Sustainable development & electricity generation: Comparing impacts of waste disposal

The IAEA and other organizations are evaluating approaches for comparing wastes and disposal methods from energy chains

by Roger Seitz

Health and environmental impacts that may result from disposal of waste are a growing concern for sustainable development of human society. Waste posing potential hazards to human health and the environment is generated in a number of industry sectors (mining/quarrying, agriculture, manufacturing, electricity generation, medical, etc.). When properly managed, this waste will pose minimal risks to human health and the environment.

However, environmental concerns arise from the fact that the quantity of waste being generated is growing (and expected to keep growing) as a result of increases in the world population, industrialization, and urbanization. Thus, one challenge in developing a strategy for sustainable development is to provide the services necessary to support economic growth and improving quality of life, while limiting the waste generated in terms of potential hazards and quantities and its health and environmental impacts.

As sustainable development brings better living conditions to a growing world population, greater use of energy, especially electricity, will be demanded. Until a suitable alternative capable of meeting the growing demand for electricity is developed, the vast majority of future electricity demand will need to be met by conventional fuels such as coal, natural gas, oil, and uranium/thorium. Thus, sustainable development strategies must include consideration of the waste that is generated throughout energy chains based on these fuels.

This article provides an overview of the initial stages of an IAEA project to compare wastes and disposal methods from different electricity generation systems and to review approaches used to assess and compare the health and environmental impacts resulting from disposal of such waste. The role of nuclear power in a strategy for sustainable development of human society is emphasized. In this respect, the article highlights the small mass of waste generated as a result of nuclear power when compared to the total mass of waste from all energy chains and other common activities. Selected waste and respective disposal methods from all steps in the energy chains for electricity generation are discussed. (Liquid and gaseous effluents that are discharged directly to air or natural water bodies are not included in this article.) Emphasis is placed on the importance of considering all steps in the energy chains, which yields information on large quantities of waste posing potential long-term impacts from electricity generation systems that are often considered "clean". Radionuclides that are present in many non-nuclear wastes are also discussed.

Waste management and sustainable development

The Organization for Economic Co-operation and Development (OECD) estimates that roughly nine billion tonnes of solid wastes were generated by its Member States in 1990. In spite of waste minimization efforts implemented in recent years in nuclear and other industries, this total is continuing to rise. Reviews by the United Nations Environment Programme (UNEP) suggest that the mining/quarrying and agricultural (manure, crop residues, etc.) sectors generate the largest amounts of wastes. Data covering OECD countries and data from the United Nations Statistical Commission and Economic Commission for Europe (UNSC/ECE) support the general UNEP conclusion. They also suggest that in

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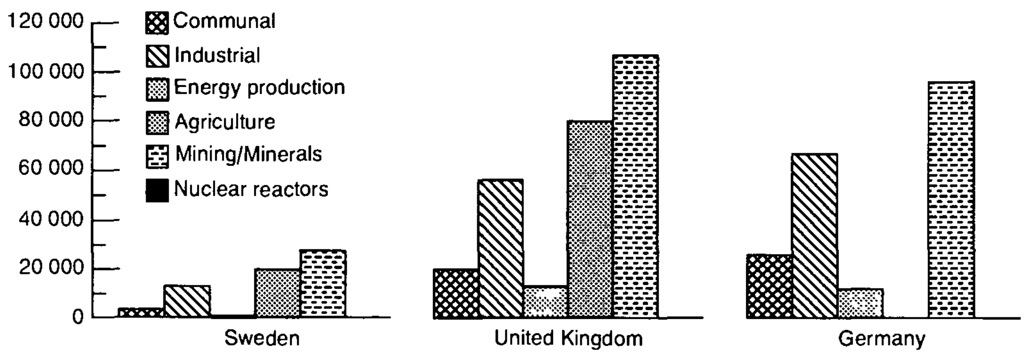
Estimated waste generation rates for three countries



