EuropeAid

EC Cooperation:

Responding to climate change

Sector Script for Energy Supply

Information Note

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This document was developed by EuropeAid in cooperation with DG RELEX, DG DEV and DG ENV with the support of the "environmental integration advisory services" project. It was designed to provide practical guidance on the links between climate change and a specific sector, together with possible responses to climate-related challenges. The purpose of this "script" is to support political dialogue on climate change implications between the European Commission, partner governments and other national partners involved in EC development and external cooperation activities, as well as to facilitate strengthened climate change integration in ongoing and future cooperation programmes and projects, with a focus on developmental benefits for the partner countries.

This sector script is one of a series prepared in a standard format. Scripts are available for the following topics:

- Introduction and Key Concepts
- Agriculture & Rural Development *(incl. forestry, fisheries and food security)*
- Ecosystems & Biodiversity Management
- Education
- Energy Supply
- Governance
- Health
- Infrastructure *(incl. transport)*
- Solid Waste Management
- Trade & Investment *(incl. technological development, employment and private sector development)*
- Water Supply & Sanitation

Note that the script is not country or region-specific, and has been prepared to cover a wide range of possible effects and responses. Users are invited to appreciate which elements, among those proposed, are relevant to their specific needs and circumstances.

Energy has connections with many other sectors. The text makes references to other related and complementary scripts.

Users of this script are advised to read it in conjunction with the Introduction and Key Concepts information note, which introduces the series and puts things in context.

Comments are welcome and can be addressed to the following e-mail:
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These documents can also be downloaded on the EuropeAid/E6 Intranet Pages.

Picture credit: Energy Leap by Ruelito R. Pine, March 2008
This picture was awarded a prize at the climate change photo competition organized by the EC Delegation to the Philippines in 2008.

RESPONDING TO CLIMATE CHANGE: SECTOR SCRIPT
SECTOR: ENERGY SUPPLY

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0. EXECUTIVE SUMMARY

Climate change impacts on the energy sector

Climate change may interfere in various ways with the availability of primary energy sources, the capacity to transform them into usable energy, and the systems used to store and distribute this energy to users. Here are some examples of possible impacts:

Climate change effects/impacts	***Energy conversion***	***Energy transmission, transport & distribution***
Increased frequency and/or severity of extreme weather events	Damage to infrastructure	Damage to infrastructure, disruption of services
More irregular streamflows	Reduced hydropower generation capacity Lack of water for cooling towers of thermal power plants	
Higher ambient temperatures	Reduced efficiency of thermal power plants	Increased transmission losses
Changes in cloud cover	Changes in solar power capacity	
Changes in rainfall and temperature patterns	Impacts on productivity of energy crops and fuelwood plantations	
Socio-economic breakdown, increase in conflicts	Damage to infrastructure	Damage to infrastructure Thefts
Climate-induced migrations	Inadequacy of supply and demand	Inadequacy of supply and demand

The relationships between climate change and the energy sector also have wider implications for society and the economy, and interact with socio-economic conditions. In particular:

- changes in the availability of energy may themselves produce other socio-economic effects, such as disruption to productive and economic activities dependent on reliable energy supply;
- structural changes in energy consumption patterns, directly or indirectly induced by climate change, may require an adaptation of supply capacity;
- climate change is already and will keep influencing technological choices in relation to energy supply, as mitigation efforts impose restrictions on the use of fossil fuels.

Adapting to climate change

Adaptation to climate change in the energy sector involves: adopting measures to reduce the exposure and vulnerability of infrastructure to the potential adverse effects of climate change; exploiting the opportunities offered by potential positive effects (if any are identified); taking account of predicted impacts in the definition of sector development strategies; and also considering how mitigation efforts will impact this development.

Adaptation and mitigation options in the energy sector are in fact intertwined, since options to mitigate greenhouse gas (GHG) emissions often increase the long-term ability of the system to cope with the risks and challenges posed by climate change, and some adaptive measures make the uptake of mitigation options more feasible. Here are some examples of possible adaptation measures:

Possible adaptation measures	***Relevance to energy conversion***	***Relevance to energy transmission, transport & distribution***	***Relevance to mitigation efforts***
Making infrastructure more resilient to extreme climatic events	√	√	
Creating backup capacity and "workaround" solutions	√	√	
Increasing the spatial distribution of power generation capacity	√	√	√
Opting for more diverse energy mixes	√		√
Protecting infrastructure against theft and intentional degradation	√	√	
Monitoring trends in migrations and population resettlements	√	√	√

While the focus of adaption measures in relation to energy supply is on making infrastructure more resilient to the potential impacts of climate change, the ultimate goal is of course to increase the resilience and adaptive capacity of human populations. Reliable access to energy is indeed an extremely important factor, that will determine to a large extent the ability to successfully implement other adaptive measures proposed in this series of sector scripts

Contributing to climate change mitigation

The energy supply sector is the largest contributor to anthropogenic GHG emissions, because it still relies very heavily on fossil fuel burning: it is deemed to account for approx. 26% of man-made emissions, while the transport sector (a big user of energy) accounts for an additional 13%. In the context of development, the major global energy sector challenge is to reduce GHG emissions while securing energy supply to meet growing demand for energy, in particular from developing countries, and providing all people (including the poor) with access to energy products and services. The planning of mitigation actions in relation to energy conversion should consider all these aspects simultaneously. More generally, choices regarding a country's energy mix (which are closely intertwined with adaptation requirements and mitigation opportunities) should be guided by a combination of technological, economic as well as strategic considerations. The high financial and opportunity cost of capital is a significant obstacle to the uptake of clean energy technologies in developing countries, but it should be surmounted if the financing opportunities associated with carbon finance mechanisms, as well as the co-benefits associated with the use of low-carbon energy sources, are taken into account.

Various types of responses exist to mitigate the GHG emissions associated with energy supply and consumption. On the policy side, supply-side measures (such as subsidies to encourage the adoption of more climate-friendly energy supply technologies and the setting up of cap-and-trade schemes) should be combined with demand-side measures (such as cutting fuel and energy subsidies for end users, and enforcing product-related energy efficiency standards) to support emission reduction goals. Demand-side measures are often more cost-effective than supply-side measures. Ultimately, both supply- and demand-side options will be needed to achieve the desirable cuts in emissions, but the cash-strapped governments of developing countries may want to focus first on those measures that produce results at the least cost for society and for their budgets.

On the technical side, many options are available to reduce the emissions of GHGs associated with energy transformation processes. In the current state of knowledge, no single technology or energy source can supply enough climate-neutral, carbon-free energy to meet humanity's growing needs – but various options can be combined to meet the challenge of increasing global energy supply while reducing the sector's adverse impacts on climate. The range of possible options includes:

- improving the energy conversion rates achieved by existing energy technologies (e.g. combined cycle technologies, combined heat and power, recovery of flared gases and coal mine methane);
- switching to cleaner fuels in thermal power plants;
- developing carbon capture and storage, a not-yet-mature but promising technology if concerns about long-term carbon storage can be reliably addressed;
- developing nuclear power, which however is far from being a panacea and is not a likely option for many developing countries in the foreseeable future since: (i) it requires huge initial investment, with a tendency to overrun initially estimated costs by several factors; (ii) there are still important environmental, health and security concerns related to the safety of operations, the decommissioning of installations, the storage and disposal of highly radioactive waste and nuclear proliferation issues;
- developing heat and power generation based on renewable energy sources, including hydropower, biomass energy, wind power, solar energy, geothermal energy, ocean energy; some renewable power technologies are more mature than others and the environmental impacts of their use (besides impacts on climate) should be considered and addressed, but all these technologies have the potential to contribute to cleaner power generation immediately or in the coming few decades;
- as far as energy for transport is concerned, investigating the possibility of developing sustainable biofuels, as well as hydrogen fuel cell-powered vehicles (a not-yet-mature technology) and battery-powered vehicles (more likely to enter the mainstream in the near future, at least in developed countries);
- as far as domestic energy is concerned, developing rural electrification based on sustainable energy sources (e.g. small-scale, household-based or community-based solar power, wind energy and hydropower), or where solid biomass fuel substitution is not an immediately feasible option, promoting the adoption of high-efficiency cooking stoves combined with the development of sustainable fuelwood plantations.

