here again as enabling technologies for changes in supply and demand, but with limited reduction potential in themselves. Other technologies, like superconductive grids and gas insulated lines or improved transformers, reduce losses in the system, but will pay off only if energy costs increase substantially.

Other potential energy infrastructures will be needed to convert urban infrastructures, such as expanding the already available natural gas filling stations and/or developing a hydrogen supply and filling infrastructure, which is still in the R&D phase. At a more supra-urban level, the development of biomethane feed-in structures to introduce biogenic gases into the natural gas grids and the development of HVDC electricity transport grids will enable the long distance transport of energy from distant renewable sources. These technologies are available and have been realised in pilot projects.

4. REVIEW: COMBINING LCTS FOR A VERY LOW CO_2 EMISSION SCENARIO

The LCTs presented above sketch the range of technical options to restructure urban infrastructures for very low-carbon futures. However, they must be combined into a complete picture in order to deliver a sort of blueprint for low-carbon cities of the future.

In the following, we review the scenario analysis *"Munich 2058 paths toward a carbon-free future"* that has been provided by Lechtenböhmer *et al.* (2009a,b). In our study we used results of the technology survey described above to conduct a scenario analysis for the city of Munich. The case study for Munich covers the 50-year period from 2008 to 2058 and combines the technologies by accounting for their systemic interactions.[3]

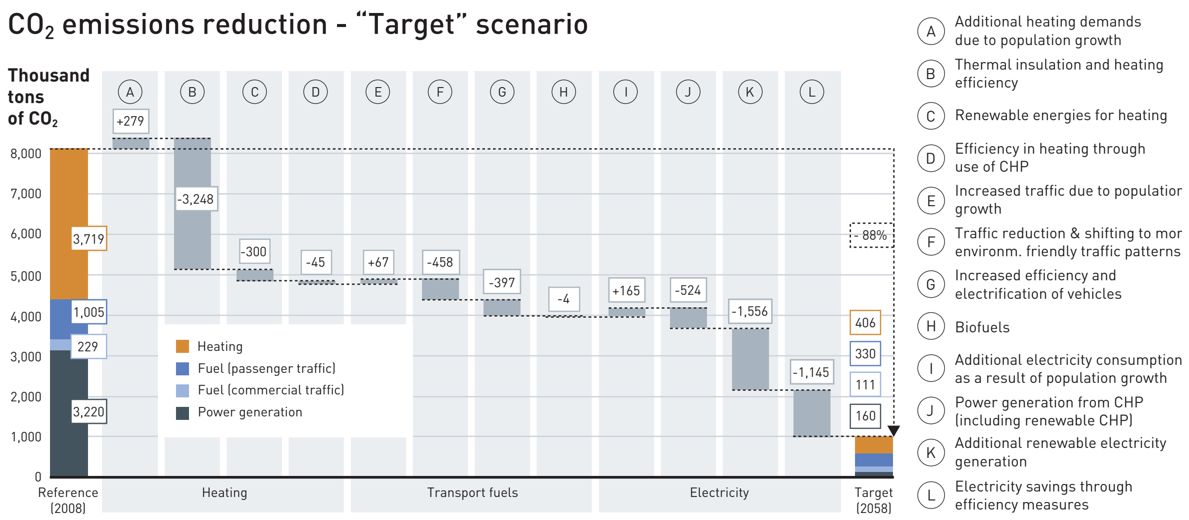

Figure 1: Key strategies for carbon emission reduction in Munich, 2058, Target Scenario
Source: Lechtenböhmer et al. (2009a)

3 In the example for Munich only CO_2 emissions have been taken into account. They are estimated to stand for more than 95% of Munich's GHG emissions.

