ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

LBNL-179304

A Review of Commercially Available Technologies for Developing Low-Carbon Eco-cities

Nan Zhou, Gang He, John Romankiewicz, David Fridley,
and Cecilia Fino-Chen

Energy Technologies Area

May 2015

This work was supported through the U.S. Department of Energy under
Contract No. DE-AC02-05CH11231.

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Table of Contents

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Introduction

Half of China's population now lives in cities whose rapidly increasing populations burden already crowded infrastructure and exacerbate environmental and climate change stresses, threatening public health and quality of life (Chinese Society for Urban Studies 2011; Zhou and Williams 2013). To help address these challenges, China's central and local governments have moved aggressively toward building low-carbon eco-cities, which have significant potential to mitigate and adapt to climate change (Zhou, He, and Williams 2012). However, there is a lack of information to assist policy makers in defining low-carbon eco-cities, evaluating progress toward low-carbon and ecological goals, and finding information on policies and technologies to improve the performance of developing a low-carbon eco-cites.

The China Energy Group at Lawrence Berkeley National Laboratory (LBNL) has developed a comprehensive solution package for city policy makers, including guidelines, policies, indicator systems, and tools to facilitate low-carbon eco-city development in China and beyond. LBNL's Eco and Low-carbon Indicator Tool for Evaluating Cities (ELITE Cities) assesses cities' strengths and weaknesses in eight categories that are key to low-carbon eco-city performance. ELITE Cities allows policy makers to compare their cities' performance to international or domestic best practices, benchmark values, or key performance indicators (KPIs) (He et al. 2013). This guide is designed to assist policy makers in acting on ELITE Cities assessment results by providing descriptions of technologies available to improve low-carbon performance, including the cost and emissions-reduction potential of each. Our overall purpose is to respond to growing demand for information on technologies that policy makers can use to improve city energy performance and reduce carbon emissions.

Rapid urbanization and a commitment to developing low-carbon eco-cities has created a huge potential market in China for low-carbon technologies, urban planning professionals, urban service companies, and related industries. The buildings, transportation, industry, electricity, waste, and water sectors are among the fastest growing in China's cities as a result, in part, of the 10 million people who move to cities each year. The low-carbon eco-cities collaboration between U.S. and China is a natural platform for strengthening the understanding of China's emerging policies and technology and services markets as well as the latest developments in low-carbon eco-cities in China and for informing U.S. industries and manufacturers of potential market opportunities.

The demand for clean, low-carbon technology in Chinese cities is vast. Beijing alone will spend 50 billion renminbi (RMB) (US$7.7 billion) to combat air pollution during the five years as part of the city's 2013-2017 programs for controlling and preventing air pollution, with a special focus on reducing coal-fired pollution, vehicle emissions, industrial pollution, and dust (“Beijing to Invest 50 billion yuan to tackle air pollution” 2014). To disseminate low-carbon technologies, the Climate Change Division of China’s National Development and Reform Commission (NDRC) in 2014 released a list of recommended low-carbon technologies. The list covers 34 technologies in five categories. Although the list does not specifically address city-level deployment, many of the technologies are appropriate for cities. The list also lacks information on technologies available internationally, particularly from the U.S.

Although substantial information is available on the advancement of low-carbon technologies, it is scattered and not readily available for city policy makers to use in planning. This guide provides a comprehensive resource, integrating information from various sources and linking technologies with KPIs that are relevant to city policy makers. Our intent is to fill the information gap for policy makers with introductory information on commercial technologies that can improve a city’s performance relative to the KPIs in the ELITE Cities analysis. Readers seeking details about any specific technology should consult original sources cited in this report for that technology.

The technology innovation cycle is often described as encompassing the phases of research and development (R&D), demonstration, deployment, diffusion, and commercial maturity. In this report, we focus on commercially available technologies that are already at the deployment and diffusion stages, in sectors that are key to low-carbon eco-city development. The technologies discussed in this report are commercially available and have been demonstrated to be technically sound and cost competitive.

The metrics we used to select technologies for inclusion in this guide are:

- Technological soundness: the technology is proven and commercialized.
- Applicable to China: the technology can address Chinese cities’ needs to improve the KPIs used in the ELITE Cities analysis. For example, in the power sector section of the guide, we do not include natural-gas technologies because, although this technology is important in the U.S., China does not use very much natural gas for electricity.
- Scope: the technologies included are complete end-user products. For example, we include electric vehicles (EVs) but not batteries in the transportation sector because batteries are components, not complete end-user products.
- U.S-based companies: this report focuses heavily on U.S.-based technologies.

This report covers six major energy-consuming sectors: industry, buildings, power, transportation, water, and waste. For each sector, we describe approximately 10 key technologies that can be adopted at a city level. In some sectors, we include categories that encompass a number of similar technologies. We do not aim to present an exhaustive list of low-carbon/ecological technologies. Our goal is simply to provide basic, preliminary information about technologies for eco-cities to which cities can turn when they are looking for technologies to meet low-carbon goals.

Table 1 provides information on the ELITE Cities KPIs that the technologies in this report can help improve.

Table 1. Primary Low-Carbon Categories and Indicator Characteristics

Primary category	Indicator name	Indicator scope	Units
Energy and Climate	CO_2* Intensity	Total CO_2 emissions/capita	Tons CO_2/ capita/year
	Residential Building Energy Intensity	All residential buildings' average energy intensity	kWhe/m^2/year*
	Public Building Electricity Intensity	Chinese government-defined public building average electricity intensity	kWh/m^2/year*
	Share of Renewable Electricity	Renewable energy produced as a share of total electricity purchased by city	% of total electricity purchased
Water and Wastewater	Municipal Water Consumption	Municipal water consumption/capita	liter/capita/day
	Industrial Water Consumption	Industrial water consumption/industrial GDP*	liter/annual 10,000 RMB
	Wastewater Treatment Rate	Percentage of wastewater receiving at least primary treatment	% of total wastewater
	Drinking Water Quality	Percentage of total drinking water meeting Grade III or above	% of total drinking water
	Recycled Water Use	Percentage of annual municipal water use sourced from water reclamation efforts	% of total municipal water
	Energy Intensity of Drinking Water	Energy intensity of drinking water	kWh/liter
Air	PM_{10}* Concentrations	Daily average city-wide PM_{10} concentration	µg/m^3*
	NO_x* Concentrations	Daily average city-wide NO_x concentration	µg/m^3
	SO_2* Concentrations	Daily average city-wide SO_2 concentration	µg/m^3
	Air Pollution Days	Proportion of days per year that air quality meets Level II standard ("blue sky" threshold)	% of total days/year
Waste	Municipal Waste Intensity	Mass of total collected MSW* per capita	kg*/capita/year
	Municipal Waste Treatment Rate	Percentage of collected MSW receiving "harmless" treatment	% of total collected MSW
	Industrial Recycling Rate	Comprehensive industrial waste utilization rate	% of industrial solid wastes
Mobility	Public Transportation Network Penetration	Public transport total route distance as a proportion of total city area	km/km^2*
	Public Transportation Share of Trips	Share of public transportation trips in all trips by registered city residents	% of all trips/year
	Access to Public Transportation	Percentage of built area that is located ≤500 meters of public transit stops	% of built area
	Municipal Fleet Improvement	Proportion of energy-efficient and new-fuel vehicles (electric, hybrid, biofuel, and cars with engines displacing <1.6 liters) in the city's vehicle and taxi fleets	% of total city and taxi vehicles
Economic Health	Employment	Registered unemployment rate	% of eligible adults
	Environmental Protection Spending Ratio	Ratio of environmental protection spending to city GDP	% of annual GDP
	R&D Investment Ratio	Ratio of R&D spending to city GDP	% of annual GDP
	Organic Certification of Agricultural Land	Percentage of total agricultural land area within PLC certified as organic	% of agricultural land

Land Use	Green Space Intensity	Average public green space within urban boundaries, per capita	m^2 of green space/capita
	Share of Mixed-Use Zoning	Percentage total urban land zoned for mixed use	% of total area
	Population Density	Land use per capita in built-up areas	m^2/capita
Social Health	Health Care Availability	Health care practitioners per 1,000 registered urban residents	Health care practitioners/1,000 persons
	Share of Workers from Higher Education	Percentage registered employed population with university degree	% of employed persons
	Internet Connectivity	Percentage households with an internet connection	% of households
	Eco-city Planning Completeness	Eco-city planning and policy completeness	100 points
	Affordable Housing Availability	Percentage total housing designated as “affordable”	% of total housing

Abbreviations:

CO_2 – carbon dioxide; kWhe/m^2 – kilowatt hour energy per square meter; kWh/m^2 – kilowatt hour per square meter; μg/m^3 - micrograms per cubic meter; MSW – municipal solid waste; kg – kilogram; km/km^2 – kilometers per square kilometer; GDP – gross domestic product; PM_{10} – 10-micron particulate matter; NOx – nitrogen oxides; SO_2 – sulfur dioxide

In the remainder of this guide, we use a standardized format to review the technologies described in each sector. For each technology we first describe **key features**, followed by the **cost or payback period** for that technology, the technology’s **applications**, its **energy-savings/emissions-reduction potential** (or comparable benefits relevant to the specific sector being discussed, for example water-saving potential for technologies applicable to the water sector), and finally we note the **KPIs** from ELITE Cities that are relevant to each technology and **sources** to which the reader can turn for additional information. Because the industrial sector encompasses numerous subsectors, that section of the guide includes an additional subsection on “cross-cutting” technologies that are broadly applicable to save energy and reduce carbon and other pollutant emissions across numerous industrial subsectors.

Table 8 at the end of this report summarizes all of the technologies and their basic attributes as described in this guide.

Industrial sector

Of all of the sectors considered in this guidebook, the industrial sector has perhaps the most diverse set of opportunities to contribute to low-carbon eco-city goals. Not only are there many different subsectors within industry, but there are also multiple processes performed at various types of facilities within each subsector, each of which offers opportunities for reducing energy use and carbon dioxide (CO_2) and pollutant emissions.

In the industrial-sector section of this guide, we address the following sectors: cement, glass, iron and steel, pulp and paper, refining, and textiles. Processing of cement, glass, iron, and steel accounts for 40% of industrial energy consumption in China; the pulp, paper, refining, and textiles sectors account for an additional 10% of industrial energy consumption.

Prior to discussing subsector-specific technologies, we review “cross-cutting” energy efficiency and pollutant-reduction technologies that are broadly applicable to numerous industrial subsectors. Because many industrial factories perform broadly similar functions – adding forms of heat and pressure) when transforming raw materials into end-use materials or products – these facilities contain similar types of equipment and face similar challenges in saving energy and reducing emissions even though their end products might differ. For example, compressors, motors, pumps, fans, boilers, and steam-distribution systems are common types of equipment found in most factories. So, although there are nuances of difference among industrial subsectors, many energy-efficiency improvements apply to most or all subsectors. Following our discussion of cross-cutting energy-efficiency opportunities, we examine energy-saving and pollution-reduction opportunities unique to each industrial subsector.

The industrial sector section of this guidebook is a general overview of energy-saving and pollution-reduction opportunities available to industry. For additional understanding of the technologies for specific subsectors, we recommend that the reader look at the series of industrial energy-efficiency guidebooks produced by LBNL. Each guidebook addresses a single specific industry in depth. References for these guides are included at the end of this guidebook, and Table 2 gives an example of the kind of in-depth consideration of an industry’s processes that is found in those guides, which address opportunities for improving the energy efficiency of boilers, steam, motors, pumps, fans, compressed air, lighting, and on-site power generation.

Improvements in industrial-sector energy use and emissions will improve a number of a city’s energy and air KPIs, including carbon intensity, daily average city-wide 10-micron particulate matter (PM10), nitrogen oxide (NOx), and sulfur dioxide (SO_2) concentrations as well as the proportion of days per year that air quality meets Level II standards. Although many direct energy-use reductions (and related carbon-intensity improvements) indirectly improve city-wide air quality, the air quality impacts depend on the nature of the energy supply. There are also water and waste KPIs relevant to industry, including industrial water consumption (industrial water consumption/industrial gross domestic product [GDP]) and industrial waste recycling.

As an example of the types of industrial efficiency improvements that can help contribute to meeting low-carbon and eco-city goals, Table 2 lists energy-efficiency opportunities for petroleum refineries. Similar types of opportunities exist for the cement, steel, glass, pulp and paper, food processing, pharmaceutical, and other industries.

The Institute for Industrial Productivity has also recently started building its Industrial Efficiency Technology Database, which identifies all of the efficiency measures available for several industrial sectors, including iron and steel, cement, glass, pulp and paper, and ammonia. Figure 1 shows an example "map" of those opportunities for the cement sector (Institute of Industrial Productivity, 2014).

Table 2. Summary of energy-efficiency opportunities and cross-cutting energy uses for industry

Management & Control	**Motors**
Monitoring energy use	Properly sizing motors
Installing a site energy control system	Using high-efficiency motors
Optimizing energy distribution in industrial process	Using power factor control
	Eliminating voltage unbalance
Energy Recovery	Using adjustable speed drives
Recovering flare gas	Using variable voltage controls
Recovering power	Replacing belt drives
Recovering hydrogen	
Performing hydrogen pinch analysis	
Recovering waste heat	
Boilers	**Pumps**
Preparing boiler feedwater	Improving operations & maintenance
Improving boiler controls	Monitoring energy use
Reducing flue-gas volume	Using efficient pump designs
Reducing excess air	Correctly sizing pumps
Improving insulation	Using multiple pumps
Performing maintenance	Trimming impellers
Installing flue-gas heat-recovery controls	Improving controls
Using blowdown heat recovery	Using adjustable speed drives
Reduced standby losses	Avoiding throttling valves
Steam Distribution	Correctly sizing pipes
Improving insulation	Reducing leaks
Maintaining insulation	Sealing
Improving steam traps	Using dry vacuum pumps
Maintaining steam traps	**Compressed Air**
Using automatic monitoring of steam traps	Performing maintenance
Repairing leaks	Monitoring air flow
Recovering flash steam	Reducing leaks
Returning condensate	Reducing inlet air temperature
Heaters and Furnaces	Maximizing allowable pressure dew point

Performing maintenance	Implementing controls
Performing draft control	Properly sizing regulators
Pre-heating air	Sizing pipes correctly
Using fouling control	Using adjustable speed drives
Using new burner designs	Using recovered heat to pre-heat water
Process Integration	**Fans**
Performing total site pinch analysis	Properly sizing fans
Performing water pinch analysis	Using adjustable speed drives
Distillation	Using high-efficiency belts
Optimizing operation procedures	**Lighting**
Optimizing product purity	Installing lighting controls
Performing seasonal pressure adjustments	Using T8 tubes
Reducing reboiler duty	Using metal-halide/high-pressure sodium lamps
Upgrading column internals	
Power Generation	Using high-intensity fluorescent (T5) lamps
Using combined heat and power	Using electronic ballasts
Using gas expansion turbines	Using refactors
Using combined-cycle gasification	Installing light-emitting diode (LED) exit signs

Source: LBNL

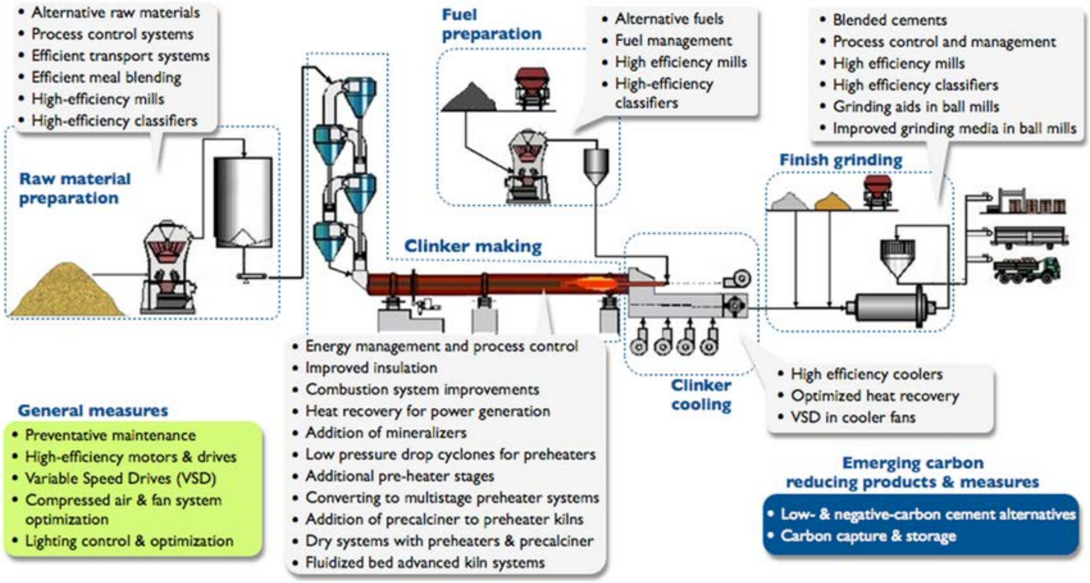

Figure 1. Energy and materials efficiency opportunities in cement sector

Source: Industrial Efficiency Technology Database 2014

Cross-sector opportunities

This section describes energy-efficiency technologies that are broadly applicable to many industrial subsectors.

Energy monitoring and control systems

Description: Energy monitoring and control systems are composed of advanced metering infrastructure (AMI) and a utilities optimizer. AMI helps inform industrial facility managers about energy usage at the level of the whole facility, individual units, or individual processes or systems, as shown in Figure 2. A utilities optimizer can track the overall performance of individual units or systems to assist managers in scheduling maintenance and to alert them to operational problems.

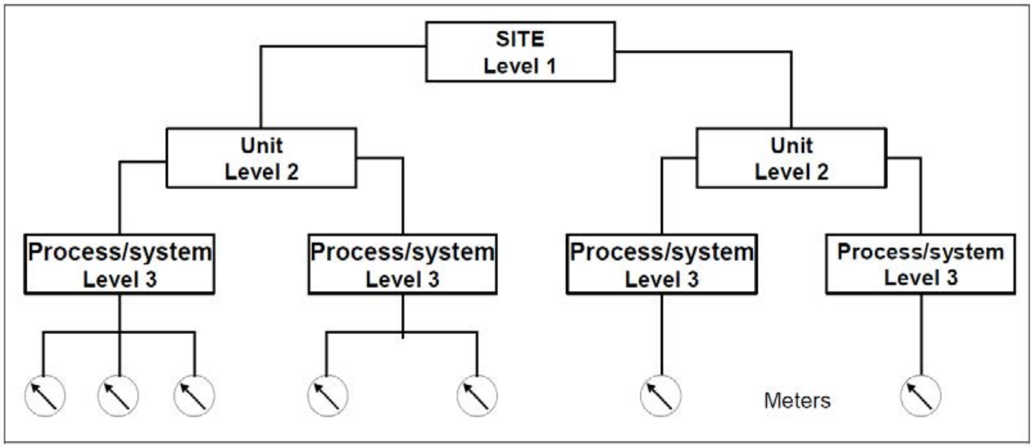

Figure 2. Diagram of site-, unit-, and system-level energy-metering system

Key features: In contrast to traditional utility meters, which are read manually, AMI collects digital data from on-site electricity, gas, and water meters and uses various communications media to send these data to facility managers. Utilities optimizers are best suited to sites that use multiple types of energy usage for multiple types of production (steam, on-site generation, cooling, etc.). Optimizers generally include a model that describes how the facility's systems are supposed to run when optimized. A utilities optimizer can be used to evaluate options for new equipment or equipment retrofits for certain units or processes, for example feed-water heating for boilers, choice of system for on-site generation, or steam processes.

Cost (or payback time): Costs will vary depending in the size of the facility and the amount of submetering desired for individual processes and systems.

Applications: Applications for energy monitoring and control systems include demand forecasting, optimal plant operation, performance evaluation, investment planning, cost accounting, and energy benchmarking. Energy benchmarking uses data collected by the AMI and identifies energy-efficiency indicators to assess the performance of the facility comparison to its own past performance or in comparison to the performance of other facilities in the same sector.

Emissions-reduction/energy-savings potential: Although a monitoring system does not produce direct energy savings, it can be used to benchmark a facility in relation to its peers and identify energy-efficiency opportunities.

Related KPIs: Carbon intensity

Sources and additional resources: (European Commission, 2009)

High-energy-efficiency motors

Description: Motors run a large portion of a factory's functions, including processes that involve altering pressure (compressing, pumping), altering physical shape (crushing, rolling, wire drawing), altering temperature (fans), or moving and transporting materials (conveyors, hoists, cranes). All of these processes add up to a significant amount of energy use. In the European Union (EU), for example, motors account for 68% of industrial-sector electricity consumption. Increasing the energy efficiency of motors usually involves either system-level optimization or replacement of fixed-speed motors with variable-speed-drive motors.

Key features: Choosing high-energy-efficiency motors involves considering motor efficiency, motor sizing, motor controls, power-supply quality, maintenance practices, and the efficiency of any end-use devices to which the motor is connected. Electric motors should be optimized as part of a larger process carried out in the following order: 1) Optimize the entire system of which the motor is a part, to reduce the load as low as possible. 2) Taking into account the optimized load, replace any motor that runs for more than 2,000 hours per year with an energy-efficient model. 3) Replace with a variable-speed-drive motor any motor that has a variable load and operates at less than 50% of capacity for more than 20% of its operating time. Figure 3 shows how a motor's efficiency drops quickly if the motor is running at less than 40% load. This is the main reason for variable-speed-drive motors.

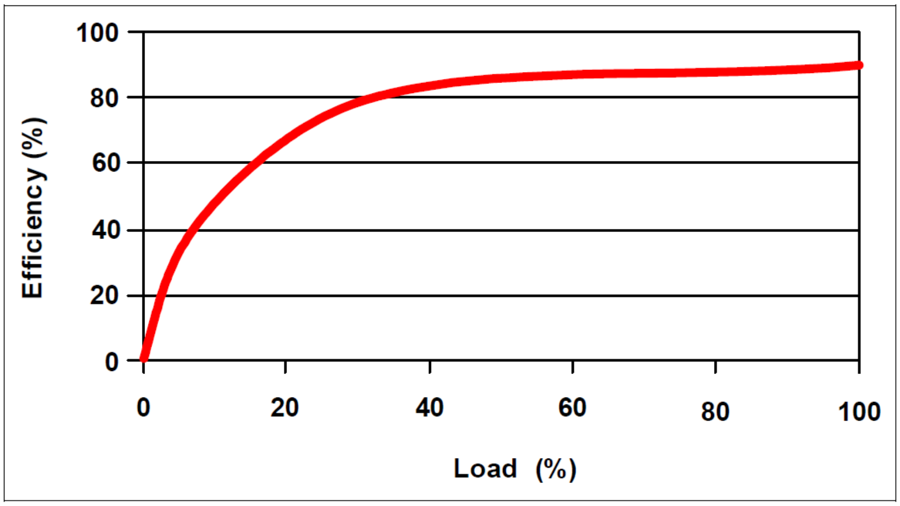

Figure 3. Efficiency vs. load for an electric motor

Cost (or payback time): The price of an energy-efficient motor is typically 20% higher than that of a conventional motor, but payback periods can be as short as one year. Sometimes, for smaller motors, the price premium can be greater than 50%. Compared to standard motors, energy-efficient motors offer benefits including lower temperature rise, longer lifetime, increased reliability, and decreased operations and maintenance.

Applications: As mentioned above, motors run many of the processes in an industrial facility. When loads vary, variable-speed-drive motors can reduce electricity consumption by up to 50% and are particularly useful for centrifugal pumps, compressors, fans, materials processing (mills and machine tools), conveyors, and elevators.

Emissions-reduction/energy-savings potential: Error! Reference source not found. shows the typical energy savings from the energy-efficiency measures for motor systems described in this section.

