Joint NEA/IAEA Expert Workshop

"Technical and Economic Assessment of Non-Electric Applications of Nuclear Energy"

OECD Conference Centre, Paris, 4-5 April 2013

BOOK OF ABSTRACTS

and

LIST OF PARTICIPANTS

LIST OF SPEAKERS

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Dr. Henri Paillère is a nuclear energy analyst at the Nuclear Energy Agency which he joined in October 2011. Prior to that appointment, he worked as an R&D Program Manager for the Alstom Power Nuclear Business (2009-2011). Before that, he worked at the French Atomic Energy Commission (CEA) for thirteen years, successively as a research engineer in the field of thermal hydraulics and severe accidents, head of laboratory and finally program manager for European cooperation activities. He holds a PhD in Computational Fluid Dynamics from the Université Libre de Bruxelles in Belgium (1995), a MS in Aerospace Engineering from the University of Michigan in the United States (1991) and a diploma from French engineering school ENSTA (1991).

Objectives of the Workshop

Nuclear energy is essentially an electricity-generating technology, providing base-load power with high availability to countries that operate nuclear reactors. A few countries operate nuclear power plants in load-following mode to cope with intermittent production from other sources or rapid changes in demand, but in all cases, nuclear reactors are valued for their capacity to produce low carbon electricity that is competitive with other technologies. Use of nuclear energy for non-electric applications, besides medical or research applications which are not in the scope of this workshop, has been known for several decades and, in some cases (e.g. district heating or desalination), demonstrated or exploited at industrial scale. But these applications have been limited. The further development of non-electric applications of nuclear energy, whether with current light water reactor technology or more advanced designs that operate at higher temperatures, will require technological challenges to be overcome. It will also require the demonstration that such applications have sound economic bases and can be competitive with fossil-fuel based processes or other technologies that deliver the same type of products.

The objectives of this workshop are therefore to identify the technological and economic challenges facing non-electric applications of nuclear energy, and to assess their potential to provide credible solutions to future energy needs. The workshop is split into thematic sessions (district heating, desalination, high temperature process heat applications including hydrogen production, energy storage via coupling of nuclear and intermittent renewable sources) in which both technical and economic aspects will be discussed. The workshop will end with a general session on economic modelling and business case assessment methodologies for non-electric applications. Proceedings of the workshop containing abstracts, presentations and summaries of the Q&A sessions and discussions will be published subsequently.

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Prospects for Nuclear Cogeneration, Economic Assessment Methodologies and Tools

Nuclear power is a reliable, clean, and economic energy source with still a huge potential beyond electricity production. Nuclear cogeneration i.e. electricity generation accompanied by other applications such as seawater desalination, hydrogen production, district heating or cooling, or any energy-demanding industrial applications could well accelerate the revival of nuclear power. It could not only improve the overall efficiency of the plant but also help enhance the economics and reduce environmental impacts of greenhouse gases. Current thermal efficiencies of nuclear power plants are about 33%, which is rather low since the rest of the energy is dissipated to the environment as heat. Such efficiency could be increased to reach up to 80% through cogeneration of electricity and other applications. Cogeneration economic benefits are not only due to the increased overall efficiency but also from all other benefits resulting from the synergies of cogeneration. Hence, planning for cogeneration has to be considered at early stages including conceptual design.

This paper discusses the benefits of cogeneration of nuclear power and aspects of exploiting nuclear energy for non-electric applications. The paper will also present some basis for economic assessment methodologies and tools typically provided for free by IAEA to Member States to assist them in their feasibility studies.

Harri TUOMISTO

Dr. Harri Tuomisto keeps currently the position of Senior Nuclear Safety Officer in Fortum's Power Division. Fortum is a Nordic energy company owning and also operating nuclear assets in Finland and Sweden. Earlier Dr. Tuomisto has led both nuclear development and nuclear engineering in Fortum as well as nuclear safety oversight.

He has more than thirty years' career in nuclear engineering, thermal hydraulics and safety research, particularly supporting the Loviisa nuclear power plant and preparatory studies for new build nuclear in Finland. He has also been engaged in many international efforts promoting and supporting the safe operation of nuclear power plants.

