GREENHOUSE GAS EMISSIONS OF ELECTRICITY GENERATION CHAINS

ASSESSING THE DIFFERENCE

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Over the past decade, there has been increasing worldwide debate concerning the impact of human activities on the global climate system due to emissions of greenhouse gases (GHG). So far, discussions have focused primarily on anthropogenic releases of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halogenated compounds that contain fluorine, chlorine and bromine. Atmospheric concentrations of these gases have increased considerably since pre-industrial time, in fact, more than doubling in the case of methane.

In an effort to stabilize atmospheric concentrations at a level that would minimize the risk of major global climate changes, more than 130 countries ratified the United Nations Framework Convention on Climate Change (FCCC) at the 1992 Earth Summit in Brazil. This initial effort was later followed by the 3rd meeting of the Conference of Parties in Kyoto (December 1997), where decision-makers agreed on country-specific GHG emission reduction targets.

Presently, industrialized, or Annex I countries, are responsible for much of the worldwide release of greenhouse gases. Nearly two-thirds of GHG emissions can be traced to activities associated with electricity production and the transport sector. Compliance with the Kyoto Protocol by Annex I countries, therefore, will require a strong commitment to develop and exploit these sources of energy that are low emitters of carbon. Improvements in fuel-to-energy use conversion technology also will play a major role, as these countries look ahead to meeting future energy demands. Because developing countries are not bound by the Kyoto Protocol and their energy consumption is increasing, the rate of GHG emission is growing quite rapidly and their share is expected to dominate global releases by the end of the first quarter of the 21st century.

Given that the electricity generation sector is a major contributor of greenhouse gases (now accounting for one-third of the overall global emissions), the IAEA has undertaken -- as part of its programme on Comparative Assessment of Energy Sources -- a review of the GHG emissions from all the activities (chains) related to the production of electricity using fossil fuels, nuclear power, and renewables. A series of six Advisory Group Meetings (AGM) were sponsored by the IAEA from October 1994 to June 1998 covering the following fuel chains: lignite, coal, oil, gas, nuclear, biomass, hydro, wind and solar power. The outcome of these meetings was twofold. Firstly, participants developed a consistent set of GHG emission factors for the full energy chain from electricity generation. Secondly, they pointed the way to fuel and technology choices that could be exploited in facilitating compliance with FCCC commitments. This article presents and discusses the results and main conclusions of these meetings.

EMISSION FACTORS FOR GREENHOUSE GASES

The range of GHG emission factors for different types of fuel have been analyzed through various studies. The results are expressed in grams of carbon-equivalent (including CO_2, CH_4, N_2O, etc.) per kilowatt-hour of electricity (gC_{eq}/kWh). The graph on page 21 shows data from existing power plants (1990s technology) and emission factors for systems that are expected to be operative in the near to medium term (2005-2020 technologies).

The estimates reflect differences in assessment methodology, conversion efficiency, practices in fuel preparation and subsequent transport to the location of the

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GREENHOUSE GASES & ENERGY DEVELOPMENT

A series of fact sheets issued by the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) highlight how human activities produce greenhouse gases. Among the major points:

- Most important human activities emit greenhouse gases, and many of these activities are now essential to the global economy.
- Carbon dioxide from the burning of fossil fuels is the largest single source of greenhouse gas emissions from human activities. The supply and use of fossil fuels accounts for about three-quarters of carbon dioxide emissions from human activities.
- Most emissions associated with energy use result when fossil fuels are burned. Oil, natural gas, and coal furnish most of the energy used to produce electricity, run automobiles, heat houses, and power factories. If fuel burned completely, the only byproduct containing carbon would be carbon dioxide. But combustion is often incomplete, so carbon monoxide and other hydrocarbons are also produced. Nitrous oxide and other nitrogen oxides are produced because fuel combustion causes nitrogen in the fuel or air to combine with oxygen in the air.
- Extracting, processing, transporting, and distributing fossil fuels also releases greenhouse gases.