Table 3. Typical energy savings from motor system energy-efficiency measures

Motor-driven subsystem energy-savings measure	Typical savings range (%)
Install energy-efficient motors	2.0-8.0
Correctly size motors	1.0-3.0
Repair energy-efficient motors	0.5-2.0
Install variable-speed drives	-4.0-50.0
Use high-efficiency transmission/reducers	2.0-10.0
Implement power-quality control	0.5-3.0
Perform lubrication, adjustment, tuning	1.0-5.0

Related KPIs: Carbon intensity

Sources and additional resources: (European Commission, 2009)

Steam-system efficiency

Description: Steam systems account for a significant portion of energy consumption within most industrial facilities. Steam is frequently used in industry because of its advantageous properties, including low toxicity, safety of use with flammable or explosive materials, ease of transportability, and high heat capacity (2,300-2,900 kilojoules per kilogram [kg]). Steam can be used to perform mechanical work through a turbine or as direct heat for process applications. In the EU, steam systems account for 83% of total energy used at pulp and paper facilities, 57% at chemical facilities, and 42% in petroleum refining. Increasing steam-system efficiency can entail improvements in any of the following phases or areas of the steam system: design, generation, distribution, recovery, or operation and control.

Key features: Proper design and sizing of steam systems – especially the steam distribution pipework – has been shown to offer the greatest opportunity for industrial energy savings at least cost. For example, adequately sizing pipes, minimizing the number of bends (because energy is lost at bends), and minimizing leaks are three simple ways to save energy in a steam system. Other distribution improvements include adding insulation to steam and condensate-return pipes. Optimization of steam distribution has high value.

On the generation side, steam is typically produced in a boiler. Basic boiler energy-efficiency measures include proper maintenance, minimizing short-cycling losses, optimizing vent rates, pre-heating feed-water (with economizers or waste heat from other processes), and adding insulation (which can be done during boiler shutdown periods). On the recovery side, condensate should be collected and returned to the boiler for reuse, and reuse of flash steam should also be considered.

Cost (or payback time): Proper sizing of steam systems has been shown to provide a rapid payback within the system’s lifetime. Minimizing leaks also has a rapid payback. The cost of boiler-related measures varies widely but often has a relatively high up-front capital cost. Normal operations can be disrupted while system retrofits and improvements are carried out.

Applications: Steam systems are found in a wide range of industrial facilities. Improvement of steam systems is a critical element of improving industrial energy efficiency.

Emissions-reduction/energy-savings potential: Steam system improvements can produce energy savings ranging from less than 1% to 35%, with an average of 7%.

Related KPIs: Carbon intensity, industrial water consumption

Sources and additional resources: (European Commission, 2009)

Compressed-air systems

Description: Compressed air is a major component of many modern industrial processes. In the EU, it accounts for 10% of industrial electricity consumption. Efficiency opportunities abound in compressed air production, treatment, and distribution.

Key features: As much as 80-95% of the electrical energy used by an industrial air compressor is lost to waste heat. A properly designed heat-recovery unit can recapture 50-90% of this waste heat to be used for heating air or water in related processes.

Other areas to address in improving efficiency include dimensioning pipework, positioning compressors, installing or increasing the volume of storage, using air-entraining nozzles, and optimizing pressure. Installing storage or increasing its volume can help reduce fluctuations and fill in for sudden spikes in pressure demand. As is the case in steam systems, pressure is lost to obstructions and bends in compressed-air pipes, so these should be avoided.

Similar to variable-speed drives for motor systems, variable-frequency drives for compressed air systems can save significant energy in systems that have variable load. As shown in Figure 4, a regular modulating compressor running at 60% load uses about 90% of its full-load rated power whereas a variable-frequency-drive compressor would only use 63%.

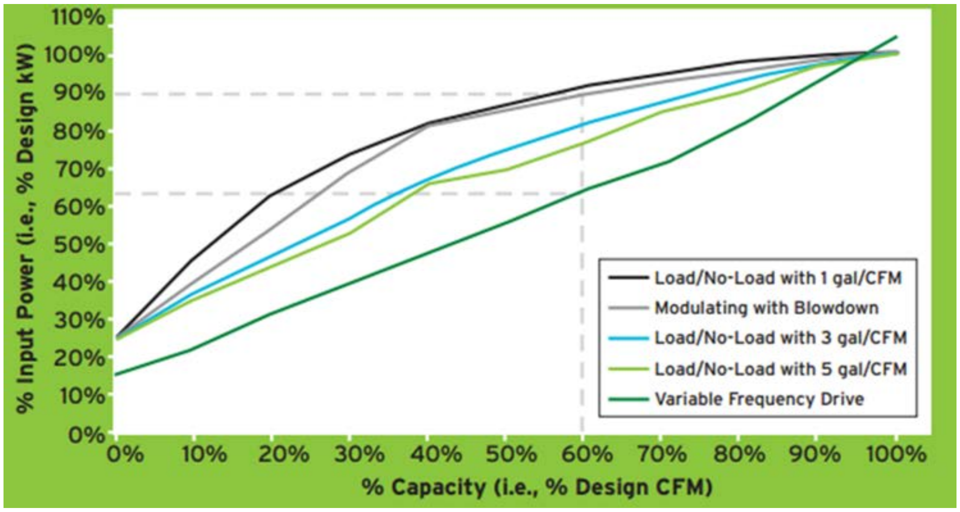

Figure 4. Input power at partial load by compressor type for various compressed-air systems

Applications: Compressed-air systems are used widely across different industrial sectors

Energy-savings potential: Error! Reference source not found.4 shows energy-efficiency measures for compressed air systems, the percentage of systems to which these measures are applicable, potential gains, and overall potential contribution to the improvement of compressed-air systems industry wide. Although the study on which Table 4 is based is specific to the EU, similar results are likely in other economies.

Table 4. Applicability and efficiency gains for energy-saving measures in compressed-air systems

Energy-saving measure	Applicability (%)	Gains (%)	Potential contribution (%)
Improving drives (high-efficiency motors)	25	2	0.5
Improving drives (speed control)	25	15	3.8
Upgrading compressors	30	7	2.1
Installing control systems	20	12	2.4
Recovering waste heat	20	20-80	4.0
Improving cooling, drying, and filtering	10	5	0.5
Improving overall system design	50	9	4.5
Reducing frictional pressure losses	50	3	1.5
Optimizing end-use devices	5	40	2.0
Reducing air leaks	80	20	16.0
Replacing filters more frequently	40	2	0.8

Related KPIs : Carbon intensity

Sources and additional resources: (European Commission, 2009), (Efficiency Vermont, 2013)

Pump systems

Description: Pump systems account for approximately 20% of global electricity demand and anywhere from 25% to 60% of energy usage in industrial facilities, e.g., 59% of energy usage in petroleum refining, 31% in pulp and paper, and 26% in chemicals. It has been said that 75% of pumping systems are oversized (some by more than 20%) and that oversizing is the number-one source of inefficiency in pump systems. Pump-system efficiency is determined by a number of process conditions, including the pump efficiency, overall system design, pump regulation and control, and maintenance cycles.

Key features: During the design phase, pump choice is a function of process need defined by a static head and flow rate but also depends on the type of liquid and on atmospheric considerations. Specifying the right pump technology for a given process is not only important for reducing energy usage but also for controlling overall operational costs. Even if a pump has a slightly higher up-front cost, most of the money spent on the system will be for maintenance and energy costs. Pump manufacturers should work closely with end users and design engineers to reduce information barriers for pump system design. Options for improving pump system control and regulation include shutting down unnecessary pumps, using variable-speed-drive pumps where appropriate, and using throttle control.

Cost (or payback time): Pump systems have a lifespan of 15-20 years, so an analysis of lifetime energy and maintenance costs in relation to initial up-front costs is crucial. Typically, the purchase cost of a pump is only 5-10% of the total life-cycle cost of pump ownership and operation. In other words, the life-cycle cost of a 100-horsepower pump system will be as high as 20 times the initial purchase price.

Applications: Pump systems are used widely in different sectors, including food processing, chemical, petrochemical, pharmaceutical, commercial and agricultural services, municipal water and wastewater, and even residential buildings.

Emissions-reduction/energy-savings potential: Proper matching of pump performance with system requirements can reduce pump energy costs by 20% on average in many cases.

Related KPIs: Carbon intensity

Sources and additional resources: (European Commission, 2009)

Waste-heat and waste-gas recovery for power generation

Description: The laws of thermodynamics impose inherent limits on the thermal efficiency of industrial processes. That is to say, there are always inefficiencies, most often in the form of waste heat. Many applications can capture this waste heat and put it to good use, such as cogeneration of electricity, combined heat and power (CHP), and direct use as process heat.

Key features: Typically, cogeneration systems are either "top cycle" or "bottom cycle." A top-cycle turbine is turned directly by waste heat. In a bottom-cycle turbine, a waste-heat boiler is first used to heat water into steam, which turns a steam turbine. Bottom-cycle turbines are more common.

In cement plants, waste heat is frequently used directly as process heat for drying raw materials and as fuel, which is more cost-effective and efficient than installing a waste-heat recovery system for power generation.

Cost (or payback time): One estimate of installation costs for waste-heat recovery systems in cement plants showed a capital cost range of US$2-4 per annual ton of clinker capacity with operating costs of US$0.20-0.30 per ton of clinker. Waste-heat recovery projects have been common applicants for carbon credits in the Clean Development Mechanism, for which financial additionality needs to be proven before funds from the sale of carbon credits can be received. Commonly, cement plants and other industrial facilities in China have internal rates of return lower than 8%, suggesting that payback is acceptable but not extremely attractive.

Applications: Waste-heat, waste-steam, and waste-gas recovery applications abound in industry. Some applications for cement plants have already been mentioned above. Common types of technologies used to recover waste heat and steam in the iron and steel industry include top-gas pressure-recovery turbines, blast-furnace-gas combined-cycle power plants, and sintering waste-heat recovery.

Emissions-reduction/energy-savings potential: The amount of energy that can be produced from waste heat is usually limited by the waste-heat temperature. For example, the generally low temperature levels of waste heat in cement plants (200-400°C) limits the thermodynamic efficiency of the waste-heat process to 25% at most and more commonly 18-20%. Still, this can be enough to power up to 30% of the cement facility's energy needs.

Related KPIs: Carbon intensity, industrial water consumption, industrial waste recycling

Sources and additional resources: (UNFCCC, 2008), (Worrell, Galitsky, & Price, 2008), (Institute of Industrial Productivity, 2014)

Subsector-specific opportunities

This section describes energy-efficiency and carbon/pollution-reduction opportunities unique to specific industrial subsectors. The applicable subsector is identified in parenthesis in the heading for each technology.

Co-firing of waste materials and use of alternative clinker materials (cement)

Description: Municipal solid waste (MSW) from landfills and sewage sludge from wastewater treatment facilities can be burned in cement kilns using a practice known as co-processing. Co-processing which can reduce the industry's use of fossil fuels as well as CO_2 emissions. This practice has been widespread in the EU, U.S., and Japan for more than 20 years. The ashes left over after combustion can be integrated into the cement clinker, which can save raw materials as well as CO_2 emissions from the calcination process. Another benefit of this practice is diverting waste from landfills, helping mitigate the increase in waste generation associated with rapid urbanization in many developing countries.

Key features: Combusting these different types of fuels in cement kilns can affect the heat energy supply per unit of fuel used. An excess air ratio may also be required. Generally, the higher the heat value of the fuel, the more efficient the combustion process. Pre-processed MSW and sewage sludge have relatively high heat values. In addition to pre-processing, kiln and equipment upgrades may be required to ensure that safety, quality, and environmental standards are met. Sampling and test combustion of materials is recommended before proceeding with a plan to regularly combust waste materials.

Cost (or payback time): Energy costs normally account for 30-40% of a cement plant's operating costs. In certain cases, cement plants using MSW or sewage sludge may be paid a fee to accept the waste although the fee is usually not high enough to cover the costs of pre-processing and co-processing the waste for combustion. As noted above, the process saves fuel costs as well as raw materials. As the externality costs of landfill-related groundwater contamination and greenhouse gas emissions are internalized through various types of energy, climate, and environmental policies, the economics of co-processing should improve.

Applications: Co-firing of waste materials is commonly practiced in the cement industry, but it is possible to co-fire biomass and other types of waste materials for heat and power production in other industrial subsectors or in power plants (e.g., co-firing of biomass in coal-fired power plants).

Emissions-reduction/energy-savings potential: In 2006, waste co-processing in the European cement industry reduced fuel use (mostly coal) by 18% and CO_2 emissions by 8 million tons per year. It is estimated that 100 kg of sewage sludge, if landfilled, will produce 183 kg of CO_2, but if the sludge is co-processed in the cement industry, 51 kg of CO_2 are absorbed, resulting in negative emissions and producing a net savings of 234 kg of CO_2 per 100 kg of sewage sludge.

Related KPIs: Carbon intensity, industrial waste recycling

Sources and additional resources: (Hasanbeigi, Lu, Williams, & Price, 2012)

Coal-mine methane utilization (mining)

Description: Coal-mine methane (CMM) is methane that is released before, during, or after coal-mining operations. Gas drained from coal seams can contain 60-95% methane, and ventilation-air methane (VAM) from the ventilation shafts of coal mines can contain anywhere from 0.1-1% methane. VAM has been estimated to account for 64% of worldwide CMM emissions although the concentrations vary as do the appropriate capture and utilization technologies. Utilizing CMM can improve mine safety, improve mine operations (by minimizing operation downtime resulting from high methane levels), increase mine revenues, and reduce greenhouse gas (GHG) emissions.

Key features: Figure 5 shows common processes for using CMM and VAM. For CMM located in coal seams, boreholes are drilled to drain methane and reduce the methane content of the coal bed. When the methane is captured, it is cleaned to remove oxygen and nitrogen so that it can be upgraded to pipeline quality or utilized on site. Generally, pipeline-grade gas has a concentration of greater than 95% methane, but medium-grade CMM can be enriched to pipeline grade.

A regenerative thermal oxidizer is used to turn VAM into energy. The thermal oxidizer contains a bed of heat-exchange material pre-heated to the oxidation temperature of methane (1,000°C). When VAM is oxidized, it releases heat, sustaining more auto-oxidation reactions. When VAM concentrations are high enough, these systems can provide heat energy for electricity generation.

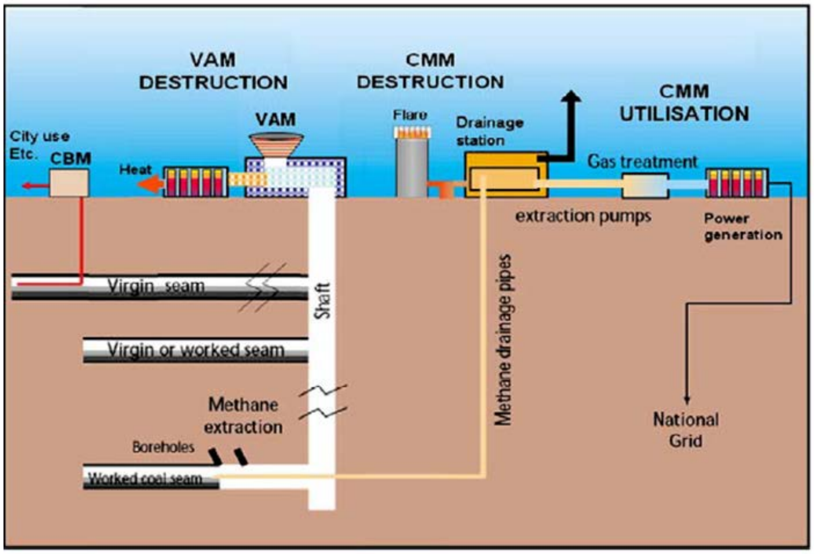

Figure 5. Multiple end-use and destruction options for underground CMM

Cost (or payback time): Costs vary widely among applications depending on which equipment is used and whether the captured CMM or VAM is used on site to generate power or is enriched for pipeline export.

Applications: CMM can be used on or off site. CMM can be used as fuel in furnaces and boilers for on-site processes or in engines or turbines for power generation. Off-site uses include injection into natural-gas pipelines (the proximity of such pipelines needs to be considered) or feedstock for the fertilizer industry. CMM also has the potential to be used as compressed natural gas in vehicles. On-site power generation is the most common use.

Emissions-reduction/energy-savings potential: Methane has a global warming potential more than 20 times greater than that of CO_2. Global CMM emissions were estimated at 432 million tons of CO_2 equivalent in 2005.

Related KPIs: Carbon/methane intensity

Sources and additional resources: (Karacan, Ruiz, Cote, & Phipps, 2011)

Coke dry quenching (iron and steel)

Description: Coke is used in the steel-making process. Coke dry quenching (CDQ) is an energy-efficient alternative to the commonly used wet-quenching process.

Key features: Coke is produced from coal in very-high-temperature coking ovens. Once the coke is prepared, it is commonly cooled ("quenched") by spraying water. This "wet-quenching" process results in significant thermal energy loss. Instead of water, the CDQ process uses an inert gas as a dry cooling medium, which allows the recovery of thermal energy in the quenching gas. CDQ equipment consists of a coke cooling tower and a waste-heat-recovery boiler. The hot coke is placed in the cooling tower, and the inert gas is blown into the tower from the bottom. The gas is heated by the cooling coke and then circulated through the heating tubes of the waste heat boiler where it is transformed into steam.

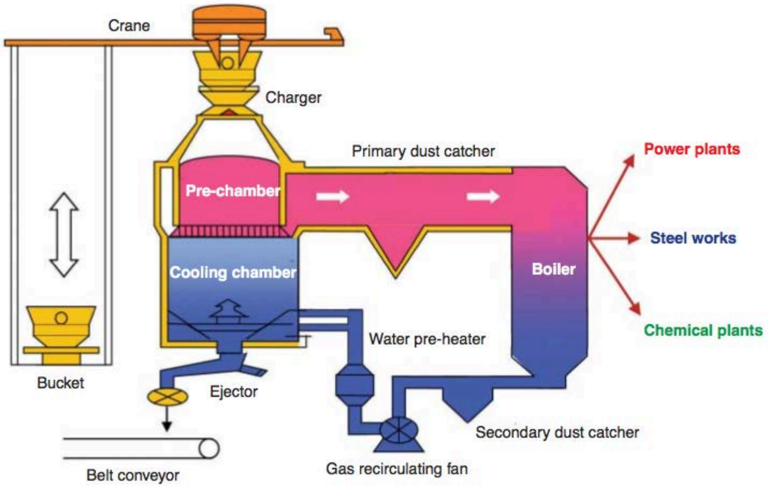

Figure 6. Coke dry-quenching process flow. Source: Japan National Energy Development Organization

Cost (or payback time): In the EU, the cost of equipment for a 2-million-ton-coke-per-year plant is estimated at EUR 70 million. If all the resulting steam is used for electricity generation, the payback can be as short as three years, depending on electricity costs. CDQ has been shown to improve coke quality, enabling reduced coke consumption in the steel blast furnace. As coke product quality improves, CDQ may also allow for the use of less-expensive non-coking coal.

Applications: The thermal energy recovered in the CDQ process can be used to produce steam or electricity, to pre-heat coking coal, or directly as heat (such as in district heating)

Emissions-reduction/energy-savings potential: The most efficient coke ovens using CDQ consume up to 40% less energy than ovens using a wet-quenching process. For a plant with a 450,000-ton annual coke capacity, 450 gigawatt-hours of steam and 150 gigawatt-hours of electricity can be produced annually. About 300 million tons of coke production worldwide do not use CDQ. Global CO_2 emissions reduction potential from those sites is about 25 million tons.

Related KPIs: Carbon intensity, industrial water consumption (industrial water consumption/industrial GDP)

Sources and additional resources: (Jones, 2012), (Worrell, Blinde, Neelis, Blomen, & Masanet, 2010), (Institute of Industrial Productivity, 2014)

Building sector

Opportunities abound for energy-saving design and energy-efficient technology in residential and commercial buildings. This section focuses on technologies available to improve the energy efficiency of buildings.[1] Improvements in energy efficiency in turn lead to improvements in performance for the following KPIs (from Table 1): 1) residential building average energy intensity, 2) Chinese-government-defined public building average electricity intensity, and 3) carbon intensity.

In this section, we describe technologies for the following building systems:

1. Envelope
2. Heating, ventilation, and air conditioning (HVAC)
3. Water heating
4. Appliances and plug loads
5. Lighting
6. Building controls, metering, and communication

The building system to which a technology applies is indicated in parenthesis in the title of the subsection describing that technology.

A building's envelope consists primarily of window, roof, and insulation technologies. From the integrated design perspective, a building's envelope system affects the sizing of and technology choices for HVAC and lighting systems. Advanced technologies for the building envelope system itself include cool roofs, smart windows, and interior and exterior shading systems. For HVAC systems, innovative technologies include hybrid ventilation and ground-source heat pumps (GSHPs).

Efficiency of both electric and gas water heaters has increased over time, but there is still room for improvement. Options include high-efficiency heat-pump water heaters and solar water heating. The latter is a cost-effective renewable-energy option for residential buildings.

As the overall efficiencies of large building systems, such as HVAC, envelope, and lighting, improve, plug loads will account for an increasing proportion, potentially more than 50%, of a building's energy footprint. Therefore, applications will be needed to increase the efficiency of equipment, appliances, and consumer electronics. In addition, lighting accounts for a significant proportion of electricity used by commercial buildings, so lighting systems are an additional potential source of energy savings. Finally, smart meters will play an important role in future energy-efficiency improvements, especially in enabling demand response.

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[1] Distributed energy generation is an energy-efficient technology that is increasingly being installed in individual buildings as rooftop solar photovoltaic (PV) or on-site CHP; we discuss distributed-energy-generation technologies in the power sector section of this report.

Integration of building systems and energy-efficient technologies is more important than any individual technology or efficiency opportunity. Integrated building design is critical for ensuring that buildings are energy efficient, for several reasons. First, when building systems are designed together to function as a single unit, the resulting building's energy footprint is much lower than when building systems are designed separately. A key element of integrated design is ensuring efficient interaction among the HVAC, lighting, and envelope systems. For instance, a well-insulated envelope that incorporates daylighting as well as exterior shading can be operated to minimize both HVAC and lighting loads. Second, many advanced building technologies can only realize their full efficiency potential when implemented with up-to-date building controls. Real-time feedback and monitoring are needed to optimize building operations, occupant comfort, and energy efficiency. Integrated building design can ensure that information on building systems is consistently collected and used for optimizing building operations. Energy management and optimization for building operation are increasingly important to ensuring that the building energy system performs efficiently.

A recent report on integrated building design by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE); American Institute of Architects; Illuminating Engineering Society of North America; U.S. Green Building Council, and U.S. Department of Energy (U.S. DOE) outlines eight essential steps to constructing a building whose energy footprint that is 50% below ASHRAE standard 90.1-2004:

1. Obtain building owner buy-in.
2. Assemble an experienced, innovative design team.
3. Adopt an integrated design process.
4. Consider using a daylighting consultant.
5. Consider energy modeling.
6. Commission the building.
7. Train building users and operations staff.
8. Monitor the building.

Figure 7 shows how important it is to make appropriate integrated design choices from the start because the opportunities for potentially cost-effective energy savings decrease rapidly once design processes are under way.

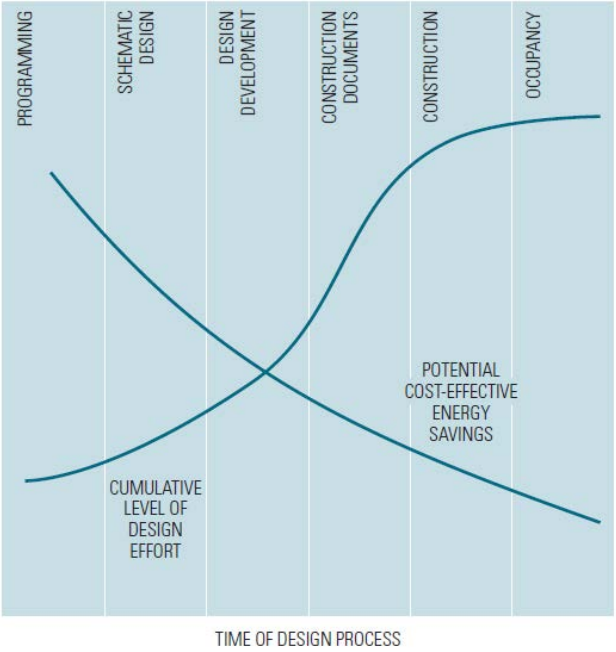

Figure 7. Energy-saving opportunities and the design sequence Source: E Source Technology

Low U-value Windows (envelope)

Description: U-value is a measure of heat loss. Energy-efficient windows have minimal heat loss and therefore low U-values. R-value is a measure of the insulating capability of a material. Energy-efficient windows with low U-values (low heat loss) will have high insulation capability and therefore high R-values.[2] In other words, U-value and R-value are inversely related. U.S. DOE defines windows with high-performance glazing having a minimum U-value of 0.2 or R-value of 5.

