CHAPTER 3

The Innovations That Are Revolutionizing Our Energy Consumption

At international negotiations on climate change such as those at the Paris Conference, the centralized, top-down approach is favoured. Similarly, when governments impose regulations or hand out subsidies, decisions are also centralized. As we saw in the previous chapter, however, policies using market mechanisms are more efficient precisely because they allow for decision-making to be decentralized.

One encouraging but largely overlooked trend is taking shape in businesses and institutions: that of constantly innovating to meet the public desire for limits on GHG emissions. This chapter deals with the new realities that could very well change the picture of GHG emissions over the coming years and decades.[142] Though their impact may sometimes be hard to measure since they are not determined by governments, emerging decentralized solutions can be particularly effective.

This trend can be seen more clearly when we focus less on the overall emissions level and more on the factors that determine this level, such as energy intensity and carbon intensity. Per capita GHG emissions in various countries around the world can be seen as the result of a combination of three factors: standard of living, energy intensity, and carbon intensity. This is presented in the Kaya identity, an equation used by the IPCC for GHG emissions scenarios, which can be represented schematically as follows:

GHGs/capita = **Standard of living (GDP/Population)** **X** **Energy intensity (Energy/GDP)** **X** **Carbon intensity (Emissions/Energy)**

This equation shows that the growth of GHG emissions depends on the variation of each of these factors. Adopted and proposed government policies on the mitigation of GHG emissions aimed at limiting climate change impose a price directly on carbon through a tax or an emission allowance trading market, for example. Government-imposed environmental regulations and standards influence one factor in greenhouse gas emissions, namely carbon intensity. The same can be said for renewable energy subsidies.

Market mechanisms, in contrast, affect greenhouse gas emissions by fostering wealth creation—in other words, by raising living standards—but also by influencing energy intensity and carbon intensity.

Reducing Energy Intensity Around the World

Various markets, through the incentives provided by price mechanisms, allow for resources—among them, energy—to be allocated optimally based on the needs of the members of society. In meeting the demands of their customers, businesses naturally seek to minimize their costs, and therefore to the least possible resources and energy per unit produced. Our ability to do more with less energy, or the capacity to perform the same amount of work with less energy, is what the International Energy Agency (IEA) calls "energy efficiency."[143]

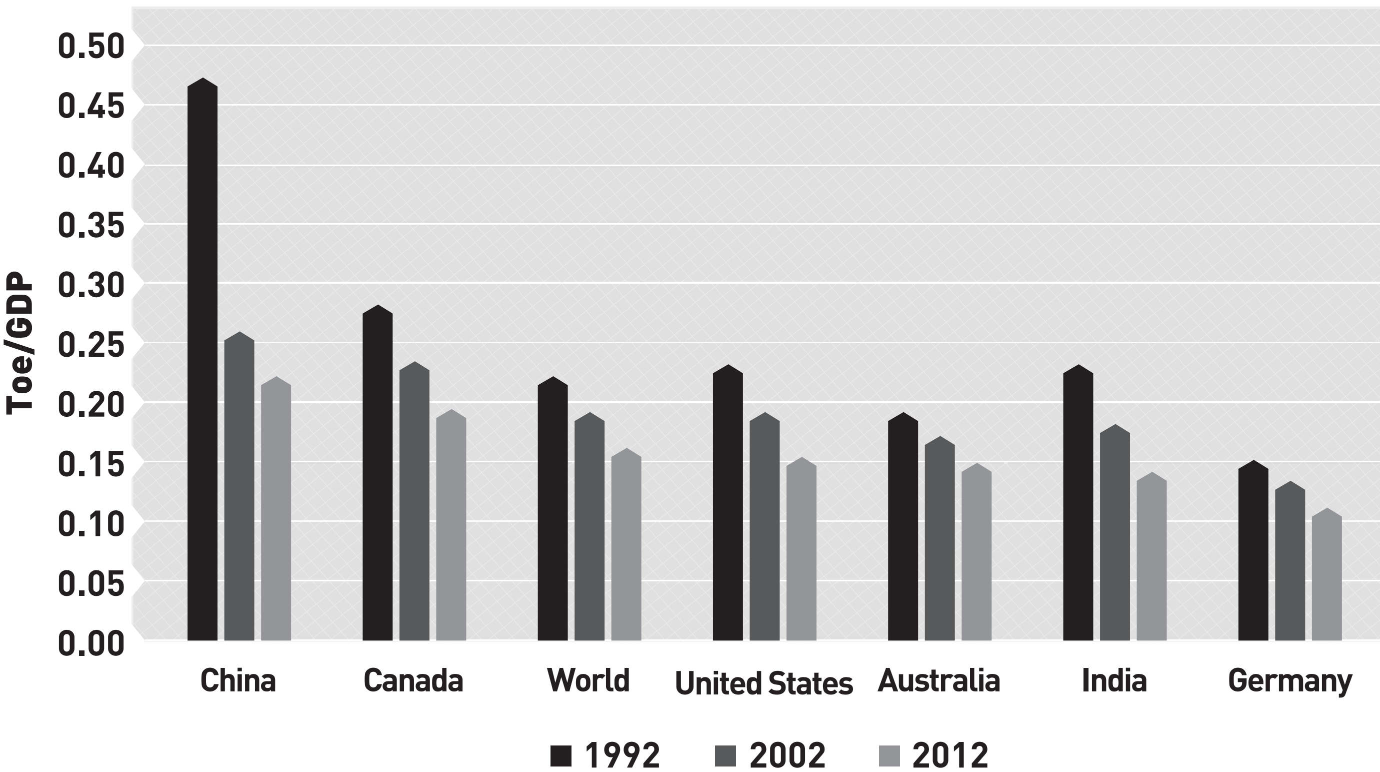
Energy intensity, which measures the quantity of primary energy used per unit of GDP, provides a good estimate of energy efficiency. The more efficient an economy is, the less energy it uses per dollar of GDP. Figure 3-1 shows that energy intensity falls with economic development, among both rich and emerging countries. China's progress in this regard has been spectacular, with energy intensity having been reduced by half in 20 years. At the global level, energy intensity fell at an annual pace of 1.25% between 1990 and 2013.[144]

142. Agence France-Presse, "Dix poids lourds du pétrole et du gaz s'unissent pour le climat," *La Presse*, October 16, 2015.

143. International Energy Agency, Energy efficiency.
144. Ren21, *Renewables 2015 Global Status Report*, 2015, p.114.

Figure 3-1

Energy intensity in tonnes of oil equivalent per thousand U.S. dollars, 1992-2012



Note: These are 2005 US dollars, adjusted for purchasing power parity.
Sources: International Energy Agency, Statistics, Report; International Energy Agency, *Energy Efficiency Market Report 2014: Market Trends and Medium-Term Prospects*, 2014, p. 210.

Energy intensity is not a perfect measure of energy efficiency since it does not take account of the structure and size of the economy nor of a region's climate. For example, a service-based economy in a mild climate will have lower energy intensity than a manufacturing-based economy in a cold climate, even though it is possible that it uses its energy less efficiently.[145]

The IEA has been attempting for the past few years to calculate energy efficiency more precisely. It estimates how high energy consumption would have been if wealth and population had grown at the same pace but without technological advances to improve energy consumption in buildings, machines, vehicles and even electric light bulbs.[146]

The amount of energy saved through efficiency gains using new approaches is substantial. The IEA estimates that in 2011, for an 11-country sample, total energy consumption avoided through technological improvements since 1973 amounted to 1,337 million tonnes of oil equivalent. As indicated in Figure 3-2, this saving is greater than the final consumption of any single form of energy.

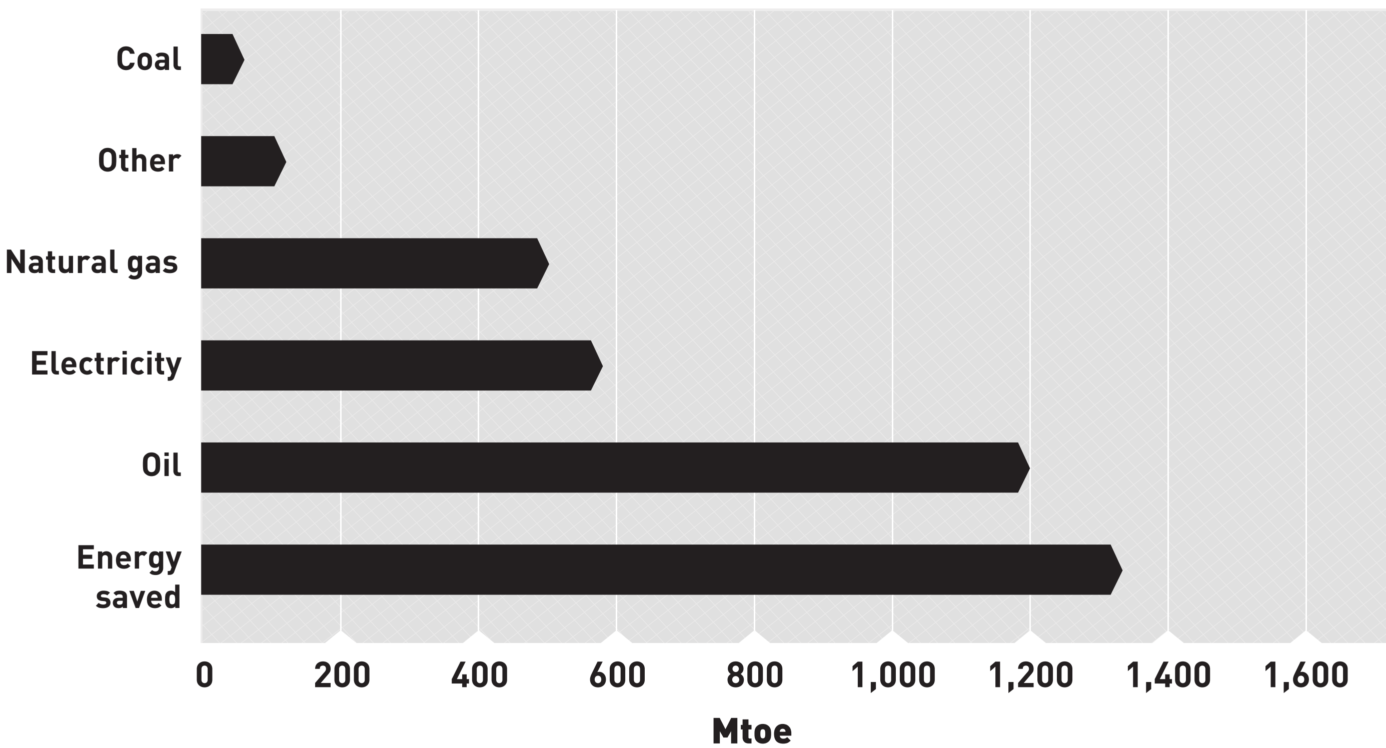
> **"One encouraging but largely overlooked trend is taking shape in businesses and institutions: that of constantly innovating to meet the public desire for limits on GHG emissions."**

These efficiency gains have two contradictory effects on greenhouse gas emissions. First, a smaller quantity of energy per unit of production obviously results in lower emissions, all else being equal.

