SELECTING FUTURE ELECTRICITY GENERATION OPTIONS IN CONFORMITY WITH SUSTAINABLE DEVELOPMENT OBJECTIVES

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Abstract

The complexity facing today’s energy planners and decision-makers, particularly in electricity sector, has increased. They must take into account many elements in selecting technologies and strategies that will impact near term energy development and applications in their countries. While costs remain a key factor, tradeoffs between the demands of environmental protection and economic development will have to be made. This fact, together with the needs of many countries to define their energy and electricity programmes in a sustainable manner, has resulted in a growing interest in the application of improved data, tools and techniques for comparative assessment of different electricity generation options, particularly from an environmental and human health viewpoint. Although global emissions of greenhouse gases and other pollutants, e.g. SO₂, NOₓ and particulate, must be reduced, the reality today is that these emissions are increasing and are expected to continue increasing. In examining the air pollutants, as well as water effluents and solid waste generated by electricity production, it is necessary to assess the full energy chain from fuel extraction to waste disposal, including the production of construction and auxiliary materials. The paper describes this concept and illustrates its implementation for assessing and comparing electricity generation costs, emissions, wastes and other environmental burdens from different energy sources.

1. INTRODUCTION

The supply of adequate and affordable energy services is an essential element of sustainable development. For the energy system in general and for the electricity sector in particular the challenge is to provide the energy services required for supporting economic development and improving quality of life, especially in developing countries, while simultaneously minimizing health and environmental impacts of anthropogenic activities. All technology chains for electricity generation encompass a certain level of health risk. As well, all technology chains--form resource extraction to the production of energy services--interact with the environment causing varying degrees of damage to the environment. Health and environmental impacts associated with current energy production and use are increasingly felt in many countries.

The need to design and implement sustainable strategies in the electricity sector has been repeatedly stressed during international fora such as the Senior Expert Symposium on Electricity and the Environment (Helsinki, 1991), the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, 1992) or the 16th Conference of the World Energy Council (Tokyo, 1995). Agenda 21, adopted by UNCED, emphasizes that environment and development concerns should be integrated into the decision making process. The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasizes that mitigation options for alleviating the risks of global climate change should be comprehensively assessed and adequate policies be implemented to promote the installation of the most environmentally benign energy conversion technologies.
2. THE DECADES PROJECT

The joint inter-agency project on Databases andethodologies for Comparative Assessment of Different Energy Sources for electricity generation, in short DECADES [1], was established at the end of 1992, when nine international organizations (EC, ESCAP, IAEA, IIASA, IBRD, OECD/NEA, OPEC, UNIDO and WMO) agreed to join efforts to enhance data bases and methodologies for comparative assessment of different energy sources and conversion technologies. The aim of the project is to facilitate the development of sustainable energy strategies as an integral part of contemporary planning and decision making in the electricity sector.

The DECADES Computer Tools developed in the first phase of the project, consist of databases and analytical software (DECPAC). These tools can be used for evaluating the always existing trade-offs between technical, economic and environmental features of different electricity generation technologies, chains and systems at the national, regional and international levels.

2.1. Databases

A comprehensive, up-to-date and consistent set of technology, economic and environmental data is a necessary prerequisite for any comparative assessment of different electricity generating pathways. For DECADES two types of technology databases were developed: the Reference Technology Database (RTDB) and Country Specific Databases (CSDBs).

2.1.1. Reference technology database

The Reference Technology Database (RTDB) provides a comprehensive, harmonized set of technical, economic and environmental data for energy chains that use fossil fuels, nuclear power, and renewable energy sources for electricity generation. RTDB addresses all stages of the source-to service chain, i.e., from energy source extraction to electricity services and waste disposal (Figure 1). The database has built in checks to verify the accuracy of information provided by the users (eg, fuel heating value or facility emission factors). The Agency has circulated the RTDB for peer review and organized several Advisory Group Meetings to verify the accuracy of information contained in the database. At present, the RTDB contains data for about 300 technologies, characterized according to their level of maturity (e.g., matured, commercially deployed, demonstration stage, etc.).

2.1.2. Country specific databases

Country specific databases (CSDBs) store data on electricity generation technologies for various countries or regions for the purpose of carrying out case studies with the DECADES analytical software or other national planning tools. The CSDBs accommodate site-specific data, which are not stored in the RTDB. More than twenty-five countries have developed CSDBs, containing a total of more than 2,500 technologies.