Table 5. U-values for multiple-pane windows with and without argon gas fill between panes

Type of window	Single pane	Double pane	Double pane with argon fill	Triple pane	Triple pane with argon fill
U-value	0.94	0.48	0.39	0.38	0.27

Source: (U.S. EPA, 2013)

Key features: Common double-pane windows have an insulating value of R-2. More efficient ENERGY STAR windows are R-3. Increasing from R-3 to R-5 can reduce average heat loss by 30%. The glazing techniques used in R-5 windows usually involved spectrally selective coatings, which filter out 40-70% of the heat transmitted through clear glass while still allowing the full amount

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[2] An R-value rates how well a specific material, such as glass, insulates. A U-value rates the performance of an entire window or door assembly rather than a specific component or material.

of light to be transmitted. Argon gas is often pumped between the panes of multiple-pane windows to increase the R-value. Because argon is heavier than air, it has good insulating properties.

Cost (or payback time): Manufacturers claim a payback time of 2-4 years for low-U-value windows. According to the U.S. government's Green Proving Ground (GPG) program, high-efficiency windows can have a price premium of US$4 per square foot but are cost effective in several climate zones on the basis of energy savings alone. Additional savings result because HVAC capacity can be downsized as a result of reduced need for space conditioning when efficient windows are used.

Applications: GPG reports that efficient window technology "is particularly applicable to commercial new construction and major reconstruction that have high window-to-wall area ratios that are fully conditioned and where the capital cost can be offset by the downsized HVAC equipment cost." GPG has also researched a clear, water-based, spray-on coating for retrofitting existing buildings and is currently testing the use of this coating and its impact on energy use in federal buildings.

Emissions-reduction/energy-savings potential: Manufacturers claim heating and cooling savings between 20-40% from energy-efficient windows, compared to heating and cooling costs with less-efficiency windows.

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (U.S. EPA, 2013)
http://www.efficientwindows.org/membership_list.php#manufacturers

Smart windows (envelope)

Description: In addition to the highly insulating windows described above, another efficient option is windows with "smart" functionality that enables them to change their transparency, light transmission, and solar heat gain factor. There are two types of smart windows: electrochromic and thermotropic. Both are used to reduce solar heat gain in warmer climates, which, in turn, reduces cooling energy use and peak electrical loads.

Key features: In a thermotropic window, organic polymers are embedded in the glass. These polymers automatically darken and lighten based on the window's surface temperature. An electrochromic window (shown in Figure 8) can vary its tinting between 2% and 60% using an electronic control (which can be altered by the occupant to suit comfort requirements). Thus, an electrochromic window requires an external power source, which can be integrated into the window frame and may have associated operations and maintenance costs.

Cost (or payback time): Energy savings from smart windows have a payback period of 1–10 years (ASHRAE 90.1-2001) and 2–18 years (ASHRAE 90.1-2007); installation costs are in the range of US\$5.40–\$43.00/square meter (m^2) (US\$0.50–US\$4.00/square foot [ft^2]). When savings from occupancy controls are also taken into account, payback times decrease to 1–8 years (90.1-2001) and 2–13 years (90.1-2007) (Fernandes, et al. 2014). In 2010, electrochromic windows cost around US\$100 per square foot (Wang 2010).

Applications: According to the GPG program, smart window technology is most applicable to new construction or major reconstruction projects where the capital costs can be offset by decreased HVAC equipment costs.

Emissions-reduction/energy-savings potential: Preliminary data show that smart windows can reduce overall cooling loads by up to 20%, according to the GPG.

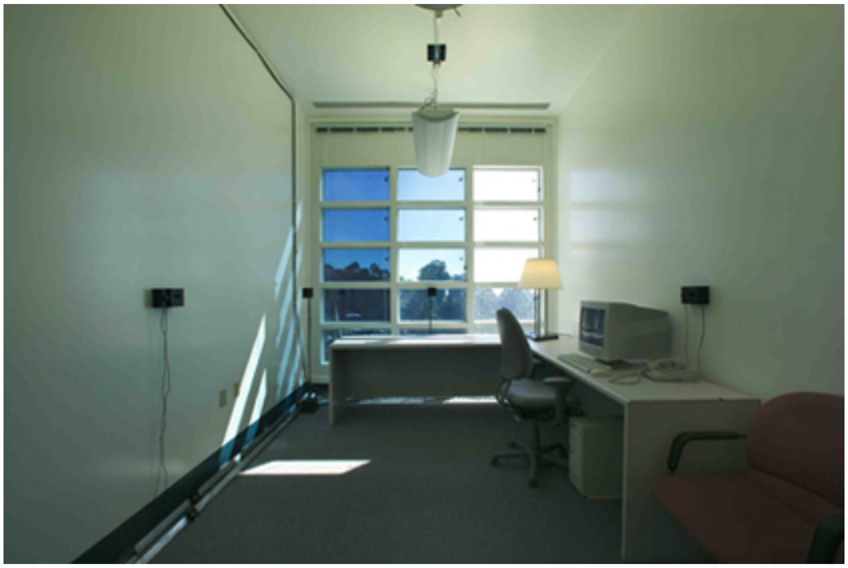

Figure 8. Electrochromic windows, Source: LBNL

Related KPIs : Residential building average energy intensity (direct), public building average electricity intensity (direct), total CO_2 emissions/capita (indirect)

Sources and additional resources: (Kandt & Lowell, 2012)

Cool roofs (envelope)

Description: Cool roofs have paints, coatings, or colorings that minimize solar absorption and maximize thermal emissions, keeping roof temperature low during sun exposure.

Key features: Minimizing solar absorption reduces the flow of heat from the roof into the building, decreasing the need for air conditioning. Cool roofs have a small heating penalty as a result of lost heating gain from winter sun on the roof.

Cost (or payback time): Table 6 shows U.S. cost data for different cool roof options.

Table 6 Cool roof options and cost estimates for different roof types

Roof Type	Non-Cool Roof Options	Non-Cool Roof Solar Reflectance	Cool Roof Options	Cool Roof Solar Reflectance	Cool Roof Material Cost*	Life Expectancy (years)	Roof Slope
Asphalt Shingle	black or dark brown with conventional pigments	0.05 - 0.15	“white” (actually light gray)	0.25	$	15 to 30	Steep slope
			medium gray or brown with cool pigments	0.25			
Built-Up Roof	with dark gravel	0.10 - 0.15	with white gravel	0.30 - 0.50	$ - $$	10 to 30	Low slope
	with aluminum coating	0.25 - 0.60	smooth surface with white roof coating	0.75 - 0.85			
Clay Tile	dark color with conventional pigments	0.20	terracotta (unglazed red tile)	0.40	$$ - $$$	50+	Steep slope
	color with cool pigments		color with cool pigments	0.40 - 0.60			
	white		white	0.70			
Concrete Tile	dark color with conventional pigments	0.05 - 0.35	color with cool pigments	0.40 - 0.50	$ - $$$	50+	Steep slope
			white	0.70			
Liquid Applied Coating	smooth black	0.05	smooth white	0.70 - 0.85	$	10	Low or steep slope
Metal Roof	unpainted, corrugated	0.30 - 0.50	white painted	0.60 - 0.70	$$	20 to 50+	Low or steep slope
	dark-painted, corrugated	0.05 -0.10	color with cool pigments	0.40 - 0.70			
Modified Bitumen	with mineral surface capsheet (SBS, APP)	0.10 - 0.20	white coating over a mineral surface (SBS, APP)	0.60 - 0.75	$	10 to 30	Low slope
Single-Ply Membrane	black (PVC)	0.05	white (PVC)	0.70 - 0.80	$	10 to 20	Low slope
			color with cool pigments	0.40 - 0.60			
Wood Shake	painted dark color with conventional pigments	0.05 - 0.35	bare	0.40 - 0.55	$	15 to 30	Steep slope

Source: (California Air Resources Board, 2013). NOTE: Materials costs (in US$ – $: $0 - $2 per ft^2; $$: $2 - $4 per ft^2; $$$: $4 - $6 per f^{t2}

Applications: The most common cool-roof applications are in warm and hot climates that have long cooling seasons and short heating seasons. Energy savings have been measured in the U.S. in California, Florida, and Texas.

Emissions-reduction/energy-savings potential: Typically, summertime air-conditioning and peak-demand reductions from cool roofs have ranged between 10% and 30% although values as low as 2% and as high 40% have been reported. One recent study found that retrofitting 80% of the 2.58 billion m^2 of commercial building conditioned roof area in the U.S. would yield annual cooling energy savings of 10.4 terawatt-hours (TWh), with an annual heating energy penalty of 133 million therms (much less than the cooling energy savings), and an annual energy cost savings of US$735 million.

Figure 9. White roof application at large Wal-Mart retail outlet in northern California Source: Walmart

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (Levinson & Akbari, 2010).

Interior and exterior shading systems (envelope)

Description: Interior or exterior shading systems physically moderate the amount of daylight entering a building, controlling the amount of solar gain for purposes of optimizing heating, cooling, and lighting energy consumption.

Key features: Options for shading systems include Venetian vs. roller blinds, manual vs. automated operation, and interior vs. exterior application.

Cost (or payback time): Interior systems may be lower cost and easier to implement, but exterior systems can offer a significant degree of solar control and will likely be important in achieving very-low-energy buildings.

Applications: Interior and exterior shading systems have significant technical potential because of their low cost and applicability to both new and retrofit construction.

Figure 10. Exterior and interior Venetian blind systems
Source: LBNL

Emissions-reduction/energy-savings potential: Table 7 shows the results of an LBNL Windows Testbed Facility experiment on interior and exterior shading systems. Both manual and automated exterior shading systems saved large amounts of lighting energy and cooling load. Interior shading systems produced much lower levels of energy savings.

Table 7. Monitored performance of innovative shading systems at LBNL

		Interior Shades		Exterior Shades	
		Manual	Automated	Manual	Automated
Lighting energy use	kWh/ft^2-yr	1.04-1.13	0.92-1.11	1.12-1.41	1.0-1.27
Lighting energy savings	%	62-65%	62-69%	53-63%	58-67%
Cooling load savings	%	Up to 15%	Up to 22%	78-94%	80-87%
Peak cooling load	W/ft^2-floor	8.0-9.4	8.0-9.8	1.6-3.1	2.0-2.5
Avg time uncomfortable	Hours/day	2.3-3.7	0.0-1.1	0.7-3.8	0.2-3.0

Related KPIs : Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (Lee, et al., 2009)

Natural and hybrid ventilation (HVAC)

Description: Mechanical cooling and fan energy account for approximately 20% of U.S. commercial building electricity consumption. Natural ventilation provides air flow – and potentially cooling – without the use of a mechanical system.

Key features: Although buildings exist that have only natural ventilation and no air conditioning, they are rare. Most common is a mixed-mode approach with one of the following operational strategies:

1. Alternating operation: In alternating mode, either the mechanical or the natural ventilation system operates alone.
2. Changeover operation: In changeover mode, either or both systems operate on a seasonal or daily basis depending on the outdoor air temperature, time of day, occupancy, user commands, etc. The system employs the most effective ventilation solution for the current conditions.
3. Concurrent operation: In concurrent mode, both systems operate in the same space at the same time (e.g., mechanical ventilation with operable windows).

Cost (or payback time): Naturally ventilated buildings typically have lower capital costs for cooling and ventilation equipment, but some additional capital must be spent on the facade and building fabric. Capital costs for natural ventilation system elements, such as automated windows, can be comparable to the costs of air-conditioning systems (Carbon Trust 2012).

Applications: Although many buildings cannot rely on natural ventilation alone without some air conditioning, the concept of integrating passive natural ventilation in conventionally air-conditioned buildings is receiving increasing attention. The most effective applications are in locations with a moderate climate and clean outdoor air. These buildings can take advantage of natural ventilation for passive cooling, reducing the need for conventional HVAC systems. The California Academy of Science in San Francisco’s Golden Gate Park uses a combination of green roofing and skylights for natural ventilation. The roof’s steep slopes act as a natural ventilation system, and the skylights automatically open on warm days to vent hot air from the building.

Figure 11. Green roof and skylights provide natural ventilation
Source: California Academy of Sciences

Emissions-reduction/energy-savings potential: Four of six natural-ventilation case-study projects in the UK saved between 24% and 71% of carbon emissions compared to industry benchmark figures for an average air-conditioned building. Cost savings were between 4,000 and 6,000 British Pounds a year (Carbon Trust 2012). In the U.S., estimated emissions reductions in 2025 from building retrofits to incorporate natural ventilation will save 56 terawatt-hours

(TWh) of electricity and 30 million tons of CO_2 per year, whereas new naturally ventilated houses will save 4 TWh of electricity and 2 million tons of CO_2 per year (Glickman, Domínguez and Tan 2014).

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: Lee, E. Double skin facades and natural ventilation from High-performance commercial building facades: http://gaia.lbl.gov/hpbf/techno_c3.htm (accessed December 11, 2012).

Ground-source heat pumps (HVAC)

Description: GSHPs, also known as geothermal heat pumps, use the earth as a heat source in the winter and as a heat sink in the summer, taking advantage of the moderate temperatures in the ground to reduce the operational costs of heating and cooling. Figure 12 shows a GSHP application.

Key features: The vertical-borehole heat exchanger is the most common GSHP application. In this system, a number of large boreholes are drilled deep (typically 150-200 feet, or 45-60 meters) into the earth.

Figure 12. Beijing's linked hybrid at Dongzhimen meets two-thirds of heating/cooling demand with GSHP technology

Cost (or payback time): Even though the installation price of a geothermal system can be several times that of an air-source system with the same heating and cooling capacity, the payback is only 5 to 10 years. System life is estimated at 25 years for inside components and more than 50 years for the ground loop. Still, high first costs remain a barrier as do lack of consumer knowledge about and trust in GSHP systems.

Applications: GSHP systems are equally applicable to residential and commercial buildings but are usually seen only in new construction.

Emissions-reduction/energy-savings potential: GSHP systems can meet 100% of some residential and commercial buildings' heating and cooling needs. For buildings with high heating or cooling demands, a GSHP system may need to be supplemented with a back-up gas-fired heating or electric cooling system. In those cases, the GSHP might meet only two-thirds of the building's heating and cooling needs (as is the case at Beijing's Linked Hybrid building).

Related KPIs: Residential building average energy intensity, public building average electricity intensity, share of renewable energy

Sources and additional resources: (Hughes, 2008)

Heat-pump water heaters (water heating)

Description: The U.S. market is dominated by storage or tank water heaters, with electric resistance and gas heaters having roughly equal market shares. Heat-pump water heaters (HPWHs) are electric resistance technologies that use a vapor-compression refrigeration cycle to concentrate ambient heat. They also dehumidify and cool the air in the space where they are installed, an attractive attribute in humid climates. Both "drop-in" integrated and "add-on" models exist; Figure 13 shows simple schematics of both. Starting in 2015, U.S. DOE will require that all electric water heaters with a capacity greater than 55 gallons be HPWHs. This requirement will likely grow incrementally to include smaller-capacity units (Sachs, Talbot, & Kaufman, 2011).

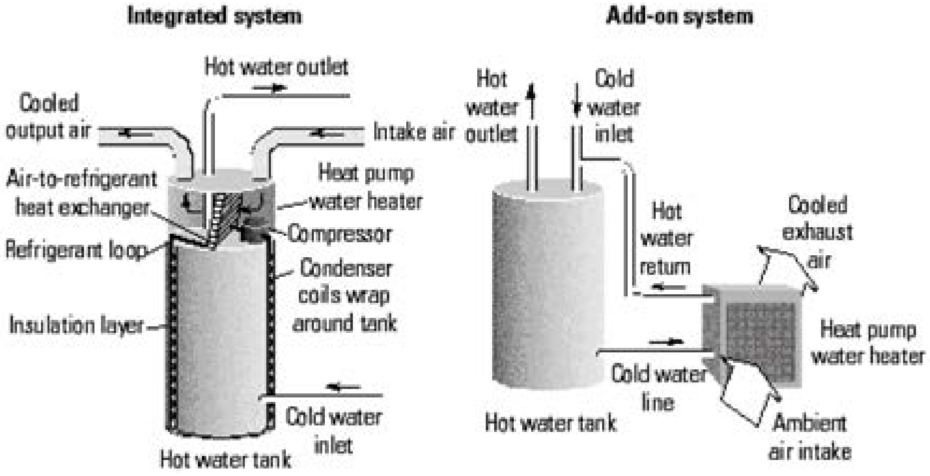

Figure 13. Drop-in Integrated and add-on heat pump water heater models
Source: Reliant Energy

Key features: In a manner roughly inverse to the functioning of a refrigerator, which extracts heat from its interior and exhausts the heat into the surrounding room, a HPWH extracts heat from the surrounding room and uses it to heat water in a tank. HPWHs need to be installed in locations whose ambient temperature stays between 40º–90ºF (4.4º–32.2ºC) year round, with at least 1,000 cubic feet (28.3 cubic meters) of air space around the water heater. HPWHs are often installed in furnace rooms, which typically have excess heat that the HPWH can use.

Cost (or payback time): HPWHs currently have slightly higher up-front costs than other tank-based water heaters, but the costs are expected to decrease over time. HPWHs have slightly lower operating costs than their conventional counterparts.

Applications: Most current applications are in residences, but HPWHs could become more common in commercial buildings in the future. Transitioning from gas to electric water heaters (especially efficient electric water heaters like HPWHs) is considered a key element of the transition to a more renewable-electricity-based future.

Emissions-reduction/energy-savings potential: Compared to a conventional water heater, a well-designed HPWH will use less than half as much electricity to heat the same amount of hot water.

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (U.S. Department of Energy, 2014)

Advanced power strips (appliances and consumer electronics)

Description: Advanced power strips (APSs) can be used in commercial building workspaces and common areas such as kitchens and printer/copier rooms.

Key features: A recent study by the General Services Administration (GSA) and the National Renewable Energy Laboratory (NREL) in the U.S. piloted APSs in eight buildings where plug loads averaged 21% of the buildings' energy footprints. Twelve APSs replaced standard power strips in each building, and plug-load reduction strategies were carried out, including schedule timer control, load-sensing control, and a combination of the two. Schedule timers allow the user to set the days and times when a circuit will be turned on and off.

Cost (or payback time): The GSA/NREL study showed that the simple payback period for schedule timers was less than 8 years for all applications: kitchens – 0.7 years; printer rooms – 1.1 years; and miscellaneous devices – 4.1 years. Even at workstations where power management was already in place, payback was 7.8 years.

Applications: As noted above, APSs can be used in various settings in commercial buildings, such as kitchens, printer rooms, individual offices, and workstations. They could also be used for home entertainment or computer systems in residential buildings.

Emissions-reduction/energy-savings potential: Study results underscored the effectiveness of APS schedule-based functionality, which reduced plug loads at workstations by 26% even though advanced computer power management was already in place, and by nearly 50% in printer rooms and kitchens. Figure 14 shows an energy-efficient workstation at NREL.

Figure 14. Energy-efficient workspace used for a net zero energy building at the National Renewable Energy Lab Source: (Metzger, Cutler, & Sheppy, 2012)

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (Metzger, Cutler, & Sheppy, 2012)

Lighting-system improvements

Description: Lighting accounts for 38% of the electricity used in U.S. commercial buildings, representing a large potential source of energy savings. Lighting-system improvements include increasing the luminous efficacy (lumens per watt [W]) of bulbs as well as decreasing system usage through lighting controls.

Key features: Linear and compact fluorescent bulbs and fixtures have offered large savings over incandescent and halogen bulbs; the newest efficiency innovation is solid-state lighting technology, e.g., LEDs, whose efficiency is shown in Figure 15.

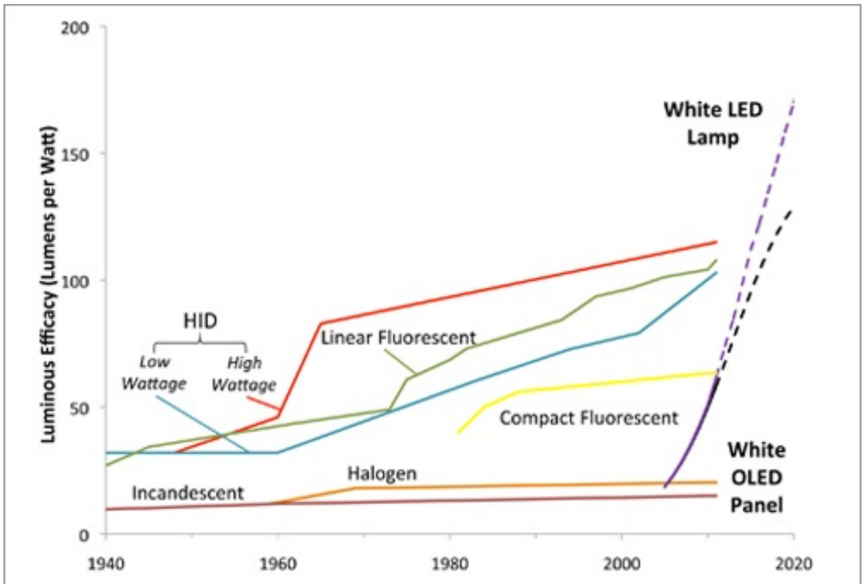

Figure 15. Efficacy potentials for solid-state lighting technologies
Source: (Bardsley, et al., 2013)

Although deploying new efficient lighting technologies will save some energy, the majority of savings can be found in daylighting design and lighting controls (such as daylighting controls and occupancy sensors). Daylighting controls adjust lighting levels according to how much light is transmitted through windows.

Cost (or payback time): LEDs are currently more costly than compact fluorescent lamps, but LED costs are expected to decrease over time. Many utilities in the U.S. and EU offer subsidies and rebates for LEDs. Occupancy sensors are relatively commonplace now and have short payback periods of six months to approximately two years.

Applications: Both LEDs and lighting controls are widely applicable in both residential and commercial buildings.

Emissions-reduction/energy-savings potential: Current LED technology has similar luminous efficacy to that of compact fluorescents although the latter technology is not improving while LED technology is improving rapidly. Improved efficacy and longer bulb lifetimes will increase LEDs' energy savings potential.

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (Bardsley, et al., 2013)

Advanced metering infrastructure/smart meters (control systems)

Description: Advanced metering infrastructure creates an interface between utilities (or other energy providers) and their residential and commercial customers. This infrastructure is viewed as a critical part of the future smart grid.

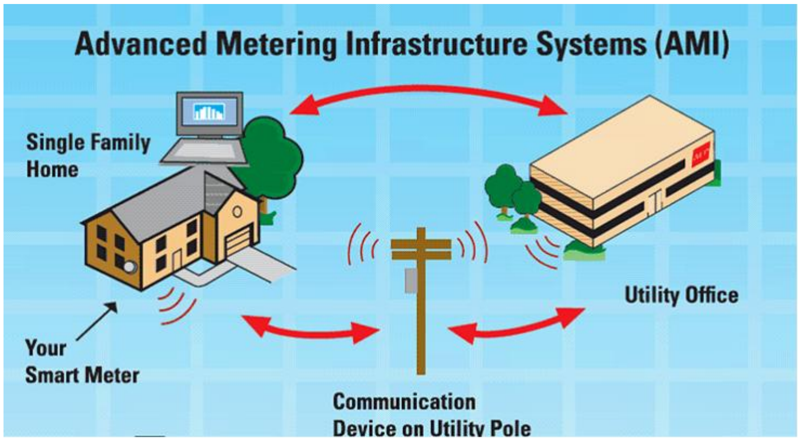

Figure 16. Advancing metering infrastructure

Key features: Unlike prior generations of automatic meter reading which entailed one-way polling of meters by the utility, smart meters allow two-way communication, measuring real-time energy use in time intervals of one hour or less and enabling communications exchange between the homeowner and the utility. Smart meters are being installed by utilities rather than building owners, in part because smart meters enable utilities to offer time-of-use pricing. Building owners can also install a home area network that allows them to receive real-time smart meter data about their energy use. Even without such a device, customers with smart meters can access their electricity use for the previous day through the utility's website. Smart meters also enable faster outage detection and restoration of electricity service.