One problem associated with the development of some renewable energy sources (in particular wind and solar energy) is their intermittency and the more or less important unpredictability of power generation: intermittent renewable energy sources must be supplemented or backed up by other sources, and irregularity in power generation makes the management of the power grid more complex technically. Solutions exist, however. Ultimately, which options and energy mixes are suitable in a given context must be determined on a case-by-case basis, based on an assessment of each country's and region's natural resource endowments, needs for energy, existing infrastructure, technical constraints, socio-economic development and investment capacity.

Finally, note that many mitigation options in the energy sector appear economically more attractive if their co-benefits (e.g. reduced air pollution and associated economic and health benefits, reduced dependency on imported fuels) are taken into account. Conversely, some mitigation options (e.g. biofuels) may inadvertently result in increased vulnerability and threaten or cancel out adaptation efforts – or even have a negative net impact in terms of mitigation. It is thus important to carefully consider the pros and cons and possible unintended effects of any envisaged mitigation measures.

1. HOW CLIMATE CHANGE MIGHT AFFECT THE ENERGY SECTOR

Climate change may affect the energy supply sector through a range of biophysical and socio-economic impacts. The table below shows the main links between such impacts and the sector.

	Energy
Biophysical effects	
Changes in temperature and rainfall patterns	√
Increase in extreme weather events / natural disasters	√
Raised sea level and increased coastal erosion	√
Changes in hydrological flows	√
Socio-economic impacts	
Damage to infrastructure	√
Reduced availability of energy (hydropower)	√
Economic and social disruption, loss of livelihoods	√
Increased probability and intensity of conflicts	√
Population displacement and human migrations	√

Primary energy sources include:

- finite, non-renewable (at the timescale of human activities) sources: coal, oil, gas, uranium[1];
- renewable sources: hydropower, biomass, wind, solar radiation, geothermal energy and ocean energy.

These primary sources are exploited and transformed into "energy carriers" which serve as intermediate devices between primary sources and actual energy uses: electricity, heat and fuels (which are available in solid, liquid and gaseous forms). These energy carriers can be stored and/or distributed and are ultimately made available to users in the form of electricity, heat (or fuels ready to generate heat) and transport fuels.

Climate change may interfere in various ways with the availability of primary energy sources, the capacity to transform them into usable energy, and the systems used to store and distribute this energy to users. Below, we start by reviewing how climate change may impact on these aspects. Acknowledging that the relationships between climate change and the energy sector have wider implications for society and the economy, and interact with socio-economic conditions, we then briefly review:

- how changes in the availability of energy may themselves produce other socio-economic effects, such as disruption to productive and economic activities dependent on reliable energy supply;
- how changes in energy consumption patterns, directly or indirectly induced by climate change (e.g. reduced demand for heating, increased demand for cooling, improved energy efficiency and demand contraction as a result of increasing energy prices), may require an adaptation of supply capacity;
- how climate change is already and will keep influencing technological choices in relation to energy supply, as mitigation efforts impose restrictions on the use of fossil fuels.

[1] Uranium reserves are finite and estimated to amount to approx. 100 years of current consumption on the basis of conventional nuclear power technologies. However, new technologies based on fuel-recycling are currently being developed and are expected to extend reserves to several thousands of years, so that for practical purposes, nuclear fission could become assimilated to a 'quasi-renewable' source of energy.

1.1. Energy conversion[2]

The increased frequency and/or severity of extreme weather events has the potential to damage, destroy or severely impair the operation of practically all types of infrastructure, including energy-related infrastructure. For instance, the operation of power generation plants may be disrupted by floods, landslides and, in coastal and low-lying delta areas, sea surges and rising sea levels; wind turbines may be damaged by storms – and cannot operate when winds are too strong; sea storms may damage offshore oil extraction platforms, off-shore wind farms and infrastructure aimed at exploiting marine energy.

Hydropower generation relies to a large extent on regular stream flows (even if dams are used to smooth out some of the fluctuations): turbines have to shut down if there is either too much or too little water. Hydropower generation capacity is likely to be constrained, in particular, on rivers that have their sources in regions affected by droughts, and/or are primarily fed by snowmelt and glaciers (as glaciers are retreating in most parts of the world).

Conventional thermal power plants (which burn fossil fuels to produce high-pressure steam used to run a steam turbine), as well as nuclear ones (based on the same principle but with a nuclear reactor as the source of heat for producing steam), rely on water flows to feed their cooling towers: water is an essential component of the energy conversion process. These plants may have to shut down during periods of reduced stream flows; even if enough water remains available to avoid a shutdown, lower stream flows may result in the amplification of the ecological damages caused by the rejection of hot water into river ecosystems, as less cold water is available to bring down its temperature.

Independently from the problems related to water availability for cooling, higher ambient temperatures also have direct adverse effects on electricity generation, as they reduce the efficiency of thermal power plants.

Increased cloud cover may reduce the productivity of solar energy installations of all types. Conversely, a decrease in cloud cover should increase the efficiency of solar energy production, thus providing an opportunity to sustainably develop solar power technologies.

The production of energy crops and fuelwood may suffer (or, in a few regions, benefit) in the same way as other agricultural and forestry productions from changes in rainfall and temperature patterns. In most developing regions, shifts in seasons, as well as an increase in the risk of droughts and heatwaves, floods, reduced water availability, wildfires, pest outbreaks etc., are widely considered to outweigh any potential benefits from climate change (see script on Agriculture & Rural Development).

1.2. Energy transmission/transport and distribution

In the same way that it can affect the energy conversion infrastructure, the increased frequency and/or severity of extreme weather events also has the potential to damage energy transmission and distribution infrastructure. For instance, overhead power transmission lines are particularly sensitive to storms, cyclones and other events involving strong winds (as well as intense cold); other power transmission and distribution infrastructure, such as power grid control centres and sub-stations, as well as oil and gas pipelines, may be damaged or temporarily shut down as a result of storms, floods, landslides or wildfires. Extreme weather events may also disrupt the distribution of energy products (e.g. solid fuels, gas bottles, diesel and gasoline) through impacts on transportation networks (e.g. disruption of road networks, railways, harbour operations, river navigation).

In the electric power sector, higher ambient temperatures may result in increased transmission losses.

[2] We refer to "energy conversion" rather than "energy production" since energy is strictly speaking not produced, but converted from a raw source into a more exploitable form. On the other hand, specific energy carriers such as electricity, heat and fuels can be "produced" in the traditional sense.

More indirectly, the reliability of energy supplies may be affected by the breakup of social capital and increased social unrest resulting from the socio-economic impacts of climate change: malnutrition, loss of livelihoods, deteriorating living conditions, rising energy prices, conflicts over access to natural resources may all contribute to an increase in the occurrence of theft and damage to infrastructure (e.g. illegal connections to the power distribution grid, breach of oil pipelines, blowing up of infrastructure in conflict areas). Also, climate-induced migrations may result in temporary or more lasting inadequacies between energy supply (in particular, electric power supply) and demand. For instance, there may not be enough supply and distribution capacity to meet the needs of fast-growing urban and peri-urban areas, resulting in frequent power cuts and difficulties in managing the grid.