145. International Energy Agency, *Energy Efficiency Indicators: Fundamentals on Statistics*, 2014, p. 19.
146. International Energy Agency, *Energy Efficiency Market Report 2014: Market Trends and Medium-Term Prospects*, 2014, p. 26.

Figure 3-2

Energy saved due to efficiency gains compared to consumption of various forms of energy, in millions of tonnes of oil equivalent, 2011



Note: The 11 countries evaluated are Australia, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, the United Kingdom and the United States.
Source: International Energy Agency, *Energy Efficiency Market Report 2014: Market Trends and Medium-Term Prospects*, 2014, pp. 26-27.

However, using less energy per unit of production does not necessarily mean that less energy will be used. The energy that is freed up also allows for more to be produced with the same quantity of resources. This increased production can therefore offset the effect of the efficiency gains, in whole or in part. Energy saved and used for other purposes is a phenomenon that economists call the "rebound effect." Various IEA reports estimate that this rebound effect would be on the order of between 9% and 30%,[147] but it could be higher.[148]

"Efficiency gains in the automobile market represent a trend that can be seen all around the world."

It is also possible that more energy is used because efficiency gains make it more abundant and reduce its marginal cost of use. The total effect on GHG emissions into the atmosphere is therefore uncertain.

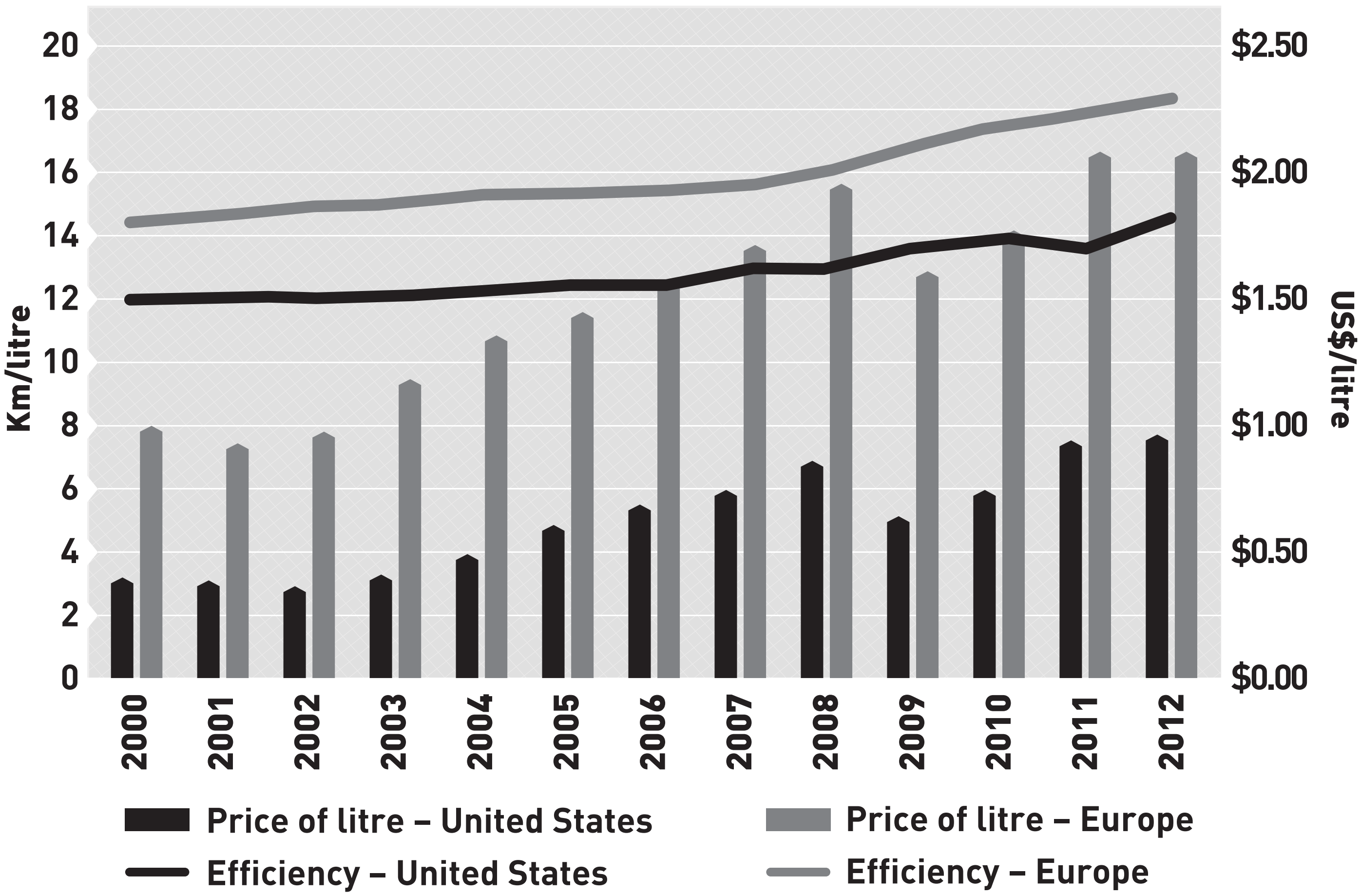
The energy intensity of automobiles provides a tangible illustration of a high rebound effect, which may even exceed 100%. Technological advances in recent decades, including in the choice of materials, have greatly reduced the amount of energy needed to travel a given distance. However, in the United States, the energy savings resulting from this improved efficiency were more than offset by the purchase of heavier, more powerful vehicles and by greater annual distances travelled. American vehicles therefore consumed 35% more energy in 2000 than in 1980 despite greater efficiency.[149]

147. *Ibid.*, p. 27.
148. Harry D. Saunders, "Recent Evidence for Large Rebound: Elucidating the Drivers and Their Implications for Climate Change Models," *The Energy Journal*, Vol. 36, No. 1, 2015, pp. 23-48.

149. Vaclav Smil, *Energy at the Crossroads: Global Perspectives and Uncertainties*, The MIT Press, February 2005, p. 333.

Figure 3-3

Gasoline prices and average vehicle efficiency in Europe and the United States



Sources: The International Council on Clean Transportation, Global Transportation Roadmap Model, Data Tables, August 2015; European Environment Agency, Nominal and real fuel prices, July 2015; U.S. Energy Information Administration, Petroleum and Other Liquids, Data, U.S. All Grades All Formulations Retail Gasoline Prices, 2015; CanadianForex, Yearly Average Exchange Rates for Currencies.

Efficiency gains in the automobile market represent a trend that can be seen all around the world.[150] It is hard to tell for sure, however, whether government-imposed standards play a greater role than consumer demand for more efficient vehicles, which is influenced by generally increasing gasoline prices.

Figure 3-3 illustrates the evolution of gasoline prices in Europe and the United States as well as the average energy efficiency of vehicles, measured in kilometres travelled per litre of gasoline. It is no surprise that cars purchased in Europe go 26% further per litre than cars purchased in the United States, given that the price of gasoline was on average 137% higher there from 2000 to 2012.

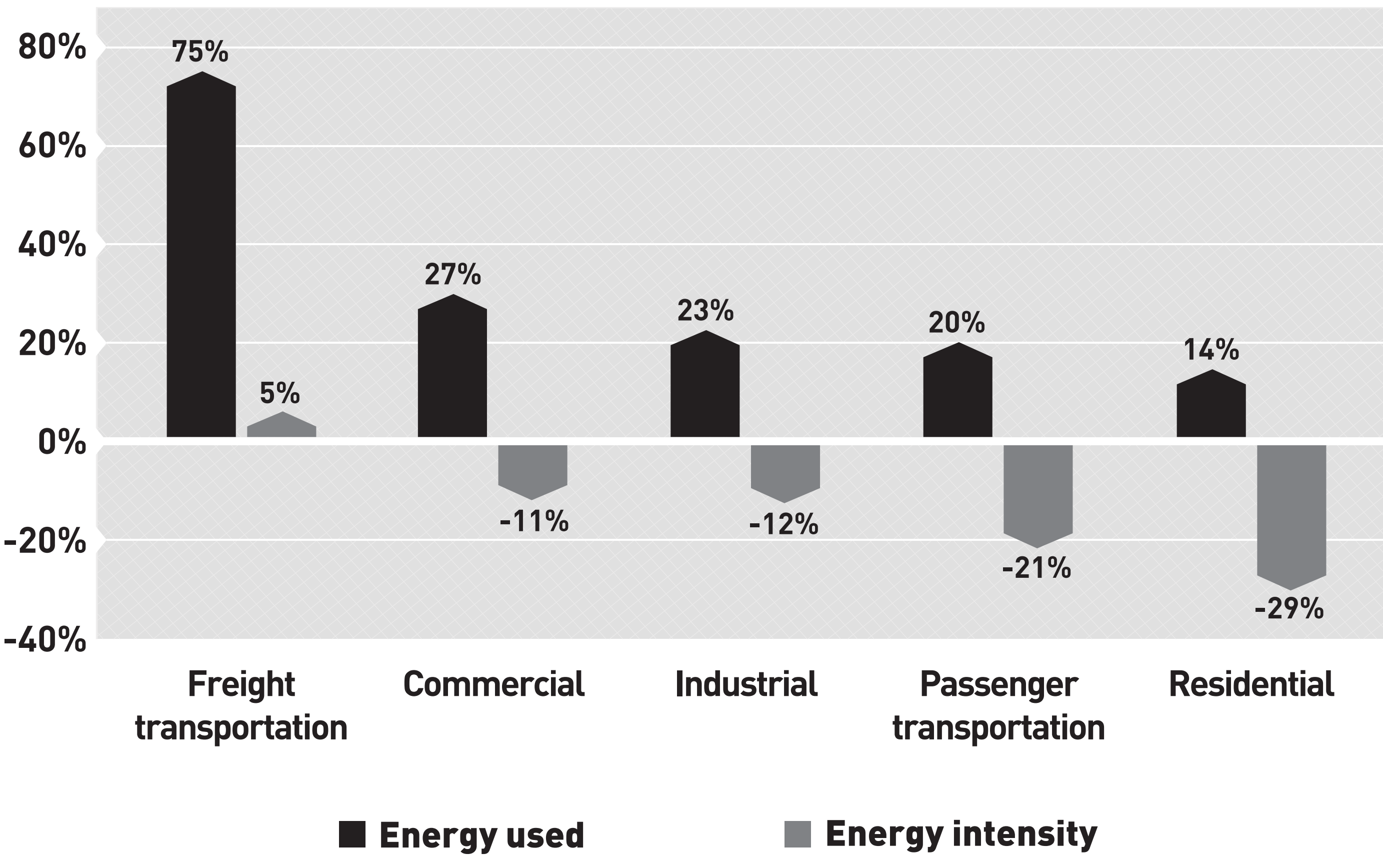
The trend toward greater energy efficiency applies to many sectors in Canada. Figure 3-4 shows the relationship between energy used and energy intensity in Canada in industry (forestry, mining, manufacturing, construction) and in the residential and commercial sectors, as well as in personal and commercial transportation. We can see that the bigger the drop in energy intensity (due to efficiency gains), the smaller the rise in total energy used. This trend demonstrates the importance of being more energy-efficient, regardless of how big the rebound effect may be.