The DECADES databases have a flexible structure which not only allows users to modify values for a predefined set of characteristics but also to add new characteristics to the facilities and energy forms. Hence, the DECADES database management system can be used to transfer data to and from analytical tools (e.g., DECPAC, ENPEP, WASP, or other national planning or impact assessment tools).
2.2. Analytical software

The specific objective of the DECADES software is to provide the users with an easy to use tool for carrying out decision support studies for the power sector. The DECADES analytical software is designed to access information stored in the technology databases for analysis and comparison of costs and environmental burdens at the power plant, energy chain and electric system levels. Its design focuses on user friendliness, short turn-around time for the optimization of electricity system expansion strategies and extensive reporting capabilities.

2.2.1. Plant level analysis

Plant Level Analysis adjusts power plant characteristics automatically based on the type of fuel and pollution abatement technology specified by the user. It also estimates air emission factors for main pollutants as well as electricity generation costs and calculates technical, economic and environmental performance changes resulting from adding a control device to a plant.
2.2.2. Chain level analysis

Chain level analysis supports the comparative assessment of full energy chains for electricity generation, from resource extraction to electricity service generation and waste disposal. A flexible interface facilitates rapid construction of energy chains and ensures the validity of energy chain representations. Chain level results include: Levelized generating costs, mass flow of fuels and waste, total greenhouse gas emissions (CO₂ equivalent), pollutants affecting local air quality and regional acidification, water effluents, solid waste generation and land use. Emissions from auxiliary material inputs and materials for construction and dismantling of generating stations are also calculated.

2.2.3. System level analysis

System level analysis allows users to quickly screen electricity system expansion strategies and to conduct comprehensive studies. The system planning tool, DECPAC, contains three analysis options, ranging from preliminary analysis tools based on screening curves to sophisticated least-cost optimization with dynamic programming. DECPAC has core features derived from the IAEA’s WASP and ENPEP models with an enhanced graphical interface, improved computation of environmental residuals (e.g., air pollutant emissions, land use and waste generation) and extensive reporting capabilities.

3. SOME ILLUSTRATIVE APPLICATIONS OF THE DECADES COMPUTER TOOLS

The following section illustrates some applications of the databases and software developed in the Phase I of the DECADES project for comparative assessment studies.

3.1. Comparison of power plants

Figure 2 compares the net generating efficiency values of several types of power plants (conventional as well as those under development) included in RTDB. It may be noted that while significant improvements in the generating efficiency may be obtained for the conventional technologies based on gas, the expected efficiency improvements for the other conventional technologies are less impressive. However, new technologies, with conversion processes other than combustion and advanced power cycles, will eventually surpass the best performance of current technologies.

The generating efficiency data are strongly influenced by the characteristics of the fuel used, maintenance of the power plant and other local conditions. Plant efficiencies vary from country to country and in many countries are lower than the values presented in Figure 2 for coal, oil and gas fueled electricity generation technologies.

Figure 3 illustrates a comparison of the CO₂ emission factors for the following types of power plants: pulverized coal with flue gas desulphurization (PC+FGD), pressurized fluidized bed coal combustion (PFBC), integrated coal gasification combined cycle (IGCC), gas turbine combined cycle (GTCC), oil fired steam turbine (OSB). The power plants have the same size (500 MW) and the coal fired plants use similar coals. The highest CO₂ emissions result from the coal-fired options. These technologies display a considerable range of CO₂ emissions as a result of variations in efficiency of power generation. The CO₂ emissions obtained from the GTCC plant are less than half of those from coal. The emissions from oil fired units are within
FIG. 2. Comparisons of net generating efficiency for RTDB technologies\(^1\) (Source: RTDB).

FIG. 3. Plant emissions of fossil-sourced electricity generation (Source: RTDB).

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the spread of the natural gas and coal, and depend upon the quality of heavy oil used. The emissions depend on the fuels’ carbon contents (highest for coal, lowest for natural gas), technologies’ generating efficiencies, pollution control measures included in different designs, and other factors. The emission factors presented in Figure 3 are given for currently best available technologies and good quality fuels. Similar comparisons [3] can be carried out for other pollutants such as SO₂, NOₓ, particulates, etc.

The economic comparative assessments carried out at the power plant level using RTDB and CSDB data show that nuclear power is a competitive option for generating electricity in many countries. Figure 4 displays the total capital requirements for pulverized coal fired plants (PC), oil steam boiler plants (OSB), gas turbine combined cycle plants (GTCC) and nuclear (PWR, PHWR) plants in several countries. As expected, the total capital requirements per unit capacity vary from country to country, but the range is not large for similar technologies.