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Nuclear District Heating Plans from Loviisa to Helsinki Metropolitan Area

Currently the district heat generation in Helsinki Metropolitan area is mainly based on coal and natural gas, producing some five to seven million tonnes of carbon dioxide emissions annually. Transporting heat generated by large-scale nuclear combined heat and power (CHP) from Loviisa could cut this figure by up to four million tonnes. This would decrease Finland’s carbon dioxide emissions up to 6%.

Fortum applied for a Decision in Principle in 2010 concerning the construction of Loviisa Unit 3 at the site located 75 km east from Helsinki at the coast of Gulf of Finland. The main alternative investigated was a co-generation plant designed for large-scale district heat generation for the Helsinki Metropolitan area. The assumption was to supply district heat at the maximum capacity of 1 000 MWth.

This presentation gives an overview of the studies performed to support the application. The CHP concept was ambitious, not only because of the large heat generation output envisaged, but also because the district heating water would have to be transported over a rather long distance. In addition to the general concept the technical assumptions as well as the general design and safety requirements both for the co-generation plant and the heat transport system. A particular attention will be given to various alternatives studied for the heat transport system, including qualitative comparison of the economics of these alternatives.

The application was not endorsed by the Finnish Government and the project is on hold pending on future decisions to go on with the Loviisa 3 project.

Henri SAFA

Henri SAFA is currently working at the Scientific Direction of the Nuclear Energy Division of CEA, running the internal nuclear training courses and the scientific evaluation of research teams through an external Scientific Committee. Henri SAFA has published many books on Nuclear Energy for general public. He previously worked in the Nuclear Physics Department on photofission applications. He is an International Expert in Nuclear Instrumentation and is part of the IAEA Working Group on Nuclear Cogeneration.

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Economics of District Heating with Light Water Reactors

Sustainable energy can only be achieved worldwide upon a better use of primary energy sources. This implies targeting for better efficiencies in any energy transformation and especially in electricity production in which all thermodynamic cycles lead to large thermal losses. In a Nuclear Power Plant (NPP), only one third of the energy released by the fission of uranium is transformed into electrical power, the other two thirds being ultimately lost in the environment as low temperature heat. Technically, a major part of this heat may actually be recovered at the expense of a reduction in the electrical output of the plant. Consequently, operating in a cogeneration mode, the efficiency of the NPP can be significantly enhanced providing a net overall gain in energy efficiency. As one of the major application for using low temperature heat is District Heating (DH), it is important to carefully work out the economics of the whole system taking in account not only the production cost but also the transport and the distribution of heat. In particular, because for safety reasons NPPs are usually located far from urban areas, long distance heat transport will be required to connect the production plant to the final DH network. In recent years, continuous progress has been made in lowering the thermal losses of industrial heat pipes, making it now affordable to transport large amounts of heat over very long distances. Today, a 100 km long main heat transport line can be designed and built with heat losses below 1%. While industrially speaking, the recovery of heat from a NPP appears at hand, the economics of the whole heat delivery system up to the customer is still to be worked out in order to compete with heat delivery of present DH systems, primarily based on fossil fuel sources.

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Roland Schmidiger works for Swiss utility Axpo Power Ltd since 2005, where he is currently heading the asset management department in the nuclear power division, and a member of the Executive Management Team.

Prior to that, he was a regional managing director for Austria and Switzerland for Honeywell Ltd, as well as a member of the European Management Team between 2003 and 2005. Between 1993 and 2003, he held several positions in the Electrowatt Group, including the position of managing director of the Business Unit Energy, head of Power Economics & Consulting Department and head of Business Development. He holds a Master of Electrical Engineering and a Master of Advanced Studies in Management, Technology, and Economics (BWI) from the Swiss Federal Institute of Technology.

Experience of Operating Nuclear District Heating in Switzerland

Nuclear power plants (NPPs) have a huge potential to supply steam and heat to industrial, commercial and residential clients. The presentation focuses on the situation in Switzerland where basically every NPP supplies local steam and/or heat clients. This is quite unique since not many other countries use NPPs as source for industrial steam supply or district heating systems. As far as the author understands in Latvia, Slovakia, Hungary, Germany, Sweden and Russia only do or did have NPPs supplying heat to off-takers.

The author will discuss the situation in Switzerland, the technical capability of nuclear power plants in general to supply heat, address nuclear safety issues, assess economic aspects and put the topic in the context of the ongoing CO_2 discussions.