1.3. "DOWNSTREAM EFFECTS" ON OTHER SECTORS

Obviously, with energy being so essential to human activities, all the effects described above can themselves be expected to impact other sectors. Agriculture (including irrigation) and mining, industry and manufacturing, transport, the building sector, financial, IT and other services (including tourism), water supply, wastewater treatment, health and educational services, etc. all depend in one way or another on the availability of energy. Households also need energy for cooking, heating or cooling, conserving food, operating a variety of electric appliances and moving from one place to another. This note will not attempt to cover all these aspects in detail. Rather, they are covered in the sector scripts dedicated to Agriculture & Rural Development, Education, Health, Infrastructure, Solid Waste Management, Trade & Investment and Water Supply & Sanitation.

1.4. CHANGES IN ENERGY DEMAND PATTERNS

With its multiple effects on all sectors and areas of human activity, climate change is likely in many regions to affect demand for energy. For instance, higher temperatures may lead to increased electricity consumption for air conditioning systems – but also possibly to reduced electricity and fuel consumption for heating purposes. Climate change also has the potential to modify the structure of economic activity, with positive or negative impacts on energy demand depending on the energy dependence of growing and declining activities. Increasing energy prices will constrain demand and encourage efficiency. Structural changes in demand patterns may thus be an indirect consequence of climate change; although some of these changes may be even less predictable than the direct effects of climate change, energy sector planners will have to take them in consideration.

1.5. IMPLICATIONS OF MITIGATION EFFORTS FOR SECTOR DEVELOPMENT

The energy sector is the most immediately concerned by mitigation efforts, since it is the largest single contributor to anthropogenic GHG emissions through the burning of fossil fuels to generate usable energy (including energy for transport): globally, energy supply remains very dependent on fossil fuels. At the moment, developing and emerging countries are not concerned by mandatory emission reduction targets – but they will increasingly be expected to adopt "low-carbon" or "climate-neutral" development paths (see Section 3). Given the long-term horizons of most investments in energy technology and infrastructure, it is therefore advisable for developing countries to start exploring now the extent to which they can:

- rely on renewable energy sources to increase their energy supply capacity;
- and, to the extent that they remain dependent on fossil fuels, opt for technologies that improve conversion efficiency and reduce carbon emissions into the atmosphere.

The quest for climate-neutral development paths will (should) have significant implications for the choice of an adequate "energy mix", and for the development of the energy sector in developing countries. This choice should be guided by technological, economic as well as strategic considerations, and should take into account the financing opportunities associated with the Kyoto Protocol's Clean

Development and Joint Implementation Mechanisms, their yet-to-be-defined successor and other carbon market mechanisms. More information on these aspects is provided in Section 3.

2. ADAPTING TO CLIMATE CHANGE IN THE ENERGY SECTOR

Adaptation to climate change in the energy sector involves adopting measures to reduce the exposure and vulnerability of infrastructure to the potential adverse effects of climate change, exploiting the opportunities offered by potential positive effects (if any are identified), taking account of predicted impacts in the definition of sector development strategies, and also considering how mitigation efforts will impact this development. These aspects are reviewed below, with the exception of the latter which is developed in Section 3. Adaptation and mitigation options in the energy sector are in fact intertwined, since options to mitigate greenhouse gas (GHG) emissions often increase the long-term ability of the system to cope with the risks and challenges posed by climate change, and some adaptive measures make the uptake of mitigation options more feasible.

2.1. ENERGY CONVERSION

Possible adaptation measures include:

- making energy conversion infrastructure more resilient to extreme climatic events (which may involve upgrading engineering standards and building norms, and retrofitting existing infrastructure);
- taking account of the potential effects of climate change, and notably of exposure to extreme weather events, in the choice of location for all new infrastructure – and selectively relocating key infrastructure, where it is identified as particularly vulnerable;
- in power generation networks, creating backup capacity and "workaround" solutions, so that a problem at one power generation site does not bring down the whole system; this may notably involve opting for increased spatial distribution of power generation capacity (which is more complex to manage than centralised generation, and requires adaptations in grid management systems);
- reducing dependence on single sources of energy, and opting for more diverse energy mixes, to improve overall resilience and adaptability; geographically distributed small-scale power plants, both on-grid and off-grid and using a variety of energy sources, have a role to play in this regard and may notably advance the goal of rural electrification;
- taking account of predicted impacts of climate change in strategic decisions on energy infrastructure development; this may involve, for instance: avoiding excessive reliance on hydropower where stream flows are expected to be reduced as a result of decreasing rainfall; taking account of water constraints for choosing the location of new power plants that depend on water for cooling; integrating current and future climatic conditions, as well as environmental, social and food security considerations, in decisions about the development of fuel crops and a biofuel industry; considering long-term climate forecasts when assessing the potential for solar energy conversion.

2.2. ENERGY TRANSMISSION/ TRANSPORT AND DISTRIBUTION

Possible adaptation measures include:

- making overhead power transmission and distribution infrastructure more resilient to extreme climatic events, if necessary by means of new engineering standards, retrofitting of existing infrastructure and selective relocation away from the most exposed areas;
- taking account of the potential effects of climate change, and notably of exposure to extreme weather events, in the choice of location for all new infrastructure;

- gradually switching to underground rather than overhead transmission lines, in particular to supply power to essential economic and social infrastructure;
- reducing electric power transmission losses (which may be aggravated by higher ambient temperatures) by producing electricity closer to the places where it is used – which implies a switch to a more decentralised electricity production infrastructure;
- in energy networks of all types (including pipeline networks), creating backup capacity and "workaround" solutions, so that a transmission problem in one location does not paralyse the whole system;
- gradually strengthening the transport infrastructure on which the distribution of fuels depends;
- adapting fuel storage and distribution systems to reduce vulnerability to temporary disruptions; where appropriate, this may involve developing local and regional storage and distribution systems;
- to the extent possible, protecting key energy transmission and distribution infrastructure against theft or intentional degradation, and strengthening systems for leak detection and control;
- closely monitoring trends in migrations and population resettlements, so as to anticipate future needs at the time of planning investments in new energy infrastructure.

2.3. "Downstream effects" on other sectors

While the focus of adaption measures in relation to energy supply is on making infrastructure more resilient to the potential impacts of climate change, the ultimate goal is of course to increase the resilience and adaptive capacity of human populations. Reliable access to energy is indeed an extremely important factor, that will determine to a large extent the ability to successfully implement other adaptive measures proposed in this series of sector scripts (see Section 2 of other sector scripts).

3. Opportunities for reducing GHG emissions in the energy sector

The energy supply sector is the largest contributor to anthropogenic GHG emissions, because it still relies very heavily on fossil fuel burning: it is deemed to account for approx. 26% of man-made emissions, while the transport sector (a big user of energy) accounts for an additional 13% (IPCC 2007).

In a development context, the major global energy sector challenges are:

- securing energy supply to meet growing demand for energy, in particular from developing countries;
- providing all people, including the poor, with access to energy products and services;
- and tackling the causes and impacts of climate change (as well as some other environmental issues such as air pollution).

The latter challenge may be seen as a constraint on addressing the first two: how can the world consume more energy, satisfy growing needs and meet development and poverty reduction objectives while reducing global GHG emissions? Specific ways of addressing these challenges vary across countries and regions.

