part IV

Energy Resources and Technological Options

Physical resources and adequate technologies for their deployment are available – or could become available – to meet the challenge of sustainable development. But without policy changes, cost differentials may favour conventional fuels for years to come. Options for using energy in ways that support sustainable development, which requires addressing social, economic, and environmental concerns, include:

- **More efficient use of energy, especially at the point of end use in buildings, transportation, and production processes.**
- **Increased reliance on renewable energy sources.**
- **Accelerated development and deployment of new energy technologies – particularly next-generation fossil fuel technologies that produce near-zero harmful emissions, but also nuclear technologies if the issues surrounding their use can be resolved.**

All three options have considerable potential, but realising this potential will require removing obstacles to wider diffusion, developing market signals that reflect social and environmental costs, and encouraging technological innovation.

Energy Resources

Careful analysis of the long-term availability of energy resources, starting with conventional and unconventional oil and gas, indicates that these resources could last another 50 to 100 years – and possibly much longer – with known exploration and extraction technologies and anticipated technical progress in upstream operations. Coal and unconventional oil resources, and nuclear materials, are so abundant that they could, respectively, last for centuries or millennia (Table 1). Moreover, although fossil fuel prices may rise slowly over time, the large, scarcity-driven increases in energy prices projected in the 1970s and 1980s are not expected to occur in the foreseeable future.

There will not be a resource-constraint driven change in the global energy system for a very long time to come.

As evidenced periodically, however, prices are subject to volatility. This may occur, for example, if cartels set prices independent of production costs or as a result of geopolitical tension. Some fluctuations in prices can also be expected, especially during the transition to large-scale use of unconventional oil and gas resources, because the timing of investments in upstream production capacities may not correspond with demand or with the objectives of maximising shareholder value. Other cost-pushing factors could arise from the technologically and environmentally more challenging extraction of unconventional oil resources.

Renewable resources are more evenly distributed than fossil and nuclear resources, and energy flows from renewable resources are several thousand times higher than current total global energy use. However, the economic potential of renewables is affected by many constraints –including competing land uses, the amount and timing of solar irradiation and wind patterns, and a variety of environmental concerns.

Although there are no real limits on future energy availability from a resource point of view, the existence of resources is only relevant in the context of how the resources can contribute to the supply of (downstream) energy services. The key issues are:

- Whether technologies to extract, harvest, and convert the vast energy stocks and flows can be developed in time to meet growing demand for energy and reduce production from conventional reserves, particularly of oil and gas.
- Whether the technologies have adverse implications.
- Whether the energy services generated from these resources will be affordable.

Historical evidence suggests that these concerns may be at least partly offset by technological progress, but that such progress needs to be encouraged – by regulations to improve market performance, temporary subsidies, tax incentives, or other mechanisms – if it is to occur in a timely fashion.

There will not be a resource-constraint driven change in the global energy system for a very long time to come. The commonly expressed concern of thirty or even ten years ago was for when the world "runs out of oil reserves". However, the World Energy Assessment makes clear that the challenge today is not a lack of resources but how to create a seamless transition to other resources than those currently used, especially from coal and oil.

Energy End-Use Efficiency

The quadrupling of oil prices in the 1970s, the growing awareness of energy-related pollution, and the possibility of climate change have all contributed to a re-evaluation of energy use. The result has been an improvement in the efficiency with which energy is used in industry and power generation as well as in lighting, household appliances, transportation, and heating and cooling of buildings. This more efficient use of energy is a major factor contributing to the improvements in energy intensity that have occurred in the last three decades in almost all industrialised countries, and more recently in many transition economies, as well as in some fast-growing developing countries such as China and Brazil.

The amount of additional energy required to provide the desired energy services depends on the efficiency with which the energy is produced, delivered, and used. Energy efficiency improvements would help reduce financial investments in new energy supply systems and reduce the amount of primary energy needed for a certain level of economic activity, and thereby also the corresponding impact. A major challenge will be to find ways of meeting the growing demand for energy services in developing countries to support desired economic growth without incurring the adverse consequences associated with current patterns of energy use. To accomplish this, significant investment is needed to supply the two-to-four fold increase in primary energy required over the next century, according to World Energy Assessment projections.

Industrialised countries are already characterised by a weaker link between economic growth and energy use than in their early development. In developing countries, consumption will grow regardless, but there is no reason why efficient technologies and processes cannot be adopted at early stages of development. Technological leapfrogging to the use of highly efficient appliances, machinery, processes, vehicles, and transportation systems offers considerable potential for energy efficiency improvements.

Today, the global energy efficiency of converting primary energy to useful energy is about one third. In other words, two thirds of primary energy is dissipated in the conversion process, mostly as low-temperature heat. Further significant losses occur when the useful energy delivers the energy service. Numerous and varied economic opportunities exist for energy efficiency improvements, particularly in the final step of converting useful energy to energy services. Taking advantage of these opportunities, which have received relatively little attention, has the largest potential for further cost-effective efficiency improvements. It would mean less costly energy services and lower energy-related pollution and emissions.