Cost (or payback time): Advanced metering infrastructure is being rolled out by utilities all over the world as a cost-effective measure for controlling demand, especially during peak periods. Constructing new power plants that operate for only a certain small number of peak hours during the year is very costly; smart meters are a more economical approach to avoiding the need for new plants by controlling peak demand. These meters are especially attractive when incentivized through time-based rates. One California utility, Pacific Gas and Electric Company, invested US$1.8 billion to install smart meters throughout its network and estimates that it will be able to recover 89% of this investment simply through operational improvements, in addition to providing savings for customers. Nevertheless, the up-front costs of smart meters are quite significant, including hardware and software purchases, labor expenses for meter installation, and consumer education.

Applications: Demand response entails changes to customers' normal end-use electricity consumption in response to changes in electricity prices or to incentive payments from a utility demand-response program. Utility demand-response programs aim to lower electricity use when wholesale market prices are high or when system reliability is jeopardized. Buildings that can control their HVAC, lighting, and other energy loads and have advanced metering infrastructure should be able to participate in demand response programs. Price signals can be sent in real time to the building's electricity meter; in response, usage can be adjusted manually or automatically. A large group of buildings (a university campus, for example) might have an incentive to set up its own demand-response-automation server (see Figure 17) so that it can save energy costs by adjusting loads to reduce demand in response to real-time price signals from the utility. Demand response programs help utilities reduce peak loads and protect system reliability.

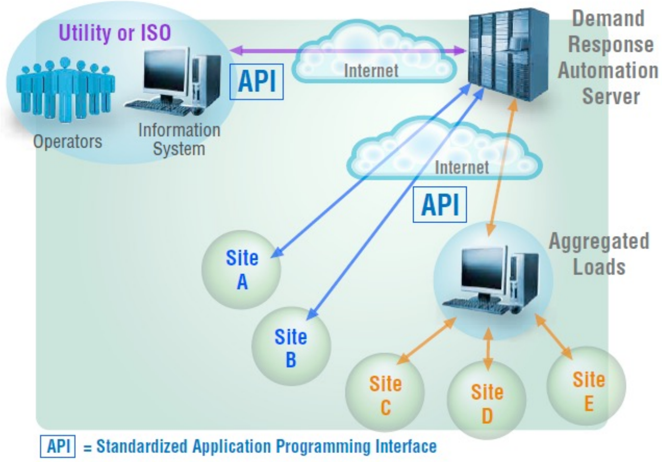

Figure 17. Interaction among utility, demand response automation server, and aggregated loads
Source: LBNL

Emissions-reduction/energy-savings potential: Utilities around the U.S. have reported peak-load reductions ranging from 26% to 43% for pilot programs pairing smart meters with time-of-use pricing.

Related KPIs: Residential building average energy intensity, public building average electricity intensity

Sources and additional resources: (Galvin Electricity Initiative, 2009)

Power sector

In 2012, the power sector was the largest source of U.S. GHG emissions, accounting for about 32% of the U.S. total. GHG emissions from electricity production have increased by about 11% since 1990 as electricity demand has grown and fossil fuels have remained the dominant source for generation (U. S. EPA, 2014). In China, the power sector accounts for about half of the country's coal consumption and about 40% of carbon emissions (CEC, 2014). The carbon mitigation in power sector will largely decide if the overall carbon mitigation goal can be achieved or not.

Although the power sector accounts for a large of a city's energy consumption and carbon emissions, cities usually have no control over fuel choices because power is typically imported from sources external to the city. In this section, we focus on technologies that are within the city's authority to affect or control.

Power-sector technologies that discussed in this section are:

- Distributed solar, including building-integrated photovoltaics (PV)
- Combined heat and power (CHP; co-generation)
- Fuel-cell power systems
- Utility-scale solar
- Utility-scale energy storage
- Microgrids
- Integrated gasification combined-cycle (IGCC) power
- Smart grids
- Carbon capture, utilization, and storage (CCUS)

Although renewable energy technologies such as solar PV and wind are seen as leading the clean energy revolution, other technologies can often save significant energy and CO_2 emissions. These include fuel cells, CHP, energy storage, microgrids, and smart grids. Although the power sector is an input to many other sectors such as buildings, industry, and transportation, this section focuses on technologies and carbon-mitigation strategies that are directly applicable to power generation.

KPIs related to power-sector performance are as follows:

- Carbon intensity of electricity generation
- Renewable share as of total electricity consumption
- Distributed generation share as of total electricity consumption

Distributed solar and building-integrated photovoltaics

Technology name: Distributed solar technology

Description: Distributed generation refers to electricity that is produced at or near the location where it is used. Distributed solar energy can be located on rooftops or ground mounted and is typically connected to the local utility distribution grid. States, cities, and towns are experimenting with policies that encourage distributed solar to offset peak electricity demand and stabilize the local grid (SEIA, 2013). An example is building-integrated photovoltaics (BIPV), which can serve as both the outer layer of a building's structure and generate electricity for on-site use or sell to the grid. BIPV systems save materials and electricity costs, reduce pollution, and can add to a building's architectural appeal (see Figure 18).

Figure 18. Example application of BIPV as an architectural element in a building

Key features: The standard element of a BIPV system is the PV module, formed by individual solar cells that are interconnected and encapsulated. Modules are strung together with cables and wires in an electrical series, forming a PV array. After the array's installation, direct or diffuse light (usually sunlight) shining on the solar cells induces the PV effect, generating unregulated direct-current electric power. Through net metering, owners of the BIPV system can receive credit electricity exported to the grid. Standards are needed to facilitate the connection of this distributed technology to the electricity grid.

Cost: The price of residential and commercial PV systems continues to fall. Average system prices were US$4.93/W in the first quarter of 2013 in the U.S, with some states well below US$4.00/W on average. There is plenty of room to reduce costs further, especially if streamlining of soft costs (contracting, permitting, and management cost, etc.) is included (Kann 2013). In general, developers claim a payback time of 5-10 years, and the solar systems last 20-25 years. Direct incentives for solar energy can take a variety of forms, including tax credits, up-front rebates, and incentives based on energy production.

Applications: For a commercial or large residential building looking into developing distributed energy resources, the most important first step is to analyze the following facility needs: electricity, refrigeration and building cooling, building heating, hot water, fuels, and other energy-consuming uses. A distributed energy supply can be designed based on desired cost, reliability, carbon footprint, or other parameters.

Emissions-reduction/energy-savings potential: A field study using DOE-2.1E building energy simulations in several U.S. cities found an annual cooling energy savings per unit of conditioned roof area of 34.6 megajoules (MJ)/m^2 (9.6 kWh/m^2), annual heating energy savings of 2.9 MJ/m^2 (0.010 therm/m^2), and annual primary energy savings of 107.1 MJ/m^2 (101 BTU/m^2 (Ban-Weiss, et al. 2013).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Source: http://www.seia.org/policy/distributed-solar; (Patrina Eiffert and Gregory J. Kiss 2000)

Combined heat and power (CHP)

Technology name: Combined heat and power (CHP)

Description: CHP, also known as cogeneration, is the simultaneous production of electricity and heat from a single fuel source such as natural gas, biomass, biogas, coal, waste heat, or oil. CHP uses the waste heat from the conversion process either directly or to run turbines that produce additional power. Facilities with high heating loads are typically the most appropriate for CHP systems from a purely economic standpoint, but in warmer regions with high cooling loads there might be good sites for combined cooling, heating, and power.

Key features: CHP generates on-site electrical and/or mechanical power; recovers waste heat for heating, cooling, dehumidification; and integrates a variety of technologies, thermal applications, and fuel types into existing building infrastructure.

Figure 19 ExxonMobil's Beaumont Refinery in Beaumont, Texas operates a 470-megawatt CHP system that achieves an operating efficiency of 88%

Cost (and/or payback time): The costs of the basic technology package and added systems needed for a particular CHP application make up the total equipment cost. Total installed costs for gas turbines, microturbines, reciprocating engines, and steam turbines are comparable. The total installed cost for typical gas turbines (5-40 megawatts [MW]) ranges from US$970/kilowatt (kW) to US$1,300/kW whereas total installed costs for typical microturbines in grid-interconnected CHP applications can range from US$2,400/kW to US$3,000/kW. Commercially available natural-gas spark-ignited engine gensets have total installed costs of US$1,100/kW to US$2,200/kW, and steam turbines have total installed costs ranging from US$350/kW to US$700/kW.

Applications: The two most common CHP system configurations are gas turbine or engine with heat-recovery unit and steam boiler with steam turbine. Analysis has shown that medium-size commercial buildings with peak electrical loads ranging from 100 kW to 5 MW are often good sites for distributed generation with CHP. Absorption technologies on the demand side can be installed to utilize waste heat to meet cooling or refrigeration loads. Although inefficient relative to standard electrical cooling, these technologies are becoming increasingly common, especially in warm and hot climate zones.

Emissions-reduction/energy-savings potential: By capturing a significant proportion of waste heat, CHP typically achieves total system efficiencies of 60 to 80% for producing electricity and thermal energy. The overall energy and emissions savings can be as high as 21% (IEA, USEPA, 2008).

Related KPIs: Residential building average energy intensity (direct), public building average electricity intensity (direct), total CO_2 emissions/capita (indirect)

Source: U.S. EPA, The Catalog of CHP Technologies. http://www.epa.gov/chp/documents/catalog_chptech_full.pdf

Fuel-cell power systems

Technology name: Fuel cells

Description: Fuel cells utilize the chemical energy of fuel to generate electricity without combustion. The process is environmentally clean and inherently efficient, varying between 40 and 60% depending on the type of fuel.

Key features: Fuel cells come in many varieties using different fuels, but all work in the same general manner. They are made up of three adjacent segments: an anode, an electrolyte, and a cathode. Two chemical reactions occur at the interfaces of the three different segments. As a result, fuel is consumed, and water or CO_2 and an electric current are created; the current can be used to power electrical devices. Table 8 lists the characteristics of several types of fuel cells.

Table 8. Characteristics of several types of fuel cells.

Type of Fuel Cell	Proton exchange membrane	Alkaline	Phosphoric acid	Molten carbonate	Solid oxide
Type of electrolyte	Hydrogen (H+) ions (with anions bound in polymer membrane)	Hydroxide ions (typically aqueous potassium hydroxide solution)	H+ ions (phosphoric acid solutions)	Carbonate ions (typically, molten $LiKaCO_3$ eutectics)	Oxide ions (Stabilized ceramic matrix with free oxide ions)
Typical construction	Plastic, metal, or carbon	Plastic, metal	Carbon, porous ceramics	High-temp metals, porous ceramic	Ceramic, high-temp metals
Internal re-forming	No	No	No	Yes, Good Temp Match	Yes, Good Temp Match
Oxidant	Air to Oxygen (O_2)	Purified air to O_2	Air to Enriched Air	Air	Air
Operational temperature	150- 180°F (65-85°C)	190-500°F (90-260°C)	370-410°F (190-210°C)	1,200-1,300°F (650-700°C)	1,350-1,850°F (750-1,000°C)
Distributed generation system level efficiency, percent higher heating value	25 to 35%	32 to 40%	35 to 45%	40 to 50%	45 to 55%
Primary contaminant sensitivities	Carbon monoxide (CO), sulfur, and ammonia (NH_3)	CO, CO_2, and sulfur	CO < 1%, sulfur	Sulfur	Sulfur

Source: Energy Nexus Group, http://www.epa.gov/chp/documents/catalog_chptech_full.pdf

Figure 20. Bloom Energy fuel-cell power system

Cost (and/or payback time): In 2013, U.S. DOE estimated that 80-kW automotive fuel cell system costs of US$67 per kW could be achieved at production volume of 100,000 automotive units per year, and US$55 per kW could be achieved at production volume of 500,000 units per year (Spendelow and Marcinkoski 2013).

Applications: Fuel cells have very broad application anywhere electricity is generated or consumed. Power-sector applications include commercial and industrial CHP systems (200-1,200 kW), residential and commercial CHP systems (3-10 kW), back-up and portable power systems (0.5-5 kW). Other applications could include distributed generation, telecommunication, smart phones and notebook computers, etc.

Emissions-reduction/energy-savings potential: Fuel cells have the potential for excellent efficiency and can convert up to 75 percent of the energy in the fuel. The overall energy savings of fuel cell micro generation were 25.3% (Cho, Kang, and Lee 2014).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Utility-scale solar

Technology name: Utility-scale solar

Description: Solar energy uses solar radiation to generate power. Two types of solar technologies are most common in utility-scale energy systems: solar PV and concentrating solar power (CSP; also known as solar thermal).

Key features: Utility-scale solar PV technologies use large arrays of solar panels to convert energy from sunlight directly into electricity. CSP technologies use mirrors to concentrate the sun's light energy and convert it into heat to create steam, which drives a turbine to generate electric power. CSP systems use three alternative technological approaches: trough systems, power tower systems, and dish/engine systems.

Figure 21. The 5MWp Green Acres solar PV project in Elk Grove, California

Cost (and/or payback time): According to Bloomberg New Energy Finance, the cost of crystalline silicon solar modules has fallen by 24% on average for every doubling in installed capacity, and the cost of thin-films modules has fallen by 12% for every doubling.

Applications: Utility-scale solar energy facilities can generate large amounts of electricity to be put directly into the electricity transmission grid. These facilities represent a new clean source of power for cities and can mitigate city carbon emissions from power generation. These projects are especially applicable where city authorities have a combination of land resources and solar resource potential available.

Emissions-reduction/energy-savings potential: Emissions reductions and energy savings depend on the scale of installed capacity and the actual power generated. Solar power is seen as renewable energy that has only small life-cycle emissions. Median values for PV technologies are below 50 gCO_2e/kWh, comparing that for coal at about 890 gCO_2e/kWh. Deploying 4 gigawatts of solar power in California could save consumers between US$60 million and US$240 million per year in the cost of natural gas that is typically used to generate electricity (SEIA, 2014).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Utility-scale energy storage

Technology name: Utility-scale energy storage

Description: Energy can be stored by devices or physical media to be used for operations at a later time. Grid energy storage (or large-scale energy storage) lets energy producers send excess electricity over the transmission grid to temporary storage sites that subsequently become energy suppliers when electricity demand increases.

Key features: Storage is described according to its efficiency, cost, use of abundant materials, and reliability. The efficiency of energy storage facilities varies widely depending on technologies, from about 60% to as high as 94%. Batteries generally have a lifetime capacity in of 5,000 to 10,000 cycles, but a few advanced batteries are rated at more than 10,000 cycles; for example, pumped hydroelectric storage, compressed-air energy storage, melting inorganic-salt energy storage, flywheels, and capacitors are rated at 10,000 to 100,000 cycles. Pumped hydroelectric storage and compressed-air energy storage have the slowest response times – on the order of minutes. Batteries, fly wheels, and capacitors have quicker response times – on the order of fractions of a second.

Figure 22. A 32-megawatt-hour lithium-ion energy storage project at the Monolith substation in the Tehachapi Mountains of California, USA

Source: Wesoff, 2014.

Cost (and/or payback time): The total cost of storage systems includes all subsystem component, installation, and integration costs. The storage component constitutes only 30% to 40% of the total system cost, so the focus needs to be on the entire system (U.S. Department of Energy 2013). Simulations of several 100-MW devices at locations where they could provide energy, spinning reserves, or regulation reserves without constraints show that a long-duration storage device that provides no reserves while charging produces an annual value of US$115/kW-yr. A device that provides reserves while charging produces annual value of US$128/kW-yr (Kirby, Ma and O'Malley 2013). Vehicle-to-grid (V2G) storage is another technology, but the economics and practical complexities involved in implementing V2G schemes make them currently commercially infeasible (Mullan, et al. 2012).

Applications: Grid energy storage can be used to suppress frequency excursions, improve short/long-duration power quality, shift load within a 10-hour time frame, avoid transmission curtailment, time-shift renewables, hedge forecasts, and suppress fluctuations. These applications can combined with load shifting, regulation control, and spinning reserves. Grid energy storage is particularly important for matching supply and demand over a 24-hour time period. A proposed variant of grid energy storage is V2G energy storage, in which modern electric vehicles are plugged into the energy grid and can release the electrical energy stored in their batteries back into the grid when needed.

Emissions-reduction/energy-savings potential:

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Source: Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies. https://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf

Microgrids

Technology name: Microgrids

Description: Microgrids differ from the traditional centralized electricity grid (macrogrid). A microgrid is a localized grouping of electricity sources and loads that normally operates connected to and synchronous with the macrogrid but can disconnect and function autonomously as physical and/or economic conditions dictate.

Key features: A key feature of a microgrid is its ability to separate and isolate itself from the macrogrid seamlessly, with little or no disruption to microgrid loads, during a utility grid disturbance. When utility grid operations return to normal, the microgrid automatically resynchronizes and reconnects itself to the grid in an equally seamless fashion. A critical feature of the microgrid is its presentation to the surrounding distribution grid as a single, self-controlled entity. This means that a microgrid avoids many of the current concerns associated with integrating distributed energy resources, such as how many of these individual resources the system can tolerate before their collective electrical impact begins to create problems like excessive current flows into faults and voltage fluctuations.

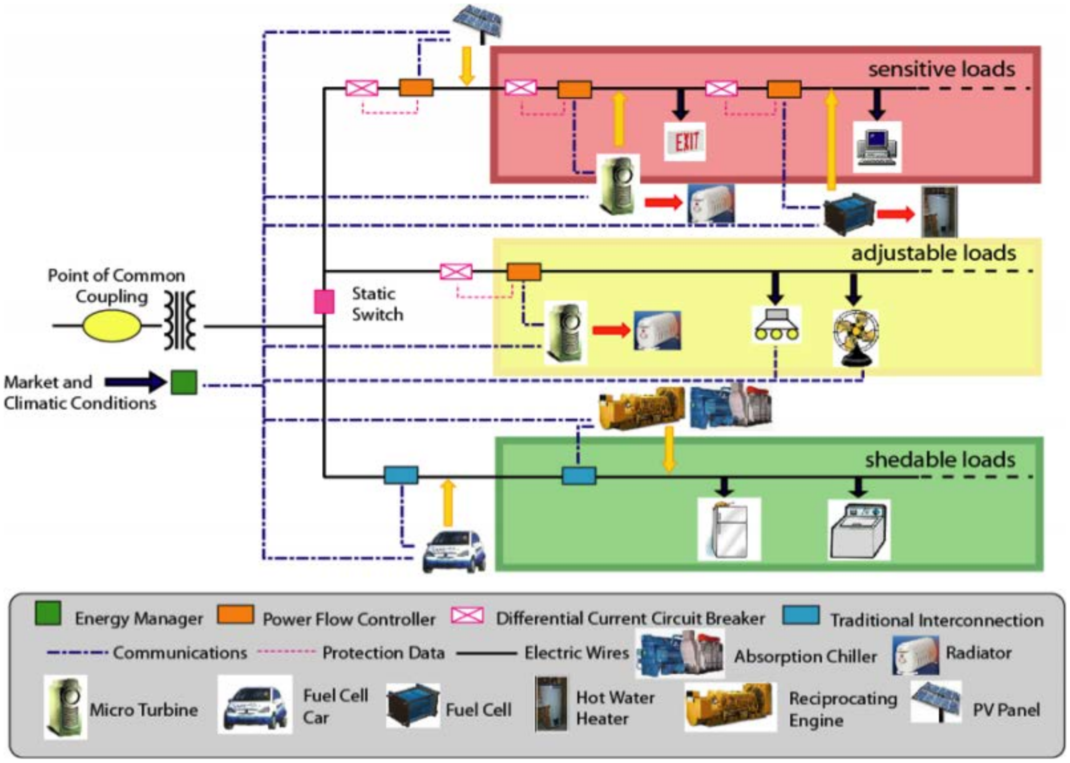

Figure 23. A schematic of a microgrid (Credit: LBNL, CERTS)

Cost (and/or payback time): California's Santa Rita Jail microgrid project cost US$14 million (including a large-scale battery, new and legacy renewable-energy sources, and a fuel cell but excluding solar PV and energy-efficiency measures). The battery cost was high, and its purchase was only feasible with federal and state government grants. Electrical storage costs need to decrease considerably to enable widespread adoption of microgrids (Romankiewicz, et al. 2014).

Applications: As noted above, a microgrid is a locally controlled system that can function both connected to the traditional macrogrid or as an electrical island. Microgrids function most efficiently when all opportunities for heating and cooling savings have been accounted for, particularly use of any waste heat generated from on-site power generation. A microgrid contains numerous elements, including loads and generation sources. Loads can be critical or non-critical. Critical loads may require high or perfect reliability and cannot lose power. Examples of critical loads include a security system at a prison or a life-support system at a hospital. Non-critical loads may be controllable, requiring lower reliability or allowing for rescheduling without a significant impact on service quality. Examples of these types of loads include heating, cooling, and refrigeration. Generation can be dispatchable or not. Dispatchable sources include fuel cells or microturbines, which can be part of CHP systems. Heat pumps (air, water, or ground-source) can often function continuously. However, many renewable sources, such as wind and solar, have limited or no dispatchability. Others can be dispatchable, such as hydropower or biogas. Energy storage is often incorporated into microgrids to deal with intermittency of renewable energy sources or to take advantage of pricing structures for grid power. Thermal storage in hot materials, water, or ice can also capture arbitrage opportunities. Finally, a microgrid includes controls whose sophistication can range widely. Challenges of microgrids include variability in availability and cost of supply as well as fluctuation in loads. Because small power systems generally have greater load variation, control and storage are especially important for microgrids.

Emissions-reduction/energy-savings potential: Microgrids can significantly reduce energy costs through whole-building energy efficiency retrofits and combined heat and power. An evaluations using home micro-grid system showed a 25% or greater reduction in CO_2 emissions was achieved compared to the conventional approach, merely by sharing power among households, and compared to the use of fuel cells independently in each home, a further reduction of 3.8% to 9.5% was obtained (Yamamoto et al., 2010).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption

Integrated gasification combined cycle for electricity generation

Technology name: Integrated gasification combined cycle (IGCC) for electricity generation

Description: IGCC uses a gasifier to turn coal and other carbon-based fuels into synthesis gas (syngas).

Key features: IGCC first converts coal to syngas, then removes impurities from the syngas before it is combusted. Some of these impurities, such as sulfur, can be turned into re-usable byproducts. Removal of impurities results lowers the emissions of SO_2, particulates, and mercury when the syngas is combusted. With additional process equipment, the carbon in syngas can be transformed to hydrogen via the water-gas shift reaction, resulting in nearly carbon-free fuel. The CO_2 resulting from the shift reaction can be compressed and stored. Excess heat from the primary combustion and syngas-fired generation is then passed to a steam cycle, similar to a combined-cycle gas turbine. This results in improved efficiency compared to conventional pulverized coal (PC).

Cost (and/or payback time): The cost varies significantly for IGCC different applications. The U.S. DOE electricity market estimates US$1,491/kW installed capacity (2005 dollars) versus US$1,290 for a conventional clean coal facility. Preliminary analysis by the U.S. National Energy Technology Laboratory (NETL) shows that if IGCC Is combined with CO_2 capture and compression using Selexol, the cost of electricity from a newly built IGCC power plant is about 30% greater than electricity from a conventional PC plant, i.e., an average of 7.8 cents/kWh for PC power to 10.2 cents/kWh for IGCC power (NETL, 2010).

Applications: IGCC significantly improves the efficiency of coal power generation. A conventional PC plant's efficiency is approximately 30-38%; IGCC efficiency can be as high as 45%. When combined with carbon capture, IGCC also eliminates CO_2 emissions.

Emissions-reduction/energy-savings potential: With carbon capture and a 1,300 °C-class gas turbine, it is possible to achieve 42% net thermal efficiency, or 45% with a 1,500 °C-class gas turbine. By contrast, a conventional PC system can achieve just over 30% efficiency with a 1,300-degree gas turbine.