Nevertheless, wealth and population increases, and to a lesser extent the rebound effect, help explain why global energy consumption has increased substantially over the past 40 years despite efficiency gains.

150. International Energy Agency, *op. cit.*, footnote 146, p. 72.

Figure 3-4

Variation in energy used and energy intensity by sector in Canada, 1990-2011



Source: Natural Resources Canada, *Energy Markets: Fact Book — 2014-2015*, p. 88.

Comparing changes in primary energy consumption between industrialized and emerging countries allows us to understand why an international climate agreement will necessarily have to include the latter. China and India have seen their primary energy consumption rise 957% and 736% respectively since 1974, while the increase has been far more modest in industrialized countries. In Germany, there was even a 6% decline in consumption over the same period (see Figure 3-5).

In Western countries, primary energy consumption has been fairly stable over the past 15 years (see Figure 3-6). Moreover, this trend should continue according to the IEA, which forecasts for example that "industrialized countries will consume no more oil in 2020 than they do today."[151]

Likewise, per capita primary energy consumption in industrialized countries has been stagnating or even declining since the early 1970s (see Figure 3-7). As the IEA remarks with unusual optimism, "the technological and economic context has changed, and that changes everything."[152] Tough environmental standards, the effect of the Internet on retail trade, and the aging of the population—older people use cars less—are three factors identified as significant and positive trends.[153]

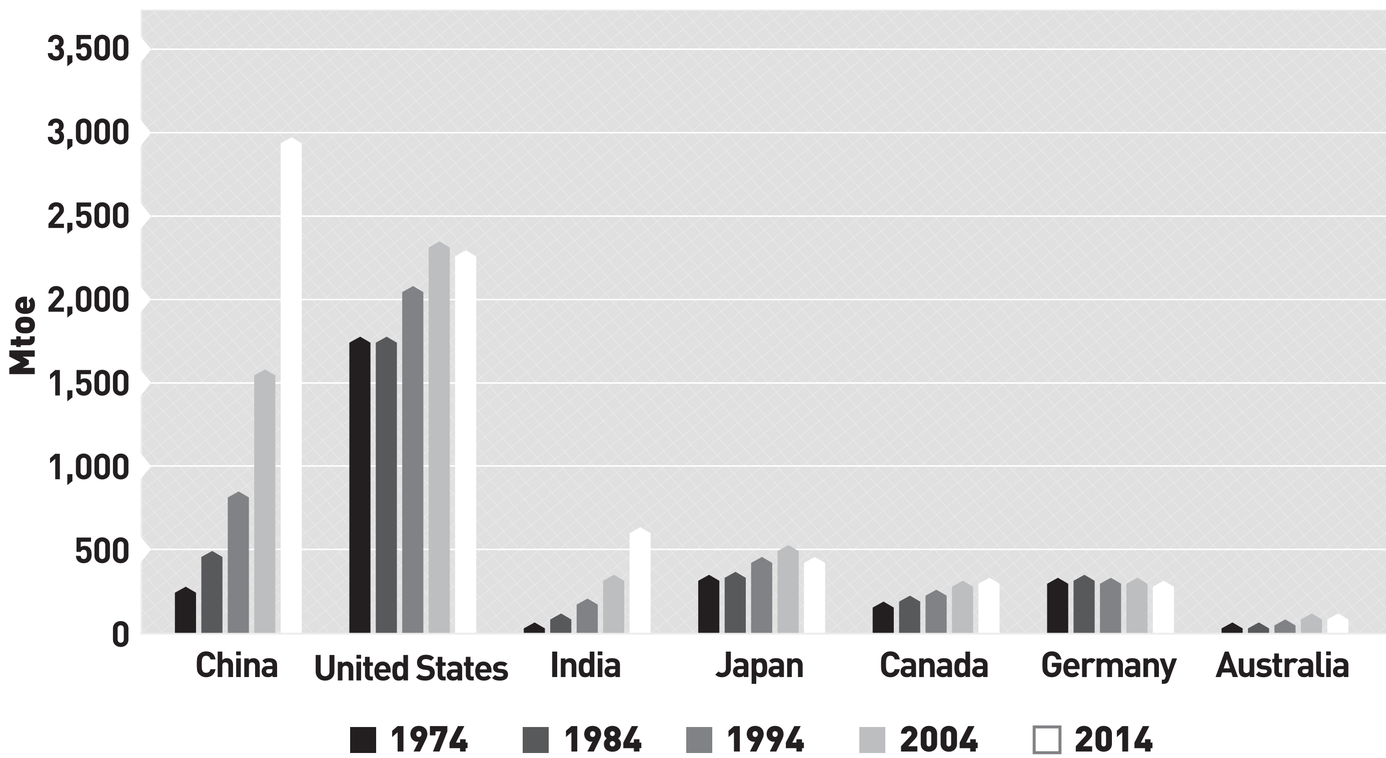
"It is encouraging to note that more efficient ways of using energy result in a tendency for per capita energy use to stabilize with prosperity."

151. André Pratte, "Le monde change… lentement," *La Presse*, February 10, 2015.

152. *Idem.*
153. *Idem.*

Figure 3-5

Change in primary energy consumption in millions of tonnes of oil equivalent, 1974-2014



Source: BP, Data Workbook – Statistical Review 2015, Primary Energy: Consumption – Mtoe (from 1965), June 2015.

It is thus encouraging to note that more efficient ways of using energy result in a tendency for per capita energy use to stabilize with prosperity. Moreover, starting at a certain level of wealth, average household size declines, which has the effect of putting a break on population growth,[154] and therefore on emissions.

The reduction of energy intensity and its positive impact on emissions do not tell the whole story, however. It is also necessary to measure the emissions produced compared to the energy used.

Carbon Intensity Depends on Which Forms of Energy Are Used

Carbon intensity is defined as the ratio of carbon dioxide emissions per unit of energy used. Technological change and the price of energy resources play a predominant role in choosing which form of energy to use, and therefore in carbon intensity. All other things being equal, we will use the resources that provide us with a given amount of energy at a lower cost. The natural resources that are the most advantageous to use therefore determine the level of GHG emissions related to energy consumption.

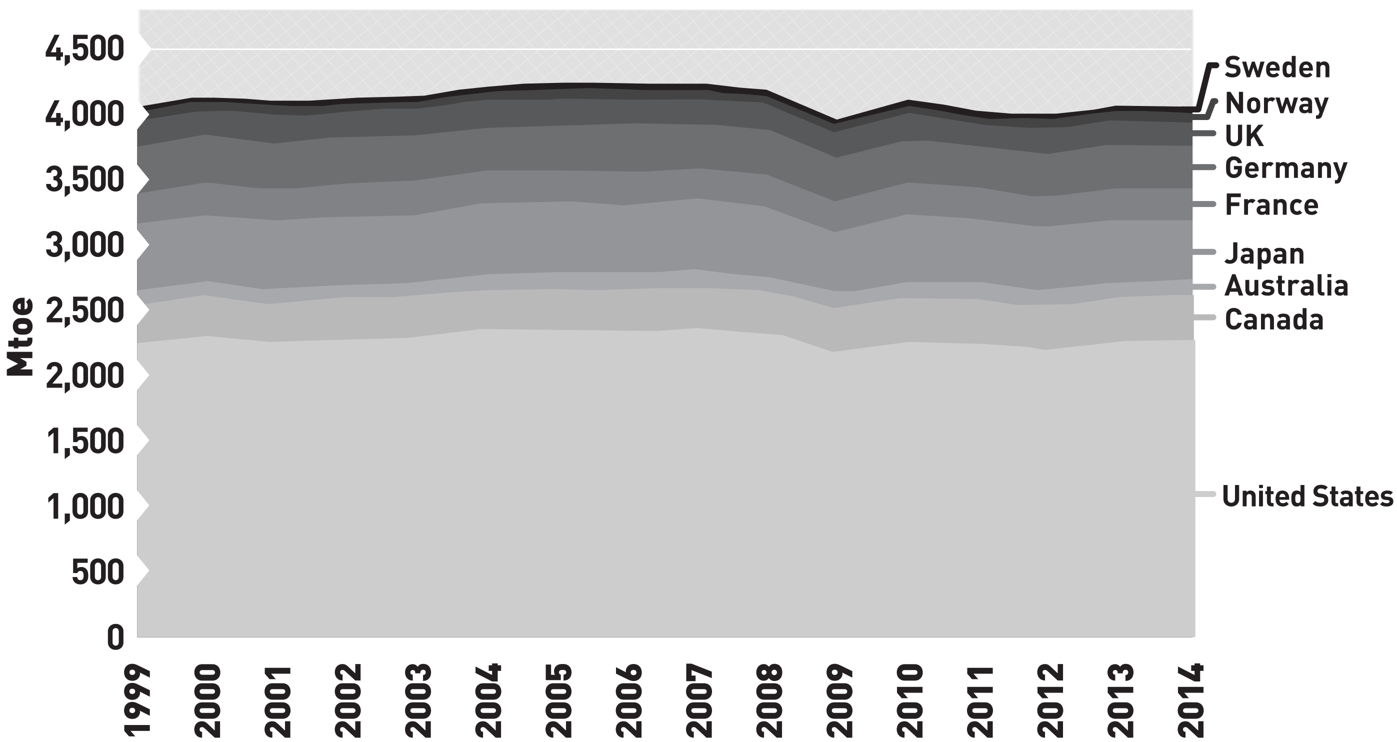
> **"A true energy revolution is underway, and it could pick up steam with the increased use of carbon-neutral energy sources and technologies."**

Large-scale coal use began around the middle of the 19th century, marking the start of the current era in which fossil fuels have almost completely replaced renewable energy. Indeed, prior to the massive use of fossil fuels, most societies depended on the burning of biomass (wood twigs, crop residues, and manure), wind energy (sailboats and windmills) and hydraulic power (watermills) to complement human and animal muscle

154. Indur M. Goklany, *The Improving State of the World: Why We're Living Longer, Healthier, More Comfortable Lives on a Cleaner Planet*, Cato Institute, 2007.