Over the next twenty years the amount of primary energy required for a given level of energy services could be cost-effectively reduced by 25 to 35 percent in industrialised countries (the higher figure being achievable by more effective policies). These reduction opportunities exist in all steps of the energy chain. Reductions are particularly important in the conversion of useful energy to energy services in residential, industrial, transportation, public, and commercial sectors, as they reduce final and primary energy demand along the energy chain. Reductions of more than 40 percent are cost-effectively achievable in transitional economies within the next two decades. And in most developing countries – which tend to have high economic growth and old capital and vehicle stocks – the cost-effective improvement potential ranges from 30 to more than 45 percent, relative to energy efficiencies achieved with existing capital stock.

The implied improvements of about 2 percent per year could be enhanced by structural changes in industrialised and transition countries, by shifts to services and less energy-intensive industrial production, and by saturation effect in the residential and transportation sectors (i.e., there is a limit to the number of cars, refrigerators, television sets, etc., that a society can absorb). Structural changes can come from increased recycling and substitution of energy-intensive materials, improved material efficiency, and intensified use of durable and investment goods. The combined result of structural changes and efficiency improvements could accelerate the annual decline in energy intensity to perhaps 2.5 percent. How much of this potential will be realised depends on the effectiveness of policy frameworks and measures, changes in attitude and behaviour, and the level of entrepreneurial activity in energy conservation and material efficiency.

With effective policies, behaviours, and successful entrepreneurship, the coming decades will likely see new processes, motor systems, materials, vehicles, and buildings designed to substantially reduce useful energy demand. Because the demand for cars is expected to grow rapidly in the developing world, gaining greater efficiencies in this area will be very important. In addition, rapidly industrialising countries could benefit from the introduction of new and more efficient technologies in their energy-intensive basic materials processing. Because these countries are still building their physical infrastructure, they have a growing demand for basic materials. This opens a window of opportunity to innovate and to improve efficiencies of production, particularly in countries undergoing market reform. Investment in new technologies often provides better opportunities than does retrofitting.

Over the long-term, additional and dramatic gains in efficiency are possible at all stages of energy conversion, particularly from "useful energy" to "energy services". Analysis shows that most current technologies are not close to reaching theoretical limits for energy efficiency, and that very significant improvements for the whole energy system may eventually be achieved by replacing traditional technologies.[12]

For a number of reasons the technical and economic potential of energy efficiency, as well as its positive impact on sustainable development, have traditionally been under-realised. Achieving higher end-use efficiency involves a great variety of technical options and players. Because it is a decentralised, dispersed activity, energy efficiency is a difficult issue around which to organise support. It has little visibility and is not generally a popular cause for politicians, the media, or individuals looking for recognition and acknowledgement. In

12. Conventionally, energy efficiency has been defined on the basis of the first law of thermodynamics. The second law of thermodynamics recognises that different forms of energy have different potential to carry out specific tasks. For example, a natural gas boiler for space heating may operate at close to 100 percent efficiency (in terms based on the first law of thermodynamics). This seems to suggest that limited additional efficiency improvements are possible. However, by extracting heat from the ground or other sources, a gas-driven heat pump could generate considerably more low-temperature heat with the same natural gas input. The second example illustrates the potential for energy efficiency improvements according to the second law of thermodynamics.

TABLE 5. SELECTED ENERGY-EFFICIENT TECHNOLOGIES AND PRACTICES FOR BUILDINGS

Building Envelope	■ Energy-efficient windows ■ Insulation (walls, roof, floor) ■ Reduced air infiltration
Space Conditioning	■ Air conditioner efficiency measures (e.g., thermal insulation, improved heat exchangers, advanced refrigerants, more efficient motors) ■ Centrifugal compressors, efficient fans and pumps, and variable air volume systems for large commercial buildings
Appliances	■ Advanced compressors, evacuated panel insulation (refrigerators) ■ Higher spin speeds in washing machines/dryers
Cooking	■ Improved efficiency biomass stoves ■ Efficient gas stoves (ignition, burners)
Lighting	■ Compact fluorescent lamps ■ Improved phosphors ■ Solid-state electronic ballast technology ■ Advanced lighting control systems (including day-lighting and occupancy sensors) ■ Task lighting
Motors	■ Variable speed drives ■ Size optimisation ■ Improvement of power quality
Other	■ Building energy management systems ■ Passive solar use (building design) ■ Solar water heaters

addition, significant barriers – primarily market imperfections that could be overcome by targeted policy instruments – prevent the realisation of greater end-use efficiencies.

Energy efficiency policies that use direct or indirect price mechanisms (such as the removal of subsidies and the incorporation of externalities) are effective in lowering consumption trends in price-sensitive sectors and applications. But even without changing the overall price environment, energy efficiency policies should be pursued to address market failures. For example, efficiency standards, appliance and product labelling, voluntary agreements, and professional training or contracting, can increase GDP growth by improving environmental and economic performance, using a given quantity of energy. Examples of energy-efficiency-enhancing technologies and practices for buildings are given in Table 5.

Legal standards (e.g., building codes; well-informed consumers, planners, and decision makers; motivated operators; market-based incentives such as certificate markets; and an adequate payments system[13] for energy) are central to the successful implementation of energy efficiency improvements.