Basically, Lechtenböhmer *et al.* applied a detailed bottom-up simulation approach. This approach first describes the current energy service demand for the main groups of appliances and sectors such as: heating of flats (by age); warm water generation; use of electricity in households, offices, or industry; transport by mode; and the supply side, mainly by power plant type; and the resulting total energy use and CO_2 emissions. Based on the status quo potential, savings over time in every field of energy use have been estimated. For this calculation, we used the technologies and their characteristics as given in Tables 1 to 4 and developed a new consistent energy system description for 2058.

Figure 1 provides an analysis of the scenario results and aggregates the CO_2 reductions to the core sectors and to seven core strategies. In total, the combination of these strategies that comprise the LCTs discussed above could reduce CO_2 emissions by about 7.5 million tons according to the analysis by Lechtenböhmer *et al.* (2009a). They would reduce current CO_2 emissions by the City of Munich from the current level of 8 million tons (plus 0.5 million added for population growth) to about 1 million in 2058.

The most promising strategies for reducing emissions have been combined by Lechtenböhmer *et al.* (2009a) into the Target Scenario. These consist of better insulation in buildings, more efficient heating and power cogeneration systems, energy-efficient appliances and lighting systems, and power generation from renewable resources and low-carbon power plants. In the following, we discuss the main strategic elements highlighted by Lechtenböhmer *et al.* (2009a) and assign the different groups of LCTs discussed above to the respective strategic elements.

Certain parts of a city's infrastructure can be clearly identified as major producers of GHG emissions. Applying efficiency measures and LCTs to those areas is particularly effective. In Munich, as the analysis by Lechtenböhmer *et al.* (2009a) given in Figure 1 shows, there is particularly high potential for CO_2 emission savings in heating and electricity.

- The main lever for a **fossil carbon-free heat demand and supply**, and also the largest lever in general, is the thermal improvement of residential and other buildings. By a rapid introduction of the currently most ambitious passive house standard for all new buildings and also for every renovation of existing buildings (see the LCTs given in Table 1.1, which are supported by the LCTs in Table 1.2), energy use for this segment can be reduced by 80% by 2058. To achieve this, virtually all buildings should be renovated over the 50 years to come. This target is technically feasible[4], but a major economic and social challenge. Implementing less ambitious standards would mean that buildings with these standards would not become fossil carbon-free by 2058 and, thus, delay attainment of the targets to a point in time when they will be refurbished again. The strategy, however, imposes an economic threat to the district heating (DH) system by massively reducing the amount of heat demand per building. The technologies given in Table 1.3 for future central and decentralised DH systems must be further developed before they will be economically feasible. However, the study assumes that this will be solved successfully and that CHP technologies will be able to supply 60% of the heat requirement and a third of the electricity demand in the Target Scenario.
- Additionally, renewable heat supply will be introduced by geothermal district heating, biomass-based decentralized CHP plants and solar thermal appliances (see Tables 4.1.1 and 4.2).

Fossil carbon-free electricity can be achieved by two strategies:

- The first strategy involves the highly efficient use of electricity by using already existing high-efficiency appliances, as given in Table 3.1 and, in the long run, applying also those LCTs given in Table 3.2. This would reduce per capita residential and office electricity consumption by almost 40%.
- The second strategy consists of producing additional renewable electricity that will be produced locally in the CHP plants, as well as from water power, and by photovoltaic systems. The latter could reach a power output of 400 MW peak by 2058 by using about 40% of the existing potential space for the installation of modules (see LCTs under 4.1.1). About 40% of the electricity in the Target Scenario will, however, be imported from off-shore wind and solar thermal power plants[5].