	Sweden*	United Kingdom*	Germany**
Communal	3 200	20 000	26 383
Industrial	13 000	56 000	67 203
Energy Production	625	13 000	11 917
Agriculture	21 000	80 000	not reported
Mining/Mineral	28 000	107 000	96 667
Nuclear Reactors***	7.7	65	20

* Estimates from Organization for Economic Co-operation and Development, *OECD Environmental Data, Compendium 1993*
** Estimates from United Nations Statistical Commission and Economic Commission for Europe, *The Environment in Europe and North America Annotated Statistics 1992.* Nuclear reactor waste estimates in Energie Wirtschaftliche Tagesfragen, Jan/Feb 1993, *Die Entsorgung von Kernkraftwerken im internationalen Vergleich.* Agricultural waste estimate not provided.
*** Estimates include low- and intermediate-level radioactive waste from *IAEA Waste Management Profiles*, April 1994 (except Germany). Low- and intermediate-level waste data are converted from cubic metres to tonnes assuming an estimate of 2 t/m^3. High-level waste would not change these figures

Notes The data should only be used as rough "order of magnitude" indicators Comparisons between countries may not be relevant because of the different definitions that are employed for waste types and the use of different counting methods. The energy production data do not include mining wastes and the reported data do not include wastes generated in other countries during mining of imported fuel

some countries the industrial, communal, and energy production sectors can account for a large proportion of the solid wastes generated. *(See graph.)* It is interesting to note that the the mass of radioactive waste from nuclear power plants is a small fraction of that resulting from all energy production.

The continuing growth in the quantities of waste being generated and the need for appropriate disposal facilities which protect human health and the environment has led to the increased involvement of a number of United Nations organizations in waste management issues. The United Nations Conference for Environment and Development (UNCED), held in Rio de Janeiro in June 1992, provided an international forum for discussing sustainable development strategies related to waste management in addition to a number of other environmental issues. Agenda 21, the programme of action for sustainable development agreed upon by the governments participating in UNCED, reflects the significance of waste-related concerns. It includes three chapters specifically directed at waste management and references to waste management issues in a number of other chapters.

Through UNCED and Agenda 21, the United Nations and world governments have called global attention to the need for a comprehensive strategy for sustainable development of human society. Agenda 21 includes a number of statements emphasizing that reduction of the amount of wastes being generated is a necessary part of any such strategy. It also includes recognition that regardless of the success of efforts for cleaner production, waste is a consequence of development and will continue to be generated, and thus disposal options capable of protecting health and the environment must continue to be available. The data available support the argument that the minimal amounts of waste generated through nuclear power may help make it a beneficial contributor to a global strategy for cleaner production and sustainable development.