Renewable Energy Technologies

If applied in a modern way, renewable energy sources (including biomass, hydropower, solar, wind, geothermal, and marine) may be highly responsive to environmental, social and economic goals. Their many advantages include:

- diversifying energy carriers, technologies, and infrastructure for the production of heat, fuels, and electricity,
- improving access to clean energy sources,
- balancing the use of fossil fuels and thus saving them for other applications and for future use,
- increasing the flexibility of power systems as electricity demand changes,
- reducing pollution and emissions from conventional energy systems,
- reducing dependency, and minimising spending, on imported fuels, and
- job creation.

Another advantage for many renewable energy technologies is that they are well suited to small off-grid applications, and thus good for remote rural areas.

The natural energy flows through the earth's ecosystem are immense, and the geographical and technical potential of what they can produce for human needs exceeds current energy use by many times. Currently, renewable energy sources supply about 14 percent of the world's primary energy use, predominantly biomass used for cooking and heating, especially in rural areas of developing countries. Large-scale hydropower supplies about 16 percent of global electricity. Its scope for expansion is limited in the industrialised world, where it has nearly reached its economic capacity. In the developing world, considerable potential still exists, but large hydropower projects often face financial, environmental, and social constraints. The World Commission on Dams has done substantial work on this issue and suggested guidelines for reconciling conflicting demands surrounding large dams (WCD, 2000).

It is estimated that together *new renewables* (modern biomass energy, geothermal heat and electricity, small hydropower, low-temperature solar heat, wind electricity,

13. An adequate payments system means using metres and payment collection to ensure that all energy services have a price that is paid by all users on a regular basis.

solar electricity, and marine energy) contributed about 9 exajoules (EJ) in 2001, or slightly more than 2 percent of the world's energy use. The amount supplied by the various renewable energy sources is shown in Table 6.

Electricity production from solar photovoltaic systems as well as grid-connected wind turbines has been growing at an impressive rate of about 30 percent per year. Even so, it will likely be decades before new renewables add up to a major fraction of total global energy use, because they currently represent only a small percentage of total energy use. Nevertheless, a few countries have adopted ambitious targets; Germany, for example, has a target of 50 percent renewables by 2050. Impressive growth rates have been achieved in recent years for geothermal and solar thermal heat production, each about 10 percent per year over the last five years (Table 7).

Substantial cost reductions in the past few decades have made a number of renewable energy technologies competitive with fossil fuel technologies in certain applications. Modern, distributed forms of biomass, in particular, have the potential to provide rural areas with clean forms of energy based on the use of biomass resources that have traditionally been used in inefficient, polluting ways. Biomass can be economically produced with minimal or even positive environmental impacts through perennial crops. Its production and use currently is helping to create international bio-energy markets, stimulated by policies to reduce carbon dioxide emissions. Wind power in coastal and other windy regions is promising in the short term as well. Other potentially attractive options include geothermal heat and electricity production, small hydropower, low-temperature solar heat production, and solar electricity production in remote applications.

Table 7 shows that substantial cost reductions can be achieved for most renewable energy technologies. Making these renewable energy sources competitive will require further technology development and market deployments and an increase in production capacities to mass-production levels.

Unlike hydropower and geothermal power sources, wind and solar thermal or electric sources are intermittent, and not fully predictable. Nevertheless, they can be important in rural areas where grid extension is expensive. They can also contribute to grid-connected electricity supplies in appropriate hybrid configurations.

Dramatic gains in efficiency are possible at all stages of energy conversion from useful energy to energy services.

Intermittent renewables can reliably provide 10 to 30 percent of total electricity supplies in the area covered by a sufficiently strong transmission grid if operated in conjunction with hydropower or fuel-based power generation. Emerging storage possibilities (like compressed air energy storage) and new strategies for operating grids offer promise that the role of intermittent technologies can be extended much further. Alternatively, hydrogen may become the medium for storing intermittently available energy production.

Significant barriers will continue to prevent accelerated development of renewable energy technologies, unless deliberate action is taken by governments, the private sector, and individual energy consumers to overcome them. These barriers include high capital costs, economic risks, regulatory obstacles, limited availability of products, lack of public acceptance, information and technology gaps, lack of infrastructure, and lack of incentives. The financial challenge of overcoming high initial costs is particularly great, even though these cost have come down significantly over the past several years. Most barriers can be overcome with appropriate institutional arrangements. Renewable energy plants are often small in size and therefore have small unit costs. This is a

TABLE 6. NEW RENEWABLES, BY SOURCE, 2001 (EXAJOULES AND PERCENT)

Source/Technology	Contribution	
	EJ	%
Modern biomass energy	6.000	68.00
Geothermal energy	2.100	23.80
Small hydropower	0.360	4.10
Low-temperature solar heat	0.200	2.30
Wind electricity	0.160	1.70
Solar photovoltaic electricity	0.004	0.04
Solar thermal electricity	0.003	0.04
Marine energy	0.002	0.03
	8.900	100.00

Note: Assumed average conversion efficiency: for biomass heat, 85 percent; biomass electricity, 22 percent; biomass combined heat and power (CHP), 80 percent; geothermal electricity, 10 percent; all others 100 percent.

Source: W.C. Turkenburg, Utrecht University, The Netherlands, March 2003. Reprinted with permission.