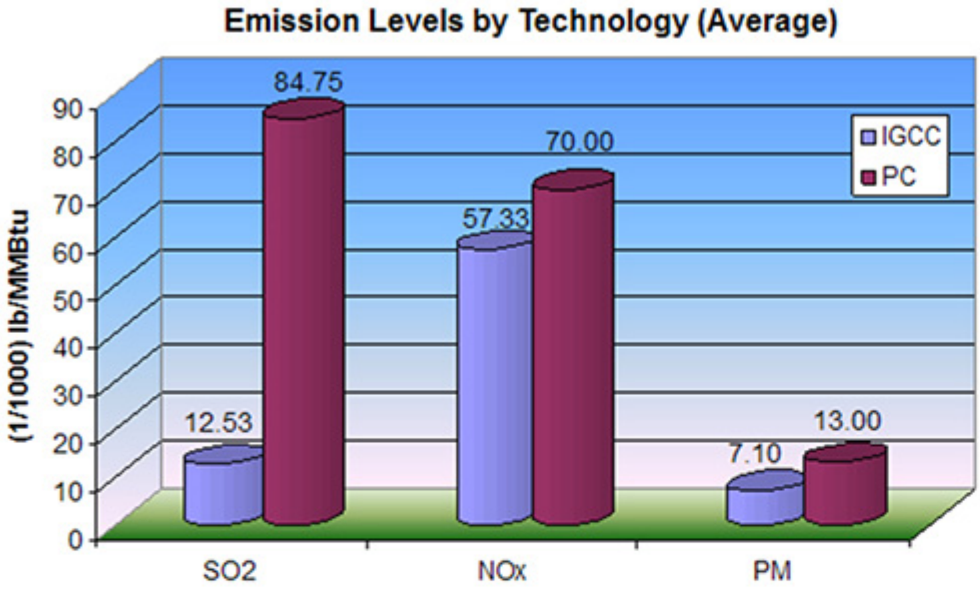

Figure 24. Comparison of average emissions from conventional pulverized coal (PC) and integrated gasification combined-cycle (IGCC) plants

Note: Includes sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) for IGCC and pulverized coal (PC; super- and subcritical) power plants, without carbon capture. Source: Data from Cost and Performance Baseline for Fossil Energy Plants, Vol. 1, DOE/NETL-2010/1397, November 2010).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/igcc

Smart grid

Technology name: Smart grid

Description: A smart power grid is uses automated communications technology to gather and act on information, for example about the behaviors of suppliers and consumers, with the goal of maximizing the efficiency, reliability, economics, and sustainability of electricity production and distribution.

Key features: A smart grid is made possible by two-way communication technologies and computer processing that have been used for decades in other industries. Key elements include integrated communication, sensing, and measurement; smart meters; variable-frequency operation; phasor measurement units; advanced controls; effective interfaces and decision support; and smart power generation.

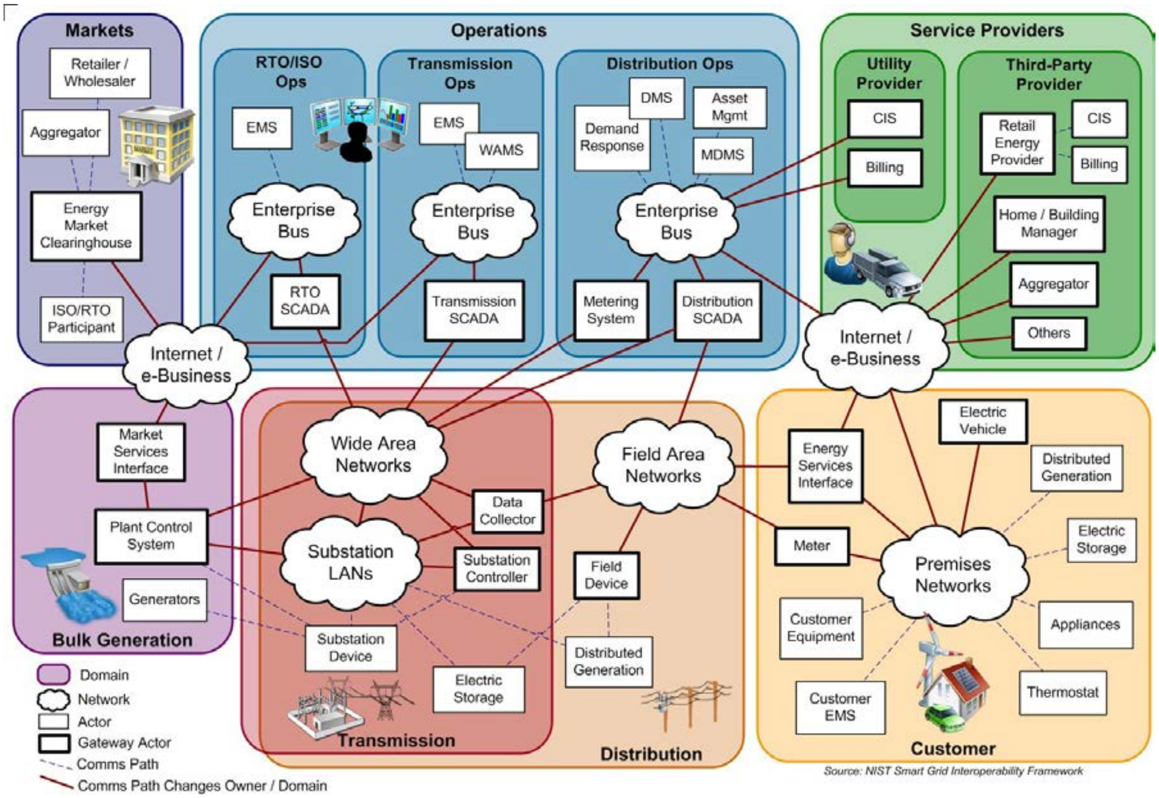

Figure 25. Smart grid concept diagram

Source: NIST.

Cost (and/or payback time): In 2009, the U.S. smart grid industry was valued at about US$21.4 billion. By 2014, it will exceed US$42.8 billion. According to the Electric Power Research Institute (EPRI), deployment of smart grid technology from U.S. utility control centers and power networks to consumers' homes could cost between US$338 billion and US$476 billion from 2011 to 2030 and could deliver US$1.3 trillion to US$2 trillion in benefits during the same period. The benefits include greater grid reliability, integration of solar rooftop generation and plug-in vehicles, reductions in electricity demand, and stronger cybersecurity.

Applications: Smart grids have wide potential application in the power system, from smart generation at power plants to smart sensors and meters at consumers' premises. In the U.S., the city of Austin, Texas' utility has been working on building its smart grid since 2003 when it replaced 1/3 of its analog meters with smart meters that communicate via a wireless mesh network. At last report, Austin's utility expected to be managing 500,000 smart devices in real time (smart meters, smart thermostats, and sensors) across its service area by 2009, servicing 1 million consumers and 43,000 businesses.

Emissions-reduction/energy-savings potential: A Pacific Northwest National Laboratory study shows the combined effect of the direct mechanisms of smart grid application is 12%, and the indirect mechanisms total 6% of energy and emissions for the U.S. electricity sector. These sum up to 5% and 2% of the U.S. total energy consumption and energy-related CO_2 emissions for all sectors (including electricity). Further, a smart grid may help overcome barriers to deployment of distributed solar renewables at penetrations higher than 20% which will further reduce emissions from power generation (Balducci, et al., 2010).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Carbon capture, utilization and storage

Technology name: Carbon capture, utilization, and storage (CCUS)

Description: CCUS encompasses methods and technologies to remove CO_2 from flue gas and the atmosphere and recycle captured CO_2 for re-utilization and/or safe, permanent storage. Although adoption of alternative energy sources and energy-efficient systems reduces the rate of CO_2 emissions, the cumulative amount of CO_2 in the atmosphere also needs to be reduced to minimize the detrimental impacts of climate change. CCUS is designed to achieve that purpose.

Key features: CCUS is at the early demonstration stage, however the CCS + enhance oil recovery (EOR) offers opportunities for commercially viable applications. There are three types of technology from the capture side: pre-combustion, post-combustion, and oxyfuel with post-combustion CO_2 capture. Demonstration systems are using multiple technologies for carbon capture and storage, such as: carbon capture in the power sector and industrial sector, carbon storage for EOR, carbon storage in the deep saline formations, and carbon storage in the unminable coal beds. Figure 26 shows an example CCUS for an oil sands facility.

Cost (and/or payback time): The cost of CCUS is uncertain because the technology is in the early demonstration stage. Some recent credible estimates indicate that the cost of capturing and storing CO_2 is US$60 per ton, which would correspond to an electricity price of about US6c per kWh (based on typical coal-fired power plant emissions of 2.13 pounds CO_2 per kWh) ("Stimulus Gives DOE Billions for Carbon-Capture Project" 2009). Geological storage in saline formations or depleted oil or gas fields typically costs US$0.50–8.00 per tonne of CO_2 injected, plus an additional US$0.10–0.30 for monitoring. When storage is combined with enhanced oil recovery to extract extra oil from an oil field, however, the storage could yield net benefits of US$10–16 per tonne of CO_2 injected (based on 2003 oil prices). However, this approach would likely negate some of the carbon capture effect when the recovered oil was burned as fuel.

Applications: Globally, there are 13 large-scale CCS projects in operation, with a further nine under construction. The total CO_2 capture capacity of these 22 projects is around 40 million tonnes per annum (Global CCS Institute, 2014). The world's first large-scale power sector CCS project – the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada (CO_2 capture capacity of 1 Mtpa) – becoming operational in October 2014. Outside the power sector, the world's first iron and steel project to apply CCS at large scale moved into construction in the UAE in the latter part of 2013. The Abu Dhabi CCS Project (CO_2 capture capacity of 0.8 Mtpa) involves CO_2 capture from the direct reduced iron process used at the Emirates Steel plant in Abu Dhabi. The injection of CO_2 into ageing oil fields to sweep residual oil has helped extend the production life of some fields by more than 25 years.

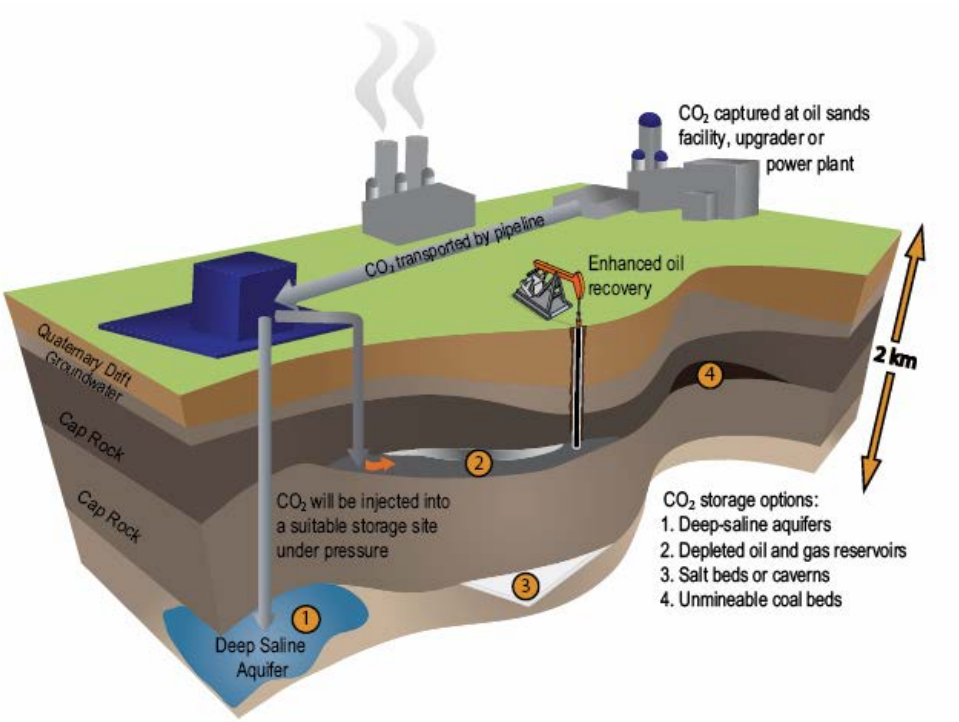

Figure 26. Options for carbon capture and storage

Source: CO_2 Solutions, http://www.co2solutions.com/en/carbon-capture-sequestration-ccs

Emissions-reduction/energy-savings potential: The theoretical merit of CCUS systems is the reduction of CO_2 emissions by up to 90%, depending on plant and application type. Under its 2°C Scenario (2DS), the International Energy Agency (IEA) estimates that CCS will provide 14 percent of cumulative emissions reductions between 2015 and 2050 compared to a business as usual scenario. Under the same scenario, CCS provides one-sixth of required emissions reductions in 2050 (IEA 2013).

Related KPIs: Carbon intensity of electricity generation, renewable share of total electricity consumption, distributed generation share of total electricity consumption.

Transportation sector

The transportation sector, which encompasses the movement of people and goods by cars, trucks, trains, ships, airplanes, and other vehicles, contributes significantly to global GHG emissions. In the U.S., the largest sources of transportation-related GHG emissions include passenger cars and light-duty trucks (sport utility vehicles, pickup trucks, and minivans). In 2012, GHGs from transportation accounted for about 28% of total U.S. GHG emissions, making it the second-largest emissions source after the electricity sector (U.S. EPA, 2013). In China in 2013, transportation accounted for about 8% of total GHG emissions. Transportation is a growing source of emissions in China as vehicle ownership has skyrocketed in major cities in recent years. This study focuses on technologies to improve the efficiency of transportation at the individual and system levels.

The following subsections discuss these transportation-sector technologies:

- EVs for municipal fleets
- Intelligent transportation systems (ITSs)
- EV charging stations
- Hydrogen vehicles
- Automatic bike-rent/share systems
- Smart parking systems
- Rapid-transit systems

China's transportation-sector CO_2 emissions doubled from 2000 to 2010 and are projected to increase by 54% by 2020, compared to 2010 levels. For China to meet its 2020 target, the country needs to reduce economy-wide carbon intensity by 17% in 2015, and growth in emissions needs to be approximately cut in half (ICCT, 2011). Reducing carbon emissions in the transportation sector is key to meeting China's long-term energy and carbon targets.

The KPIs for the transportation sector are listed below:

- Municipal fleet improvement
- Public transportation share of trips
- Public transportation network penetration
- Access to public transportation

Electric vehicles for municipal fleets

Technology name: EVs for municipal fleets

Description: EVs use electric or traction motors for propulsion and include plug-in electric vehicles (PEVs); hybrid electric cars; hydrogen vehicles; and electric trains trucks, airplanes, boats, motorcycles, scooters, and spacecraft. This section focuses on electric cars, plug-in electric vehicles (PEVs), and hybrid electric cars.

Key features: A PEV is any motor vehicle that can be recharged from an external source of electricity. A hybrid electric vehicle combines a conventional (usually fossil-fuel-powered) powertrain with some form of electric propulsion. The type of battery, traction motor, and motor controller vary according to the size, power and proposed application of an EV. Most electric vehicles use Lithium-ion batteries. Battery cost, life span, efficiency, and safety are key to the development of EVs.

Figure 27. EV municipal fleet in Houston, Texas USA

Source: Zipcar Fast Fleet for Houston EV Sharing 2012.

Cost (and/or payback time): EV COST varies according to the mode of operation over a period of time, but with government subsidies the cost can be comparable to that of conventional cars. In 2010, with the goal of improving air quality and reducing reliance on fossil fuels, China began a two-year pilot program of subsidizing purchase of alternative-energy cars in five cities: Shanghai, Changchun, Shenzhen, Hangzhou, and Hefei. The subsidy will be as much as 60,000 RMB for battery electric cars and 50,000 RMB for plug-in hybrids.

Applications: EVs can replace conventional city buses, taxis, and official government vehicles. EVs release almost no air pollutants at the location where they are operated; although electric vehicles use electric power to charge, it is generally easier to add pollution-control systems to centralized power stations than to retrofit large numbers of individual cars. EVs can also be plugged into the electricity grid when not in use, and plugged-in battery-powered vehicles could even out electricity demand by feeding their stored battery power into the grid during peak-use periods (such as during midafternoon air-conditioning use) while doing most of their charging at night when there is unused generating capacity.

Emissions-reduction/energy-savings potential: A 2009 life-cycle-cost analysis of China's regional power grid shows that energy savings and CO_2 emissions reduction vary depending on the share of coal-fired power in each region. However, nationally, energy savings were 35.57% for pure battery-electric vehicles and 17.78% for plug-in hybrid electric vehicles. The CO_2 emissions reductions were 17.13% and 8.56%, respectively, for the two types of vehicles (Zhou, Qu, and Zhang 2013).

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Intelligent transportation systems

Technology name: Intelligent transportation system (ITS)

Description: ITSs are advanced applications that provide innovative transport and traffic management, informing transportation system users about traffic conditions and enabling safe, coordinated, "smart" use of transport networks.

Key features: ITSs vary in the technologies used but can be divided into two general categories: basic and advanced management systems. Basic management systems include car navigation, traffic-signal control systems, container management systems, variable message signs, and monitors such as automatic license plate recognition, speed cameras, and security closed-circuit television systems. Advanced applications can integrate live data and feedback from a number of sources, such as parking guidance and information, weather information, and bridge de-icing systems. Additionally, predictive techniques are being developed to allow advanced modeling and comparison using historical baseline data.

Figure 28. Schematic of an intelligent transportation system

Source: http://www.etsi.org/index.php/technologies-clusters/technologies/intelligent-transport.

Cost (and/or payback time): The major costs of ITSs are for installation and maintenance of the camera, electric billboard, control system, or other similar elements.

Applications: ITSs can be used for emergency-vehicle notification systems, automatic road enforcement, variable speed limits, collision avoidance, and dynamic traffic light sequencing to avoid congestion and accidents.

Emissions-reduction/energy-savings potential: No single approach can be used to predict emission reductions contributed by ITSs because the applications included in these systems vary (U.S. Department of Transportation 2011). However, increasing the efficiency of both private-vehicle and public-transport system travel and reducing congestion are anticipated to reduce transportation emissions.

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Electric vehicle charging stations

Technology name: EV charging stations

Description: EV charging stations, also called charging points, are elements of an infrastructure that supplies electrical energy for the charging of PEVs, including all-electric cars, neighborhood electric vehicles, and plug-in hybrid vehicles.

Key features: As plug-in hybrid electric and battery electric vehicle ownership are expanding, publicly accessible and widely distributed stations that support fast charging are in demand. Many existing charging stations are on-street facilities provided by electric utilities. Recently introduced mobile charging stations “E-MOVE” provide one or more heavy-duty or special connectors and/or parking places equipped with inductive charging mats that do not require a physical connector.

Cost (and/or payback time): The major cost of EV charging systems is installation of the charging facility. The cost of charging itself varies by mode and charging time. Deployment of public charging stations is promoted in many parts of the world to ensure accessibility.

Applications: Charging stations are usually connected to the electricity grid, which means that their electricity often originates from fossil fuel or nuclear power plants. Solar and wind power can also be used to charge EVs depending on local resources and conditions.

Emissions-Reduction/Energy-Savings Potential: A study of commercial and residential EV charging stands (Level 2 [240-volt AC] charge stands) shows that choosing an efficient model over a standard model would result in unit savings of 21kWh/yr for basic products and 53kWh/yr for products with network connectivity. When calculated based on 2015 U.S. shipments, the nationwide savings potential is 4,791MWh/yr, which translates to 73,77,924 pounds CO_2/yr (U.S. Environmental Protection Agency, 2013).

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Hydrogen vehicles

Technology name: Hydrogen vehicles

Description: Hydrogen-powered vehicles convert hydrogen’s chemical energy to mechanical energy either by burning the hydrogen in an internal combustion engine or reacting hydrogen with oxygen in a fuel cell to run an electric motor. The concept of a hydrogen economy includes widespread use of hydrogen for fueling transportation as a key element.

Key features: Cars with hydrogen internal combustion engines are different from cars with hydrogen fuel cells. The hydrogen internal combustion engine is a slightly modified version of the traditional gasoline internal combustion engine; both burn fuel in the same manner. By contrast, a fuel cell converts hydrogen’s chemical energy into electricity through a chemical reaction involving oxygen or another oxidizing agent.

Cost (and/or payback time): In 2011, U.S. DOE estimated that automobile fuel cells might be manufactured for US$51/kW, assuming high-volume manufacturing cost savings. (U.S. DOE 2011) The projected cost, assuming a manufacturing volume of 500,000 units/year, using 2012 technology, was estimated by U.S. DOE to be US$47/kW for an 80-kW proton exchange membrane fuel cell.

Applications: Hydrogen can be used to power buses, trains, taxis, bikes, bicycles, and other forms of transportation.

Emissions-reduction/energy-savings potential: Hydrogen fuel-cell vehicles are more energy efficient than gasoline-powered vehicles. For example, the Honda FCX Clarity for model year 2011 had a fuel economy equivalent to 60 miles per gallon of gasoline, and the 2011 Mercedes-Benz F-Cell had a fuel economy of 53 miles per gallon, compared with 33.8 miles per gallon for a gasoline vehicle for passenger cars in model year 2011. Fuel-cell vehicles emit only heat and water but not tailpipe GHGs during operation, so these vehicles have much lower lifecycle GHG emissions compared than conventional vehicles (Pew Center on Global Climate Change 2011).

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Automatic bike-rent/share system

Technology name: Automatic bike rent/share system

Description: An automatic bike-rent or bike-share system makes bicycles available to individuals on a very-short-term basis. Bike shares allow people to travel short distances by bike – for example, solving the "last-kilometer" problem in public transportation – without having to own their own bicycles.

Key features: The system is usually composed of a card reader, rental machine, lock/unlock gate, and bike(s). The system provides users with several ways to pay or register in order to release a bicycle. Once users arrive at their destinations, they can return the bike to any of multiple stations located in the area. The bike will automatically locks in place, ready for next user.

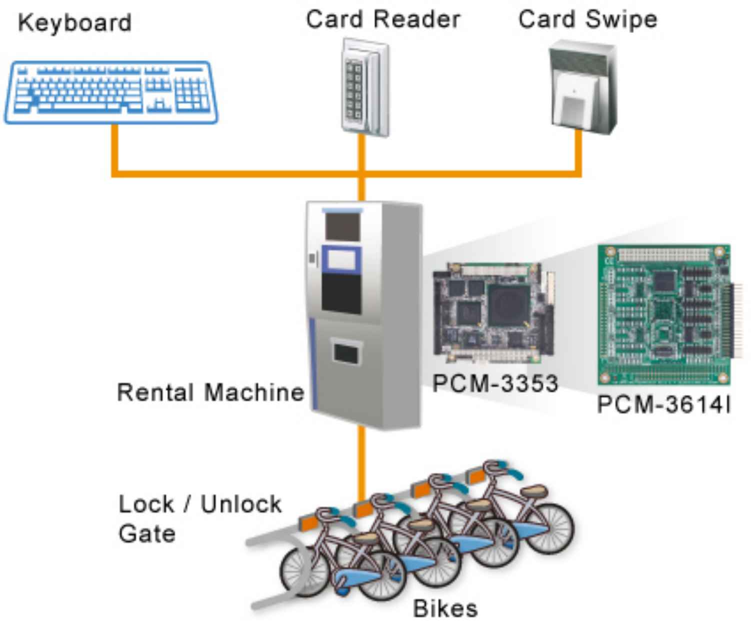

Figure 29 . A simplified automatic bike rental system (Credit: Advantech)

Cost (and/or payback time): A bike-share system has capital costs (e.g., for design and construction of bike stations, and purchase of bikes and permits) and monthly operating costs. In North America, these costs can be partially covered by user fees, sponsorships, and advertising. A cost-benefit analysis for the Capital Bikeshare program in Washington D.C., USA weighed monetary and non-monetary costs and benefits and projected a benefit-cost ratio of 1.72 over 20 years, using a 7% discount rate (Johnston 2014).

Applications: Bike-share programs have experienced explosive growth worldwide during recent years. As of April 2013, there were approximately 535 bike-share programs around the world, with a total estimated fleet of 517,000 bicycles. Several Chinese cities are starting to build bike-share systems, with those in Wuhan and Hangzhou among the largest. Many other cities are exploring bike-share systems to address the need for low-carbon transportation.