For more information, check the Climate Change Information Kit on the UNFCC's Internet site at www.unfccc.de.

power plant, and local issues, such as the fuel mix assumed for electricity requirements related to plant construction and manufacturing of equipment. Future rates include improvements in the fuel-to-energy service conversion process, reductions during fuel extraction and transport, and lower emissions during plant and equipment construction.

For the fossil fuels, the total rate of emission is the sum of stack emissions during fuel combustion and releases from up- and down-stream activities or chains. Typically, GHG emissions from power plant construction and decommissioning, and contributions from power lines connecting the plant to the grid are negligibly small. For instance, only 1% of the overall GHG emission can be attributed to plant construction and decommissioning.

For hydropower, solar and wind technologies, the size and type of the plant are key factors in the analysis. Considerations such as geographical siting and local construction regulations strongly influence the emission rate. The impact of these factors on the greenhouse gas rate or emission is shown in the graph.

Results of the IAEA-supported AGM meetings consistently show that fossil fuel technologies have the highest emission factors, with natural gas about half as much as coal or lignite and two-thirds of the estimate for fuel oil. Nuclear and hydropower, on the other hand, have the lowest GHG releases, 50 to 100 times lower than coal (depending on technology). GHG emissions from solar power are in between, about an order of magnitude higher than nuclear.

ANALYTICAL APPROACH

In a Life-Cycle Assessment (LCA), the goal is to account for the environmental burdens associated with the creation of a product by taking into account mass and energy flows at each step of the procedure. In the case of electricity generation, the final product is 1 kWh of energy.

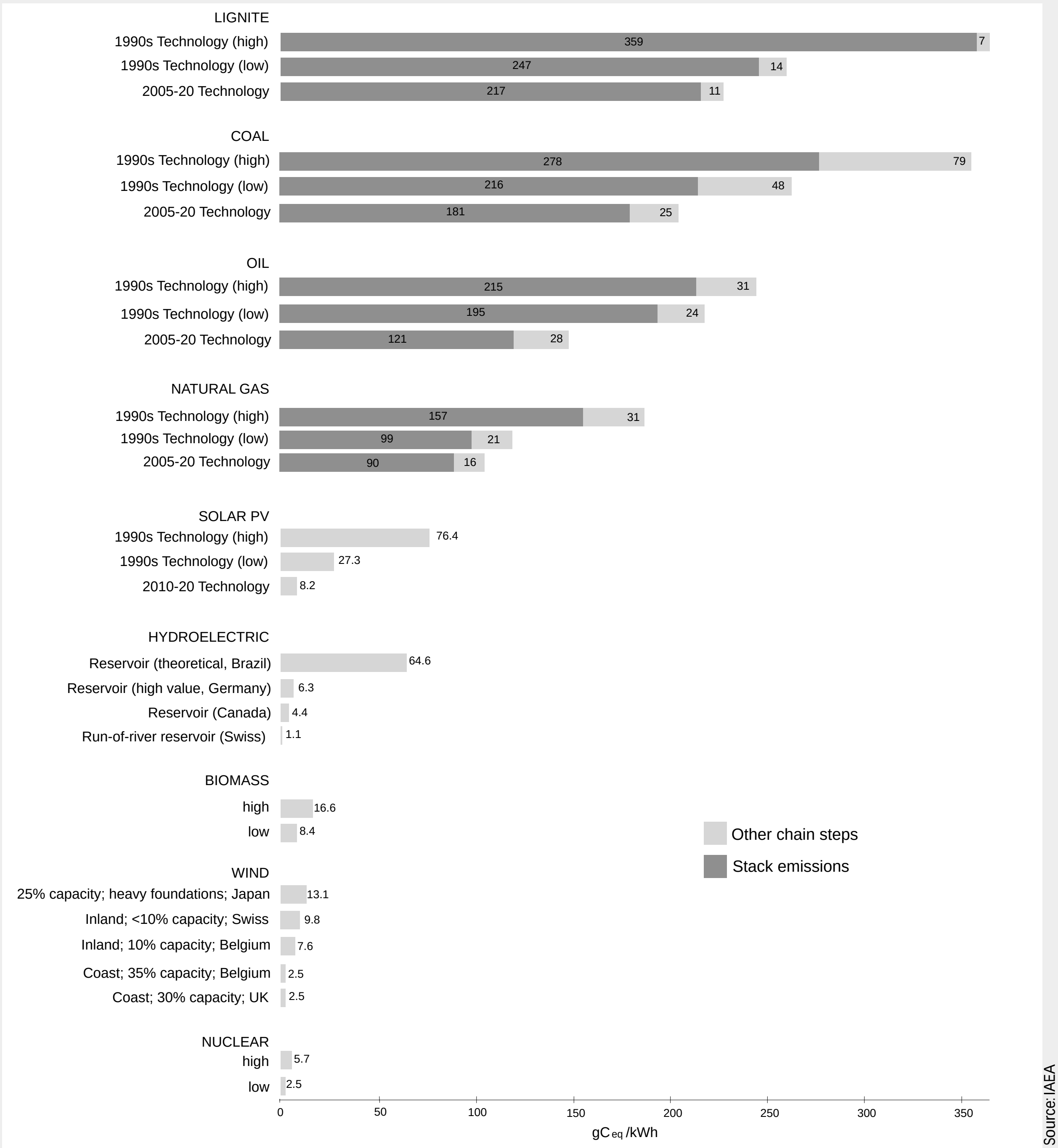
Sometimes, an LCA or Process Chain Analysis (PCA) is complemented by an Input-Output Analysis (IOA). Such an analysis takes into account the indirect emissions attributed to the different economic sectors that contribute to the creation of the final product, such as electricity used in processing, machine design and labor.