TABLE 7. STATUS OF RENEWABLE ENERGY TECHNOLOGIES, END 2001

Technology	Increase in energy production, 1997–2001 (percent per year)	Operating capacity, end 2001	Capacity factor (percent)	Energy production, 2001	Turnkey investment costs (2001 US$ per kilowatt)	Current energy cost	Potential future energy cost
Biomass energy							
Electricity	~ 2.5	~ 40 GWe	25–80	~ 170 TWh (e)	500–6000	3–12 ¢/kWh	4–10 ¢/kWh
Heat[a]	~ 2	~ 210 GWth	25–80	~ 730 TWh (th)	170–1000	1–6 ¢/kWh	1–5 ¢/kWh
Ethanol	~ 2	~ 18 bln litres		~ 450 PJ		(8–25 $/GJ	(6–10 $/GJ
Bio-diesel	~ 1	~ 1.2 bln litres		~ 45 PJ		15-25 $/GJ)	10-15 $/GJ)
Wind electricity	~ 30	23 GWe	20–40	43 TWh (e)	850–1700	4–8 ¢/kWh	3–10 ¢/kWh
Solar photovoltaic electricity	~ 30	1.1 GWe	6–20	1 TWh (e)	5000–18000	25–160 ¢/kWh	5 or 6–25 ¢/kWh
Solar thermal electricity	~ 2	0.4 GWe	20 – 35	0.9 TWh (e)	2500–6000	12–34 ¢/kWh	4–20 ¢/kWh
Low-temperature solar heat	~ 10	57 GWth (95 million m^2)	8–20	57 TWh (th)	300–1700	2–25 ¢/kWh	2–10 ¢/kWh
Hydro energy							
Large	~ 2	690 GWe	35–60	2600 TWh (e)	1000–3500	2–10 ¢/kWh	2–10 ¢/kWh
Small	~ 3	25 GWe	20–90	100 TWh (e)	700–8000	2–12 ¢/kWh	2–10 ¢/kWh
Geothermal energy							
Electricity	~ 3	8 GWe	45–90	53 TWh (e)	800–3000	2–10 ¢/kWh	1 or 2–8 ¢/kWh
Heat	~ 10	11 GWth	20–70	55 TWh (th)	200–2000	0.5–5 ¢/kWh	0.5–5 ¢/kWh
Marine energy							
Tidal	0	0.3 GWe	20–30	0.6 TWh (e)	1700–2500	8–15 ¢/kWh	8–15 ¢/kWh
Wave	–	exp. phase	20–35	0	2000–5000	10–30 ¢/kWh	5–10 ¢/kWh
Tidal stream/Current	–	exp. phase	25–40	0	2000–5000	10–25 ¢/kWh	4–10 ¢/kWh
OTEC	–	exp. phase	70–80	0	8000–20000	15–40 ¢/kWh	7–20 ¢/kWh

a. Heat embodied in steam (or hot water in district heating), often produced by combined heat and power systems using forest residues, black liquor, or bagasse.

Source: W.C. Turkenburg, Utrecht University, Netherlands (March 2003), with contributions from André Faaij (Netherlands), Peter Fraenkel (United Kingdom), Ingvar Fridleifsson (Iceland), Carlo Hamelinck (Netherlands), Geyer (Germany), David Mills (Australia), Jose Roberto Moreira (Brazil), Wim Sinke (Netherlands), Bart van der Ree (Netherlands).

mixed blessing. On the one hand, there is no need to seek large capital investments; on the other hand, transaction costs weigh more heavily, unless many small projects are bundled into larger initiatives.

Because they are small in scale and modular, many renewable technologies are good candidates for continued cost cutting. The cost reductions of manufactured goods, which are typically rapid at first and then taper off as the industry matures, are called experience curves. These curves resulted in industry-wide cost declines of 10 to 20 percent for each cumulative doubling of production for solar photovoltaics, wind generators, gas turbines, and other technologies – due to learning effects, technology improvements, and economies of scale (Figure 14). Similar declines are expected for several other small-scale renewable energy technologies.

At the World Summit on Sustainable Development in September 2002, it was agreed that the contribution of renewables to world energy use should be substantially increased "with a sense of urgency". Increased use of renewables, it was agreed, should be achieved by "joint actions and improved efforts to work together at all levels", by "public-private partnerships", and by "intensifying regional and international co-operation in support of national efforts". A broad coalition of countries, including Brazil, Canada, New Zealand, Iceland, Norway, and the European Union and its member states, have indicated a willingness to go one step further by committing themselves to targets and timetables.