Emissions-reduction/energy-savings potential: The Capital Bikeshare program saved an estimated 1.6 million pounds of CO_2 in 2013 based on the number of miles traveled by users (Johnston 2014). Estimating overall CO_2 reduction from bike-share programs is difficult because every program works and collects data differently.

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Smart parking systems

Technology name: Smart parking system

Description: Smart parking systems use low-cost sensors, real-time data, and mobile-phone-enabled automated payment systems that allow customers to reserve parking in advance or accurately predict where they can find a parking spot. Smart parking thus reduces car emissions in urban centers by reducing the need for drivers to circle city blocks searching for parking. It also permits cities to carefully manage their parking supplies.

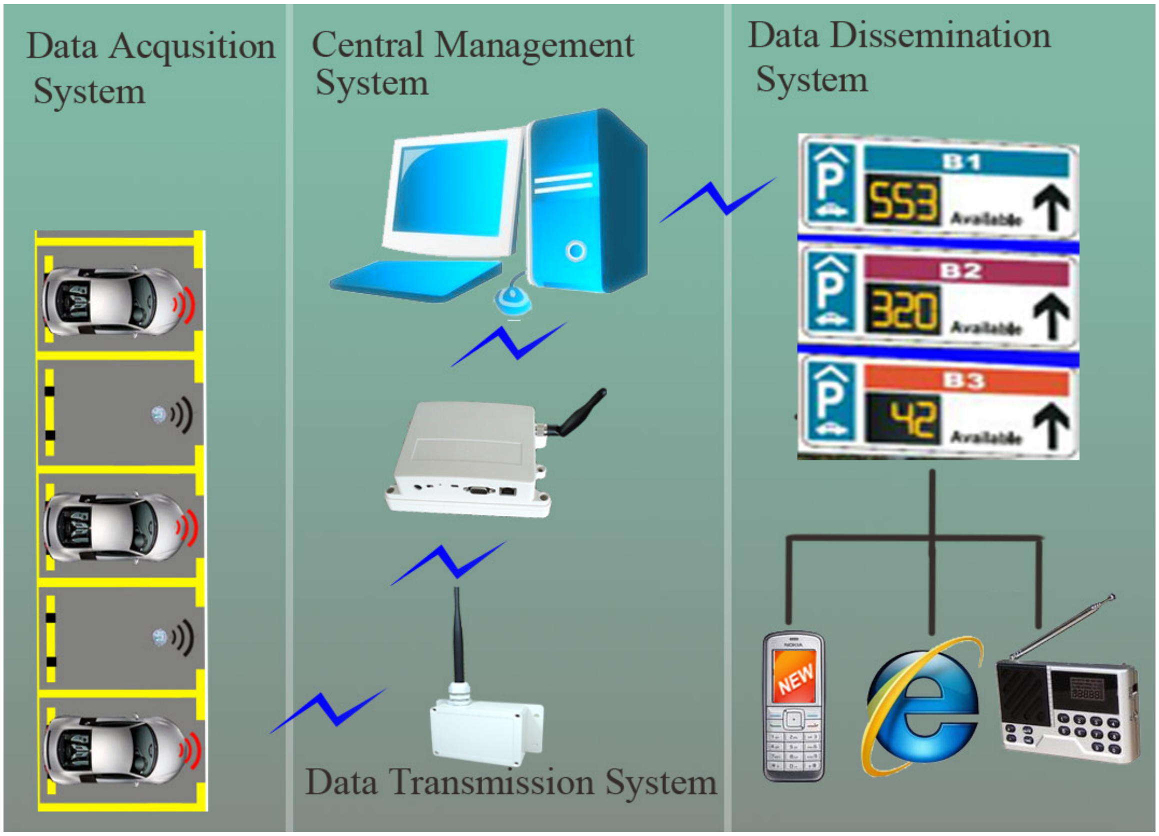

Figure 30. Schematic of a smart parking system (Credit: ROSIM)

Key features: A smart parking system can accurately sense, in real time, whether a vehicle is present in a parking space and can guide drivers to available spaces, simplifying parking and adding value for drivers, merchants, and other parking stakeholders. The system enables drivers to make intelligent decisions based on real-time data and historical analysis and provides tools to optimize workforce management.

Cost (and/or payback time): A smart parking system typically has initial capital costs of US$150 to US$250 per parking space and continuing operations and maintenance costs of US$40 to US$60 per space per year (Shaheen and Rodier 2007).

Applications: Smart parking systems can be used in public garages, parking lots, and street parking and transit. Individual parking lot or neighborhood programs can make a local differences, but widespread deployment is needed for smart parking to contribute significantly to transportation-sector GHG and pollution reductions.

Emissions-reduction/energy-savings potential: A smart parking system in Ellicott City MD, USA reduced the time drivers spent looking for open parking places by 21%; San Francisco's SF park, a smart parking project that adjusts parking prices according to local demand by pairing demand-responsive price management with smartphone applications, reduced CO_2 emissions and excess vehicle-miles traveled by 30% compared to a control area (Shaw et al., 2010).

Source: http://www.navigantresearch.com/research/smart-parking-systems

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Rapid-transit systems

Technology name: Rapid-transit system

Description: Rapid-transit systems are high-capacity public transport systems usually found in large cities. Unlike buses and trams, rapid-transit systems operate on an exclusive right-of-way, such as a tunnel or railway, that is usually grade-separated from other traffic. Some rapid-transit systems use buses.

Key features: Modern rapid transit uses designated lines between stations. Train stations typically have high platforms at the same level as train entrance doors, which require custom-made trains to avoid gaps between the platform and train car. Rapid transit is typically integrated with other public transport and often operated by the same authorities but can include fully segregated light-rail service. Rapid-transit is unequaled in its ability to transport large numbers of people quickly over short distances using small land area.

Figure 31. Bus rapid-transit system in Cleveland OH, USA

Cost (and/or payback time): Building and operating rapid-transit systems entail high fixed costs. Significant capital costs of construction are often subsidized with soft loans and ancillary revenue such as income from real-estate portfolios. Some systems are financed by the sale of land whose value has been increased as a result of system construction, known as value capture.

Applications: According to the World Metro Database, as of 2012, 184 cities had rapid-transit systems, among which the New York City Subway system is the largest. Many Chinese first- and second-tier cities are in the process of building or expanding rapid-transit systems, creating a huge opportunity for carbon savings as well as for business.

Emissions-reduction/energy-savings potential: The success of bus rapid-transit projects is typically measured by an increase in ridership, typically ranging from 5% to 25% compared to previous local bus service in the same corridor. The Los Angeles Metro Rapid reported an increase of 26,800 (42%) in weekday ridership on the on the Wilshire/Whittier corridor and 3,600 (27%) on the Ventura corridor after installation of bus rapid transit. This was estimated to have reduced 9,188 metric tons of CO_2 emissions -- 12,424 metric tons from mode shift, countered by an increase of 3,235 metric tons from additional transit service (Millard-Ball and Standard University 2008).

Related KPIs: Municipal fleet improvement, public transportation share of trips, public transportation network penetration, access to public transportation.

Water sector

The water sector faces significant challenges, including stricter water-quality standards, increasing demand for water, and the need to adapt to climate change while reducing GHG emissions (Rothausen and Conway 2011). Greater focus on water-sector energy requirements will be a crucial element of the policy response to these challenges. This section focuses on commercially available technologies that can be used to improve the efficiency of water supply, distribution, demand, and treatment. Reuse and recycling of water, and byproducts for power generation are also discussed. The particular area to which each technology applies is listed in parenthesis in the subsection title.

This section reviews the following technologies:

1. Gray-water recycling
2. Water-efficient appliances
3. Smart water-distribution networks
4. Rainwater harvesting
5. Reverse osmosis
6. Ultraviolet treatment
7. Anaerobic digesters
8. Co-digestion at wastewater treatment facilities
9. Controlled-atmosphere separation technology
10. Recirculating and dry cooling for power plants

Climate change could challenge the ability of municipal drinking water, wastewater, and storm water utilities to protect public health and the environment. The water sector needs to be able to respond to climate alterations such as extreme weather events, sea-level rise, shifting precipitation and runoff patterns, temperature changes, and resulting changes in water quality and availability. Resilient and adaptable water utilities will ensure clean, safe water supplies to protect public health and sustain the communities served.

1. Municipal water consumption/capita
2. Industrial water consumption/industrial GDP
3. Percentage of wastewater receiving at least primary treatment
4. Percentage of total drinking water meeting Grade III or above
5. Percentage of annual municipal water use sourced from water-reclamation efforts
6. Energy intensity of drinking water

Gray-water recycling (demand-side efficiency)

Description: The United Nations Economic and Social Council proclaimed in 1958 that "No higher quality water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade." This quote could have foreshadowed the practice of gray-water recycling, which uses non-potable water harvested from other processes such as clothes washing for activities that do not require potable water, such as toilet flushing. Most plumbing uses potable water to flush toilets even though it is energy intensive to treat water to potable grade.

Key features: In dual-distribution systems, reclaimed water from sinks and other drains is delivered to customers through a network of distribution mains that is parallel to but separate from the community's potable-water distribution system. Reclaimed water distribution adds a third network to a typical system of two networks – one for wastewater (outflow) and one for potable water (inflow). Gray-water recycling systems are otherwise operated, maintained, and managed in a manner similar to potable water systems. However, gray water can only be used for certain designated activities and often has to go through some basic treatment. In the U.S., a majority of states have published treatment standards or guidelines for one or more types of water reuse. Some states require specific treatment processes for gray water, and others simply impose effluent quality criteria.

Cost (or payback time): Gray-water recycling remains costly in many cases, often because of regulatory fees on gray-water systems. Although simple residential systems that save used laundry water for backyard irrigation can cost less than US$1,000, complex systems that recycle water from showers, bathtubs, and washing machines to be used for activities like toilet flushing can cost as much as US$10,000. At the residential scale, such high up-front costs will not be recovered through water cost savings over time. The economics are more advantageous for many office and other types of commercial buildings where toilet-flushing accounts for a significant portion of water usage and cost.

Applications: Common applications for gray-water recycling and reuse include irrigation (parks, playgrounds, athletic fields), commercial activities (vehicle washing or laundry facilities), fire protection, and toilet and urinal flushing.

Water-savings potential: Approximately 1.7 billion gallons of water are reused per day in the U.S. Although this number seems large, the U.S. uses about 3.9 trillion gallons of water per month, or 130 billion gallons per day, so water reuse accounts only for 1.3% of total water use. Water treatment and supply accounts for 3% of electricity use in the U.S., so any water reuse will result in meaningful energy as well as water savings.

Related KPIs: Municipal water consumption/capita, energy intensity of drinking water, carbon intensity (indirect)

Sources and additional resources: (Legget, Brownd, Stanfield, Brewer, & Holliday, 2001), (U.S. EPA, 2004)

Water-efficient appliances (demand-side efficiency)

Description: Water-efficient appliances are widely available including toilets, faucets, showers, washing machines, dishwashers, and irrigation systems.

Key features: Water-efficient appliances typically employ basic technologies, and a labeling program informs customers which appliances are the most efficient. WaterSense is one such campaign, run by the U.S. Environmental Protection Agency. One example of WaterSense labeling is for toilets, which, in the U.S. account for 30% of residential water use. WaterSense-labeled toilets use only 1 gallon per flush compared to 3.5 gallons per flush by a typical toilet. Figure 32 shows an example of a U.S. EPA WaterSense campaign for showerheads.

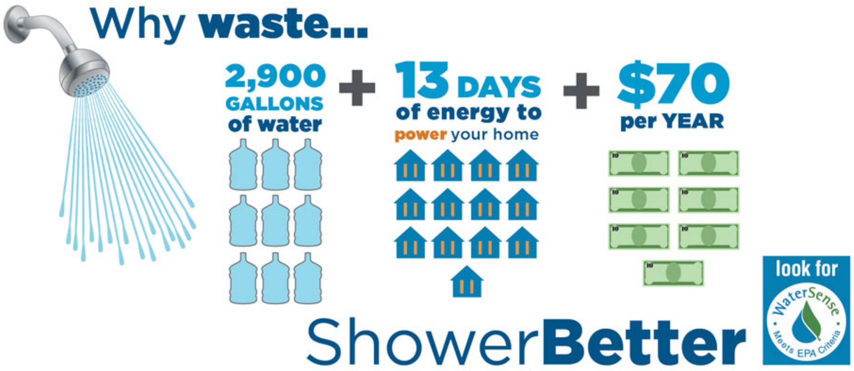

Figure 32. Example of EPA WaterSense campaign for low-flow showerheads

Cost (or payback time): Low-water-flow appliances typically do not have a cost premium, or, if they do, it is small. Manufactured no-flow (composting) toilets can be very costly, however.

Applications: Nearly every residential and commercial building has toilets and faucets that can benefit from low- or no-flow water applications. Additionally, most buildings have landscaping that can benefit from smart irrigation controllers. Finally, most residential buildings have washing machines, dishwashers, and showers that can benefit from low- or no-flow water applications.

Water-saving potential: With respect to household water uses, most water-efficient appliances use anywhere from 25-75% less than their conventional counterparts. Lawns and other landscapes are often overwatered by up to 50%. It has been estimated that if every home in the U.S. with an automatic sprinkler system also installed a WaterSense-labeled controller, there would be a savings of 120 billion gallons of water annually as well as US$435 million in water costs. Because there are energy costs associated with heating and supplying water, reducing water use also directly improves energy intensity and indirectly improves in carbon intensity.

Related KPIs: Municipal water consumption/capita, residential building average energy intensity, public building average electricity intensity, carbon intensity (indirect)

Sources and additional resources: (U.S. EPA, 2014)

Smart water-distribution networks (distribution system)

Description: Globally, water utilities spend US$184 billion each year on supplying clean water, US$14 billion of which is to pay for the energy associated with pumping and distribution. At the same time, there is a huge amount of leakage in many countries' water-distribution networks. Leakage is estimated to be 11% in the U.S. and 36% in China, and 33% of utilities report leakage losses greater than 40%. Smart water-distribution networks – which utilize controls, smart meters, leak detection, and monitoring, among other technologies – can help minimize leaks and water-distribution costs. Figure 33 shows a breakdown of global water utility expenditures.

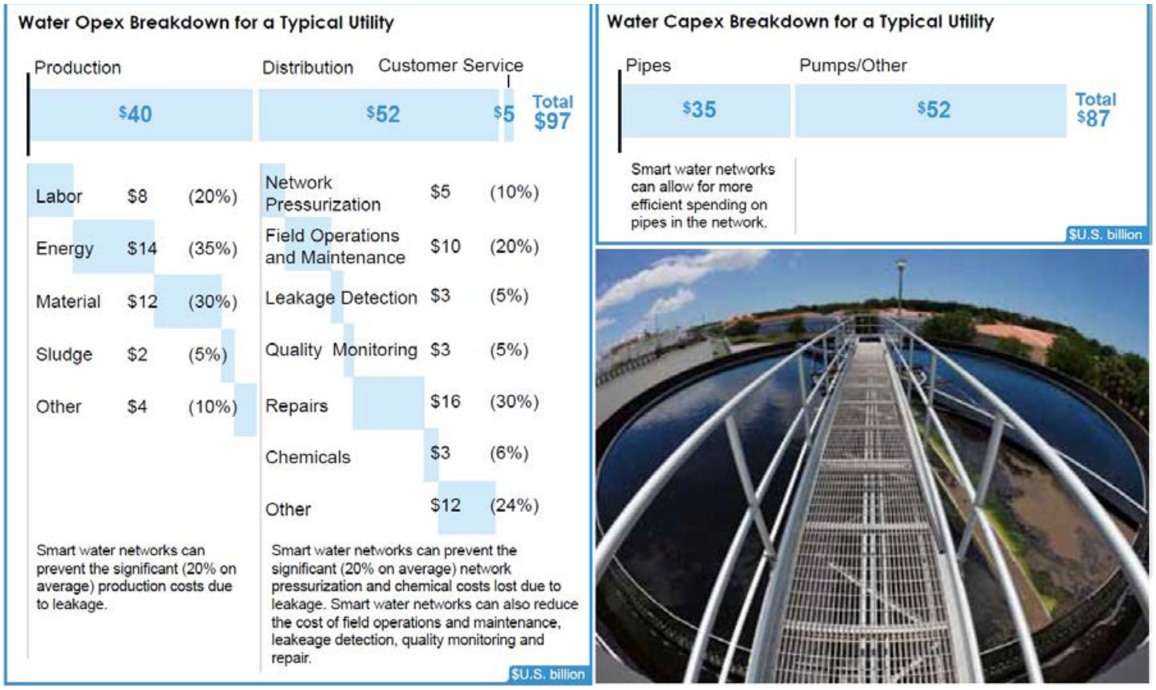

Figure 33. Cost breakdown of global water utility expenditures by process steps, Source: (Sensus, 2012)

Key features: Smart water-distribution networks gather data via measurements and sensors, analyze the data using algorithms to detect patterns that could indicate leaks, and send real-time data back to the utility regarding potential leaks as well as system operations, flow, etc. Pressure sensors and pressure-regulating valves can allow automated changes to be made to the system without direct human intervention, as seen in Figure 34.

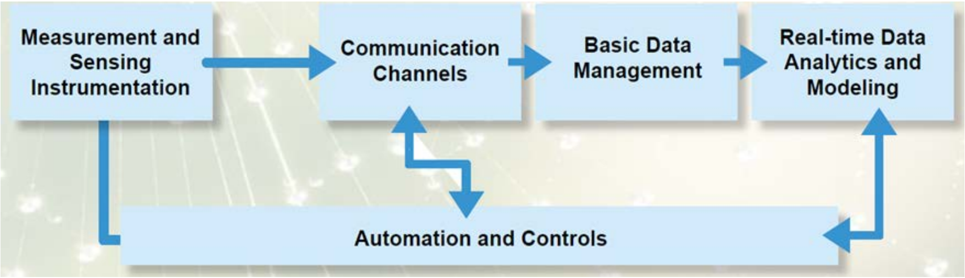

Figure 34. Measurement, communication, and automation in smart water-distribution networks

Finally, smart water-distribution networks can enable two additional capabilities: providing regulatory bodies with information on water quality and conservation compliance and providing water customers with information and tools to help them make decisions about water usage.

Cost (or payback time): Reducing leaks by 5%, coupled with up to a 10% reduction in pipe bursts, could save utilities up to US$4.6 billion annually worldwide.

Applications: The application is mainly for municipal water utilities to improve their distribution networks.

Water- and energy-savings potential: By reducing water leakage, smart water networks can reduce monetary and energy expenditures related to purchasing, treating, and pumping water.

Related KPIs: Municipal water consumption/capita, carbon intensity (indirect)

Sources and additional resources: (Sensus, 2012)

Rainwater harvesting (supply)

Description: Rainwater harvesting collects rainwater from a building's roof and stores the water for later non-potable uses such as irrigation and toilet flushing. Good candidates for rainwater harvesting are places with a large amount of annual rainfall and industrial and commercial buildings (such as warehouses and schools) with a large amount of roof space and potentially large demand for non-potable water.

Key features: Large cisterns at the base of a building are typically used to store collected rainwater. There are numerous types of designs for rooftop collection and conveyance, but in all cases drainpipes and roof surfaces should be constructed using chemically safe materials such as wood, plastic, aluminum, or fiberglass, to avoid adversely affecting the quality of the harvested water.

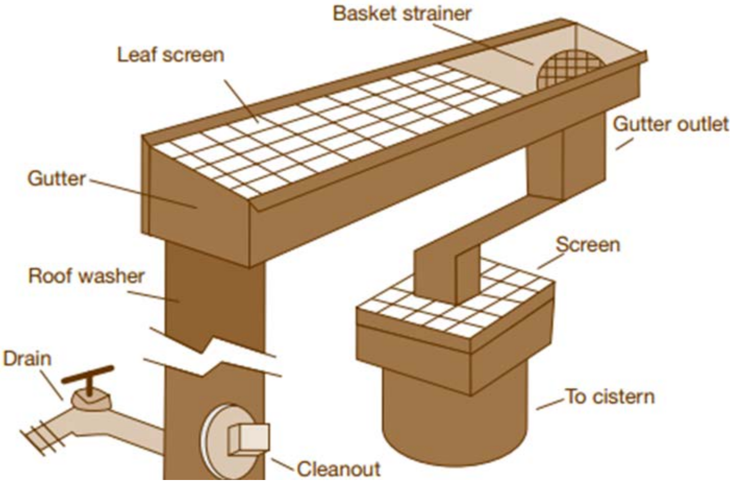

Figure 35. Basic rainwater harvesting system

Cost (or payback time): Rainwater harvesting is not as cost effective as water-efficient appliances, which should be implemented as a first priority before water reuse and rainwater harvesting.

Applications: Commercial or residential buildings with relatively large roof-area-to-height ratios.

Water-saving potential: A 1,000-square-foot roof will collect 620 gallons of water per 1 inch of rainfall.

Related KPIs: Municipal water consumption/capita

Sources and additional resources: (Waterfall, 1998)

Reverse osmosis (industrial treatment)

Description: Wastewater reclamation has become a viable option for supplementing water supplies in areas where there are water shortages or high discharge costs or requirements. Membrane treatments are playing a growing role in treating industrial wastewater. One membrane treatment is reverse osmosis (RO). RO membranes have been shown to significantly reduce total dissolved solids, heavy metals, organic pollutants, viruses, bacteria, and other dissolved contaminants in industrial wastewater. RO-treated wastewater is of sufficient quality to be used for boiler feedwater or semiconductor process water.

Key features: Wastewater subject to RO treatment is typically pressured between 150-600 pounds per square inch gauge and then passed through either a thin-film composite or cellulose acetate membrane. Some form of pre-treatment is key to protect the membrane against organic fouling, mineral scaling, and chemical degradation. A wide range of pre-treatment technologies is available. Indicators of substances with the potential to foul the membrane, such as high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels, should be checked.

Figure 36. Reverse osmosis equipment at an industrial facility

Cost (or payback time): Capital cost data are not available, but using RO processes can help reduce water and sewer costs for industrial facilities.

Applications: Applications include treatment and recycling of wastewater generated from metal finishing, semiconductor manufacturing (treatment and recycle of rinse water used in electroplating processes), automotive manufacturing (treatment and recycle of water used for cleaning and painting), food and beverage production (concentration of wastewater for reuse and reduction of BOD), and groundwater and landfill leachate (removal of salts and heavy metals prior to discharge).

Water-pollution reduction potential: Effluent that has been treated with an RO membrane and discharged to the sewer typically contains anywhere from 200 to 10,000 parts per million total dissolved solids. With the proper pre-treatment technology followed by RO, this water can be recycled within an industrial facility.

Related KPIs: Industrial water consumption/industrial GDP, percentage of wastewater receiving at least primary treatment

Sources and additional resources: (Siemens, 2014), (Bartels, 2014)

Ultraviolet treatment (municipal treatment)

Description: As an alternative to chemical chlorination, which has been the most popular method for treating municipal wastewater around the world to date, ultraviolet (UV) treatment uses UV lamps to disinfect water. Bacteria die off when exposed to UV light of different types for different exposure periods. Proponents of UV technology emphasize its safety advantages for communities, wastewater-treatment facility employees, and local water bodies. There are growing concerns that chlorine adversely affects aquatic life when effluent is released to neighboring water bodies. Chlorine can also react with organic materials in water to form harmful disinfection byproducts. Figure 37 shows some benefits of UV disinfection.

	Chlorine Disinfection	UV Disinfection
No Disinfection Byproducts (DBPs)	✗	✓
No Chemical Residual	✗	✓
Non-corrosive	✗	✓
No Community Safety Risks	✗	✓
Effective Against Cryptosporidium and Giardia	✗	✓
Well-Suited for Changing Regulations	✗	✓

Figure 37. Benefits of UV disinfection compared to chlorine disinfection

Key features: UV disinfection equipment is often installed at facilities that already use chlorination so that the amount of chlorine can be reduced.

Cost (or payback time): UV treatment entails energy and lamp replacement and maintenance costs. Costs also depend on the degree to which the water transmits UV radiation, which affects the UV dose selection. In comparison to chlorination, UV treatment has lower overall operating costs (although higher energy use and higher up-front capital costs.