The core strategies of the Scenario towards a **fossil carbon-free transport** are:

- First, to gradually change mobility patterns. Here the enabling LCTs given in Table 3.2 are applied to modify spatial structures, to increase the service quality of public transport, to enable a better combination of transport modes and to improve the regulation of individual transport vehicles. In addition, the average transport distances could be slightly reduced and the share of public transport, walking and biking could be increased.
- Second, to adopt the use of more efficient vehicles and effect a shift in urban transport towards electric vehicles that contribute to significant energy savings and, indirectly, to an increased share of biofuels and renewable electricity in the transport fuel mix. These changes can be achieved by using the LCTs given in Table 3.1. As the lifetime of vehicles is limited, several generations will be seen on the roads until 2058. Thus, Table 3.1 contains also "bridge technologies" for intermediate timeframes. For 2058, the Target Scenario assumes that about 80% of motorized inner city individual mobility will be covered by

4 As given in table 1.1 there are sufficient examples of building renovations which achieved almost Passive House standards – which would mean savings of typically around 90% vs. current energy consumption. As these standards cannot achieved with every single building because of e.g. historical facades or partly insufficient solar access in the older, denser parts of the city an average of 80% savings has been used here.

5 These have not been described in detail here as they are not specifically "urban" technologies. However, this strategy has already been introduced by the municipal utility. About 40% of the wind capacity envisaged for 2058 will be on the grid in the German North Sea as early 2013 and a board decision has been made to buy a share of a projected solar thermal power plant in southern Spain. Electricity generated abroad will of course not physically be consumed in the city of Munich. Therefore it is necessary not only to invest into renewable generation facilities but also to purchase the respective electricity e.g. by green certificates (as introduced by the European Renewable Energy Directive) or comparable instruments. Further, also for the electricity generated within the city and the region, double counting has to be avoided by appropriate mechanisms.

electric vehicles. These will be either specific, small vehicles used for short distances or plug-in hybrids. The hybrids will operate for the shorter distances on electricity and outside the city on fuels. The remaining vehicles will be particularly light in weight and driven by highly efficient combustion engines.

Tables 1 to 4 give a qualitative impression that energy-saving measures can largely be economically viable. On the demand side (Tables 1.1, 1.2 and 2), all LCTs that are quoted are expected to deliver comparable or lower life cycle costs than standard technologies. Most of them are already mature or will become so during the next five to ten years. However, the picture is less clear for the supply infrastructures. Here, renewable technologies and CHP-district heating systems will lead to increased investments versus current fossil systems. The increased investments may not fully be recovered by savings in fuel costs. However, these technologies are needed to achieve overall CO_2-savings of 80% and more. In combi-nation with the savings achieved by the demand side efficiency, the overall economic balance may still remain positive – regardless further savings of external and CO_2-costs.

This can be shown in our case study of Munich. A new quarter will be developed from an existing quarter with ten thousand inhabitants and new developments for almost another twenty thousand. The whole quarter should be developed or renovated according to the passive house standard[6]. More than 75% of its heat will be supplied by a geothermal plant and a local district heating grid. Overall, without even taking carbon or other external costs into account, this system has been estimated to have lower life cycle costs compared to a conventional quarter with less ambitious energy standards and much cheaper conventional heating systems (Lechtenböhmer *et al.* 2009a).

The total additional investment needed to redesign all residential buildings of a city like Munich was estimated at €13 billion (Lechtenböhmer *et al.* 2009 a,b). This estimate includes refurbishing virtually all older buildings (about 34 million square metres) by 2058. The average additional refurbishment costs are estimated to be 310 euros per square metre, based on the results of a number of case studies documented by IWU (2007). New homes (about 14 million square metres) will be constructed according to the efficient passive house standard. The estimated additional costs at the current state of the art are about 140 euros per square metre (Lechtenböhmer *et al.* 2009 a,b). That comes out to roughly 200 euros annually per Munich resident—about one third of an annual natural gas bill. However, these additional investments will be offset over their lifetimes by rising annual energy savings, which, it is estimated, will reach between €1.6 billion and €2.6 billion in the year 2058. That would equal annual savings of between €1,200 and €2,000 per capita, meaning energy savings of more than €30 billion over the course of 50 years (Lechtenböhmer *et al.* 2009 a,b).