The planning of mitigation actions in relation to energy conversion should consider all these aspects simultaneously. More generally, choices regarding a country's energy mix (which are closely intertwined with adaptation requirements and mitigation opportunities) should be guided by a combination of technological, economic as well as strategic considerations. One significant obstacle to investment in renewable energy infrastructure is that it often requires a significant upfront investment – and the cost of capital (both in financial terms and in terms of opportunity cost) tends to be higher in emerging and developing countries. When determining the financial and economic sustainability of mitigation options, two aspects in particular should be taken into account:

- the financing opportunities associated with the Kyoto Protocol's Clean Development and Joint Implementation Mechanisms, their yet-to-be-defined successor and other carbon finance mechanisms: the sale of emission reduction credits or assimilated financial assets may make otherwise unaffordable or unprofitable technological options financially viable;[3]
- the co-benefits associated with the use of low-carbon energy sources and technologies, which do not affect financial sustainability but may significantly improve the economic returns from such investments: this point is addressed in more detail in the last part of this section.

The section below looks into "broad" policy options, arguing that supply-side measures must but complemented with demand-side measures if emission reduction goals are ever to be made achievable. We then review a series of technical options related to energy conversion, transmission (or transport) and distribution. The importance of considering the positive and negative side effects of mitigation options is addressed as a final point.

3.1. POLICY MEASURES

A) SUPPLY-SIDE POLICY MEASURES

Possible supply-side policy measures, aimed at promoting the development of climate-friendly energy conversion and curbing the use of fossil fuels in energy conversion processes, include:

- cutting subsidies for the generation of fossil fuel-based energy (or even taxing this activity);
- providing subsidies for the adoption of more climate-friendly energy conversion technologies;
- setting up "cap-and-trade" schemes, i.e. schemes in which the government auctions or allocates limited emission credits to large emitters of GHGs (typically, power stations and large industrial operations), and then lets them trade these credits among themselves so as to achieve targeted emission reductions at the lowest possible economic cost (e.g. EU Emissions Trading Scheme); such schemes are best established at the international level, both to improve market liquidity and economic efficiency and to alleviate concerns about distortions in trade competitiveness;
- setting and enforcing standards that impose minimum technical efficiency requirements for energy conversion, or phase out the use of outdated, inefficient energy supply infrastructure;
- setting mandatory targets for the use of low-carbon/renewable energy sources in total national power generation and/or in transport fuel consumption;
- making the purchase of excess renewable power generated by (grid-connected) small, medium-sized and large producers, at stable feed-in tariffs, mandatory for grid operators: this may significantly improve the financial sustainability of private investments in renewable energy, boost investment in the renewable sector, increase the share of renewable energy in overall power generation and support job creation, including in rural areas; however, this is an option with far-reaching consequences since it involves a switch from a (usually) centralised to a more distributed infrastructure for generating electricity, and requires adaptations in grid management systems;
- generally speaking, identifying and removing the policy, legislative and regulatory barriers to investments in climate-friendly renewable energy infrastructure;
- financing research aimed at improving energy conversion rates (see below).

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[3] A sizable proportion of the projects submitted so far for validation under the Clean Development Mechanism are related to energy, in the form of energy efficiency, fuel substitution, coal mine methane and landfill gas recovery, and renewable energy projects (WB 2008). Over two-thirds of the GHG mitigation methodologies approved under the CDM are energy-related (de Gouvello et al. 2008).

All these measures have the potential to promote the faster and wider adoption of the technical mitigation options described further in this section.

B) Demand-side policy measures

The supply-side policy measures described above, assuming they actually lead to the adoption of suitable technical mitigation measures, may contribute to a reduction in GHG emissions, but their effectiveness will be limited if, on the other hand, insufficient efforts are undertaken to improve efficiency in the use of energy. Policies and measures aimed at promoting energy efficiency in all sectors are absolutely necessary in order to manage a reduction in emissions without impairing development efforts: the goal is to reduce the amount of energy used per unit of GDP, on a global scale. Possible demand-side measures include:

- cutting fuel and energy subsidies for end users (while ensuring, however, that the poor keep access to a minimum guaranteed level of energy consumption at affordable prices);
- taxing the use of the most "climate-damaging" energy carriers (e.g. gasoline taxes);
- providing subsidies to encourage the adoption of energy efficiency measures (e.g. insulation of buildings);
- regulating some sectors, setting standards and enforcing efficiency measures that may otherwise not be spontaneously taken up by producers and consumers (e.g. limits on the energy consumption of electrical appliances when they are not in use);
- running awareness and sensitisation campaigns on energy efficiency, targeted at enterprises and individuals;
- financing research aimed at improving the energy efficiency of processes, infrastructure (notably buildings), vehicles and equipment.

Sector-specific options to improve energy efficiency are not described here but can be found in other sector scripts, in particular the one dedicated to Infrastructure (which also covers buildings, communication and industrial infrastructure). Opportunities to improve energy efficiency exist in practically all economic sectors, as well as in relation to household consumption.

Note that up to a point at least, demand-side measures are often more cost-effective than supply-side measures (i.e. the marginal cost of achieving a given reduction in emissions through energy efficiency measures is less than the marginal cost of achieving the same reduction through changes in energy supply and distribution systems). Ultimately, both supply- and demand-side options will be needed to achieve the desirable cuts in emissions, but the cash-strapped governments of developing countries may want to focus first on those measures that produce results at the least cost for society and for their budgets.

3.2. Technical options associated with energy conversion

Many options are available to reduce the emissions of GHGs associated with energy conversion processes. In the current state of knowledge, no single technology or energy source can supply enough climate-neutral, carbon-free energy to meet humanity's growing needs – but various options can be combined to meet the challenge of increasing global energy supply while reducing the sector's adverse impacts on climate. A range of possible options are reviewed below. Which options and energy mixes are suitable must of course be determined on a case-by-case basis, based on an assessment of each country's and region's natural resource endowments, needs for energy, existing infrastructure, socio-economic development and investment capacity.

Consideration of the distribution, size, mix and flexibility of energy conversion infrastructure and associated distribution networks with respect to promoting low-carbon options is particularly relevant to countries planning long-term energy strategies. Opportunities exist to "leap-frog" and not necessarily follow conventional, industrialised-country energy development pathways (as for example, in another sector, the rapid development of mobile phone networks has replaced the need for high-investment-cost fixed-line infrastructure in many parts of Africa).

A) Improved energy conversion rates

Whatever the source of energy and the technology used, efforts should be made to improve the rates at which primary energy is converted into energy carriers and, ultimately, "usable" energy. This approach, which depends in part on technological innovation but also to a large extent on the deployment of existing technologies (some high-tech, some as simple as improved biomass stoves), can lead to both direct and indirect reductions in GHG emissions:

- direct reductions occur when a similar amount of heat or electricity can be generated using fewer fossil fuels (or more heat or electricity can be squeezed out of a given quantity of fossil fuels, with no additional GHGs emitted);
- indirect reductions are obtained whenever the rate of energy conversion from renewable sources improves – since this allows energy substitution and/or reduces dependence on fossil fuels to meet growing needs for energy.

Many technologies have been and keep being developed to improve energy conversion rates. We cannot present or even name them all here, but here are a few examples of mature technologies that are increasingly being adopted, including in developing countries:

- combined cycle (CC) technologies: they substantially increase the energy output of thermal and gas turbine power plants, with no additional GHG emissions, by adding one (or possibly more) thermodynamic cycle to the primary power generation cycle; concretely, the waste heat generated by the primary process, rather than being dissipated, is recovered and used to produce steam that will power a secondary steam turbine; note that the principle of combined cycles is now also being applied to solar power plants;
- combined heat and power (CHP), also known as co-generation: this technology combines the production of electricity with the production of "useful" heat, for use in industrial processes or municipal/domestic heating systems; this is another way of using the waste heat generated by primary electricity generation processes – and thus of extracting more energy with no additional GHG emissions; note that CC and CHP technologies can be combined for even higher conversion efficiency; co-generation is used in large power plants but is also applicable to smaller installations, such as mini- or micro-power stations, waste incinerators and even internal combustion engines;
- technologies to recover flared gases (i.e. those gases that escape from oil wells and are, in most cases, simply burned at the exit) and coal mine methane, both being by-products of traditional fossil fuel exploitation with a (too often untapped) potential for useful exploitation at zero additional emissions.