Figure 3-6

Change in primary energy consumption in industrialized countries in millions of tonnes of oil equivalent, 1999-2014



Source: BP, Data Workbook – Statistical Review 2015, Primary Energy: Consumption – Mtoe (from 1965), June 2015.

power.[155] The economic growth brought on by the coal revolution was accompanied by a proportionate increase in GHG emissions.[156]

The fact that coal remains the cheapest source of electricity is not unrelated to the staggering growth in coal consumption in recent decades. Coal was partly replaced by oil and natural gas in the early 20th century, but for several decades, consumption of coal has increased more quickly than that of other fossil fuels.[157] Since 2004, CO_2 emissions from the burning of coal have exceeded those from oil (see Figure 3-8).

It is therefore no surprise that the economies of emerging countries, whose growth continues to depend on coal, show rising carbon intensity. As Figure 3-9 shows, China[158] and India emit more CO_2 per unit of energy used than in the early 1970s, in contrast with industrialized countries, which are emitting less.

The five countries with the fastest growth in CO_2 emissions per kg of oil equivalent in the period from 1971 to 2011 are Cameroon, Angola, Benin, Vietnam and Nepal, all of which are developing countries (see Figure 3-10). These five countries have seen their energy intensity increase by an average of 188%, while the euro zone, Canada and the United States have reduced their energy intensity by 15%, 6% and 3% respectively during the same period.

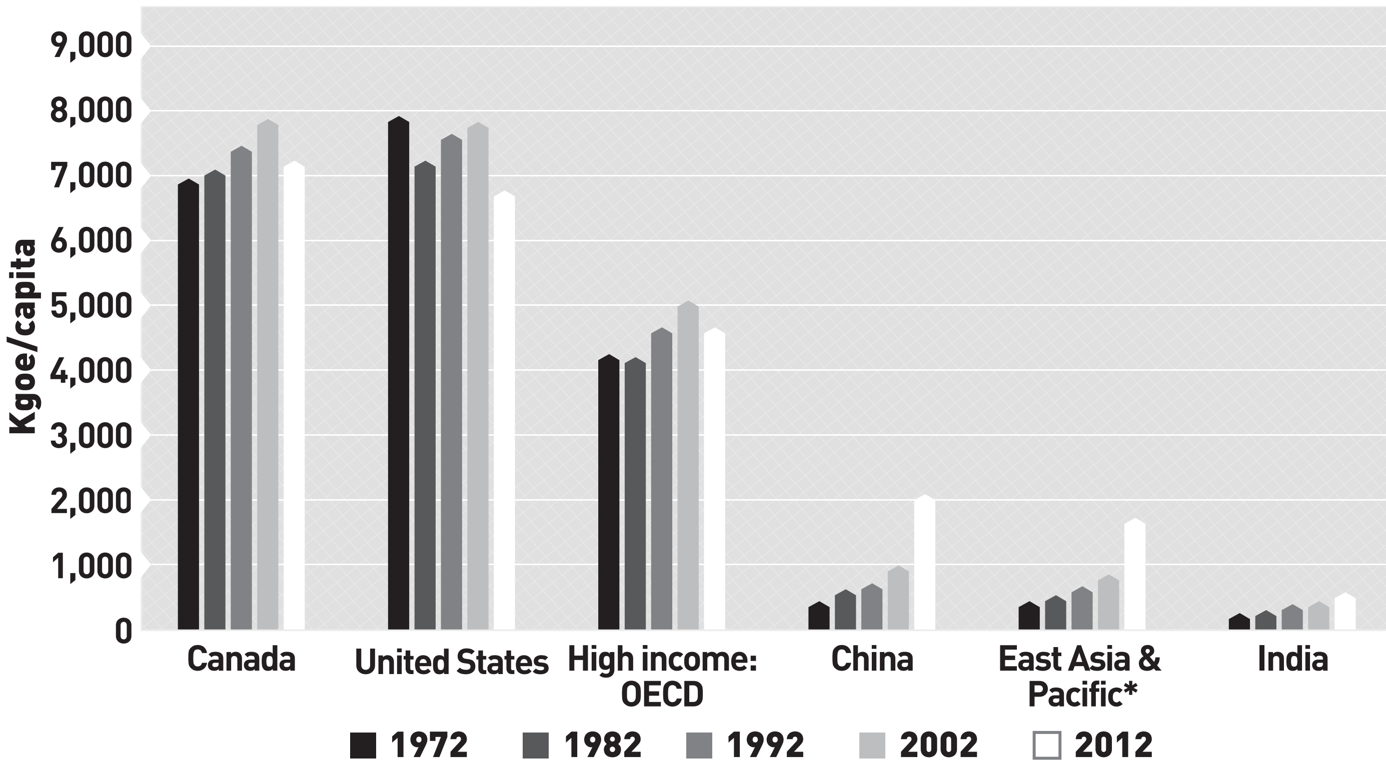
Technological change and new approaches can also have a positive impact on GHG emissions. In the United States over the past 10 years, hydraulic fracturing and horizontal drilling have allowed for the exploitation of

155. Pierre Desrochers and Hiroko Shimizu, *Innovation and the Greening of Alberta's Oil Sands*, Research Paper, Montreal Economic Institute, October 2012, p. 9.
156. Indur M. Goklany, "Humanity Unbound: How Fossil Fuels Saved Humanity from Nature and Nature from Humanity," Policy Analysis No. 715, Cato Institute, December 2012, p. 3.
157. BP, Statistical Review—Data Workbook, June 2015.

158. However, coal consumption and production in China fell by 2.9% and 2.5% respectively in 2014. See Timothy Puko and Chuin-Wei Yap, "Falling Chinese Coal Consumption and Output Undermine Global Market," *The Wall Street Journal*, February 26, 2015.

Figure 3-7

Change in primary energy consumption in kilograms of oil equivalent per capita, 1972-2012



* Includes only developing countries.
Source: World Bank, Data, Energy use (kg of oil equivalent per capita), October 2015.

shale gas deposits that were not previously economically viable. These technological advances have had a remarkable impact on natural gas prices in North America. Indeed, the gap between the price of natural gas in the United States and the prevailing prices in Europe and Japan has widened considerably since 2008 (see Figure 3-11).

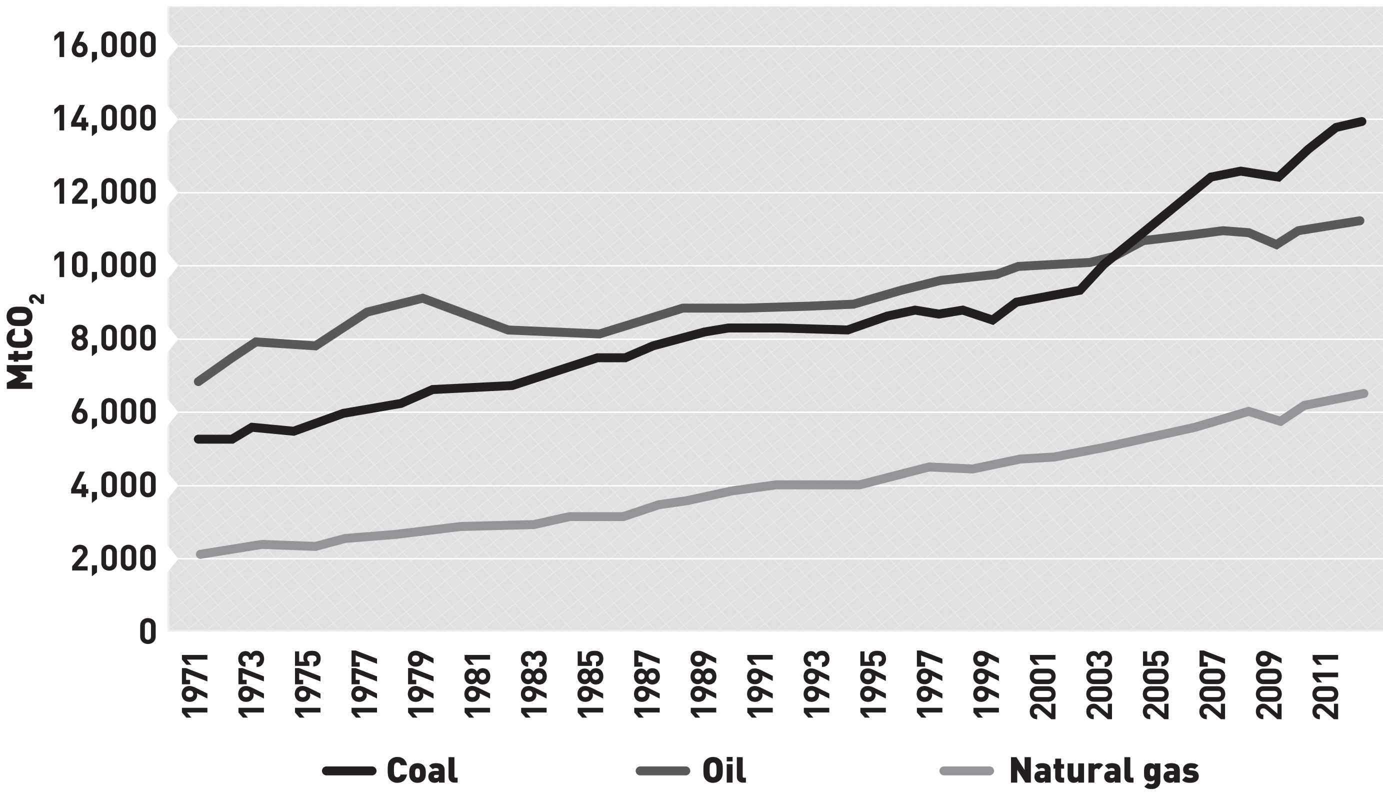
The use of natural gas emits less CO_2 than coal for a given amount of energy.[159] As was the case in the early 20th century when less polluting fossil fuels were substituted for coal, the abundance of natural gas means that less coal need be used, and therefore leads to lower GHG emissions and lower carbon intensity (see Figure 3-12).[160] The shale gas revolution, although it involves a fossil fuel, has therefore led to a reduction in GHG emissions in the production of electricity. Moreover, this reduction in emissions was a side effect of the economic growth associated with affordable energy: It is estimated that hydraulic fracturing raises American GDP by $283 billion per year.[161]