5. CONCLUSION

To achieve the ambitious GHG emission reduction goals globally needed to contain global warming below 2°C, a transition of our cities' infrastructures towards sustainable low-carbon infrastructures is clearly needed.

This survey presents an overview of a significant number of low-carbon technologies (LCTs) in the relevant urban infrastructure fields of buildings, electricity use, transport and energy supply. What can be seen from this collection is that numerous technologies to achieve low emission infrastructures are already available on the market or are pilot applications. The remaining are technologies that are well advanced in R&D and may be available soon. Many of these technologies are linked to higher up-front investments than required for standard solutions. However, increasing market shares and further R&D will reduce substantially the investments for many technologies. Depending on future energy prices, most of them will become cost-efficient in the long run or even help to mitigate further cost increases of the energy system due to price increases of fossil fuels.

Further, we reviewed the results of a scenario analysis that combined the surveyed technologies in an integrated scenario for the very-low-carbon city of Munich in 2058. The results of that study demonstrate that large-scale climate protection for a large city with a service-oriented economy would be feasible by using technologies that are already available or are in advanced R&D, and that it could even be economical as fundamental improvements to buildings and energy systems can save energy costs. Additionally, the investment in LCT strategies may also provide strong economic stimuli to the local economies.

Based on our survey and the results from the scenario analysis, we can identify three key strategies for the redesign of existing urban infrastructures:

- The first is to become highly efficient in all sectors of demand (households, service sector, industry, if relevant, and transport); i.e. to achieve the same level of convenience and utility through significantly less energy consumption. The most effective measures to achieve high efficiency are:
  - The renovation of almost all buildings to the passive house standard. This can be done by using already available technologies plus innovative technologies.
  - A rapid increase in the market share of electric appliances with the best available standards to 100%.
  - In the transport sector, public and non-motorised transport should be improved to achieve higher shares of environmentally friendly modes and—on a longer time scale—conventional cars should be replaced by fully electric and plug-in hybrid cars.
- The second is to adapt their heating, electrical, and transport infrastructures to accommodate a demand that has been substantially reduced through greater efficiency

6 As proposed in the study reported here. However, in spite of high environmental standards planned, it is not yet clear whether the realisation will fully meet the proposals of the study.

and to support this demand reduction by appropriate infrastructure solutions. The most important strategies to adapt the energy and transport infrastructures are:

- A significant expansion of the existing district heat grid with CHP technologies and the development of small local heat grids fed by renewable energies supported by innovative heat storage. New technical solutions for the central system, in particular, must still be developed in order to cope economically with the significantly reduced heat demand.
- A "smart" electricity grid that is capable of integrating multiple decentralised generation and is linked to a supranational high voltage DC grid.
- An improved public transport grid, combined with modified street infrastructures that support more cycling and walking plus settlement structures that promote short distances.

• The third is to convert the cities' energy bases to renewable and low-carbon energy sources by:

- A strong exploitation of local renewable heat and electricity sources from biomass CHP, geothermal and photovoltaic electricity generation.
- The replacement of conventional electricity supply by renewable electricity from local sources and particularly from remote on- and off-shore wind power plants and concentrated solar power plants.

Overall, we can conclude that rigorously concentrating on the goal of a carbon-free environment can completely alter a large city's buildings and infrastructure, thereby offering the metropolis, its businesses, citizens, and research institutes a valuable head start on the future. After all, the entire world will soon have to become a low-carbon society. In addition, such advances will help ensure that cities remain liveable in the future.

Acknowledgements

The authors would like to thank Siemens AG and particularly Stefan Denig and Daniel Müller for commissioning the underlying study and for contributing valuable input to the technology matrix discussed here. We also thank our colleagues Susane Böhler, Rüdiger Hofmann, Kora Kristof and Frederik Rudolph who are co-authors of the underlying study. We are grateful to George Robinson for his assistance in editing the English as well as to Gaell Mainguy for his great editorial support.

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