Chapter 4 of the IPCC (2007) Working Group III report on climate change mitigation in the energy supply sector provides a comprehensive review of current energy conversion rates, as well as existing and emerging energy conversion technologies.

B) Electric power and industrial heat production

Reductions in GHG emissions in relation to heat and power production can be achieved by a variety of means, most of which involve switching away from fossil fuels as the primary source of energy. Note however that the net gains (net emission reductions) from a change in technology vary across countries and situations, and should always be calculated on the basis of full lifecycle analysis. That is, emissions related to the use of a given energy source in a given country should be calculated taking into account all the emissions related to extraction processes (if any), transformation processes, transportation and distribution to end users, and decommissioning of installations at the end of their lifetime. For instance, photovoltaic panels do not provide an entirely 'carbon-free' energy, because a lot of fossil fuel energy consumption may in fact be "hidden" in the manufacturing and (to a lesser extent) the transportation and recycling of panels; furthermore, the fossil fuel content of electricity is not the same everywhere, so the manufacturing of the same photovoltaic panel may give rise to very different indirect emissions, depending on whether the electricity used in the process was produced on the basis of fossil fuels or, say, hydropower. Hidden emissions should be taken into account, alongside other criteria, to guide the choice of mitigation options; the effectiveness and efficiency of various options may depend significantly on a country's endowment with natural resources, and how it produces its electricity.

- **Fuel switching among fossil fuels, and gas turbine power plants**

Among fossil fuels, coal is the one that generates the most GHG emissions per unit of energy generated. Oil is also a significant source of emissions, but less so than coal. Emission levels can vary across oil types, but are higher (especially if one considers the entire lifecycle, from basic extraction to final conversion into an energy carrier) for new, non-conventional sources of hydrocarbons such as oil shales and tar sands. Per unit of energy generated, natural gas, which consists primarily of methane, is the cleanest of fossil fuels from the point of view of GHG emissions (and of other emissions as well).

Many thermal power stations and industrial boilers are or can be equipped to switch between different fuel sources (in particular coal and various qualities of oil), and do actually switch based on fluctuations in the availability and market prices of various fuels. The switch from coal to oil and to natural gas (or to renewable sources of energy, of course) can be encouraged by some of the supply-side policy measures described above.

Gas turbine power plants also use natural gas as a fuel, although with a different technology. Compared with thermal power plants, these plants are appreciated for their efficiency (especially in the combined cycle setup), relative cleanliness and high degree of flexibility (since they can start and shut down at short notice to accommodate changes in demand or sudden drops or surges in production capacity on the grid).

Two considerations may hinder the increased use of natural gas for heat and power generation. First of all, a network of gas pipelines for gas distribution has to cover the country's territory (or at least some key areas such as industrial and power generation centres); it is not the case everywhere, and initial investment costs are significant. Second, reliance on natural gas may increase a country's dependence on a single source of supply, with adverse strategic implications. However, in future it should become easier to diversify gas supplies as the transcontinental transport of gas by ship, in the form of liquefied natural gas (LNG), is undergoing considerable development.

- **Carbon capture and storage (CCS)**

CCS is a technology that captures carbon dioxide in the exhaust fumes of large fossil fuel combustion installations (e.g. thermal power stations, large industrial boilers) and moves this CO_2 to a geological or deep marine reservoir where it can be safely stored for long periods – and thus prevented from adding up to the stock of atmospheric GHGs.[4]

CCS is not yet considered a mature technology and it remains unclear how much of a role it will play in global warming mitigation efforts in the coming decades. The "capture" part, although still expensive, is not much of a problem but the "storage" aspect is technically more challenging. Geological reservoirs (e.g. depleted oil fields) are considered somewhat safer than oceanic ones because, provided they do not leak (a problematic aspect), the carbon should remain stored for longer periods (being subtracted from the complex carbon exchanges between the oceans and the atmosphere

[4] CCS also sometimes refers to techniques aimed at capturing carbon dioxide from ambient air, but this technology is immature and has little connection with the energy sector.

that characterise the carbon cycle) and it does not contribute to ocean acidification. Much more research is still needed to determine the feasibility and reliability of long-term storage options – and even if technological problems are solved, costs could remain prohibitive unless a relatively hefty carbon tax becomes generalised[5]. If CCS ever becomes a mainstream technology, it may be useful in particular for countries that have large reserves of coal and want to exploit them while minimising their impacts on climate.

- **Nuclear power**

Nuclear power, based on the fission of atoms, is not an entirely "carbon-free" source of energy since considerable amounts of energy, some of which of fossil fuel origin, are required to extract and enrich uranium, to build infrastructure, and for operations, waste management and facility decommissioning. Nevertheless, nuclear power has a lower carbon footprint than fossil fuels, and it is advocated by many experts as one of the solutions to increase world energy supply while reducing GHG emissions.

Nuclear power is not a panacea, however, since:

- even with technological improvements, there are still important environmental, health and security concerns related to the safety of operations, the decommissioning of installations, the storage and disposal of highly radioactive waste and nuclear proliferation issues;
- it requires huge initial investment, with a tendency to overrun initially estimated costs by several factors – and has not so far been financially viable without significant public subsidies.

Large, fast-growing industrialised countries such as China and India have embarked on programmes to develop their nuclear power production capacity, but this is not a likely option for many developing countries in the foreseeable future.

- **Hydropower**

In the widest sense, hydropower refers to all forms of energy derived from the fall or flow of water, including mechanical energy (water wheels), as well as tidal and wave energy. In this document, hydropower is used in a narrower sense, to refer to hydroelectricity generated from river flows; tidal and wave energy are addressed further, in the sub-section dedicated to ocean energy.

On a global scale, hydropower is the most prominent source of renewable energy; in some regions of the world however, notably the African continent, it is still a largely untapped source of energy. Various techniques are used to tap the energy contained in running water. Large hydropower installations, connected to the grid, are usually coupled with a dam that allows the storage of water and its release at chosen times, to meet daily or seasonal peaks in demand; electricity production from such installations may conflict with other uses and priorities, such as making water available for downstream irrigation or creating artificial floods as a replacement for natural seasonal floods. Smaller installations, referred to respectively as mini- and micro-hydropower[6], do not necessarily involve the existence of a dam nor any diversion of water; they typically use only part of the stream flow, and can work in run-of-the-river setups. They can be used to produce off-grid electricity for local use in remote areas.

Significant social and environmental risks and issues are associated with large dams, which often require the displacement of populations and induce considerable changes in hydrological regimes, with multiple potential adverse effects such as the non-replenishment of some downstream aquifers, the destruction of fisheries, the proliferation of invasive aquatic plants, the destruction of biodiversity and ecosystems, a surge in water-related conflicts, etc.; in contrast, few or negligible risks and

[5] The Economist (2008), based on a study by the MIT, estimates costs at 25$/tonne to capture CO_2 and pressurise it, and an additional 5$/tonne to transport it to its final storage place.
[6] The capacity limits used to define the boundaries of 'mini' and 'micro' hydropower vary significantly across sources.

damages are usually associated with small-scale, run-of-the-river installations. There is no doubt that hydropower has a role to play in the development of the energy sector in many developing countries. This can be achieved at reasonable social cost if enough effort goes into preventing and mitigating the most adverse environmental and social consequences, the mechanisms of which are getting increasingly documented and understood – or if preference is given to decentralised, medium- and small-scale installations over large hydroelectric dams.