It is a safe bet that the shale gas revolution will continue, thanks to "re-fracking," or fracking a well for a second time with more efficient extraction technologies. This innovation is now being considered by gas companies for horizontal wells. A second round of fracking, which is about one quarter as expensive as building a new well, would allow for production levels to approach initial levels, which can fall by 70% one year after the initial fracking.[162] Increased natural gas production at

159. Kristin Suleng, "Using fossil fuels buys us time to develop alternative energies that will shape our future," *Open Mind*, October 14, 2014.
160. David G. Victor *et al.*, "Introductory Chapter," in Ottmar Edenhofer *et al.* (eds.), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014, p. 119.
161. Bjørn Lomborg, "Examining the Threats Posed by Climate Change: The Effects of Unchecked Climate Change on Communities and the Economy," The Senate EPW Committee, Subcommittee on Clean Air and Nuclear Safety, July 29, 2014, p. 21.
162. Trefis Team, "Oilfield Services Companies Are Betting On Re-Fracking. Will It Catch On?" *Forbes*, June 23, 2015; Dan Murtaugh, Lynn Doan and Bradley Olson, "Refracking Is the New Fracking," *Bloomberg Business*, July 7, 2015.

Figure 3-8

Change in global emissions in millions of tonnes of CO_2, 1971-2011



Source: International Energy Agency, CO_2 Emissions From Fuel Combustion Highlights 2014, Excel tables.

lower cost will help keep the price of this fuel relatively low compared to other energy resources and is likely to favour electricity production at natural gas power plants.

Innovation also allows coal power plants to have a lower carbon intensity. Their ability to convert thermal energy into mechanical energy (thermal efficiency) is inversely proportional to their GHG emissions. In other words, in addition to allowing for the generation of more electricity per gram of coal burned, technological innovations also have the benefit of leading to lower CO_2 emissions per kilowatt-hour produced. Table 3-1 illustrates this phenomenon by using the thermal efficiency of several technologies used by coal power plants.

All of these trends in emission intensity augur well. In the United States, the world's second largest emitter, natural gas is partly replacing coal. Although global coal use is growing, it can be exploited more efficiently all while reducing its environmental impact. This also applies to the exploitation of synthetic oil, as can be seen in the Alberta oil sands, where energy intensity fell 29% between 1990 and 2009.[163] A true energy revolution is therefore underway, and it could pick up steam with the increased use of carbon-neutral energy sources and technologies.

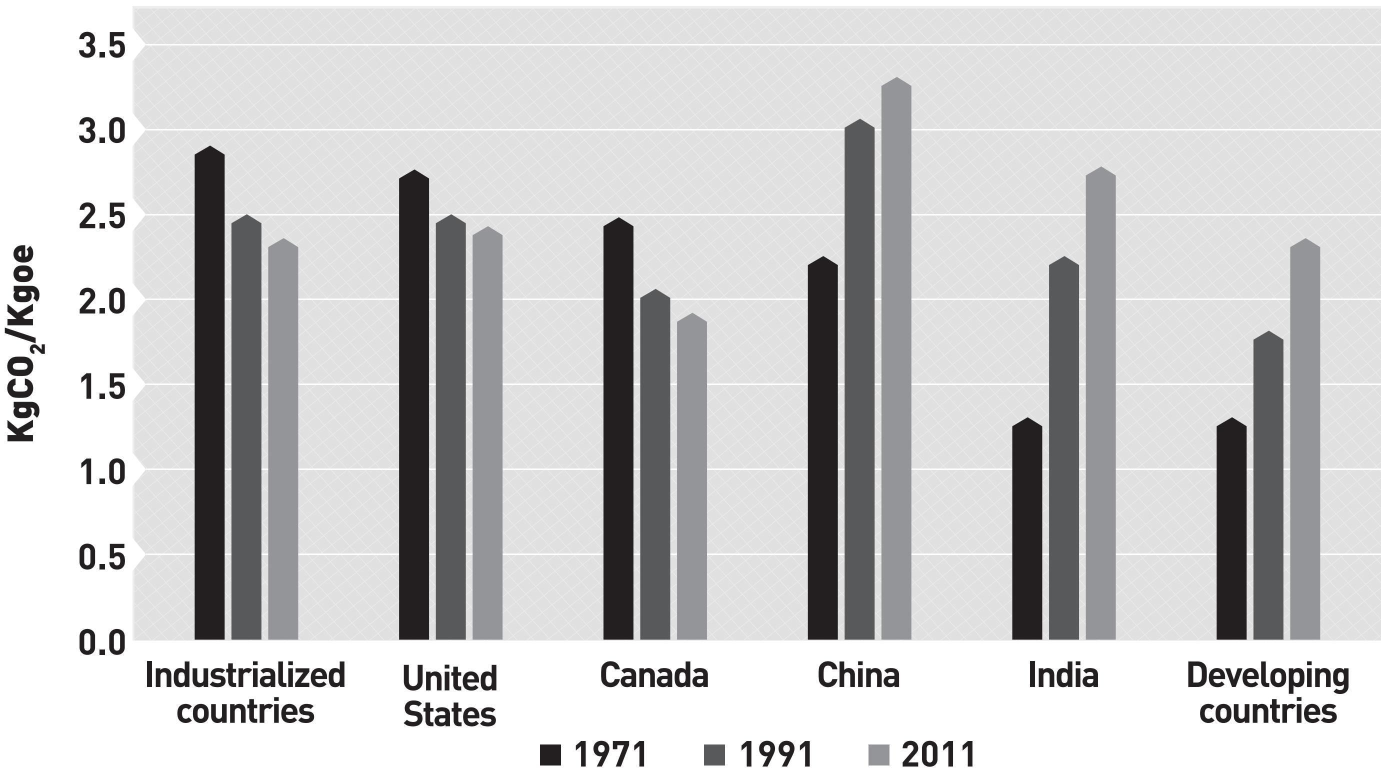
Toward a Carbon-Neutral Economy Thanks to Innovation

Breaking the Kaya identity down into its component parts is highly relevant, because it shows that energy consumption is not a problem in itself. It is possible for energy consumption to rise at a sustained pace without a substantial environmental impact, as measured in terms of CO_2 emissions. Indeed, the environmental impact could be almost nil if any of the following three factors gains in importance: renewable energy, large-scale carbon capture and storage technologies, or commercial applications for carbon.

163. Pierre Desrochers and Hiroko Shimizu, *op. cit.*, footote 155, p. 28.

Figure 3-9

Carbon intensity, 1971-2011



Note: This shows CO_2 in kilograms emitted for each kilogram of oil equivalent consumed.
Source: World Bank, Data, CO_2 intensity (kg per kg of oil equivalent energy use), October 2015.

1. Renewable Energy

The economic viability of using renewable energy has the potential to speed up the transition to a carbon-neutral or carbon-negative economy.

Growing investment in renewable energy can be a good indicator of future viability.[164] These investments have advanced at a dizzying pace over the past 10 years. Between 2004 and 2014, investment in the solar and wind industries jumped by 1,147% and 456% respectively.[165]

During the same period, global solar and wind capacity grew by 4,684% and 671% respectively. Global wind energy capacity had reached 370 gigawatts in 2014, compared to 177 gigawatts for solar energy (see Figure 3-13).

Massive investments have also helped lower the price of crystalline-module photovoltaic solar panels, down by an average of 66% over the past five years in Germany, China and Japan, the three countries with the largest installed solar capacity (see Table 3-2).[166]

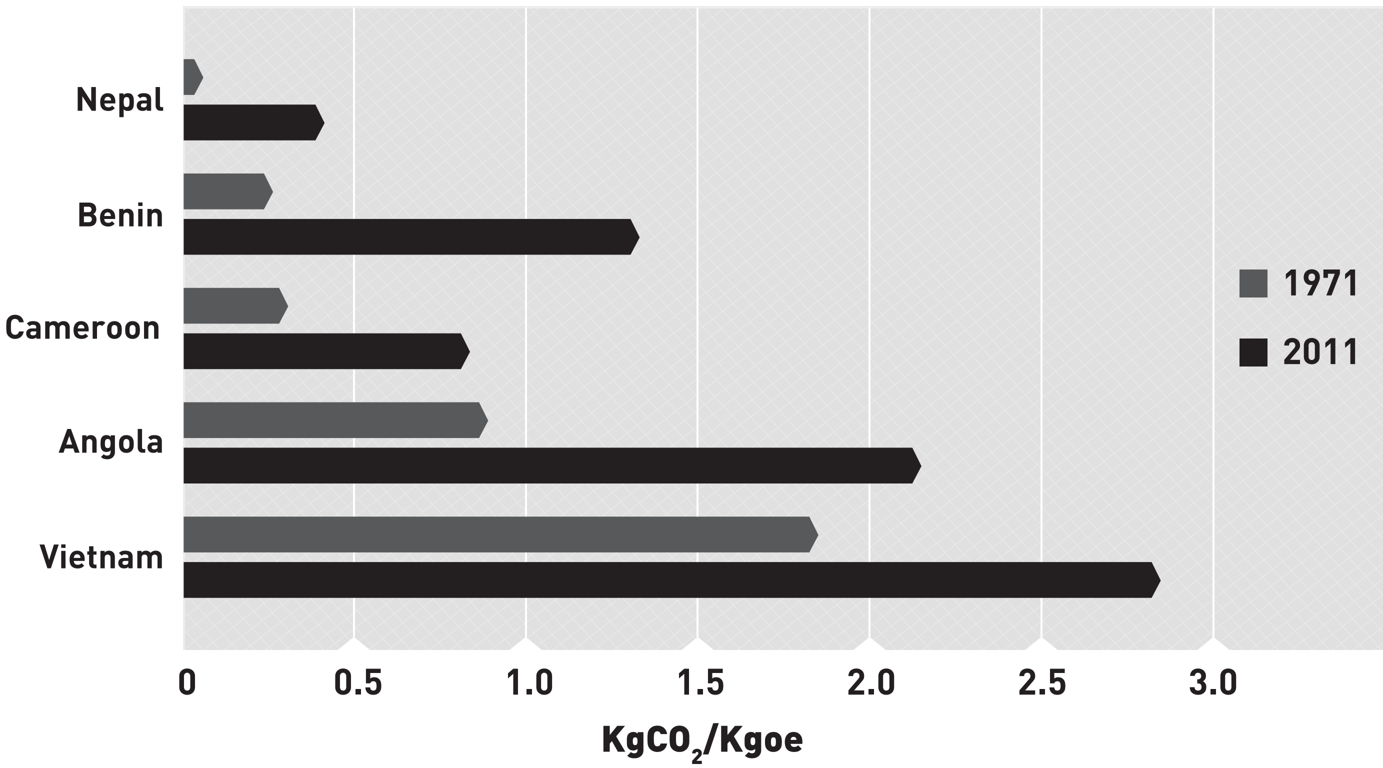
> **"Although global emission levels continue to rise due to increased production, the picture is improved by a combination of energy efficiency and reduced carbon intensity."**

164. Subsidies can, however, alter economic calculations and make a project attractive even if it would not be viable without financial incentives, as shown by the experience of certain countries where renewable energy industries are in trouble following the abandonment of subsidies. See Brady Yauch, "Governments rip up renewable contracts," *Financial Post*, March 18, 2014.
165. During this period, more than 82% of renewable energy investments were in the wind and solar sectors. Ren21, *op. cit.*, footnote 144, p. 136.