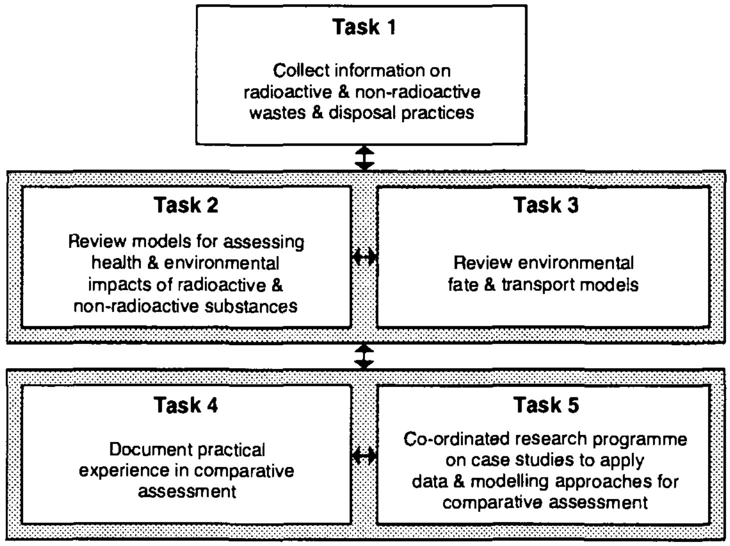
IAEA projects and programmes

The IAEA is undertaking a comparative assessment programme to address the role of nuclear power in a global strategy for cleaner production and sustainable development in the electricity generation sector. This programme is considering health and environmental impacts and costs for many aspects of electricity generation, including normal operations and accidents in all steps of the energy chains for electricity generation. The DECADES project being undertaken by the IAEA in collaboration with a number of other international organizations is a focal point for the programme. Its objective is to enhance capabilities for incorporating health and environmental issues into comparative assessments of different energy chains and strategies in the process of energy planning and decision-making. The project emphasizes the development of computerized tools (data bases, modeling software, etc.) that can be used to facilitate this decision-making.

One part of the IAEA's comprehensive programme, being conducted somewhat independently from the DECADES project, is the subject of this article. In 1995, the IAEA started a project focusing on comparison of approaches for assessing health and environmental impacts from disposal of radioactive and non-radioactive wastes resulting from nuclear and other electricity generation systems. The objectives of the project are (1) to collect, evaluate, and disseminate to Member States data and information on the potential health and environmental impacts associated with disposal of radioactive and non-radioactive waste from nuclear power and other sources; and (2) to evaluate and test approaches for assessing and comparing the potential health and environmental impacts from disposal of waste from nuclear and other energy systems.

A number of organizations — the United Nations Industrial Development Organization (UNIDO), the United Nations Educational, Scientific, and Cultural Organization (UNESCO), UNEP, the UNEP Secretariat for the Basel Convention, the World Health Organization (WHO), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the International Maritime Organization (IMO) — have all contributed, formally or informally, to the project through active participation in meetings, contributions to or reviews of reports, or simply providing information useful for the project.

Tasks in project on comparative health and environmental impacts of wastes from nuclear power and other electricity generation systems



The project is planned to include five tasks which are iterative and parallel in nature. *(See diagram.)* The first task is to identify and compare quantities and general characteristics of wastes and disposal methods from electricity generation systems and other sources. The second and third tasks are respectively planned to include reviews of approaches being used to assess health and environmental impacts from radioactive and non-radioactive substances and models being used to assess the environmental fate and transport of different types of wastes. These two tasks will provide information to enable the health and environmental hazards associated with the waste to be assessed and compared in a quantitative manner. The fourth and fifth tasks are planned to include practical experience through testing of the approaches from the second and third tasks on assessments of the potential health and environmental impacts of wastes from nuclear and other electricity generation systems. In the fifth task, this experience is planned to be obtained through case studies from a Co-ordinated Research Programme involving experts from a number of different countries.

The data on wastes and disposal methods can be used to supplement the databases being developed as part of the DECADES project. However, given the diversity of wastes, disposal methods, and environmental conditions at sites and unique problems associated with modeling long-term release and transport of waste from disposal facilities, assessment approaches for this project are being reviewed somewhat sepa-

Radionuclide contents of selected materials

Material	Radionuclide concentrations (average or maximum as indicated)
Scale and sludges in pipes and equipment for handling produced waters	up to 5000 Bq/g (Ra-226) (average one to hundreds of Bq/g)
Sludges in natural gas supply equipment	up to 100 Bq/g (Ra-226)
Sludges from ponds of produced water	up to ~40Bq/g
Coal/lignite	0.001 - 100 Bq/g (uranium)
Peat	up to 50 Bq/g (uranium)
Geothermal wastes	~ 5 Bq/g (Ra-226)
Uranium mining overburden	~ 1 Bq/g (Ra-226)
Drinking water treatment waste	sludges - ~1 Bq/g (Ra-226) resins - ~1,000 Bq/g (Ra-226)
Phosphate fertilizer	~5 Bq/g (U-238)
Phosphate rock processing waste	slag - ~1 Bq/g (Ra-226) scale - ~40 Bq/g (Ra-226)
Mineral processing waste	~1 Bq/g (Ra-226)