Neglecting these inputs leads to an under-estimation of the environmental consequences by artificially reducing the system boundaries of the analysis. For example, a comparison of GHG emission rates for fossil fuels using the IOA approach is 30% higher than the equivalent which is obtained following the PCA method. In the case of nuclear power, the deviation can be even more pronounced, up to a factor of two.

SYSTEM BOUNDARIES OF ANALYSIS

When comparing different energy systems, the choice of system boundary is important. For example, ignoring up- and

RANGE OF TOTAL GREENHOUSE GAS EMISSIONS FROM ELECTRICITY PRODUCTION CHAINS



down-stream activities for the fossil fuel cycles would underestimate the total GHG emission rate between 5% and 25%. For nuclear power and renewable fuels, there are no GHG emissions at the point of generation, but there are atmospheric releases during fuel mining, preparation and transport, plant construction and decommissioning, manufacturing of equipment and decay of organic matter. The level of emissions depends strongly on technology and geographical siting of the power plant.

A Full Energy Chain (FENCH) calculation, which considers all the steps from "cradle-to-grave", is perhaps the fairest way to compare climate and environmental burdens of different fuels and different technologies for producing electricity. Analytical capabilities and common sense will ultimately dictate the choice of system boundaries. At the very least, emission intensities should include the fuel supply chain, the power production stage and for nuclear and renewables, contributions from plant construction and materials requirements. A more detailed analysis could extend the system boundary all the way to energy end-use, i.e., down to the appliance level.

For intermittent technologies such as wind, solar and hydropower to a lesser degree, the question arises whether the system analyzed should include backup (secondary) power or not. The preferred approach is to calculate the emissions for primary and backup systems separately. The advantages are threefold. Firstly, the emissions for the primary system are determined strictly on the use of a given technology. Secondly, the influence of annual yield or availability (hours of operation per year) can be clearly ascertained. And thirdly, it permits comparison of different backup options.

GLOBAL WARMING POTENTIAL

The Global Warming Potential (GWP) is a measure of the ability of a gas in the atmosphere to trap heat radiated from the earth's surface compared to a reference gas, which is usually assumed to be carbon dioxide. The atmospheric lifetime of gases varies greatly, and therefore, the results are integrated over different time intervals. Usually, a time horizon of 100 years is selected.