166. Ren21, *op. cit.*, Note 144, p. 20; pvXchange, Price index.

Figure 3-10

The five countries with the fastest growth in carbon intensity, 1971-2011



Note: This shows CO_2 in kilograms emitted for each kilogram of oil equivalent consumed.
Source: World Bank, Data, CO_2 intensity (kg per kg of oil equivalent energy use), October 2015.

This price decline is reflected in the "levelized cost of electricity" (LCOE), a widely used measurement for assessing the competitiveness of the various energy sources in electricity generation. This measurement calculates the cost per megawatt-hour of an electric power plant over its lifespan, including investments as well as operating and maintenance costs.[167]

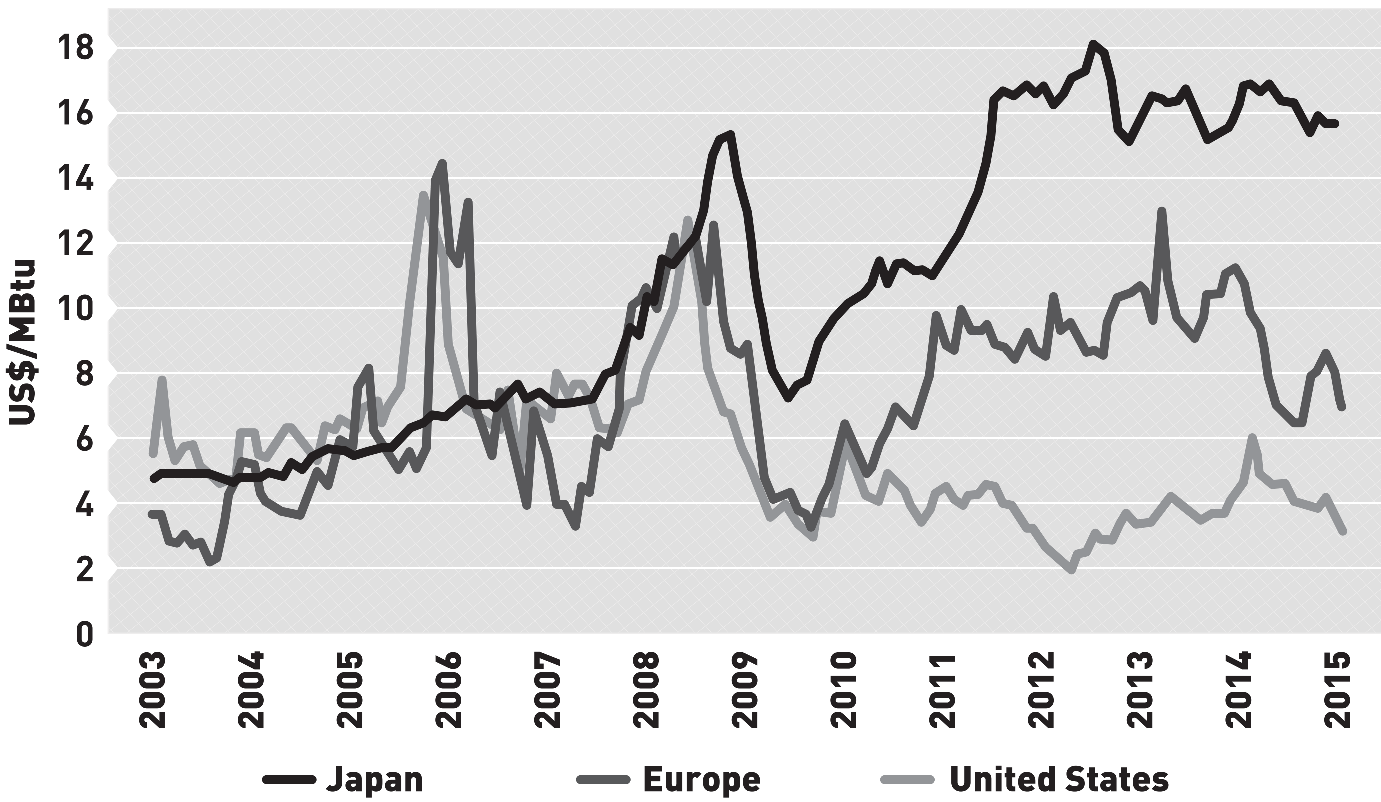
According to Bloomberg New Energy Finance, the global average LCOE of wind energy has remained fairly stable over the last five years, while that of crystalline silicon photovoltaic panels has fallen by 48%.[168] The IEA has made a similar observation, finding that the LCOE in some twenty countries has remained relatively stable for wind energy while falling considerably for solar projects.[169] In some countries, bids to supply solar energy have even been made at prices competitive with those of fossil fuels.[170]

The LCOE of electricity produced from solar or wind energy is not comparable, however, with the LCOE of energy produced by gas, coal or nuclear power.[171] Indeed, since the wind and the sun are not available on demand and their energy is intermittent, the economic value of electricity produced by these sources is not the same as electricity from a source available at all times. In other words, even if the costs of electricity produced from solar and wind are getting closer to the costs of energy from traditional sources, these renewable energy forms cannot fully replace fossil fuels and uranium. Until there is an economically feasible way of storing electricity on a large scale, our basic energy needs will be met

167. U.S. Energy Information Administration, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015," June 2015.
168. Frankfurt School, Global Trends in Renewable Energy Investment 2015 (Datapack), March 2015.
169. International Energy Agency, *Projected Cost of Generating Electricity—2010 Edition*, 2010, p. 62; International Energy Agency, "Executive Summary: Projected Cost of Generating Electricity—2015 Edition," 2015, p. 6.
170. Ren21, *op. cit.*, footnote 144, p. 62.
171. U.S. Energy Information Administration, *op. cit*, footnote 167, p. 3.

Figure 3-11

Natural gas prices in Europe, Japan and the United States, in U.S. dollars per million BTUs, 2003-2015



Source: International Energy Agency, Tracking Clean Energy Progress 2015, Power Generation.

by fossil fuels and nuclear power. To ensure the reliability of the network, solar and wind will complement traditional sources at peak periods.

Renewable energy subsidies therefore have only limited potential. In 2012, renewable energy generated just 5% of electricity worldwide, or 21% if hydro is included (see Figure 3-14).

2. Large-Scale Carbon Capture and Storage Technologies

Carbon capture and storage (CCS) is a technology that will be necessary, according to the IPCC, if we want to have a high probability of respecting the 2°C limit.[172] To respect this limit, the IEA estimates for its part that CCS will have to increase considerably from current levels and that it will have to account for 14% of emission reductions in 2050.[173]

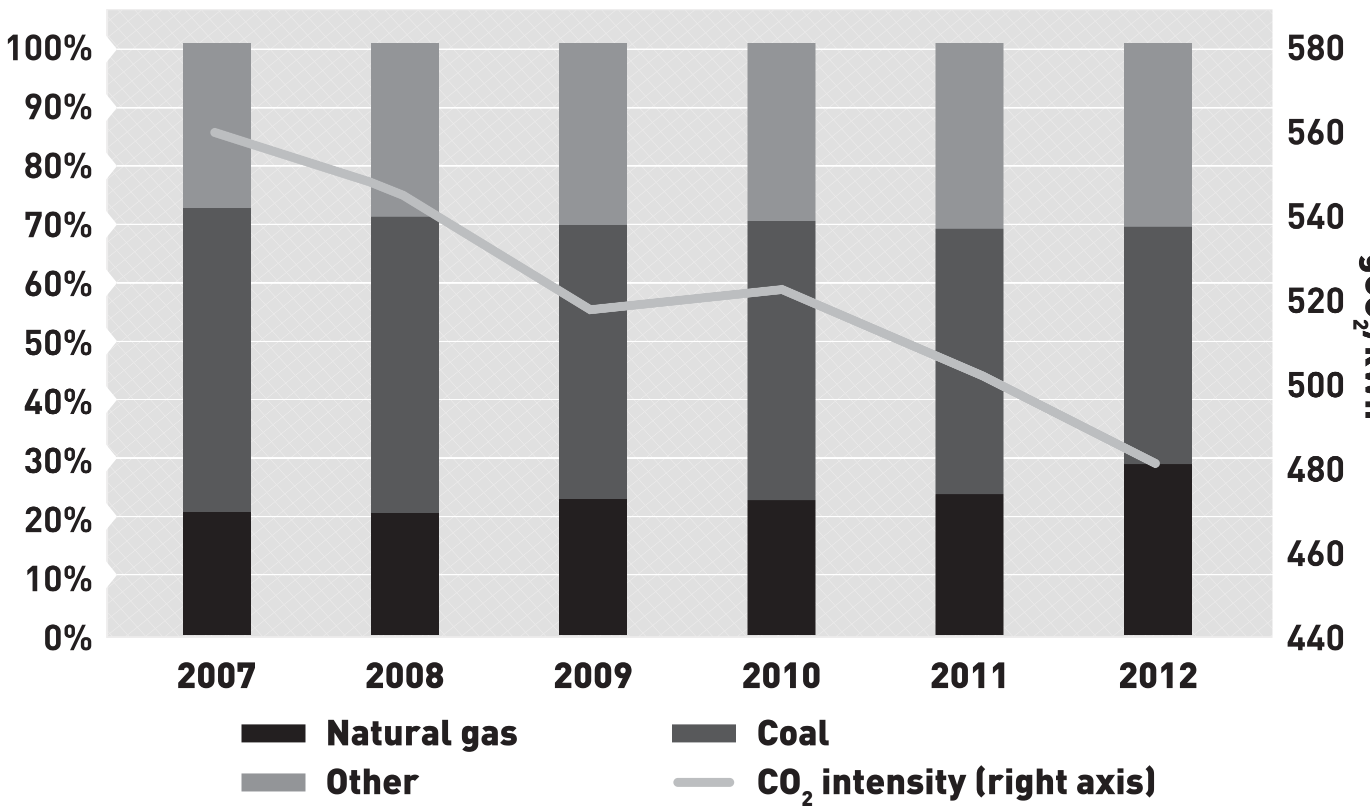
CCS involves selectively removing CO_2 from the effluent gases of a power plant or other industrial source and permanently storing the emissions deep underground.[174] Storage happens in depleted oil and gas deposits or in deep saline formations. At the end of 2014, only 13 large-scale CCS projects were in operation, with a total annual capture capacity of 26 megatonnes of CO_2.[175] This small number of projects is due to the fact that CCS is very expensive to set up. For example, the cost of a cement plan with CCS would be double that of

172. Ottmar Edenhofer *et al.*, "Summary for Policymakers," in Ottmar Edenhofer *et al.* (dir.), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014, p. 12.