Notes: These values include maximums, averages for specific sets of data, or general ranges of value. In many of the values, the radioactivity associated with only one radionuclide is given, when it is known that a number of other radionuclides will also be present. Thus, the data should be used as rough indicators of the levels of radioactivity that would be found in these materials.

rately from the more traditional atmospheric and operational risk assessment approaches. The emphasis of these tasks is to review and test independent modeling approaches for assessing and comparing the short- and long-term impacts associated with disposal of different energy chain wastes and provide feedback, regarding the effectiveness of different modeling approaches in different situations, that will help Member States to select and use approaches to assess impacts of disposal in their specific conditions.

The results of comparative assessments of the health and environmental impacts of different types of solid wastes may have several potential applications. They may be used (1) as part of an overall comparison of the impact of different energy systems; (2) as an aid to decision-making on waste management policies, by allowing the comparison of impacts of different types of wastes and of alternative management/disposal strategies; and (3) in the evaluation of the potential impacts of the disposal of wastes containing radionuclides, non-radioactive toxic elements/compounds, or both.

Wastes from energy chains for electricity generation

A variety of different sources of energy is used to generate electricity. Generally, these energy sources are classified as "conventional", including fuels such as coal, oil, natural gas, and uranium/thorium, or "renewable", including energy sources such as solar radiation, wind, surface water, biomass, and geothermal. Although some of these energy sources (e.g., solar radiation, wind, water) do not necessarily generate waste as a result of operations other than from maintenance and other general activities, there are wastes posing long-term hazards associated with mining and processing raw materials and manufacturing and decommissioning of solar cells, wind machines, and dams.

In order to identify the different radioactive and non-radioactive wastes associated with a selected electricity generation system, it is convenient to categorize the wastes in respect of the different steps in an energy chain. For the purposes of this article, a generic energy chain is defined as including steps for extraction, fuel preparation, plant operation, and decommissioning. Note that wastes from construction, maintenance, transportation, and treatment processes, as appropriate, should be addressed in each of the steps of the chain.

Often, because of the focus of public attention, there is a perception that the majority of the waste associated with electricity generation using conventional fuels is the result of operation of the facility (e.g., ashes, spent nuclear fuel). However, as discussed earlier, data from the UNEP, OECD and UNSC/ECE suggest that one of the two largest sources of wastes in the world is the mining industry.

This is reflected in the electricity generation sector as well. Relatively large quantities of waste are generated for a number of the electricity generation systems during extraction of the fuel (coal, natural gas, oil, and uranium/thorium). For example, over 80% of the mining/mineral waste reported by the UNSC/ECE for Germany is due to coal mining. Likewise, mining for minerals used in construction materials (metals, concrete, etc.), treatment processes (e.g., limestone for flue gas desulfurization, or FGD), fertilizers for biomass fuels and manufacturing of specialty components such as solar cells result in waste arisings. The quantity and toxicity of waste arisings will vary depending on the extraction method, amount of fuel/mineral needed, and quality of the resource.

Due to the large fuel requirements for production of a given amount of electricity, coal mining generally results in the largest amounts of mining wastes. However, uranium/thorium mining can also result in a large amount of the waste from the nuclear energy chain. Likewise, large volume mining waste is also associated with a number of other energy chains (e.g., photovoltaics used to generate electricity from solar radiation require a number of metal compounds in their construction; phosphate is often used for fertilizers for production of biomass fuels; and numerous raw materials must be mined to produce the materials necessary for construction of dams, power plants, transport vehicles, etc). Another large source of waste for the mining industry is groundwater that is pumped from the mine during excavation or water that flows through the mine after closure. This water can contain a variety of contaminants including naturally-occurring radioactive material, generally abbreviated as NORM (e.g., thorium, uranium, radium), trace metals (e.g., aluminum, mercury, chromium, cadmium, lead, zinc, arsenic, etc.), salts, and sulfur. Coal mine water can also include elevated levels of hydrocarbons.