Provided below are the most recent estimates of the GWPs (100 year time horizon). They were calculated by the International Panel on Climate Change for the most commonly emitted greenhouse gases from the electricity generation chain:

- carbon dioxide (CO_2)= 1;
- methane (CH_4)= 21;
- nitrous oxide (N_20) = 310;
- sulphur hexafluoride (SF_6) = 23,900;
- tetrafluoromethane (CF_4)= 6500;
- hydrofluorocarbons (HFCs): HFC-134a = 1300;
- chlorofluorocarbons (CFCs): CFC-114 = 9300;
- hydrochlorofluorocarbons (HCFCs): HCFC-22 = 1700.

CONVERSION EFFICIENCY

Fuel-to-electricity conversion efficiency and power plant load factor both influence the rate of emission of GHG during fuel combustion. The GHG emission factor decreases when either the conversion efficiency or the load factor is increased. CO_2 emissions depend on the carbon content of the fuel and the conversion efficiency; N_2O rates are driven primarily by process considerations, while methane discharges are linked primarily to fossil fuel supply practices. Roughly speaking, the emission rate varies inversely with conversion efficiency. At exactly 40% efficiency, an additional increase of 1% reduces the GHG emission rate by 2.5%. For lower efficiencies, the reduction in the emission rate is more pronounced, while for higher conversion rates the opposite is true. The thermal efficiency always decreases with decreasing load factor, and the change is highly dependent on technology.

Typical conversion efficiencies for present day operating systems are in the range: 27% to 40% for lignite-fired plants, 30% to 45% for coal, 34% to 43% for oil and 35% (for peak load applications) to 55% for natural gas. Power plants with lower efficiencies are usually those located in developing countries.

In the medium term, conversion efficiencies for best available technologies are expected to be in the range of 50% to 55% for coal and 60% to 65% for gas-fired power plants.

For nuclear and renewable fuels, environmental emissions from improvements in power conversion will have a smaller impact because there are no stack emissions, rather releases are related to fuel supply, plant construction and manufacturing of materials. Indeed, fuel requirements and total emissions will decrease as newer technologies contribute to higher efficiencies.

FUTURE GENERATION SYSTEMS

Newer and more efficient technologies will inevitably displace current systems, although in the near to medium term (over the next

CONTRIBUTING FACTORS TO EMISSION RATES

The rate of emission of greenhouse gases is influenced by numerous factors. The dominant parameters for each fuel type are summarized here.

Fossil Fuels

- Fuel characteristics such as carbon content and caloric value;
- Type of mine and location;
- Fuel extraction practices (affecting transport requirements and methane releases);
- Transmission losses for natural gas;
- Conversion efficiency;
- Fuel mix for electricity needs associated with fuel supply and plant construction/decommissioning.

Hydropower

- Type (run-of-river or reservoir);
- Plant location (tropics vs. northern climate);
- Energy use for building the dam;
- Emissions from plant construction (concrete and steel), which dominate the total for run-of-river type and "Alpine-type" (mountainous) reservoirs. For large reservoirs whose surface-to-volume ratio is large (typically located in northern areas such as Canada and Finland) and in humid tropical regions (Brazil), the GHG emission rate is influenced by the decay of biomass covered during flooding and oxidation of surface sediment (responsible for large CH_4 emissions). CO_2 emissions exceed CH_4 rates by at least a factor of ten for "northern-type" reservoirs.

Biomass

- Feedstock properties (moisture content and heating value);
- Energy use for feedstock requirements (growth, harvesting, and transport);
- Plant technology.

The carbon dioxide emission factor for biomass combustion is neutral. This means that the carbon released during the burning of the biomass is equal to the biogenic uptake during plant growth.

Nuclear Power (light-water reactor)

- Energy use for fuel extraction, conversion, enrichment and construction/decommissioning (plus materials);
- Fuel enrichment by gas diffusion, which is an energy intensive process that can increase GHG releases by an order of magnitude when compared to enrichment by centrifuge;
- Emissions from the enrichment step, which are highly country-specific since they depend on the local fuel mix;
- Fuel reprocessing (uranium oxide or mixed oxide), which can account for 10% to 15% of the total nuclear GHG burden.

Wind

- Energy use for blade manufacturing and building of installation (tower and foundation);
- Electricity mix and construction regulations, which are highly country- and site-specific (inland vs. coastal unit, for example);
- The annual yield or capacity factor (depends on natural siting situations), which identifies the frequency of operation (availability) of the installation. The average wind speed is the key parameter when estimating the degree of intermittence in the generation (an increase of 50% in wind speed, roughly doubles the annual yield).