173. International Energy Agency, About carbon capture and storage; International Energy Agency, *Tracking Clean Energy Progress 2015*, 2015, p. 33.
174. CO_2 Solutions, Carbon Capture and Sequestration (CCS).
175. International Energy Agency, *Tracking Clean Energy Progress 2015*, 2015, p. 32.

Figure 3-12

Proportion of natural gas used in the production of electricity and carbon intensity in the United States, in grams of CO_2 per kilowatt-hour, 2007-2012



Source: International Energy Agency, Tracking Clean Energy Progress 2015, Power Generation.

a conventional cement plant.[176] The cost of this technology will therefore remain prohibitive, unless the global price of carbon is much higher or commercial applications for carbon are developed.

3. Commercial Applications for Carbon

One thing that has the potential to improve the current energy system's environmental impact quite considerably is the use of carbon for commercial purposes. If it were economically viable to use carbon as an input for various industrial processes, its value would lead to its being captured instead of discharged into the atmosphere. Research in this field abounds, and to date, several companies have already developed promising technologies.

Carbon Recycling International is an Icelandic company that takes carbon discharged by a geothermal electric power plant and turns it into methanol. Methanol can be used as a transportation fuel and as a raw material for various substances.[177] In Denmark, one gas station is already offering drivers of electric cars with methanol fuel cells the chance to fill up their tanks. The methanol is converted to electricity while driving, saving drivers from having to wait several hours for a battery recharge.[178]

Carbon nanofibres are used in various industries because of their conductivity, flexibility and resistance. Producing carbon nanofibres is very expensive, however, requiring 30 to 100 times more energy than the production of aluminum.[179] Researchers at George Washington

176. The Energy and Climate Change Committee, *Carbon Capture and Storage Ninth Report of Session 2013–14*, Information document prepared at the request of the House of Commons of the United Kingdom, May 21, 2014, p. 25.

177. Carbon Recycling International, Methanol.
178. Carbon Recycling International, First renewable methanol fuel station in the world for electric cars, August 31, 2015.
179. Jiawen Ren *et al.*, "One-Pot Synthesis of Carbon Nanofibers from CO_2," *Nano Letters*, No. 15, 2015, pp. 6142.

Table 3-1

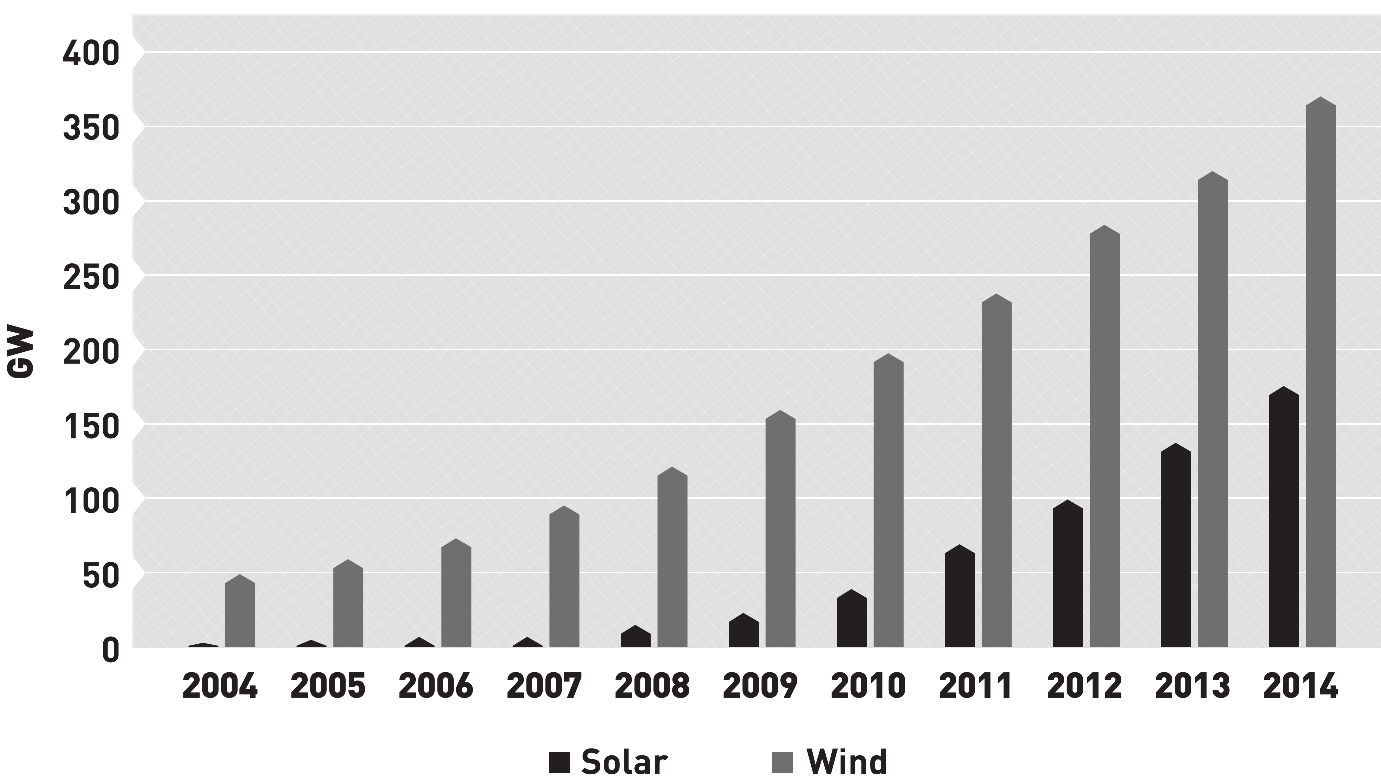
Thermal efficiency and carbon intensity of different technologies for coal power plants

TECHNOLOGY	MAXIMUM THERMAL EFFICIENCY	COAL CONSUMED PER KWH (GRAMS)	CO_2 EMISSIONS PER KWH (GRAMS)
Subcritical	**38%**	**379**	**881**
Supercritical	**42%**	**343**	**798**
Ultra-supercritical	**45%**	**320**	**743**
Advanced ultra-supercritical	**50%**	**288**	**669**

Source: Shoichi Itoh, "A New Era of Coal: The 'Black Diamond' Revisited," 2014 Pacific Energy Forum Working Papers, April 2014, p. 6.

Figure 3-13

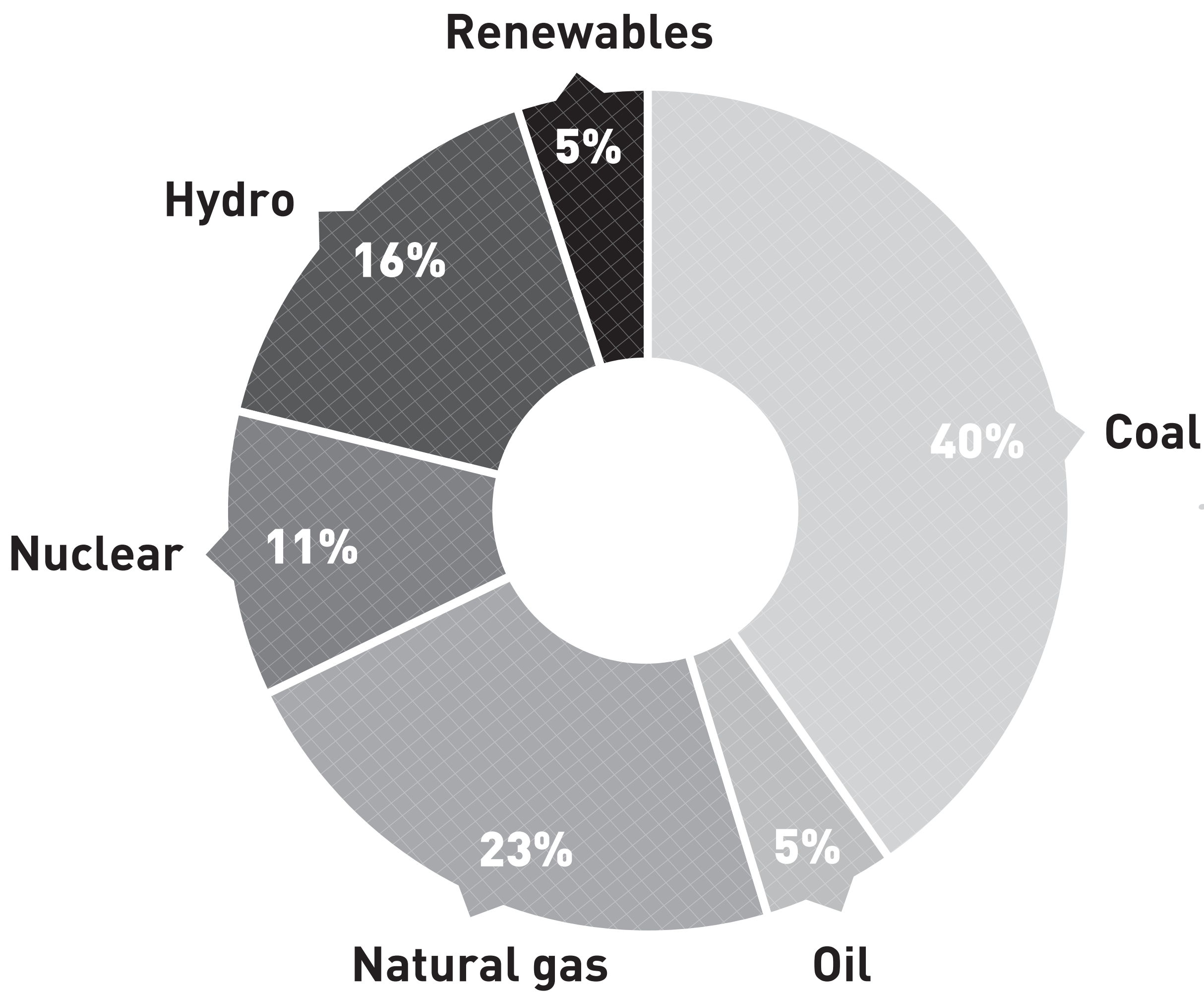
Global installed capacity in solar and wind energy in gigawatts, 2004-2014



Source: Ren21, *Renewables 2015 Global Status Report*, 2015, pp. 59 and 71.