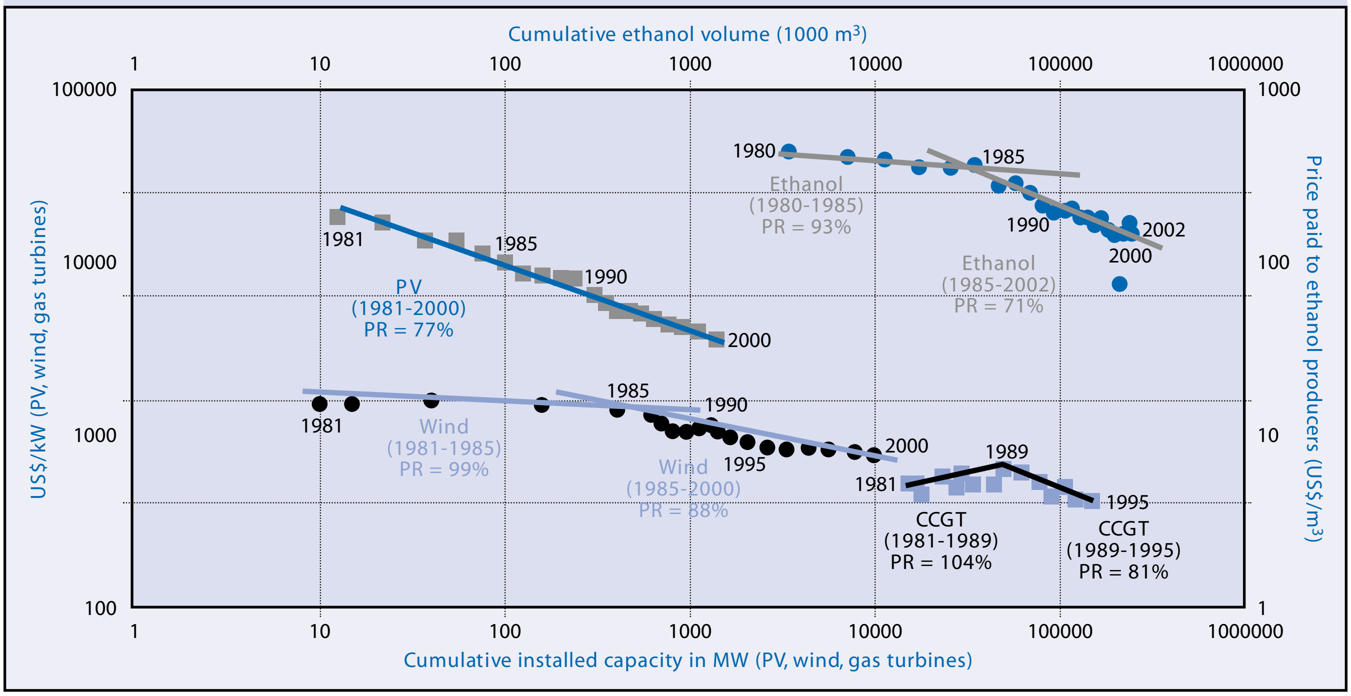
Rapid expansion of a renewable-based energy system will require actions to stimulate the market. This expansion can be achieved by finding ways to drive down the relative cost of renewables in their early stages of development and commercialisation, while still taking advantage of market place economic efficiencies. Pricing based on the full costs of conventional energy sources (including phasing out subsidies and internalising externalities) will make renewable energy more competitive. "Green" pricing of electricity and heat (which lets consumers choose to pay more for environmentally benign energy supplies) is another option some industrialised countries use to stimulate investment in renewables. Other successful incentives include: the use of ambitious but realistic targets and timetables; green certificates that can be traded at a national or international market combined with agreements to reduce emissions (e.g., carbon dioxide); favourable uptake prices for renewable electricity delivered to the grid; tax credits for investments in renewables; subsidies with "sunset" clauses; and concessions for the development of renewable energy resources.

Fossil Energy Technologies

Fossil energy technologies must evolve toward the long-term goal of near-zero air pollutant and greenhouse gas emissions without complicated end-of-pipe control technologies if sustainability goals are to be met. Near-term technologies and strategies should be supportive of this long-term goal.

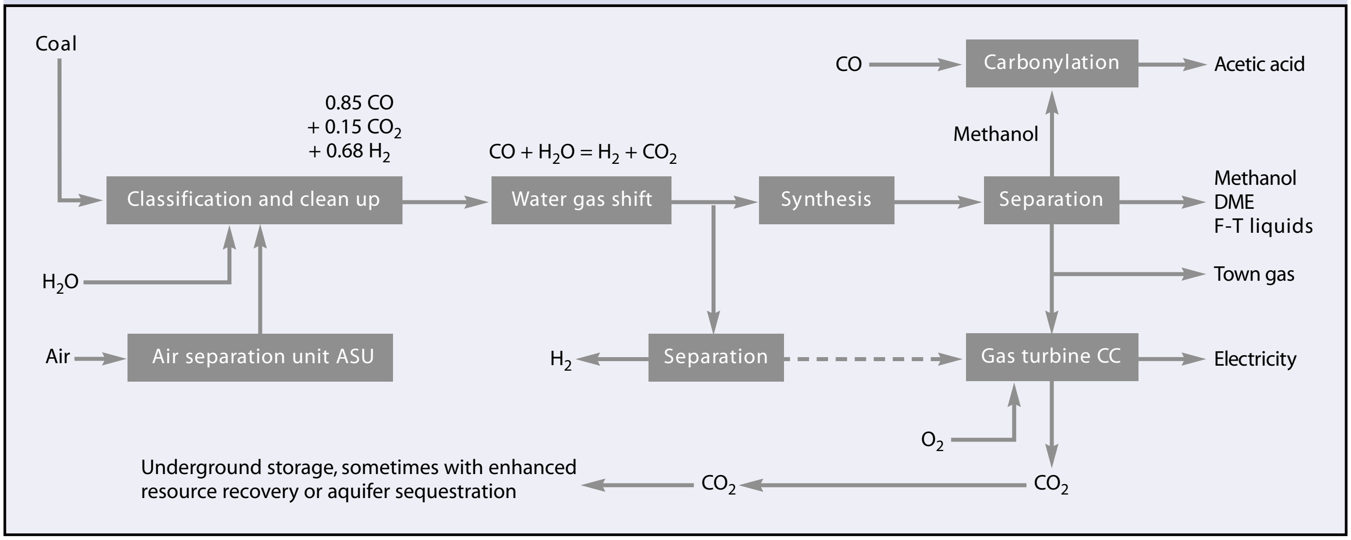
The technological revolution currently underway in power generation, where advanced systems are replacing steam turbine technologies, is a step in the right direction. Several examples can be cited. Natural-gas-fired combined cycle plants offer low cost, high efficiency, and low environmental impact; they are being chosen wherever natural gas is readily available – in some countries even taking the place of new large-hydropower projects. Co-generation (i.e., the combined delivery of heat and power or CHP) based on gas turbines and combined cycles is more cost effective and can play much larger roles in the energy economy than co-generation with steam turbines. Reciprocating engines and emerging micro-turbine and fuel cell technologies are also strong candidate technologies for co-generation at smaller scales, including commercial and apartment buildings. Coal gasification by partial oxidation with oxygen to make "syngas" (mainly carbon oxide and hydrogen) makes it possible to provide electricity via integrated gasifier combined cycle (IGCC) plants at high efficiencies and with air