Solar Photovoltaic (PV)

- Quantity and grade of silicon used for cell manufacture;
- Type of technology (amorphous vs. crystalline material);
- Type of installation (rooftop vs. facade);
- Fuel mix for electricity requirements;
- Annual yield and assumed lifetime of installation, which are important considerations when calculating emissions per kWh (this is also true for wind energy). Solar and wind power have relatively low emissions per kW, but high values per kWh due to lower capacity factors (i.e., intermittent technologies).

10 to 20 years) in industrialized countries, sweeping changes in electricity generation technologies are not anticipated given the large sums of money already invested in energy technology and infrastructure. The development of new energy systems is not so clear for developing countries, which are faced with tough choices involving economic, social, political, and environmental issues.

Environmental mitigation, economic, and political factors will drive the interest in promoting and implementing the use of improved technologies and expansion in the use of renewable sources such as biomass, wind, and solar power.

For fossil fuel systems, the biggest changes will come from improvements in conversion efficiency of existing technologies (ex., combined cycle operation), reductions in methane leakage rate from transmission of natural gas, enhanced recovery of methane during fuel mining, controlling of fuel chemical properties (for instance, washing of coal to improve its caloric value) and optimal location of the power plant so as to minimize emissions from fuel transport and power transmission losses. In Europe, experts have estimated that emissions from future fossil-fueled systems could be lower than current rates by 35% to 50%.

For nuclear power, major changes will involve enrichment of fuel by centrifuge (or laser technology) rather than the energy intensive gas diffusion process, improvements in conversion efficiency, expanded use of fuel reprocessing and future advances in nuclear technology for generating electricity. *(See related articles, pages 43 and 51.)*

Improvements in turbine technology will influence emissions from hydropower, while for intermittent systems reduced material and component requirements and changes in conversion efficiency will boost performance. This in turn will lower costs and emissions. Geographical siting of hydropower plants, as well as the type of installation, will remain important issues.

CONCLUDING REMARKS

Greenhouse gases have to the potential to influence global climate change by interfering with the natural process of heat exchange between the earth's atmosphere and outer space. Reducing atmospheric GHG concentrations have become an international priority as evidenced by the signing of the Kyoto Protocol, which would reduce emissions from industrialized countries (Annex I) by about 5% below 1990 levels during the commitment period 2008-12.

There are a number of technical options that could be implemented in order to achieve the proposed reduction target. As for emissions related to electricity generation, perhaps the most important factor over the near term is the improvement in efficiency of using energy at all the stages of the fuel cycle, including fuel preparation and transportation, fuel-to-electricity conversion at the power plant and at the point of end-use (which has not been considered here).

Strategies for reducing methane releases during fuel mining and during gas transmission are very relevant. Switching to less carbon intensive or low carbon fuels, such as gas, nuclear power and renewables, will play a major role in reducing emissions. These changes are technically feasible using present day knowledge and experience, require minimal changes in consumer lifestyle, and represent reasonable capital turnover (gas and nuclear for baseload generation and renewables in niche markets or for peak load applications).

This article has presented information on GHG emission factors for different fuels using a Full Energy Chain approach, which attempts to quantify the environmental emissions from all stages of electricity generation, i.e. "cradle-to-grave". Fossil-fueled technologies have the highest emission factors, with coal typically twice as high as natural gas.

Considering the large variations in fuel-to-electricity conversion technology, it can be said that GHG emission factors can be an order of magnitude higher than current solar PV systems and up to two orders of magnitude higher than nuclear and hydropower. GHG estimates for wind and biomass chains lie between solar and nuclear results.

One important conclusion cannot be stressed enough: it is that no technology used in connection with energy supply and use -- be it electricity production, transport or other -- is associated with zero greenhouse gas emissions. Variations in the emission factor for different options, however, can be quite significant. This fact certainly will have an influence in the decision-making process affecting the choice of power plants that will be included in future national energy systems. ❐