Although natural gas is often considered a "clean" energy source, exploration and drilling for natural gas and oil are large sources of waste. Waste from these operations include radioactive scale that accumulates on the inside of pipes, drilling muds, and soil contaminated by spills of oil and treatment of produced water. Scale that accumulates on the inside of pipes can contain significant amounts of radionuclides *(see table)* and can require disposal as a radioactive waste. Drilling muds can be contaminated with salts, trace metals (selenium, arsenic, magnesium, curium, zinc, chromium, nickel, aluminum, and iron), and oils and other lubricants. Extraction of oil and gas also includes large quantities of "produced" water from the gas or oil bearing formation (up to 3,000,000 L/day). Such produced water contains a variety of contaminants including NORM (especially radium), trace metals, ammonia, salts, aliphatic and aromatic petroleum hydrocarbons, phenols, and naphthelenes. Sludges resulting from ponds of such water are contaminated with elevated concentrations of the metals, hazardous substances, and radionuclides that were present in the water. Drilling operations also result in a variety of hazardous wastes including asbestos, pesticides, PCBs, and trichloroethylene.

The second step in the generic energy chain is fuel preparation. Fuel preparation can also be a large source of wastes. For conventional fuels, fuel preparation includes cleaning raw coal to remove impurities, refining petroleum products, and milling and fuel fabrication for nuclear power. These wastes from post-mining activities include tailings, water, and solids contaminated with similar materials to the mining wastes (e.g., trace metals, salts, metals and NORM). Refineries generate waste oil and water, a variety of sludges contaminated with NORM, hydrocarbons, trace metals, PCBs, and other contaminants. Fuel fabrication for nuclear power plants results in waste including ashes and sludges contaminated with NORM and trace metals. The manufacture of solar cells (photovoltaics) can be considered an analogue to fuel preparation in the context of solar power. Manufacture of photovoltaics for solar cells results in a variety of toxic or hazardous waste contaminated with arsenic, copper, cadmium, gallium, and zinc compounds.

The third step in the energy chain includes waste generated during operation of the electricity generation plant. These are the most recognized wastes as they tend to receive the most attention. Coal-fired plants generate large quantities of combustion waste including fly ash (airborne combustion products) and bottom ash (heavier combustion products) that result from the burned fuel, as well as gypsum and sludges from different FGD techniques. These wastes are contaminated with NORM and trace metals. It is somewhat ironic that the use of flue gas desulfurization to reduce the greenhouse gases emitted from fossil fuel facilities results in more waste being produced than the ash from the burned fuel. Recycling of fly ash and FGD wastes is being heavily promoted and large quantities are being used for other purposes (e.g., cement additive, backfill, gypsum in construction materials, and many other uses). However, even with recycling, the enormous quantities of ash and FGD waste that are generated far exceed the demand (it is estimated that more than 450 million tonnes of these wastes are unused in the world each year). Oil-fired plants generate lesser quantities of ashes, but can be a large source of FGD waste. Furthermore, some of the boiler cleaning and waste water treatment wastes also contain hazardous materials.

Waste from the operation of nuclear power plants is probably the most studied waste in the world, especially spent nuclear fuel. However, data show that the amount of waste generated by a nuclear power plant is very small compared to the waste generated by electricity generation systems as a whole. The main concern for nuclear waste is the high levels of radioactivity in the much smaller quantities of high-level waste. Reprocessing of the spent fuel is conducted in several countries, which reduces the long-term hazards associated with the waste that must be disposed. Low- and intermediate-level waste also results from nuclear power plant operations. This waste includes various trash, piping, and used equipment that are contaminated by radionuclides with relatively short half-lives.