In some countries or regions, however, hydropower's potential may be significantly constrained by the effects of climate change, in particular reduced or more irregular and unpredictable water flows, and increased erosion (which leads to sediment accumulation in reservoirs). This should be taken into account when making strategic decisions and calculating returns on investment. Note also that environmental protection to prevent deforestation in critical watersheds is one of the best ways of securing the regular stream flows required for optimal production of hydroelectricity.

Low GHG emissions are generally associated with hydropower: the building of infrastructure (in particular large dams) typically involves the use of fossil fuels – but subsequent emissions are low. Studies have demonstrated that some water reservoirs, in particular shallow ones in tropical regions, release some methane (a more powerful GHG than carbon dioxide) into the atmosphere because of the anaerobic decomposition of vegetation in water – a problem that can be alleviated by removing vegetation from the area to be flooded prior to filling up the reservoir. Little is known at this stage about the complex mechanisms of carbon exchange between reservoir water and the atmosphere. In spite of these reservations, there is no doubt that the net carbon footprint of hydroelectricity is less than the footprint of fossil fuel-based electricity.

- **Biomass energy**

There are multiple sources of biomass, including forests, other types of terrestrial ecosystems (e.g. savannahs and grasslands), lakes and rivers (e.g. pilot projects are now testing the use of typha australis, an invasive plant species that has to be removed manually from rivers and irrigation channels, as a source of biomass energy), oceans (e.g. algae biomass) and agricultural lands. Residues from agricultural and industrial processes, as well as all types of organic wastes, can potentially be transformed into energy carriers such as heat, electricity, solid fuels (e.g. chips, pellets, briquettes), liquid fuels (e.g. methanol, bio-ethanol, biodiesel) and gaseous fuels (e.g. synthetic gas, biogas, hydrogen). The combustion of biomass and derived fuels, like the combustion of fossil fuels, generates GHG emissions. However, these emissions are not counted as net emissions as long as the biomass originates from renewable sources (e.g. forests, savannahs or fields in which vegetation re-growth will offset emissions from burning), or comes in the form of waste used to displace fossil fuels in energy conversion.

Biomass wastes from industrial and agro-industrial production, such as sugar bagasse and the by-products of the forestry, wood, paper and food industries, are increasingly being used as fuel for producing electricity, heat or a combination of both; they are also used in "co-combustion" or "cofiring" processes, in which they are burned together with fossil fuels. All types of organic wastes, including the organic fraction of municipal waste, can also be used to produce gas by means of anaerobic digestion processes (see script on Solid Waste Management).[7]

Biomass waste is of course not the only source of biomass energy. Biomass is exploited directly or with little transformation as a source of energy for households, and grown specifically to produce substitutes to fossil fuels for transport and other applications. These aspects are reviewed below in sub-section c), dedicated to transport fuels and domestic energy.

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[7] An alternative use for biomass waste is the production of biochar, i.e. charcoal produced from biomass using pyrolysis techniques. It can be used as a soil amendment, and has the advantage of allowing the storage of significant amounts of biomass carbon into soils, in a stable form. Biochar itself is not generally used as a fuel, but the oil and gas that are the by-products of the pyrolysis process can be used as such. (Source: Wikipedia)

- **Wind power**

Wind power enjoys growing success and installed capacity is growing fast (at a global rate of 30% per year recently), primarily in the developed world but also in some developing countries, and increasingly as a result of private rather than public initiatives (e.g. in India). Technology is improving fast, and wind energy is increasingly competitive with fossil fuels, especially if a carbon tax or similar mechanism is included in the price of fossil fuel-based energy. Infrastructure building often involves the use of fossil fuels, but beyond that stage wind turbines operate without generating emissions.

Wind farms can be installed on-shore and off-shore[8] and, unlike conventional power plants, they can be built gradually, reinvesting the revenues of initial operations to expand capacity as new capital becomes available. They generate some environmental impacts (although usually more local and less serious than some other types of energy infrastructure). The main drawback of wind turbines is that they are intermittent rather than continuous sources of energy – although in some very windy regions, reliability of supply can be rather good; some sites are clearly better than others from the point of view of generation capacity and reliability.

- **Solar energy**

Direct solar energy[9] is currently exploited on the basis of three technologies:

- solar water heaters, which accumulate heat to produce hot water for domestic or industrial applications;
- photovoltaic (PV) panels, which directly convert photon energy into electricity;
- concentrating solar power (CSP) plants, which use mirrors, parabolic reflectors and other devices to concentrate solar heat, transfer it to a working fluid, which in turn transfers the energy to a thermal power conversion system.

As in the case of wind energy, some locations are clearly superior to others from the point of view of generation capacity and reliability of supply. Lower latitudes have more potential than higher ones, and so do generally cloud-free areas compared with rainy areas. Fossil-fuel emissions are usually associated with infrastructure development (in particular the manufacturing of PV panels, which is energy-intensive) but not with operation. Solar energy has significant potential in particular in arid and semi-arid areas at low latitudes, including for instance in the Sahara desert; this potential could be enhanced by the development of direct current transmission grids, which compared with traditional alternating current grids involve reduced transmission losses: this would allow transporting electricity over the large distances that may separate power generation from consumption. Because of lower energy conversion rates, solar power usually makes much less sense (even from the strict point of view of mitigation, if the entire lifecycle is considered) at high latitudes.

Technological breakthroughs expected in the coming decade, notably in the field of photovoltaic energy, will make solar power technologies more affordable and versatile; they will modify the calculation of costs and benefits and the geographical ranges in which solar electricity can be considered sustainable.

- **Geothermal energy**

Geothermal energy plants exploit the heat naturally available in some fractured zones of the terrestrial crust to generate hot water and electricity (using steam turbines). With a few exceptions, it has been relatively little exploited so far but there is renewed interest at the moment, and the energy potential is significant in some developing countries (e.g. Great Rift Valley countries in eastern Africa). This

[8] Offshore wind farms require the development of direct (rather than alternating) power transmission networks, since unlike alternating current, direct current can be transported onshore by means of cables laid on the seabed.
[9] Fossil fuels, biomass, wind energy and wave energy all originate from solar energy, but in an indirect way.

source of energy can be more or less environmentally friendly, depending on local conditions. Fields of natural steam are rare: in most cases, steam has to be separated from hot water. Systems should be built to recover and re-inject the water into the reservoir – otherwise, to maintain pressure water has to be pumped from other sources and injected into the system, with a clear risk of over-exploiting local water resources. Other environmental concerns are related to the possibility of land subsidence and chemical pollution of waterways.

- **Ocean energy**

Oceans and seas contain energy that can be captured in various ways:

- tidal power and tidal stream power capture energy from the horizontal and the vertical movement of tides;
- wave power captures the (wind-driven) energy contained in waves;
- marine current power captures the energy generated by oceanic currents;
- ocean thermal energy conversion exploits differences in temperature between deep and surface waters (some systems also exploit differences in salinity gradients).

With perhaps the exception of tidal power, the exploitation of the energy contained in oceans is not yet in the mainstream, as most piloted technologies are not yet economically exploitable. However, there is great potential and research has recently shown some renewed interest in harnessing this source of energy for electricity production. As technologies improve, this may in future become a viable option for some developing countries.

C) TRANSPORT FUELS AND DOMESTIC ENERGY

- **Biofuels**

Increasingly, biomass is grown specifically for the purpose of producing liquid, solid or gaseous fuels, known as "biofuels" or "agrofuels", aimed at substituting fossil fuels. The primary use of liquid biofuels is as transport fuels, but other applications are possible (e.g. heating fuel, fuel for power generators); solid biofuels used for domestic applications include wood chips, pellets, briquettes and logs; biomass can also be converted into synthetic gas or "syngas" (made up essentially of a mix of carbon monoxide and hydrogen) that can be burned directly or converted into liquid fuels. Brazil, for instance, has a long tradition of producing ethanol from sugar cane to reduce its dependency on fossil fuels. Biomass can be used to produce substitutes for both gasoline (bio-ethanol) and diesel (biodiesel made from vegetal oils). Liquid biofuels can be mixed with traditional fuels of fossil origin, or completely replace them; an adaptation of engines is required in some cases (notably if the biofuel fraction exceeds a certain proportion).