Figure 5 illustrates the variation of electricity generation costs for the several candidates for generating capacity expansion for an energy importing developing country (Pakistan). Here nuclear power appears to be a least-cost option for base load electricity supply. Algorithms were developed to support a modular approach to air pollution abatement technologies. This allows analysis of the impact of pollution abatements on the emissions and costs of a power plant. The analysis is based on the data stored in RTDB/CSDBs and includes: capital and overnight costs, fixed and variable operation and maintenance (O&M) costs, reagent consumption, if any, internal electricity consumption, and the impact on efficiency of adding abatement devices to the power plant.

3.2. Comparison of chains

Figure 6 illustrates maximum and minimum GHG emissions for solid, liquid, gaseous, hydro, nuclear, wind, solar and renewable electricity generation pathways. Taking into account the entire up-stream and down-stream energy chains for electricity generation, nuclear power emits 40 to 100 times less carbon dioxide than currently used fossil-fuel chains. Greenhouse gas emissions from the nuclear chain are due mainly to the use of fossil fuels in the extraction, processing, and enrichment of uranium and to fuels used in the production of

![Graph showing investment costs for power plants of different technologies](FIG. 4. Investment costs - power plant level (RO - Romania, PK - Pakistan, TR - Turkey, HR - Croatia) (Source: CSDBs))
steel and cement for the construction of reactors and fuel cycle facilities. These emissions, which are negligible relative to those from the direct use of fossil fuels for electricity generation, can be reduced even further by energy efficiency improvements. Such improvements at the enrichment step include, for example, replacing the gaseous diffusion process by less energy-intensive processes such as centrifugation or laser isotope separation. Figure 6 also shows uncertainty ranges. Among the fossil fuel chains, natural gas has the widest uncertainty, mainly due to different assumption concerning methane releases to the atmosphere during drilling, extraction and transportation of natural gas.

The emissions listed here are calculated for full load power operation of a particular power plant without considering possible interaction with other chains or load dispatch impacts. Significant differences may result when such interactions are taken into consideration, as is provided at system level analysis.

It may be also pointed out here that the very low levels of radioactive emissions from routine operation of nuclear energy facilities are generally considered to be harmless for human health and the environment as the public exposure due to these emissions are far below those from the natural background. Furthermore, in the case of nuclear power, the external costs arising from ensuring safety, and for radioactive waste management and decommissioning of facilities, are internalised by including them explicitly in the price of electricity generated from nuclear power [4]. On the other hand the external costs arising from

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2 DCOAL: Domestic coal; FOIL: Fuel Oil; GT: Gas Turbine; GTCC: Natural Gas Combined Cycle; WFGD: Imported coal pulverized Coal + Wet Scrubber, NUCL: Nuclear (Source: CSDBs)
the adverse environmental and health impacts of other electricity generating pathways have not yet been properly estimated and, as such, still remain to be fully internalised.

3.3. Power system expansion

The DECPAC software can be used to determine environmentally sound least-cost expansion plans for electricity generation systems or to analyze whether a particular project fits into the robust long-range least-cost development plan for a country or region. It can also be used in an iterative manner to investigate least-cost methods to reduce environmental burdens (e.g., minimum system costs to meet targets for reducing sulfur dioxide or greenhouse gas emissions).

The optimization of the expansion plan is performed taking into consideration the capital investment costs, the operation and maintenance cost, the fuel cost, the fuel inventory cost and the cost of energy not served.

Once the optimum expansion plan has been developed, DECPAC allows for the calculation of air emissions, land requirements and production of solid wastes, year by year and step by step, for every energy chain included in the system, so that the totals for the entire electricity system are given.

3.4. Comparative assessment case studies

Under the DECADES project, twenty-two country case studies on comparative assessment of alternative strategies and policies for the electrical power sector were carried
out, supported by the IAEA through a Coordinated Research Programme (CRP). The case studies sought to identify electricity generation strategies that would meet the objectives of environmental protection, in particular reduction of atmospheric emissions at acceptable cost. A broad range of issues such as: assessing the potential role of nuclear power in reducing the greenhouse gas emissions; effects of CO$_2$ taxation and/or emission constraints on future generation mix and impact of privatization and deregulation of electricity sector on electricity system expansion strategies and others have been addressed in these case studies.