FIGURE 14. EXPERIENCE CURVES FOR PHOTOVOLTAICS, WINDMILLS, GAS TURBINES, AND ETHANOL PRODUCTION



Sources: For wind turbines, L. Neij., P. Dannemand Andersen., M. Durstewitz, P. Helby, M. Hoppe-Kilpper, and P.E. Morthorst, Experience Curves: A Tool for Energy Policy Assessment *(March 2003); for gas turbines, U. Claeson Colpier and D. Cornland, "The Economics of the Combined Cycle Gas Turbine: An Experience Curve Analysis",* Energy Policy *30, no. 4 (2002), pp 209-216; for photovoltaics, V. Parente, R. Zilles, and J. Goldemberg, "Comments on Experience Curves for PV Modules",* Progress in Photovoltaics: Research and Applications, *John Wiley & Sons, Ltd (2002); for ethanol, J. Goldemberg, S.T. Coelho, P. M. Nastari, and O. Lucon, "Ethanol Learning Curve: The Brazilian Experience",* Biomass and Energy *(in publication).*

FIGURE 15. COAL POLY-GENERATION



pollutant emissions nearly as low as for natural gas combined cycles. Today power from IGCC co-generation plants would often be competitive with power from coal/steam electric plants in either co-generation or power-only configurations.

Very clean syngas, derived synthetic fuels such as synthetic middle distillates and dimethyl ether, can soon play significant roles supplementing conventional liquid fuels (for transportation, cooking, peak power generation, etc.) both to alleviate oil supply security concerns and to facilitate implementation of toughening air pollution regulations. Such fuels can often be produced for global markets at competitive cost from huge low-cost natural gas supplies that would otherwise be stranded assets at remote sites. In natural-gas-poor, coal-rich regions, a promising strategy for producing such fuels is via coal gasification and "poly-generation" – the co-production of various combinations of clean fuels, chemicals, and electricity (Figure 15).

Such systems might include production of extra syngas for distribution by pipelines to small-scale co-generation systems in factories and buildings, thereby making possible clean and efficient use of coal on small as well as large scales. Rapidly growing poly-generation activity is already underway in several countries based on gasification of low-quality petroleum feedstocks – activity that is helping to pave the way for coal-based systems.

Barriers to widespread deployment of advanced co-generation/poly-generation systems are mainly institutional. Most systems will produce far more electricity than can be consumed onsite, so that achieving favourable economics depends on being able to sell co-product electricity to electric grids at competitive prices. Under competitive market conditions, co-generation/poly-generation systems will often be the system of choice (although utility policies have sometimes made selling the excess electricity difficult).

If carbon-based fuels were replaced by hydrogen (H_2), greenhouse gas emissions from combustion would be zero and the only pollutant emissions would be oxides of nitrogen, which can be readily controlled to low levels. If H_2 were used in fuel cells, emissions of oxides of nitrogen would also be reduced to zero.

Near-term pursuit of a syngas-based energy strategy could pave the way for widespread use of H_2 as an energy carrier, because for decades the cheapest way to make H_2 will be from fossil-fuel-derived syngas. Concerns about climate change, urban air pollution, and oil supply insecurity have catalysed world-wide interest in hydrogen, especially as a transport fuel. Fuel cells are getting intense attention, because they offer high efficiency and near-zero air pollutant emissions. Successful development of fuel cells would, in turn, facilitate introduction of H_2, the preferred energy carrier for fuel cells. Automobile manufacturers are racing to develop fuel cell cars, with market entry targeted for 2010-2015 and small demonstration fleets planned as early as 2004. (Small demonstration fleets have been on the U.S. market since December 2002.) The fuel cell car will compete for the role of "car of the future" with the internal combustion engine/hybrid-electric car that is already being introduced into the market.