Figure 3-14

Electricity generation by fuel, 2012



Source: International Energy Agency, *Key World Energy Statistics 2014*, 2014, p. 24.

Table 3-2

Change in the price of crystalline module photovoltaic solar panels (euros per peak watt*)

	AUGUST 2010	AUGUST 2015	VARIATION
Germany	**1.87**	**0.57**	**-70%**
China	**1.61**	**0.57**	**-65%**
Japan	**1.82**	**0.65**	**-64%**

Source: pvXchange, Price index.
* Peak watts are a unit of measurement representing the maximum power of a device.

University have developed a method for converting carbon dioxide into oxygen and carbon nanofibres using an electrochemical process that is apparently less expensive than other existing methods. With favourable economic conditions, these researchers estimate that their method could remove enough carbon from the atmosphere to return to the atmospheric CO_2 concentrations of the pre-industrial era. This could be done in 10 years, using an area equal to 10% of the Sahara Desert.[180]

"Each dollar of economic growth generated tends to be cleaner and cleaner."

Carbon capture technologies can also be used to capture methane, a GHG with a global warming potential 25 times greater than that of CO_2. New Light Technologies is a company that can decompose the carbon (C) and hydrogen (H) in previously captured methane (CH_4). The carbon and hydrogen are then combined with oxygen to form a long-chain polymer called AirCarbon.[181] This type of plastic is used to make carbon-negative items. The Dell computer company uses it as a material for laptop computer bags, while the KI furniture company uses it in the production of chairs. Large-scale production of this plastic has the potential to have a substantial environmental impact. In addition to reducing the quantity of methane in the atmosphere, it could replace oil in the manufacture of plastics since this substance is similar to petroleum-based plastics.[182]

Algae-based fuels are also promising for reducing GHGs. Algae feed on CO_2 and sunlight as they are cultivated. The oil accumulated during their growth is then extracted and refined to produce algofuels. CO_2 capture during the process means that CO_2 emissions can be reduced by 50% to 70% compared to petroleum-based fuels.[183]

In addition to absorbing CO_2, algae cultivation provides other environmental benefits since it can be done on infertile land or in wastewater or saline basins of low economic value. It therefore does not require the use of scarce resources.[184] According to a report prepared for the IEA, biofuels derived from algae have the potential to replace a significant portion of the diesel fuel used today while leaving a reduced environmental footprint.[185]

Wealth: A Non-Negligible Factor

The Kaya identity allows us to understand which factors influence the growth of GHG emissions. Although global emission levels continue to rise due to increased production, the picture is improved by a combination of energy efficiency and reduced carbon intensity. These positive trends result in declining GHG emissions per unit of GDP worldwide, with each dollar generated around the world being increasingly green.

This trend is all the more impressive in that it is also occurring in certain emerging countries such as China and India, both of which are making increasing use of coal to generate electricity. China emitted 52% less carbon dioxide per unit of GDP in 2011 than in 1991, while India succeeded in becoming 25% cleaner over the same period (see Figure 3-15).

As the IEA notes, global CO_2 emissions from the energy sector did not grow in 2014 despite world economic growth of 3%. This is the first time in 40 years that stagnating emissions are not connected to an economic downturn. This "decoupling" of emissions and growth is a very encouraging first according to Fatih Birol, the IEA's executive director.[186]

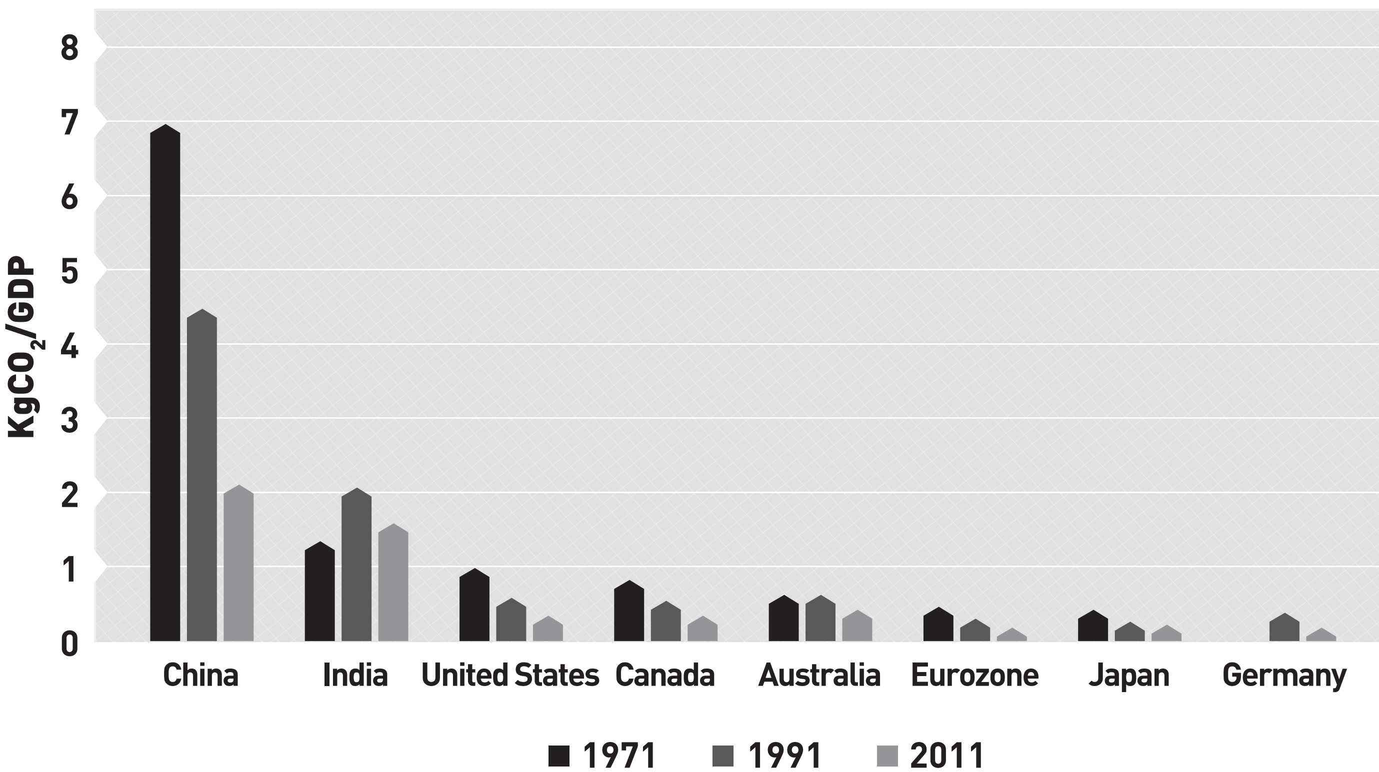
With increased wealth, a reduction can be seen in energy intensity and in per capita energy use.[187] Moreover, each dollar of economic growth generated tends to be cleaner and cleaner. Sustained economic growth also allows for the investments needed for carbon-neutral technologies (CCS, electricity storage) to be deployed on a large scale.

History shows that wealth, energy used, and technological change are interdependent factors in a virtuous circle generating greater wealth and technological innovation.[188] Material wealth not only stimulates the

180. Mike Orcutt, "Researcher Demonstrates How to Suck Carbon from the Air, Make Stuff from It," *MIT Technology Review*, August 19, 2015.
181. New Light Technologies, Our Technology: Greenhouse Gas to Plastic.
182. Nate Berg, "AIRCARBON : Et si le plastique était la solution au réchauffement climatique?" *El Watan*, September 20, 2014.
183. Xiaowei Liu *et al.*, "Pilot-Scale Data Provide Enhanced Estimates of the Life Cycle Energy and Emissions Profile of Algae Biofuels Produced Via Hydrothermal Liquefaction," *Bioresource Technology*, Vol. 148, 2013, pp. 163-171.
184. Al Darzins, Philip Pienkos and Les Edye, *Current Status and Potential for Algal Biofuels Production*, Information document prepared on the request of the IEA Bioenergy Task 39, Report T39-T2, August 6, 2010, p. ii.
185. *Ibid.*, p. vi.
186. International Energy Agency, "Global energy-related emissions of carbon dioxide stalled in 2014," Press release, March 13, 2015.
187. Jason Channell *et al.*, *Energy Darwinism II: Why a Low Carbon Future Doesn't Have to Cost the Earth*, Citi GPS, August 2015, p. 25.
188. Pierre Desrochers and Hiroko Shimizu, *op. cit.,* footnote 155.

Figure 3-15

Kilograms of CO_2 emissions per unit of GDP, 1971-2011



Source: World Bank, Data, CO_2 Emissions (kg per 2005 US$ of GDP), October 2015.

technological innovation needed to enhance environmental conditions, but also helps the most vulnerable groups adjust more effectively to climate change.

> **"The increasingly green direction that the world economy seems to be taking has come about without an international climate treaty and without a global carbon price."**

The increasingly green direction that the world economy seems to be taking has come about without an international climate treaty and without a global carbon price.[189] This is hardly surprising since, historically, choosing which form of energy to use has been influenced mostly by local factors, such as economic development, national security, and air quality.[190]

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190. Gary Dirks *et al.*, *High Energy Innovation: A Climate Pragmatism Project*, Consortium for Science, Policy & Outcomes and Breakthrough Institute, December 2014, p. 5.

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