Significant reductions of emissions and other environmental burdens can be obtained by improving the efficiency of existing facilities at different levels of the energy chains. The rehabilitation of existing power plants, in particular by adding pollution control technologies, was often found a cost effective measure for mitigating local air quality and regional acidification impacts. Improving the overall efficiency of energy systems by promoting co-generation was identified as a cost-effective option in many countries, especially where heat distribution networks already exist for district heating. In most of the studies addressing capacity expansion, nuclear power proved cost-effective for reducing emissions of SO$_2$, NO$_x$, CO$_2$ and other greenhouse gases. Figure 7 illustrates the results obtained for a gas expansion scenario versus a nuclear expansion scenario in Romania. Large reduction of CO$_2$ emissions may be obtained by using nuclear power plants in the power system expansion without any significant increase in the total system expansion cost. For the gas scenario, although the CO$_2$ emissions are reduced in comparison with coal dominated scenarios they are significantly increasing over the study period. The SO$_2$ and NO$_x$ emissions (see Figures 8 and 9) will decrease in both scenario but, in the nuclear expansion scenario, the decrease is approximately 30% higher that in the gas scenario.

Some studies also showed that, although CO$_2$ emission reduction targets could be achieved without nuclear power, its use would lead to significantly lower costs. It may be pointed out here that the implementation of environmental protection measures and policies, including more stringent atmospheric emission limits are likely to increase the cost of electricity from fossil-fueled power plants that will have to comply with these regulations by adding pollution abatement technologies and/or switching to higher quality fuels (e.g. low sulfur coal) that are generally more expensive. Furthermore, global climate change concerns are leading many countries to consider policy such as carbon taxes, that would affect the competitiveness, and/or limit the use of fossil fuels for electricity generation. In the Romanian case, CO$_2$ abatement costs based on the accelerated use of nuclear power are approximately US$5/ton CO$_2$ or US$18/ton C which is at the bottom end of the range US$0 to US$120/ton C reported in IPCC [6].

In most of the case studies carried out the natural gas combined cycle power plants which are very attractive from the point of view of generating efficiency (58% or higher), capital requirements and short construction periods were considered as candidates for electric system expansion. However, operating experience for 1995 shows problems in the reliability of such plants. Furthermore, the limited resources of natural gas and the escalation of the natural gas price, the losses of methane during pipeline transportation as well as the service and technical support problems in developing countries are additional reasons to be taken into account when considering this option.

The cooperation that has been established through this CRP, involving experts from different countries and having different scientific backgrounds, has proven to be extremely valuable and effective. In particular, the cooperation and exchange of information and
experience between different teams who are confronted with similar difficulties, such as
data collection, technology description, fuel chain definition and comparison, and electric
generation system analysis, resulted in identifying and implementing common approaches for
solving such problems. The participation of experts in the fields of electricity system analysis,
macro-economics and environmental impact assessment led to a recognition of the need to
reconcile various concerns and priorities - e.g., alleviating local and global environmental
impacts and also addressing economic, social and security of supply issues - within a
comprehensive assessment of alternatives.

FIG. 7. $CO_2$ emissions in Romania over the study period (Source: DECADES Case Studies).

FIG. 8. $SO_2$ emissions in Romania over the study period. (Source: DECADES Case Studies).
4. CONCLUDING REMARKS

The comparative assessment of comprehensive source-to-service pathways of different energy sources and conversion technologies is key to the development of sustainable energy supply strategies. The DECADES project provides the necessary methodology and tools for performing such assessments. The dissemination of the DECADES activities and results to Member States is an ongoing process. Inter-regional workshops on the use of the DECADES Computer Tools were held at Argonne National Laboratory (ANL) in USA (1995 and 1996), in Poland (1996) and in Brazil (1997). Also, seminars and workshops were held in Canada, USA, UK, Brazil and Republic of Korea. The high interest manifested by institutes, organizations and universities in Member States in participating in these events is a good indicator for the usefulness of the DECADES approach.

The comparative assessment studies based on DECADES show that nuclear power is economically competitive with other base load generation options and generates significantly lower emissions of SO$_2$, NO$_x$ and CO$_2$ than any fossil-sourced option. While coal and/or gas fired power plants may be attractive in countries having access to inexpensive domestic fossil sources, their economic competitiveness might become questionable in the context of more stringent environmental protection regulations and standards requiring the implementation of pollution control devices and limitations to greenhouse gas emissions. Most renewable energy sources offer interesting prospects for environmentally friendly electricity generation systems. However, the potential role of renewable energy sources, other than conventional hydro power, for large scale electricity generation, may be limited by physical constraints in some regions and, moreover, they are unlikely to be economically competitive with fossil fuels and nuclear power in the short and medium term.
REFERENCES


[2] Reference Technology Database (RTDB) - Overview and General Description (in preparation), IAEA.