The use of oxygen rather than air for gasification allows, after the water-shift reaction and the separation of hydrogen by means of membrane technologies, a nearly pure flow of CO_2. Syngas-based energy production strategies thus facilitate capture and storage of carbon dioxide from fossil-fuel energy systems. For hydrogen and/or electricity production, CO_2 capture and storage can lead to near-zero CO_2 emissions with only modest energy penalties. For the production of hydrogen or hydrogen-rich fuels such as dimethyl ether from coal (Figure 15), the cost of capturing the CO_2 co-product would also be low. Thus if hydrogen can be established in the market as a major energy carrier, it can be provided from coal with near-zero total-fuel-cycle emissions of both greenhouse gases and air pollutants for the low incremental cost for capturing and storing CO_2 underground. Syngas can also be produced from biomass sources such as crop residues, and thus provides another route for hydrogen production in the future.

Substantial cost reductions in the past few decades have made a number of renewable energy technologies competitive.

Recent research suggests that the global capacity for secure disposal of CO_2 in geological reservoirs might be adequate to dispose of CO_2 from fossil fuel use for hundreds of years. However, more research and large-scale demonstration projects are needed to verify CO_2 storage as a viable strategy for widespread applications.

Other advanced technologies (for example, ultra-supercritical steam plants, pressurised fluidised bed combustion, and coal IGCC based on partial oxidation in air for power generation; and direct coal liquefaction for synthetic fuels production) offer some benefits relative to conventional technologies. But unlike syngas-based technologies, these near-term options do not offer clear paths to the long-term goal of near-zero emissions without significantly increasing energy costs.

Nuclear Energy

World-wide, nuclear energy accounts for 7 percent of energy use and 17 percent of electricity production. Although it dominates electricity generation in some

BOX 3. CARBON DIOXIDE CAPTURE AND STORAGE

In order achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, the Intergovernmental Panel on Climate Change (IPCC) has indicated that deep reductions in greenhouse gas emissions will be needed in his century. One option is to capture and store carbon dioxide from fossil fuel conversion processes.

In the short term, carbon dioxide can already be removed (i.e., captured, compressed, transported, and stored) from industrial facilities producing concentrated CO_2 streams that are vented to the atmosphere, such as natural gas treatment facilities, refineries, and ammonia plants. CO_2 can also be removed from power plants. One route is to capture CO_2 from the flue gases, using chemical adsorption techniques. Another route is fossil fuel combustion in an O_2/CO_2 atmosphere producing a flue gas mainly consisting of CO_2 that can be stored. Yet another option is the conversion of fossil fuels into CO_2 and hydrogen using steam reforming or a partial oxidation technique followed by a water-gas shift reaction. The CO_2 can be separated from the hydrogen using, for example, membranes or a physical absorption technique. The hydrogen can be combusted in a power plant or further purified to fuel cars or to supply energy to the domestic sector.

Carbon Dioxide Removal (CDR) has an energy and cost penalty. In the case of a power plant, CDR can reduce CO_2 emissions by 90 to 100 percent. However, it will increase the primary energy consumption of electricity production by 15 to 40 percent and electricity production costs by 30 to100 percent, depending on the type, scale, and status of the technologies involved. Capture, compression, transport, and storage of CO_2 is already used for many related applications.

CO_2 can be stored in depleted oil and natural gas reservoirs, deep saline aquifers, and unmineable coal seams. The capacity of safe CO_2 storage in the underground is estimated at one or many thousands Gt of CO_2. In addition, it may be possible to store CO_2 in deep oceans, if the associated environmental concerns can be addressed in an acceptable manner. Early opportunities for CO_2 storage, providing not only costs but also direct economic benefits (fuel), are Enhanced Oil Recovery (EOR) and Enhanced Coal Bed Methane production (ECBM) using CO_2.

RD&D is needed to reduce costs and to improve confidence in the ability of CDR to deliver emission reduction safely and securely. Nearly all investigations in the CDR field started after 1988. Currently most attention is given to the potential, costs, impacts, reliability, and acceptance of underground CO_2 storage. In the United States, there are some seventy CO_2 EOR operations underway which, in total, inject some 33 Mt of CO_2 annually, most of which comes from natural CO_2 accumulations. Other CO_2 EOR projects are planned or underway in Argentina, Trinidad, Turkey, Canada and the North Sea.

In Canada, there are some 31 acid gas injection projects in operation. The acid gas streams consist mainly of hydrogen sulphide (H_2S) and carbon dioxide. In 2001, approximately 1 Mt CO_2 was injected into geological reservoirs including disused oil and gas fields and deep saline reservoirs.

In Western Europe, there is currently one commercial CO_2 injection project, operated by Statoil (Norway). The CO_2 comes from treatment of the natural gas that is extracted from the Sleipner West field. It is injected into a deep saline aquifer that lies at a depth of 800 to 1,500 metres below the floor of the North Sea. To date, over 5 Mt CO_2 have been injected at a rate of 1 Mt per year. A research team is monitoring the fate of the injected CO_2. Several related projects are planned in Algeria, the Barents Sea, Western Australia, and off-shore Netherlands.