Decommissioning of closed power plants is the last step in the generic energy chain. For coal, oil, and gas-fired plants, decommissioning waste would include building rubble, old equipment from the facility, and contaminated soil resulting from operations. These materials would be contaminated by combustion byproducts and other substances associated with plant operation. Wastes from nuclear power plant decommissioning differs from those from other power plants in the respect that materials that were near the reactor core or primary coolant may require special handling due to elevated levels of primarily short-lived radionuclides. Decommissioning of solar cells, dams, and wind machines would also result in wastes that must be managed. The solar cells, in particular, will contain hazardous compounds posing potential long-term health hazards.

A number of wastes are generated as a result of construction, maintenance, transportation, and waste treatment processes in each of the steps of the energy chain. General construction, maintenance, and transportation wastes would, for the most part, be typical for all of the energy chains, although the quantities and types and levels of contamination will be different depending on the energy chain. For example, waste associated with transportation can be very significant for coal-fired plants due to the enormous volumes of fuel and resulting ash and waste that must be transported on a daily basis. It has been estimated that fifty 40-tonne trucks per day would be required to transport the fly ash and FGD wastes from a typical 1000-MWe coal-fired power plant to a disposal site (rail or other transport can also be used when available). A complete life-cycle analysis would need to include the waste generated while producing the fuel for the trucks or trains and the waste associated with maintaining the vehicles. Disposal of secondary waste resulting from treatment processes that are used for many of the wastes will also need to be considered in a comprehensive comparison.

Naturally occurring radioactive materials

Many of the wastes discussed above, especially those associated with extraction, fuel preparation, and combustion byproducts, contain naturally occurring radioactive materials (NORM). NORM includes isotopes such as carbon-14, potassium-40, uranium-238, radium-226, and thorium-232. *(See table.)* One important aspect of waste containing NORM is that it consists of long-lived radionuclides (e.g., uranium-238 whose half-life is 4.5 billion years), thorium-232 with a half-life of 14 billion years, and their progeny, including radium). The primary radiological health concern associated with NORM is due to radium and its progeny.

Because of the focus on radioactive waste from nuclear power plants, the radionuclides in waste from other energy chains have historically received comparatively little attention. However, more recently, due to the long half-lives and potential hazards associated with the radionuclides in NORM containing wastes, regulators have been forced to consider the radionuclides in the waste from non-nuclear energy chains in the context of the increasingly strict regulations applied to nuclear waste.

Two examples of NORM waste from the oil and gas industry can be used to provide perspective. Firstly, scale that precipitates on the inside of wells and production piping is now often considered a radioactive waste. It is interesting to note that, in some cases, this scale has been shown to contain concentrations of radium-226 that rank at the upper end of international levels for alpha concentrations in low- and intermediate-level wastes that may be disposed of in near surface facilities. Secondly, studies of the large quantities of produced water from wells at oil and natural gas drilling sites have indicated that 50% to 78% of the wells that were surveyed in three states in the United States yielded produced water with average radium concentrations in excess of 1.85 Bq/L (50 pCi/L). Other data suggest that average radium concentrations in water from some wells can be as high as 111 Bq/L (3000 pCi/L). As a comparison, the radium concentration limit for discharges of water from nuclear facilities in the United States is approximately 2.2 Bq/L (60 pCi/L) . Although industry specific requirements may be necessary in some cases, clearly the comparisons to requirements in the nuclear power industry will be made.

Disposal methods for electricity generation wastes

Agenda 21 emphasizes cleaner production, but until new technologies are available, energy fuel chains can be expected to result in a substantial amount of waste. Thus, suitable disposal methods will need to be available. The eventual health and environmental impacts of an energy fuel chain will depend to some extent on the disposal method used. A variety of disposal methods are currently used for waste from energy chains for electricity generation. A brief summary of these methods is provided here.