The use of biofuels as a substitute for fossil fuels is a very controversial mitigation option – that is often driven as much by strategic considerations (reduced dependency on imports of fossil fuels) as by climate-related ones. The main environmental and social problems associated with the wide-scale development of fuel crops are the following:

- environmental damage (deforestation, destruction of natural ecosystems, loss of biodiversity, unsustainable use of water resources, pollution from the use of fertilizers and pesticides, …) resulting from the conversion of wilderness, forested or mixed agricultural land into large monoculture areas;
- competition with food crops, as well the production of livestock fodder and fibres; potential consequences of this competition include food security problems, rising prices of agricultural commodities (which hurt the urban poor in particular, and from which the rural poor may not benefit much) and increased malnutrition;

- adverse social consequences for rural and indigenous populations, who in situations of insecurity of tenure may lose access to their traditional lands to make way for large plantations or fields, and not be happy to have their livelihood options narrowed down, at best, to poorly-paid labour on large fuel crop estates; generally speaking, monocultures are not a source of balanced local development.

This is not to say that biofuels are never a sustainable mitigation option, but clearly the consequences of a switch to biofuels should be pondered very carefully and specifically in each situation. The problems described above may result in increased vulnerability of populations and ecosystems to the effects of climate change – in which case mitigation efforts result in maladaptation and are likely to do more harm than good. Furthermore, net emission savings may also be much less than expected, if the growing of fuel crops involves the use of fossil fuels (for tractors and machines and the production of synthetic fertilisers), destruction of peatlands and natural forests (which store more carbon than plantations and annual crops), and/or significant emissions of nitrous oxide as a result of excessive use of fertilisers. The mitigation potential of biofuels depends on the type of crop or biomass used, cultivation and harvesting techniques, energy conversion efficiency, the efficiency of end uses, and whether the produced biofuels are used locally or transported over large distances; it must be assessed on a case-by-case basis.

In spite of these reservations, there are cases in which the development of fuel crops may be a suitable and sustainable option. For instance:

- second-generation biofuels (which are not yet commercially available but are the subject of intense research) are likely to be much less damaging to the environment, and to avoid competition with food crops, since they will rely on improved conversion technologies (energy extraction from ligno-cellulosic biomass) and on a wider range of biomass resources (e.g. crop residues, forestry by-products), including resources that grow on marginal lands (e.g. grass);
- it may be possible to develop some fuel crops on lands that are not suitable for agriculture nor currently hosting rich ecosystems; for instance, jatropha, a drought- and pest-resistant, oil-rich plant from which biodiesel can be extracted, can grow with very little water on marginal lands in semi-arid regions; it is currently grown as a fuel crop in some Asian countries (e.g. Philippines, India), but could also be used in semi-arid African regions such as the Sahel; the pressed seeds that remain after oil extraction can be used to extract further energy, in bio-digestion and combustion processes; some sources indicate that jatropha can also be used to reclaim land threatened by desertification, control erosion and improve soil quality – but pursuing these goals may involve tradeoffs with fuel production;
- the small-scale, decentralised growing and processing of some fuel crops, in ways that: (i) respect environmental constraints and make limited use of water and fertilisers; (ii) do not involve the agricultural conversion of large tracts of wilderness; (iii) do not compete with local food production; and (iv) generate local employment, could provide some rural communities with a source of income as well as a cheap, local source of energy to meet their basic needs (e.g. use of vegetal oil as fuel for lamps, stoves and local power generators).

- **Hydrogen fuel cells**

Hydrogen, like oil products such as gasoline and diesel, is an energy carrier. Hydrogen-powered fuel cells, which use an electrochemical reaction between hydrogen and oxygen to produce electricity, have been identified over a decade ago as the next revolution in the field of energy (in particular for transport), but remain to a large extent experimental and unaffordable. This technology may become commercially available some time in the next two decades but is not yet mainstream. A big advantage of hydrogen fuel cells is that they emit only water as a by-product of the electricity-generating reaction – which would be a way of considerably reducing the air pollution generated by transport. However, there are still important technical hurdles to solve, notably regarding the distribution and storage of hydrogen.

In any case, hydrogen production involves environmental externalities and a more or less significant amount of GHG emissions:

- extraction from methane or natural gas by steam reforming methods (the most frequent case), or from coal by coal gasification, involves the use of energy as well as emissions of carbon dioxide;
- extraction from water by electrolysis is an energy-intensive process, so the extent to which hydrogen may contribute to reducing GHG emissions depends on whether the electricity is produced from carbon-intensive or low-carbon sources.

As a result, even assuming the technology matures in the coming one or two decades, its potential for mitigating GHG emissions will have to be assessed on a case-by-case basis. Furthermore, large-scale deployment would require the development of a “hydrogen economy” with integrated production, storage and distribution systems – which is likely to require significant upfront investment.

- **Battery-powered vehicles**

Whereas hydrogen fuel cell-powered vehicles are unlikely to become mainstream in the foreseeable future, battery-powered vehicles have better chances to become commercially available in the coming decade. At the moment, two types of vehicles powered by electric current are already available:

- hybrid cars store mechanical energy (generated when the brakes are used) into a battery, which is used to power the vehicle; since the battery’s range is limited, a traditional petrol engine takes over when the battery is exhausted or when travelling at high speeds;
- plug-in vehicles use conventional batteries recharged from the mains; their main drawback is their limited range.

‘Plug-in hybrids’ – i.e. vehicles that recharge their battery from the mains while also having a petrol-powered engine as a backup – may be close to mass production and soon become a favourite technical choice, at least in developed countries with solid power grids. Since most cars are used over short distances most of the time, plug-in hybrids may contribute to considerable emission reductions IF the electricity used to recharge them is produced from low-carbon sources of energy. Adoption by developing countries may be delayed by two main factors:

- the fact that batteries remain expensive, and may have to be changed several times over the lifetime of a vehicle;
- the dependence on a reliable supply of electricity for battery recharging.

- **Domestic fuels**

Solid biomass is exploited directly or with little transformation as a source of domestic energy, for cooking and heating (e.g. fuelwood, charcoal, dried cow dung). This type of energy is in principle renewable, but several problems are associated with it:

- in more and more places, population growth, demand from urban areas and increasing environmental and climatic pressures combine to make the collection of fuelwood unsustainable, with deforestation and accelerating desertification as a result;
- solid biomass fuels are often used in unsuitable conditions (e.g. inside houses without chimneys and with little or no ventilation, so that the smoke causes serious indoor air pollution), with adverse health consequences in particular for women and young children;
- solid biomass fuels are also often used without stoves or in very inefficient ones, in which as much as 90% of the heat produced is dissipated without being used.

The use of solid biomass as a substitute for fossil fuels for domestic use is therefore not usually considered a sustainable mitigation option; on the contrary, most development specialists advocate substituting solid biomass with electricity or “modern” fuels such as bottled gas, to improve health and reduce deforestation pressures. If electricity or gas comes from a renewable, low-carbon source, then this substitution should be neutral or even positive (avoided deforestation) in terms of GHG emissions. Otherwise, increased access to electricity and in particular rural electrification, and/or the increased use of gas bottles for cooking, may lead to an increase in net GHG emissions – which however should be balanced against considerable health, environmental and other benefits.