A pilot project involving the injection of CO_2 into coal seams is underway in the San Juan Basin of the United States, and additional projects are planned in China, Canada, and Poland. The Intergovernmental Panel on Climate Change is preparing a Special Report on Carbon Dioxide Capture and Storage, scheduled for publication in the first half of 2005.

Source: Wim C. Turkenburg, Utrecht University, The Netherlands, with input from John Gale (IEA GHG Programme, United Kingdom).

countries, its initial promise has not been widely realised. Current projections of nuclear's contribution to global energy are that it will not grow, will grow only slowly, or may even decline during the initial decades of the twenty-first century. Nuclear power is more costly than originally projected, competition from alternative technologies is increasing, and there has been a loss of public confidence because of concerns relating to safety, radioactive waste management, and potential nuclear weapons proliferation. However, because nuclear power can provide energy without emissions of conventional air pollutants and greenhouse gases, it is worth exploring whether advanced technologies could simultaneously offer lower costs, build broad public confidence in the safety of nuclear reactors, ensure that nuclear programs are used for peaceful rather than military purposes, and demonstrate effective nuclear waste management practices. Unlike the Chernobyl-type reactors, the light water reactors (LWRs) that dominate nuclear power globally have had a good safety record, although this record has been achieved at considerable cost in order to minimise accident risk.

Very clean syngas, derived synthetic fuels such as dimethyl ether, can soon play significant roles in supplementing conventional liquid fuels.

The potential linkage between peaceful and military uses of nuclear energy was recognised at the dawn of the nuclear age. Steps taken to create a "non-proliferation regime" through the Nuclear Non-Proliferation Treaty and a series of regional treaties, controls on commerce in nuclear materials and goods and services that might be used to further military ambitions, and safeguards applied on nuclear materials in peaceful nuclear applications, have been successful, by and large, in keeping peaceful and military uses separate. If nuclear power is to contribute more than it currently does, strengthened institutional measures will be needed to maintain this separation, complemented by technological advances aimed at limiting opportunities to acquire nuclear weapons under the guise of peaceful nuclear energy applications and to steal weapons-usable nuclear materials.

Near-term improvements in nuclear reactors can be achieved both through continued evolution in LWRs and through development of new reactor concepts. Already available are LWRs with improved safety features and standardised designs for which there can be a high degree of confidence that performance and cost targets will be met. LWRs can also be modified to make them more proliferation-resistant via a denatured uranium/thorium fuel cycle. Another concept being revisited, the pebble-bed modular reactor (PBMR) – a gas-cooled, helium reactor – claims to have the potential for a high degree of inherent safety without the need for complicated and capital-intensive safety controls; it could also be operated on a proliferation-resistant denatured uranium/thorium fuel cycle.

A lack of low-cost uranium supplies might ultimately constrain nuclear power development based on LWRs. The plutonium breeder reactor, which requires reprocessing spent fuel to recover plutonium for recycling in fresh fuel, was once thought to be a major option for addressing this challenge. But electricity costs for breeders would probably be higher than for LWRs. In addition, preventing proliferation is much more challenging with reprocessing and plutonium recycle than for LWRs operated on once-through fuel cycles.

Alternative long-term options for addressing inadequate uranium supplies include alternative breeder concepts, including particle accelerator-driven reactors, thorium based reactors, uranium from seawater, and thermo-nuclear fusion. Alternative breeder concepts would take decades to develop with no certainty about prospective costs, safety, and proliferation-resistance features. Uranium exists in seawater at low concentrations but in vast quantities; recent research suggests it might be feasible to extract it at relatively low cost. If this technology could be deployed at globally significant scales, it might be feasible to avoid making major new commitments to nuclear fuel reprocessing and plutonium recycling. Although thermo-nuclear fusion could provide a virtually inexhaustible energy supply, it will not be commercially available before mid-century.

Radioactive waste by-products of nuclear energy must be isolated so that they can never return to the human environment in concentrations that could cause significant harm. Although the safety of long-term waste disposal has not been proven, the technical community is confident that this objective can be realised – in large part because of the small volumes of wastes involved. However, in most countries there is no social consensus about the goals and standards for radioactive waste disposal and about strategies (both interim and long-term) for moving forward to implement them. The issues involved are only partly technical. The current social stalemate regarding waste disposal not only clouds the prospects for nuclear expansion but also has made spent-fuel reprocessing a *de facto* interim "nuclear waste management strategy" in some countries. However, fuel reprocessing does not offer economic gains and does not "solve" the waste disposal problem – it merely "buys time" and, unless it is blended as mixed oxide fuel (MOX) for use in LWRs, will create large inventories of plutonium that must be safeguarded.

No long-term disposal facility exists yet for waste from civilian nuclear power plants, and most nuclear power countries have made little or no progress in that direction. Even in Finland, Sweden, and the United States, which have advanced furthest, operating depositories remain more than a decade away. As national waste strategies continue to evolve, it may be of benefit to consider multinational approaches to the management and disposal of spent fuels and other radioactive waste. Considerable economic, safety, security, and non-proliferation advantages may accrue from programmes to collaborate on the construction and operation of international waste repositories. ■