Applications: UV treatment can be used in municipal and industrial water treatment as well as in the developing world where there is no centralized treatment infrastructure.

Water-pollution reduction potential: Chlorination and UV can treat water to similar levels of safety, but chlorine can adversely affect bodies of water (bays, lakes, rivers) that receive the treated water whereas UV-treated water does not negatively affect other water bodies. Therefore, use of UV treatment reduces overall water pollution.

Related KPIs: Percentage of wastewater receiving at least primary treatment

Sources and additional resources: (Martin, 2004)

Anaerobic digesters (energy generation from wastewater)

Description: Anaerobic digestion is a process in which microorganisms break down biomass material in the absence of oxygen to produce biogas (a blend of methane, CO_2, and other gases) and solid residuals that can be used for animal bedding and fertilizer. Anaerobic digestion is a long-established process commonly used by wastewater treatment facilities to treat sewage sludge.

Key features: In the U.S., 83% of the 1,500 wastewater treatment facilities with anaerobic digesters flare their biogas, wasting this potential energy source. The remaining treatment facilities with digesters use the biogas to produce heat and power on site using engines and turbines.

Cost (or payback time): The average anaerobic digestion project payback time is five to seven years, but some feasibility studies estimate longer periods. A digester is a major investment with an approximate initial cost of up to US$600 per annual ton of capacity. Capital costs are high because of the equipment required, in particular for feedstock pre-processing, storage, digestion, energy generation, and hydrogen-sulfide management. Operating costs are also substantial and depend heavily on individual project characteristics, ranging between US$40 and US$150 per ton of waste delivered. Turbine costs for providing electricity and heat are additional to the digester costs and can range from US$500-2,000 per kW of capacity depending on the type of turbine and system.

Applications: Anaerobic digestion is commonly used at wastewater treatment facilities, at dairy farms for treating animal waste, and at food-processing facilities for producing energy from food-related waste streams.

Figure 38. Anaerobic digesters at a wastewater treatment facility

Emissions-reduction/energy-savings potential: Converting sewage sludge provides a source of renewable energy and reduces GHG emissions.

Related KPIs: Municipal waste treatment rate, share of renewable electricity, carbon intensity

Sources and additional resources: (King County, 2013), (Lono-Batura, Qi, & Beecher, 2012)

Co-digestion at wastewater-treatment facilities (energy generation)

Description: Co-digestion at wastewater treatment facilities adds energy-rich organic food-waste materials (such as fats, oils, and grease also known as "FOG," slaughterhouse products, and food scraps) to anaerobic digesters with excess capacity. Co-digestion is not as widespread in the U.S. as in the EU. One pioneering agency practicing co-digestion in the U.S. is the East Bay Municipal Utility District in Oakland, California, which is turning 40 tons of post-consumer food waste per day into energy.

Key features: A typical co-digestion facility has six major components: a waste-receiving area where haulers deliver loads in either solid or liquid form, equipment to pre-treat and remove contaminants from hauled-in waste, the digester where biological degradation occurs, infrastructure to treat the resulting solid byproduct, infrastructure that cleans the biogas and uses the resulting methane (typically methane is combusted to heat steam that turns a turbine and generator, producing electricity), and a biofilter to ensure that offensive odors do not leave the facility. Figure 39 shows a diagram of the co-digestion process.

Cost (or payback time): If a facility already has an anaerobic digester, then the main capital expenses are for a food-waste-receiving and pre-treatment station.

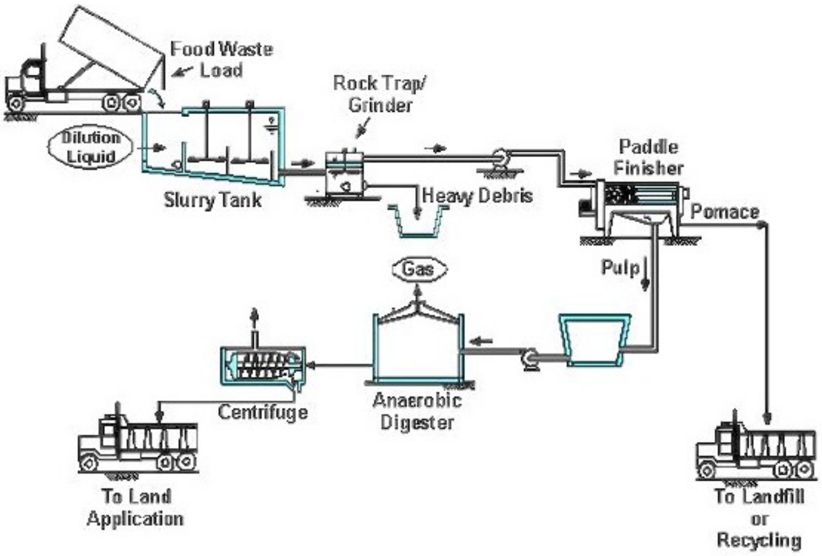

Figure 39. Co-digestion process (Source: EBMUD)

Applications: Co-digestion is typically practiced at wastewater treatment facilities but can also be practiced at other facilities using anaerobic digestion, such as dairy farms. Co-digestion typically involves haulers who bring in the waste and can also involve municipal food-waste collection programs.

Emissions-reduction/energy-savings potential: Co-digesting waste materials has many benefits. Co-digestion diverts food waste and FOG from landfills and public sewer lines, reduces GHG emissions, produces renewable energy (biogas), can reduce water pollution, and can save money or create or additional revenue streams.

Related KPIs: Municipal waste intensity, municipal waste treatment rate, share of renewable electricity, carbon intensity

Sources and additional resources: (U.S. EPA, 2014).

Controlled-atmosphere separation technology (Industrial water recycling and reuse)

Description: Controlled-atmosphere separation technology can be used at industrial chemical facilities to treat wastewater up to standards suitable for industrial reuse or agricultural (but not potable) uses. For industrial processes that produce a large amount of effluent, this technology can help reduce costs for the treatment and disposal of that effluent. The treatment technology is also designed to capture valuable nutrients or materials from the wastewater. Although designed for industrial purposes, the technology can also be used for municipal wastewater treatment, especially where effluent standards are very high (with respect to nitrogen, for example).

Key features: The technology combines heat and flash-vacuum distillation to remove pollutants from wastewater.

Applications: Companies producing this technology claim it can be used in the chemicals, food and beverage, and metal-finishing sectors. There may also be applications for cleaning the water associated with natural-gas fracking. Applications include recovery of ammonia from municipal and industrial wastewater, recycling and reuse of wastewater, removal of biological oxygen demand, and recovery of valuable chemical or metal resources from wastewater streams (including volatile organic compounds and alcohols, gold and other metals, and even starches and yeasts depending on the type of wastewater produced). Figure 40 shows one application of the technology for ammonia recovery at wastewater treatment plants where a usable fertilizer is produced in the end.

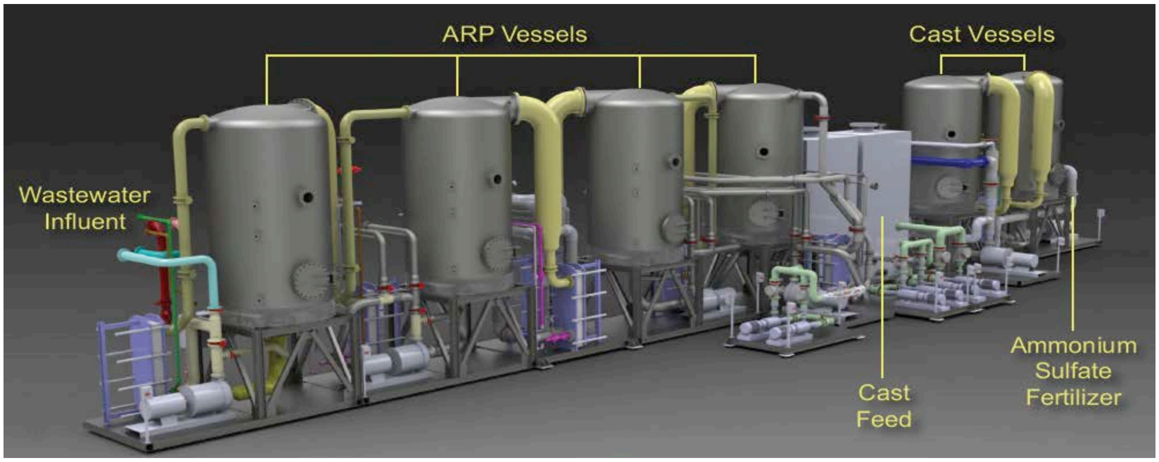

Figure 40. ThermoEnergy controlled-atmosphere separation technology applied to ammonia recovery

Emissions-reduction/energy-savings potential: Controlled-atmosphere separation technology is expensive, and deployment of the technology has been limited. However, it has been proven to treat industrial wastewater effectively, with the potential to recover valuable nutrient or material waste streams.

Related KPIs: Industrial water consumption/industrial GDP, percentage of wastewater receiving at least primary treatment

Sources and additional resources: (ThermoEnergy, 2014)

Recirculating and dry cooling for power generation (Industrial water recycling and reuse)

Description: Thermoelectric power plants (including coal, natural gas, nuclear, and solar thermal) burn or react fuel to heat water, creating steam, which turns a turbine. The steam then needs to be cooled back into water so it can be reused. This cooling is accomplished in one of three ways: 1) once-through cooling, 2) wet-recirculating or closed-loop cooling, or 3) dry cooling. In the U.S., about 43% of thermoelectric generators used once-through cooling, 56% recirculating, and only 1% dry cooling.

Key features: Whereas once-through cooling systems draw water from nearby rivers and oceans and circulate it through pipes and condensers to absorb the heat from the steam, wet-recirculating systems use cooling towers to expose water to ambient air. Some water evaporates, and the rest is sent back to the condenser in the power plant. Because wet-recirculating systems only withdraw water to replace any evaporated water, these systems consume less water than once-through systems. Dry-cooling uses only air to cool the steam exiting a turbine.

Applications: Wet-recirculating cooling can be installed at most coal-fired and natural-gas power plants and is typically incorporated in new power plant construction. Dry cooling systems are typically used only in smaller natural-gas combined-cycle and large solar thermal power plants. There may be some safety concerns with using dry-cooling systems for nuclear power plants.

Cost (or payback time): Dry cooling has higher installation and operation costs, higher efficiency penalties, and greater limitations on the hottest days; however, it consumes the least water and has no entrainment losses. A case study shows that dry cooling will result in a 1–2% point reduction in overall plant efficiency and a US$3–$6 megawatt-per-hour increase in the levelized cost of electricity compared to a similar plant with wet cooling (Zhai and Rubin 2010).

Water-saving potential: Dry-cooling systems use no water and can decrease total power-plant water consumption by more than 90%. Dry-cooling systems for solar thermal power plants use only 26 gallons per megawatt-hour of electricity produced whereas wet-cooling systems for solar thermal power plants use 786 gallons per megawatt-hour. The Ivanpah facility in California’s desert – the world’s largest solar thermal power plant – utilizes dry-cooling technology.

Figure 41. Ivanpah, world's largest solar thermal power plant, uses dry cooling technology

Related KPIs: Industrial water consumption/industrial GDP

Sources and additional resources: (Union of Concerned Scientists, 2013)

Waste sector

Approximately 42% of U.S. GHG emissions are associated with the energy used to produce, process, transport, and dispose of the food we eat and the goods we use (EPA 2009). Extracting, harvesting, processing, transporting, and disposing of these materials emits GHGs, in part because of the large amounts of energy required for all of the life-cycle stages. The manufacture, distribution, and use of the goods and food we rely on in our daily lives—as well as management of the resulting waste—all require energy. This energy mostly comes from fossil fuels, which are the largest global source of GHG emissions.

Source reduction, reuse, and recycling of materials are more sustainable ways to manage materials. This study focuses on the technologies that city policy makers can adopt to improve municipal waste management and treatment.

Many technologies are available for the waste management and treatment. We categorize them by waste-sector treatment or processing methods:

- “Reduce-reuse-recycle” management
- Thermal treatment
- Digestion treatment
- Hydrolysis treatment
- Chemical processing
- Mechanical processing

Urbanization and growing urban populations along with increasing affluence drive the increasing volume of urban waste. It is projected that China’s total MSW will be at least 585 million tons by 2030 (Hoornweg, Lam, and Chaudhry 2005). This growth in waste generation is leading not only to greater financial burdens for cities, but also producing GHG emissions and other environmental impacts. For city policy makers who want to develop a low-carbon path, solid waste is of particular interest because the emissions from this sector are usually within a city’s control and relatively straightforward to address. The metrics to evaluate waste-sector technology performance include:

- Average waste disposed per capita per year
- Waste-recycling rate
- Waste harmless treatment rate

Integrated Solid-Waste Management

Technology name: Integrated solid-waste management (reduce-reuse-recycle)

Description: Integrated solid-waste management involves all key stakeholders in planning the elements of a waste-management system, from source-waste generation to ultimate disposal. Integrated solid waste management is commonly known as "reduce-reuse-recycle" which means: buy and use less, use elements of the discarded items again, and separate discarded materials into components that can be incorporated into new products. This management approach, sometimes referred to as the "3R" approach, addresses all supporting aspects of such a system, including institutional, financial, regulatory, social, and environmental.

Key features: The key feature of integrated solid-waste management is the "hierarchy" of managing waste, which targets an optimal combination of reducing, reusing, and recycling, each representing a form of source reduction (Figure 42). In this hierarchy, the preferred way to manage waste is to first reduce waste generation and separate recyclable waste at the source, to improve the quality of materials for reuse. Source reduction is typically measured by efficiencies and waste cutbacks. When waste cannot be reduced, materials should be reused to the greatest extent possible. If not reduced or reused, materials can be recycled. If they cannot be recycled, they should be recovered. (Hoornweg and Xie 2012).

Figure 42. The integrated waste management hierarchy

Source: (Hoornweg, Lam, and Chaudhry 2005)

Cost (and/or payback time): Integrated waste management is low cost but needs incentives – regulations, legal requirements, or cost savings – to encourage reduction, reuse, and recycling.

Every ton of waste diverted from a landfill may save US$10 to US$25, and every ton incinerated may save US$50 to US$150 (Hoornweg and Xie 2012).

Applications: China used to have a very efficient recycling system based on human labor that has been lost in a wave of consumerism. Integrated waste management is an optimal approach for reducing China's waste generation and encouraging reuse, recycling, and recovery to minimize the amount of waste requiring disposal.

Emissions-reduction/energy-savings potential: Using fewer materials can reduce GHG emissions from raw materials acquisition and manufacturing; recycling reduces GHG emissions by reducing the need for virgin materials, which generally also results in lower energy demand during production (Environment and Plastics Industry Council 2002). The reduce-reuse-recycle approach can reportedly decrease MSW emissions by up to 90% (Chowdhury, et al. 2014). Phitsanulok Municipality in Thailand reportedly avoided 50.5 tonnes of CO_2 equivalent per day by recycling 36 tonnes of material per day (24% paper, 15% plastic, 43% glass, 4% aluminum, and 14% steel) (Sang-Arun and Menikpura 2014).

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate

Thermal treatment of municipal solid waste

Technology name: Thermal treatment

Description: Technologies to thermally treat solid waste include gasification, pyrolysis, cracking, and plasma. All use or produce a significant quantity of heat and include exothermic or endothermic chemical reactions that change the composition of the organic fraction of MSW.

Key features: In general, thermal processes take place in a high-temperature reaction vessel, and the final products are affected by the quantity of air and oxygen added to the reaction. The inorganic and organic fractions of MSW can be processed separately: the inorganic fraction may be sorted out prior to treatment or treated along with the organic fraction. The organic fraction will produce syngas (i.e., synthesis gas composed of hydrogen gases, carbon monoxide, and CO_2), char (a carbon-based solid residue), and organic liquids (e.g., light hydrocarbons) after processing. These products are unoxidized or incompletely oxidized compounds and are left over only from innovative thermal treatment technologies, not from the more complete combustion implemented in traditional waste-to-energy projects.

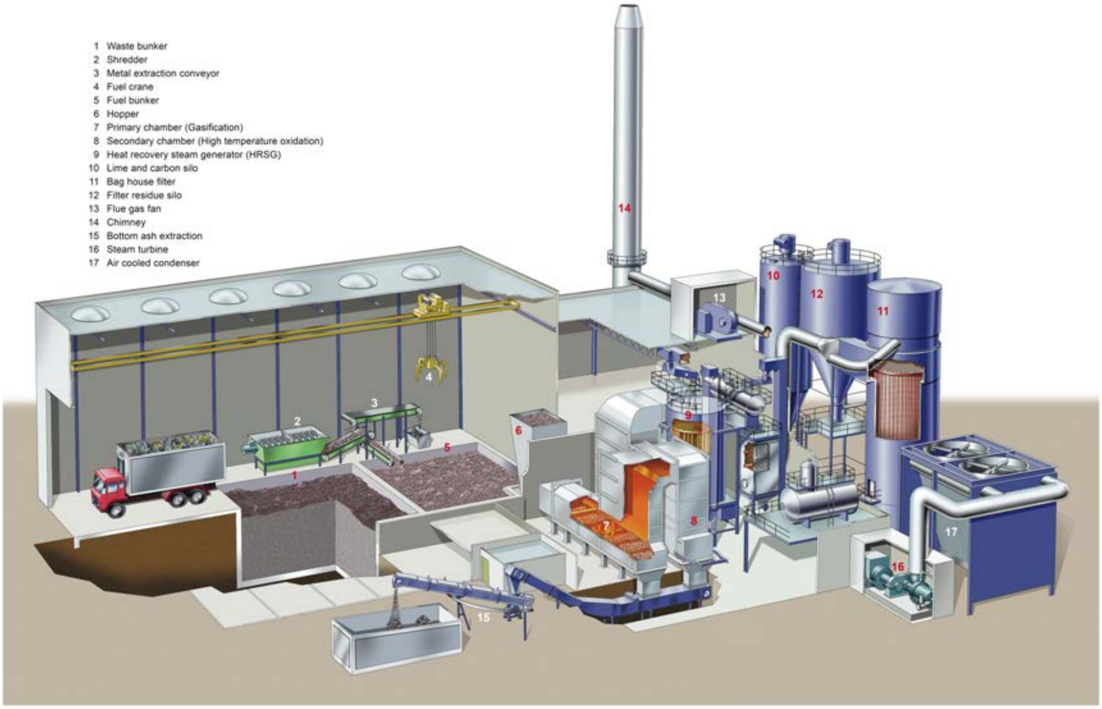

Figure 43. A schematic chart of waste gasification

Cost (and/or payback time): Thermal treatment costs range from US$75 to US$150/ton, with labor being a large component of the total. The capital cost of incineration- and desorption-based thermal treatment technology that processes between 3 and 10 tons of waste/hour ranges from US$3 to US$5 million dollars.

Applications: A number of new and emerging technologies can produce energy from waste and other fuels. Many of these technologies have the potential to produce electric power and fuel that can be sold to cities.

Emissions-reduction/energy-savings potential: MSW thermal combustion facilities avoid emissions in three ways: by producing electricity that can offset electricity produced at conventional, petroleum-based, power plants; by recovering ferrous and/or non-ferrous metals for recycling; and by removing material from the landfill waste stream, thus eliminating methane emissions. A study on three California MSW thermal facilities estimates that net negative GHG emissions, -0.16 to -0.45 million tonnes CO_2 equivalent (MT CO_2e) per ton of waste disposed, can be achieved (Municipal Solid Waste Thermal Technologies 2013).

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate

Digestion treatment

Technology name: Digestion treatment

Description: Digestion is a biological process in which microbes break down solid organic waste, producing liquids and gases. Digestion can be aerobic or anaerobic, depending on whether air (containing oxygen) is introduced into the process. Anaerobic digestion produces a solid byproduct (digestate) and a gas (biogas). Both can be put to beneficial use.

Key features: The biogas produced by anaerobic digestion is composed primarily of methane and CO_2, which is usually burned in an internal combustion engine to generate electricity but has other potential end uses. The digestate can be used as a soil conditioner or compost after a period of aerobic stabilization. The anaerobic digestion process may be either "wet" or "dry," depending on the percent solids in the reactor. Anaerobic digestion has been used extensively to stabilize sewage sludge and has been adapted more recently to process the organic fraction of MSW.

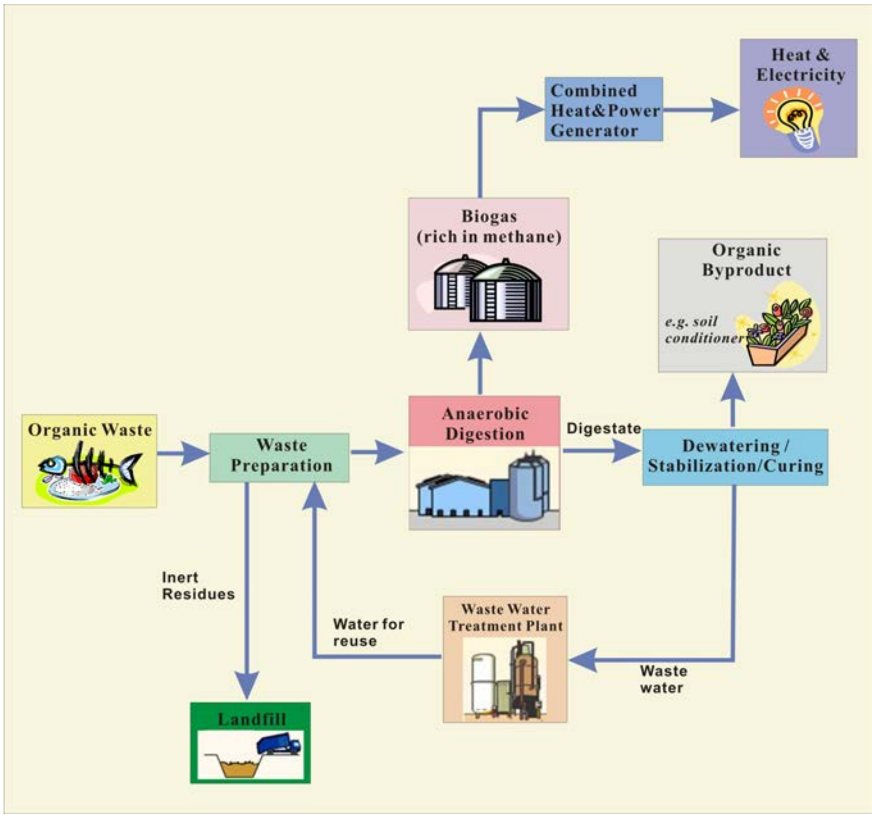

Figure 44. Schematic flow chart of an anaerobic digestion system

Cost (and/or payback time): Although the initial cost of a digestion system can be high, the digestion of food waste can be quite lucrative as a result of fees charged to waste hauler and displacement of other energy sources by methane byproducts of the digestion process. As a result, the payback period can be less than three years depending on the existing infrastructure at the wastewater plant.

Applications: Wastewater treatment facilities are ideal locations for digestion treatment because they already have the infrastructure and expertise needed for such application, and also because they are typically near densely populated urban areas, which means abundant source of organic waste and opportunities for selling the energy, produced (U.S. Environmental Protection Agency 2014).

Emissions-reduction/energy-savings potential: The energy potential of food waste (376 m^3 gas/ton) is three times greater than that of biosolids (120 m^3 gas/ton), so a wastewater treatment facility that digests food waste can not only offset the amount of energy the facility uses but potentially sell excess energy back to the grid (U.S. Environmental Protection Agency 2014).

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate

Hydrolysis treatment

Technology name: Hydrolysis

Description: Hydrolysis is a chemical reaction in which water reacts with another substance to form two or more new substances. For treating MSW, hydrolysis refers to an acid-catalyzed reaction of the cellulose fraction of the waste (e.g., paper, food waste, yard waste) with water to produce sugars.