In some cases and in particular in isolated rural communities that are not connected to the grid and have little chance of being able to afford the use of gas bottles (not to mention probable logistic problems), the continued use of solid biomass fuels can also be made more sustainable, from an environmental and climatic point of view, by the adoption of improved, high-efficiency cooking stoves: with these simple, low-tech and relatively inexpensive devices, much less fuelwood is required to meet household needs, so the chances of sustainable use of local vegetation resources are improved. Fuelwood can be collected, but also grown locally in individual or community-managed plantations. Experiments are ongoing to produce charcoal on a sustainable basis.

- **Other sources of energy for households**

Solar power, wind energy and hydropower can all be used in small-scale, household-based or community-based installations to generate energy for households and small businesses. Possible applications include hot water production, lighting, recharging mobile phones and other batteries, basic refrigeration, cereal grinding mill operation, sugarcane crushing, extraction of oil from seeds, use of electrical tools in small workshops, etc. From the perspective of development, these local uses are particularly valuable in isolated rural communities, which don't have any immediate prospect of getting connected to the power grid. The availability of even small quantities of energy can bring about significant improvements in living standards and the ability to generate income. In places connected to a power grid, there is also a possibility for small producers to sell the excess electricity they produce, and thus recover their investment faster; however, this is unlikely to occur unless regulation exists to mandate the purchase of such electricity by grid operators.

D) ADDRESSING INTERMITTENCY IN THE SUPPLY OF SOME RENEWABLE ENERGIES

One problem associated with the development of some renewable energy sources (in particular wind and solar energy) is the intermittency and more or less important unpredictability of power generation: wind does not always blow at the required speed, sunshine is not continuous; hydropower generation, especially if of the run-of-the-river type, is also constrained by the availability of relatively regular stream flows. This may not matter too much in rural areas with local power generation systems unconnected to the national grid, where intermittent electricity supply is usually considered better than no electricity at all. At the national level however, and in particular when it comes to powering cities and industries that require constant and reliable supply, intermittency is a potentially serious problem. It has the following consequences:

- intermittent renewable energy sources cannot be relied on to meet demand for electricity at all times, and must thus be supplemented or backed up by other sources; natural gas power stations and hydropower stations with large reservoirs (if water availability is reasonably secure) offer the most flexible technical solution for backup, as they can be started and switched off at short notice; another option is to store surplus energy to release it when needed: for instance, some countries use "pumped storage" systems, in which the surplus power generated during some periods is used to pump water uphill and store it into dams: the water is then released at times when demand exceeds baseline supply; generally speaking, the use of diversified sources of energy, as well as increased geographical distribution of power generation facilities, reduce vulnerability to fluctuations in supply capacity; beyond measures adopted at the national level, developing grid connectivity at the sub-continental or continental scale, by allowing cross-country imports and exports of energy, reduces vulnerability to local drops in energy supply capacity and increases the resilience of the whole system;

- irregularity in power generation makes the management of the power grid more complex technically and potentially more vulnerable to incidents and blackouts; technical solutions exist (notably the use of backup supply resources that can be started and shut down at short notice) and are increasingly being perfected, but at the moment there are still clear technical limitations to the amount of power from "intermittent sources" that can be reliably connected to a national grid; in future, it is anticipated that "smart grids" will not only manage supply, but also use advanced software to manage and smooth demand, taking some particular users or systems (e.g. air conditioning systems, car battery recharging systems) offline (with prior consent and in exchange for lower tariffs) when demand threatens to exceed supply.

3.3. TECHNICAL OPTIONS ASSOCIATED WITH ENERGY TRANSMISSION/TRANSPORT AND DISTRIBUTION

Energy transmission and distribution offer fewer mitigation opportunities than energy conversion, but generally speaking, any gains in efficiency have the potential to contribute to mitigation efforts. Possible mitigation measures include:

- taking action to reduce as much as possible the energy losses associated with the transmission/transport and distribution of energy and energy products; this may involve, for instance, producing electricity closer to the places where it is used or, in pipeline networks, strengthening leak detection and automatic control systems;
- reducing power transmission losses by developing long-distance electricity transmission networks based on direct rather than alternating current (northern Europe is pioneering this approach): this technology is interesting because it could allow efficient power transmission over long distances, making solar fields or wind farms located in deserts and other remote places economically viable[10]; it also allows the laying of cables on the seabed – and thus the transfer of electricity from offshore wind farms to coastal areas;
- streamlining the distribution of fuels and other energy products and, if necessary, re-designing distribution circuits and transport modes to reduce the emissions associated with distribution (e.g. choice of low-emission means of transport); the GHG emissions associated with the distribution of fuels and other energy products should be taken into account when calculating their "carbon footprint" over a complete lifecycle.

3.4. CO-BENEFITS AND NEGATIVE SIDE EFFECTS OF SOME ENERGY-RELATED MITIGATION OPTIONS

Achieving emission reductions at the least cost for society should be the concern of all governments, in developed as well as developing countries. Many mitigation options in the energy sector appear economically more attractive if their co-benefits, i.e. the benefits other than those associated with GHG emissions, are taken into account. For instance:

- a switch from fossil-fuel combustion to combustion-free renewable energy sources is likely to result in a significant decrease in air pollution, and thus generate immediate health and environmental benefits at the local (as well as regional) level;
- even if some dependence on fossil fuels remains unavoidable in the short and medium term, switching from coal and oil to gas for power and heat generation already involves significant benefits in terms of reduced air, soil and water pollution (e.g. oil and coal extraction and transport are overall associated with more environmental damage than gas extraction and transport; coal combustion tends to generate more emissions of sulphuric acids, the cause of acid rains, than oil or, even better, gas combustion; the ashes that are the by-product of coal burning are toxic and frequently end up polluting the air, the soil and water at and around their storage place);
- environmental improvements can translate into significant health, productivity and other benefits (e.g. a cut in air pollution by acid particles reduces the incidence and severity of respiratory diseases,

[10] With the currently used technologies, electricity has to be produced closer to urban and industrial centres.

is beneficial for the productivity of agriculture, forestry and freshwater fisheries, and reduces the amount of damage caused to historical monuments and infrastructure);

- improving the efficiency of cooking stoves not only reduces emissions per unit of "useful energy" produced, but also reduces indoor air pollution and pressures on forests and the vegetation of other ecosystems;
- from a macroeconomic point of view, the replacement of fossil fuels with domestically available renewable energy sources has a positive effect on the balance of payments of countries that are net importers of fossil fuels;
- many investments in energy efficiency measures result in net financial gains (savings), both for enterprises and for consumers; for instance, replacing incandescent bulbs with compact fluorescent ones reduces consumers' overall energy bill (after amortization of the initial investment); so does the use of energy-saving household appliances; targeted subsidies may be useful in particular to help poor households make the required initial investments, which may otherwise be unaffordable for them.

These co-benefits are important not only because they may tilt the balance of cost-benefit analysis in favour of the adoption of climate-related mitigation measures, but also because they provide an incentive in the form of local and immediate benefits. Budget-constrained countries with poor populations cannot usually afford to make investments that provide most of their benefits at the global rather than the local level[11] and in the long run only – but such investments become much more attractive if they provide some direct, short-term benefits as well as indirect, long-term ones.

Conversely, some mitigation options may inadvertently result in increased vulnerability and threaten or cancel out adaptation efforts (e.g. biofuels may have adverse impacts on food security, water availability and ecosystems) – or even have a negative net impact in terms of mitigation (e.g. increased deforestation to accommodate cropland extension for producing biofuels). It is thus important to carefully consider the pros and cons and possible unintended effects (including negative ones) of any envisaged mitigation measures, from the point of view of climate change adaptation and mitigation and from other perspectives.

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