In the extraction and fuel preparation steps, the large volumes of waste that are produced generally exclude any substantial engineered disposal technology. In some cases, the spoils (waste rock) are placed back in the mined cavities or spread on the ground surface. However, in a number of cases, mining spoils (waste) are now protected using engineered covers to divert infiltration around the potentially harmful waste. Oil and gas drilling waste is typically reinjected into the formation, placed in pits at the drilling site, or spread on the ground surface at the site.

Fuel preparation waste from coal and nuclear energy chains includes large amounts of liquids that are often disposed of in impoundments (man-made ponds or lagoons). Solid waste from fuel preparation (e.g., tailings and evaporation residues) are often covered with an engineered soil cap to minimize infiltration into the waste and to limit the release of gases from the waste. Oil refinery waste is often disposed of using land farming or pit disposal. Hazardous waste from refineries or the manufacture of photovoltaics for solar power is generally sent to a licensed facility. A typical hazardous waste disposal facility includes a lined trench with leachate collection systems and an engineered soil cover to limit water contact with the waste. Other waste associated with fuel preparation will typically be disposed of in landfills or, in the case of some nuclear waste, engineered trenches, or concrete vaults.

Operational waste from coal and oil-fired power plants such as fly ash and FGD waste are typically disposed of in ponds, landfills, mine cavities, or surface waste piles. After evaporation and drainage of the water, the sludge remaining at the base of disposal ponds is typically covered with soil. Boiler wash waste for coal, oil, and gas plants may have to be treated as a hazardous waste, which would require disposal in a licensed facility. Low- and intermediate-level waste from nuclear power plants is often disposed of in engineered trenches, concrete vaults, or mined cavities. This waste is also typically packaged prior to disposal. The high-level waste, including spent fuel, is planned to be disposed of in deep geologic formations or stored in a retrievable form.

Future directions

Agenda 21, the programme of action for sustainable development agreed upon by world governments at UNCED, has identified cleaner production (i.e., the need to reduce the amount of waste that is being generated) as a critical element of a strategy for sustainable development of human society. Electricity generation, which is essential for development, is one source of waste where reduction is necessary. In order to assess the potential role of nuclear power in a global strategy for cleaner production and sustainable development, the IAEA initiated a project entitled Comparative Health and Environmental Impacts from Solid Wastes from Energy Systems.

The first task in the project focuses on identifying quantities and types of wastes from energy chains for electricity generation and their associated disposal practices. Subsequent tasks in the project include reviewing and testing of methods that can be used to compare the potential health and environmental impacts associated with waste disposal, for example, from release and subsequent transport in the environment of the radioactive and non-radioactive constituents in those wastes. These reviews will include discussions regarding other comparative assessment studies that have been conducted. Approaches for comparing the health and environmental impacts of radionuclides and non-radioactive toxic elements/compounds and modelling fate and transport of those contaminants in the underground and surface environment will be a crucial part of a waste disposal-related comparative assessment.

This article has summarized some of the information obtained to date for the first task in the project. In this regard, some perspective was provided regarding the nature of the wastes and the masses generated by nuclear power and other energy chains. The mass of wastes from nuclear power was shown to be both a small fraction of the total wastes generated and also a small fraction of electricity generation wastes. This fact supports the potentially desirable role of nuclear power in the context of cleaner production and a strategy for sustainable development of human society.

The importance of considering all steps in the energy chains for electricity generation has also been emphasized in this article. Detailed consideration of each step in the energy chains shows that even energy chains that are thought of as "clean", such as solar power (hazardous metallic compounds) and natural gas (radioactive and hazardous drilling and pipeline waste), result in the generation of waste posing potential long-term health and environmental impacts. Also, the large mass of waste generated in some energy generation chains (e.g., fly ash and flue gas desulfurization waste) creates disposal problems.

Future work on this project will focus on more accurately defining and quantifying wastes and disposal practices typical of current energy fuel chains; reviewing and testing available approaches for modelling the fate and transport of the contaminants in those wastes; and calculating the associated health and environmental impacts. ❐