Key features: In most cases, hydrolysis is the first step in a multi-step technology. For example, several vendors propose following hydrolysis with fermentation and distillation to convert the sugars to ethanol. Another proposal is to convert the sugars to levulinic acid, which has been identified as a commonly used feedstock for other chemicals with emerging markets such as tetrahydrofuran, diphenolic acid, and succinic acid. The organic fraction of MSW must be separated out for hydrolysis, i.e., excluding glass, metal, and other inorganic materials. The organic material is then shredded and put in a reactor vessel where an acid catalyst is added, initiating a process of reducing complex organic molecules to simple sugars. Because the acid only catalyzes the reaction and is not consumed in the process, it is extracted and recycled.

Cost (and/or payback time): The District of Columbia (DC) Water and Sewer Authority built the world's largest thermal hydrolysis plant in its Blue Plain facility. The hydrolysis plant started operation in 2014. The project cost US$400 million, including construction of four Cambi thermal hydrolysis trains, four digesters, and installation of new dewatering equipment and a CHP system that generates 13 MW. The project is estimated to save US$20 million/year from the energy it produces, diversion of biosolids for use in agriculture rather than disposal, and avoidance of the use of lime (Brown and Caldwell 2010, Menco 2012). One study suggests that the thermo-pressure-hydrolysis process has the potential to reduce biosolids disposal costs by 25% (Phothilangka, Schoen and Wett, 2008).

Applications: This technology is designed to treat wastewater treatment plant sludge prior to anaerobic digestion (Menco 2012).

Emissions-reduction/energy-savings potential: The DC project is expected to reduce 61,000 tCO_2/year (Menco 2012).

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate

Chemical processing

Technology name: Chemical processing

Description: Chemical processing generically refers to technologies that utilize a single or a combination of chemical means to convert MSW into usable products through depolymerization and associated refining processes. Chemical processing is a very general term that can encompass many specific processes such as digestion and hydrolysis (discussed separately above), as well as gasification and pyrolysis. This subsection focuses on the underlying process of depolymerization.

Key features: Depolymerization is the permanent breakdown of large molecular compounds into smaller, relatively simple compounds. This process appears to be "thermal" in nature. It utilizes water as a solvent, converting the organic fraction of MSW into energy products (steam and electricity), oil and specialty chemicals, and carbon solids, which could be activated and used as a filter medium or soil amendment. Depolymerization involves a number of complex and interrelated processing steps, with some multiple-step reactions similar to petroleum refining.

Cost (and/or payback time): In 2009, Envion built a US$5 million facility in Montgomery County, Maryland USA, using a process similar to depolymerization. The Envion facility uses infrared energy to heat plastic waste and processes 6,000 tons of plastic annually into about 1 million barrels of a light crude oil. The higher the price of oil, the more economical this technology will be (Livingston 2011).

Applications: Thermal depolymerization can be used to reduce waste of various types (e.g., biological, anatomical, plastic, glass, needles) as well as to produce oil from agricultural plant wastes (e.g., hog manure and other animal wastes) (Walker 2013).

Emissions-reduction/energy-savings potential: Thermal depolymerization can recycle the energy content of organic materials without removing the water (Walker 2013). The process can also eliminate CO_2 and toxin emissions associated with other fuels by replacing those fuels with depolymerized organic materials (Livingston 2011).

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate

Mechanical processing for fiber recovery

Technology name: Mechanical processing to recover fiber

Description: Mechanical processing technologies to recover fiber include innovative refuse-derived fuel (RDF) technologies that produce a clean source of secondary fiber. This mechanical process recovers fiber from MSW to use in papermaking.

Key features: In general, mechanical processing for fiber recovery starts with steam conditioning of MSW in an autoclave, followed by mechanical screening to recover recyclables and separate the organic (or biomass) fraction from the inorganic fraction. The biomass fraction is then pulped with water to recover long-fiber pulp for paper making, and the sludge generated in the process is anaerobically digested. The organic fraction that is not recoverable as a paper pulp substitute is combusted as a conventional RDF. This up-front processing to recover fiber is innovative compared to the conventional RDF process, which typically shreds the incoming MSW and uses magnetic separation to recover ferrous metal.

Cost (and/or payback time): Heat-recovery systems for pressurized refiners can generate 1.1 to 1.9 tons of clean steam per ton of pulp. Payback periods vary widely depending on capital costs but can be as short as a few months. Average installation costs are estimated at US21/ton of pulp (year-2000 U.S. dollars), with significant increases in operations and maintenance costs. One study estimated an electricity savings potential of 11% through mechanical refining improvements, at a capital cost of around US$7.7/ton (US2000 dollars) of pulp production (U.S. Environmental Protection Agency 2010).

Applications: Because mechanical pulping does not dissolve lignin and because mechanical grinding produces shorter fibers, the fiber strength and age resistance of the pulp resulting from this process are low. Consequently, most mechanical pulp is used for lower-grade papers such as newsprint, magazines, and catalogues.

Emissions-reduction/energy-savings potential: Thermopulping can reduce specific energy consumption by up to 20%. A study on a pressurized ground-wood systems claims 20-36% savings in electricity compared with atmospheric mechanical pulping processes (U.S. Environmental Protection Agency 2010). The specific energy of the RTS (Retention time, Temperature, Speed) pulping process is reported to be 20% lower than thermo-mechanical pulping, and the emissions-reduction potential is estimated at 128 kg CO_2/t-pulp; Low-consistency refining is estimated to save 16.3 kg CO_2/t-pulp.

Related KPIs: Average waste disposed per capita per year, waste recycling rate, waste harmless treatment rate.

Sources and additional resources: Industrial Efficiency Technology Database. "Mechanical Pulping." Industrial Efficiency Technology Database. http://ietd.iipnetwork.org/content/mechanical-pulping (accessed October 2014).

Technology summary

Table 9. Summary table of technologies

Sector	Technology	Application	Cost	Mitigation potential
Industry	Energy monitoring and control systems	Demand forecasting, optimal plant operation, performance evaluation, investment planning, cost accounting, and energy benchmarking	Depends on facility size and amount of sub-metering desired for individual processes and systems	Produces no direct energy savings but can be used as benchmark tool
	Energy-efficient motors	Centrifugal pumps, compressors, fans, materials processing (mills and machine tools), conveyors, and elevators	Typically 20% more than conventional motors, but payback period as short as 1 year	Typical energy saving potential ranges from2% to 8%
	Stream-system efficiency	Mechanical work through a turbine or direct heat for various processes	Payback period short or within system lifetime for proper sizing and minimizing leaks but very long for boiler-related improvement	1% to 35 %, with 7% average savings
	Compressed-air system	Used widely across different industrial sectors	Cost data not available	0.5% to 16.0% for various measures
	Pump systems	Used widely across different industrial sectors	Pump purchase cost only 5-10% of total life-cycle cost of ownership and operation	20% on average
	Waste-heat and waste-gas recovery	Many applications in industry	In cement plants, capital cost range:$2-4 per annual ton of clinker capacity; operating costs: $0.20-0.30 per ton clinker	30% of cement facility's energy needs
	Co-firing of waste material and use of alternative clinker materials	Common in cement industry	Savings of fuel costs and raw materials	Net savings of 234 kg CO_2 per 100 kg of sewage sludge co-fired
	Coal-mine methane utilization	On site (most common): as fuel in furnaces and boilers for processes or in engines or turbines for power generation. Off site: injection into natural-gas pipelines as feedstock for fertilizer industry, or potentially as compressed natural gas In vehicles	Depends on which equipment is used and whether captured coal-mine or ventilation-air methane is used on site to generate power or enriched for pipeline export	Global coal-mine methane emissions were estimated at 432 million tons of CO_2 equivalent in 2005
	Coke dry quenching	Producing steam or electricity, pre-heating coking coal, or using heat	Equipment costs for a 2-million-ton-coke-per- year plant estimated at EUR 70 million	Up to 40% less energy

		directly		
Sector	**Technology**	**Application**	**Cost**	**Mitigation potential**
Building	Low-U-value windows	Fully conditioned commercial new construction and major reconstruction with high window-to-wall area ratios (if capital cost can be offset by the downsized HVAC equipment cost)	Price premium of \$4 per square foot but cost effective in several climate zones on the basis of energy savings alone	20% to 40% reduction in heating and cooling
	Smart windows	Most applicable to new construction or major reconstruction projects where capital costs can be offset by decreased HVAC equipment costs	Dimming controls: payback periods from energy savings of 1–10 years (ASHRAE 90.1-2001) and 2–18 years (ASHRAE 90.1-2007) for installed costs in the \$5.40–43.00/m^2 (\$0.50–4.00/ft^2) range; electrochromic window designs: approx.. \$100 per ft^2 in 2010.	20% reduction in cooling loads
	Cool roofs	In warm and hot climate regions that have long cooling seasons and short heating seasons	Asphalt shingle: \$2/ft^2; built-up roof: \$2-\$4/ft^2; clay tile: \$2-\$6/ft^2; concrete tile: \$2-\$6/ft^2 ; liquid applied coating: \$0-\$2/ft^2; metal roof: \$2-\$4/ft^2; modified bitumen: \$0-\$2/ft^2; single-ply membrane: \$0-\$2/ft^2; wood shake: \$0-\$2/ft^2	10% to 30% reduction in peak demand
	Interior and exterior shading systems	New and retrofit construction	Cost data not available	Exterior shades: 53% to 67% energy savings in lighting; 79% to 94% savings in cooling loads
	Natural and hybrid ventilation	In locations with moderate climate and clean outdoor air	Naturally ventilated buildings: typically lower capital costs for cooling and ventilation equipment but additional capital for facade and building fabric; capital costs for natural ventilation system elements, e.g., automated windows, comparable to cost of air-conditioning systems	Emissions reductions: In 4 of 6 UK case studies , 24% to 71% fewer carbon emissions compared to industry benchmark figures for an average air-conditioned building; cost savings between 4,000 and 6,000 British Pounds a year.
	Ground-source heat pumps	Only in new residential and commercial construction	High up-front cost recouped in 5-10 years through energy savings	Can cover 2/3 to all of a building's heating and cooling needs
	Heat-pump water heaters	Common in residential buildings; increasingly common in commercial buildings	Slightly higher up-front cost but slightly lower operating costs	Up to 50% reduction in electricity use
	Advanced power strips	Kitchens, printer rooms, individual offices, and workstations in	Payback period less than 8 years in all applications	26% reduction in plug loads at workstations and about 50% at printer rooms and kitchens

		commercial buildings; home entertainment or computer systems in residential buildings		
	Lighting-system improvements	Residential and commercial buildings	LEDs more costly than compact fluorescents; occupancy sensor payback period 6 months to several years	Large savings potential from improved efficacy and longer bulb lifetimes
	Advanced metering infrastructure	Buildings that can control their HVAC, lighting, and other energy loads	Significantly high up-front cost, including hardware and software purchases, labor expenses for meter installation, and consumer education	26% to 43% reduction in peak load in a pilot program
Sector	**Technology**	**Application**	**Cost**	**Mitigation potential**
Power	Distributed solar and BIPV	Commercial or large residential buildings	Average system price \$4.93/W with a payback period of 5-10 years	Annual energy savings in cooling per unit conditioned roof area: 34.6 MJ/m^2 (9.6 kWh/m^2); in heating: 2.9 MJ/m2 (0.010 $therm/m^2$); annual primary energy savings in total source: 107.1 MJ/m^2 (101 $kBTU/m^2$)
	Combined heat and power	Medium-size commercial buildings with peak electric loads ranging from 100 kW to 5 MW	Gas turbines (5-40 MW): \$970/kW to \$1,300/Kw; micro-turbines: \$2,400/kW to \$3,000/kW; natural gas spark-ignited engine gensets: \$1,100/kW to \$2,200/kW	For New York City, estimated carbon savings of 2.3 Mt CO_2e for the building system and 5.0 Mt CO_2e for the microgrid scales respectively, that use CHP
	Fuel-cell power systems	Power generation, cogeneration, fuel-cell electric vehicles, buses, forklifts, motorcycles, bicycles, boats, airplanes, submarines; commercial and industrial CHP (200-1,200 kW), residential and commercial systems for CHP (3-10 kW), back-up and portable power systems (0.5-5 kW)	\$67 per kW in vehicles (with 100,000 automotive units production per year); \$55 per kW assuming volume production of 500,000 units per year	The overall energy savings of fuel cell micro generation is about 25.3%.
	Utility-scale solar	Electricity transmission grid	24% decrease in cost of crystalline-silicon solar modules for every doubling in installed capacity; 12% decrease in cost of thin-film modules for every doubling	Median values for PV technologies are below 50 gCO2e/kWh, comparing that for coal at about 890 gCO2e/kWh.
	Utility-scale energy storage	Grid energy storage; vehicle-to-grid energy storage system	100-MW long-duration storage devices that provide no reserves while charging: annual value of \$115/kW-yr; device of the same capacity that provides reserves while charging: annual value of \$128/kW-yr; V2G not currently commercially practical	Median values for PV technologies are below 50 gCO_2e/kWh, comparing that for coal at about 890 gCO_2e/kWh. Deploying 4 gigawatts of solar power in California could save consumers between US\$60 million and US\$240 million per year.

	Microgrids	Critical or controllable load source; Dispatchable generation (fuel cells or microturbines) or limited-dispatchability generation (solar, wind)	California’s Santa Rita Jail microgrid project costs: $14 million, including a large-scale battery, new and legacy renewable-energy sources, and a fuel cell and excluding solar PV and energy-efficiency measures; battery cost high, feasible only with federal and state government grants; widespread adoption only if electrical storage costs fall considerably	An evaluations using home micro-grid system showed a 25% or greater reduction in CO_2 emissions was achieved compared to the conventional approach.
	Integrated gasification combined cycle	Chemical and hydrogen production	$1,491/kW installed capacity versus $1,290 for conventional clean coal facility	42% net thermal efficiency (with a 1300 °C-class gas turbine); 45% with a 1500 °C-class gas turbine
	Smart grid	Smart generation in power plants, smart sensors and meters for consumers	Estimated cost for deployment of smart grid technology from U.S. utility control centers and power networks to consumers' homes: $338 billion to $476 billion from 2011 to 2030; benefits expected to be $1.3 trillion to $2 trillion during same period	The direct and indirect mechanism of smart grid in U.S. sum up to 5% and 2% of the U.S. total energy consumption and energy-related CO_2 emissions for all sectors (including electricity).
	Carbon capture, utilization, storage	ExxonMobil's Shute Creek gas processing plant in Wyoming	Recent credible estimates of cost of capturing and storing CO_2: $60 per ton, corresponding to electricity prices increase of about 6c per kWh (based on typical coal-fired power plant emissions of 2.13 pounds CO^2 per kWh)	Up to 90% reduction in CO_2. 14 percent of cumulative emissions reductions between 2015 and 2050 compared to a business as usual scenario under IEA’s 2°C Scenario.
Sector	**Technology**	**Application**	**Cost**	**Mitigation potential**
Transport	Electric vehicles	City buses, taxis, government official vehicles	Cost varies by mode over a year but with government subsidy could be comparable to conventional cars	From research on China’s regional power grid using life-cycle-cost-analysis in 2009, varied energy savings and CO_2 emissions reduction among regions because of share of coal-fired power in each region, but national energy savings of 35.57% for pure battery electric vehicles and 17.78% for plug-in hybrid electric vehicles; CO_2 emissions reduction 17.13% for battery EVs and 8.56% for plug-in hybrid EVs
	Intelligent transportation systems	Emergency vehicle notification systems, automatic road enforcement, variable speed limits, collision avoidance system, dynamic traffic light	Capital cost of transportation management center from $1.8 million to $11.0 million per facility; operations and maintenance cost from $50,000 up to $1.8 million per	Variety of applications within systems, so not possible to predict emissions reductions

		sequences	year	
	EV charging stations	Solar-powered automotive recharging, E-Move charging, and wind power charging stations	Major cost of EV charging systems – installation; cost of charging varies by modes and charging time	In study on commercial and residential (level 2) charge stands, unit savings of 21kWh/yr for basic products and 53kWh/yr for products with network connectivity; based on 2015U.S. shipments, nationwide savings potential of 4,791MWh/yr, which translates to 73,77,924 pounds CO_2/yr
	Hydrogen vehicles	Buses, trains, taxis, bicycles, and other forms of transportation	Estimated $47/kW for an 80 kW proton exchange membrane fuel cell with annual production of 500,000 units	FCVs more energy efficient than gasoline-powered vehicles; fuel economy of Honda FCX Clarity, model year 201, equivalent to 60 miles per gallon (mpg); 2011 Mercedes-Benz F-Cell fuel economy of 53 mpg, compared with 33.8 mpg for a gasoline passenger vehicle from model year 2011. FCVs also much lower life-cycle GHG emissions because FCVs emit only heat and water during operation and no tailpipe GHGs
	Automatic bike-rent/share systems	Last mile transportation in urban areas and towns	Capital costs (e.g. bike stations, bikes, permits, and design plans) and monthly operating costs; can be partially covered from user fees, sponsorships, and advertising. Cost-benefit analysis for Washington DC Capital Bikeshare program projected a benefit-cost ratio of 1.72 over 20 years, using 7% discount rate	Estimated CO_2 savings from Capital Bikeshare program in Washington DC and surrounding counties: 1.6 million pounds in 2013, based on number of miles traveled by users
	Smart parking systems	Parking garages, parking lots, street parking and transit	Initial capital cost typically $150 to $250 per parking space plus continuing operations and maintenance cost of $40 to $60 per space per year	In smart parking system in Ellicott City, Maryland USA, 21% reduction in time drivers spent looking for open spots; in San Francisco's SF park smart parking project, 30% reduction in CO_2 emissions and excess vehicle-miles traveled compared to control area
	Rapid-transit systems	184 cities as of 2012	Capital cost high, often subsidized with soft loans and ancillary revenue	Typical ridership gains in bus rapid-transit projects 5% to 25% over previous local bus service on same corridor; on Los Angeles Metro Rapid, reported increase of 26,800 (42%) in weekday ridership on the on the Wilshire/Whittier corridor and 3,600 (27%) on the Ventura corridor for estimated reduction of 9,188 metric tons of CO_2 emissions -- 12,424 metric tons from mode shift, countered by increase of 3,235 metric tons from additional transit service

Sector	Technology	Application	Cost	Mitigation potential
Water	Gray-water recycling	Irrigation (parks, playgrounds, athletic fields), commercial uses (vehicle washing, laundry facilities), fire protection, and toilet/urinal flushing.	$1,000 for simple residential system to use laundry water for backyard irrigation; $10,000 for complex system to recycle shower, bathtub, and washing machine water for toilet flushing	Currently, 1.3% of total U.S. water consumption reused , which avoids water treatment energy use; current U.S. water treatment energy use: 3% of total U.S. electricity use
	Water-efficient appliances	Residential, commercial building toilets, faucets, smart landscape irrigation controllers	Minimum cost premiums for low-flow water appliances; some no-flow toilets very costly.	25% to 75% less water than conventional appliances; improves energy intensity associated with heating and supplying water
	Smart water-distribution networks	Primarily municipal water utilities to improve their distribution networks	Can save utilities up to $4.6 billion annually through 5% leak reduction coupled with up to 10% reduction in pipe bursts	Can reduce monetary and energy expenditures related to purchasing, treating, and pumping water
	Rainwater harvesting	Commercial, residential buildings with relatively high roof-area-to-height ratios	Not as cost-effective as water-efficient appliances, which should be adopted before water reuse and rainwater harvesting	620 gallons water per 1-inch rainfall from1,000-square-foot roof
	Reverse osmosis	Treatment and recycling of wastewater from metal finishing, semiconductor or automotive manufacturing, food and beverage processing, groundwater and landfill leachate	Capital cost data not available; reduction in water and sewer use costs at participating facilities	Recycling of pre-treated and RO water; volume depends on individual facility use.
	Ultraviolet treatment	Municipal and industrial water treatment; locations with no centralized water treatment infrastructure	High up-front capital costs but lower operating costs compared to chlorination	Reduces overall water pollution compared to chlorination
	Anaerobic digesters	Mostly wastewater treatment facilities, dairy farms, food-processing facilities	Overall costs high – initial cost of digester up to $600 per annual ton capacity; operating costs $40-$150 per ton of waste delivered	Source of renewable energy, reduces GHG emissions
	Co-digestion at wastewater treatment	Primarily wastewater treatment facilities	Main capital cost: food-waste receiving and pre-treatment station	Diverts food waste, fats/oil/grease from landfills and public sewer lines; produces biogas
	Controlled atmosphere-separation technology	Cleaning water associated with natural-gas fracking, recovering ammonia from municipal and industrial wastewater, recycling and reusing wastewater, removing biological oxygen demand	Expensive, therefore limited deployment to date	Very effective for treating industrial wastewater; potential to recover valuable nutrient or material waste streams

	Recirculating and dry cooling for power plants	Wet-recirculating mostly for coal-fired and natural-gas power plants; Dry-cooling systems only for smaller natural-gas combined-cycle and large solar thermal power plants	Case study, dry cooling: 1-2% point reduction in overall plant efficiency; \$3–\$6/MWh increase in levelized cost of electricity compared to similar plant with wet cooling	Can reduce water consumption more than 90%

Sector	Technology	Application	Cost	Mitigation potential
Waste	Reduce-reuse-recycle management	Countries with unmanaged landfill sites or open dumps	Low up-front cost but incentives needed to increase penetration	Can reduce MSW up to 90%
	Thermal treatment	Electric power production	For technology that processes 3 to 10 tons/hour: \$3 to \$5 million dollars.	Net negative GHG emissions: -0.16 to -0.45 MT CO_2e per ton waste disposed at 3 California MSW thermal facilities
	Digestion treatment	Primarily wastewater treatment facilities	High initial cost; can be covered by methane production and fee income from water hauler	Food-waste energy potential (376 m^3 gas/ton) 3x greater than biosolids (120 m^3 gas/ton)
	Hydrolysis treatment	Wastewater treatment plant sludge prior to anaerobic digestion	DC Water's Blue Plain plant: \$400 million; energy savings from project estimated \$20 million/year	DC Water project expected to reduce 61,000 tCO_2/year
	Chemical processing	Category of thermal depolymerization processes for reducing waste (e.g., biological, anatomical, plastic, glass, needles); producing oil from agricultural wastes (e.g., hog manure, other animal wastes)	Envion \$5 million facility processes 6,000 tons plastic annually into 1M barrels light crude oil	Can recycle energy content of organic materials and eliminate CO_2 and toxin emissions when output products used as fuel
	Mechanical processing for fiber recovery	At MSW facilities; mostly for lower-grade papers, e.g., newsprint, magazines, and catalogs	Estimated installation cost of heat recovery for thermo-mechanical pulping: \$21/ton of pulp; estimated capital cost of mechanical refining improvements: \$7.7/ton of pulp	Estimated electricity savings from thermopulping up to 20% (pressurized ground-wood system: 20%-36%); estimated emissions reduction from RTS: 128 kg CO_2/t-pulp and low-consistency refining 16.3 kg CO_2/t-pulp.

Summary and Discussion

As China experiences unprecedented urbanization, central and local government entities are moving aggressively toward building low-carbon eco-cities to accommodate increasing urban populations while minimizing environmental impacts. City policy makers need comprehensive, accessible information on what constitutes a low-carbon eco-city, how to evaluate progress toward low-carbon/eco-city goals, and what policies and technologies are available to improve the performance of developing a low-carbon eco-cites. This report attempts to fill this information gap by describing 53 technologies or technology categories in six key sectors: industry (11 technologies), buildings (10 technologies), power (9 technologies), transportation (7 technologies), water (10 technologies), and waste (6 technologies). For each technology, we review key features, applications, cost, and energy-/water-/carbon-saving potentials. This report does not present an exhaustive list of low-carbon/ecological technologies but includes applications and references that policy makers can use to look for other similar commercially available technologies.

Low-carbon eco-technologies are a very dynamic area that is developing and changing rapidly as a result of innovation, competition, cost changes, and local adaptation, resulting in ongoing evolution of the technologies that are commercially available. This report is a snapshot of types of technologies available currently.

Commercially available technologies are not necessarily precisely customized to local circumstances. Potential barriers to local deployment of low-carbon ecological technologies include intellectual property issues, lack of financing, lack of local capacity, and other concerns. Incentives and supportive policies to promote those technologies merit further in-depth, case-by-case analysis.

Acknowledgments

We would like to thank Brian Holuj, Mingchao Xu, and Stephanie Ohshita for their review and comments. This work was supported by the Oak Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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