In Switzerland all NPPs supply heat and/or steam to clients. The theoretical potential is exhausted in none of the plants – in Gösgen and Beznau only the supply shows a notable impact on the power generation. Mühleberg supplies local residential customers with heat, Gösgen supplies steam to pulp and paper industry and residential clients and Leibstadt supplies residual heat of the cooling circuit (cooling tower) to a local farmer. Beznau finally supplies heat to a regionally active district heating operator supplying commercial and residential clients (partly via re-sellers).

In most the cases (fossil-fired) thermal power plants supply district heating systems. Since NPPs are thermal power plants at the end of the day the technical capability to supply a district heating system is no technical issue. Due to the separated systems, clients are not affected by any radioactive contamination of heat supplied and since the supply is set-up in the non-nuclear part of the plant, it does not affect any nuclear safety issues. The reduced power generation due to the supply of heat can be valuated either from an operator's or off-taker's perspective. On the basis of the first, the price fluctuates with the whole sale price of electricity. On the basis of the latter, the price fluctuates with the price of alternative (fossil) energy sources. Since NPPs do not emit any CO_2, the heat supply is not charged with this greenhouse gas.

Conclusions: In Switzerland the operators of NPPs have a long and positive track record in supplying heat and steam to clients. A NPP as supplier for district heating systems:

- is technically possible;

- fully respects nuclear safety standards;
- is economically favorable if heat supplied is charged at least on an avoided cost basis from a nuclear operators perspective;
- could play an important role in the efforts to reduce CO_2 emissions and last but not least;
- contributes to the political acceptance of nuclear power.

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Vladislav Sozoniuk is currently Head of Analytical Department at Floating Nuclear Power Plants Construction Directorate, JSC "Concern Rosenergoatom" (Moscow, Russian Federation) and expert for the OECD Nuclear Energy Agency.

He is certified project management associate (IPMA) and member of the Russian Federation Nuclear Society. His scientific interests include small and medium sized reactors, non-electric application of nuclear energy.

Experience of Operating Nuclear District Heating in Russia

It is well known that cogeneration is the most energy-effective solution for simultaneous electricity production and district heating. It's especially true for regions with cold climate, where district heating is needed most part of the year. Russian Federation is a good example and historically has great experience in this field. Many Russian towns possess developed district heating systems based on fossil-fueled cogeneration plants.

Currently the total share of cogeneration plants in district heating in Russia is about 30% and tends to stabilize on this level. The main drawbacks are high capital and O&M costs of heat transmitting infrastructure and government-regulated pricing policy, favorable for households but forcing industry to rely on its own heat sources.

All abovementioned factors are applicable for the nuclear power plants as well. In the Russian Federation there are 10 NPPs with different reactor types; most of them used to supply heating for the surrounding area. Heat is transmitted from the reactor to district heating grid by watertight intermediate circuit with pressure gradient to prevent radioactive contamination of district heating system in case of any leakage. Regardless of the reactor type (PWR, uranium-graphite channel-type reactor or fast liquid metal-cooled one) the heating water is circulated in the third outer circuit at least, with highest pressure.

Typical NPP in Russia has power of 6-8 GW(t) of which only 200-300 MW are used for heat supply. Key factor is the location of NPPs. All of them located far from large cities and has in close vicinity only a small town where the NPP personnel lives and auxiliary services are situated. So in most cases the NPP in Russian Federation only provides heat for its own site structures and close "auxiliary" town. It's rather effective and greener way of waste heat utilization and personnel's living conditions improvement but it doesn't add much to NPP revenue.

Important exclusions are Bilibino NPP operating in the extreme North of Russia and Floating NPP under construction. Both these plants have low power and designed as autonomous energy sources for remote, isolated regions. For these plants electricity and heat are regarded as equally important products.

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Dr. Xavier Leflaive heads the Water Unit in the OECD Environment Directorate. For OECD governments, he investigates issues related to water as a driver for green growth and to the use of economic instruments for water management. He contributed to several publications on the outlook for water, water pricing, financing water resources management, and innovative approaches to water supply and sanitation. He coordinates ongoing work on water allocation and urban water management. He is also involved in the review of water policies in selected countries (Mexico, the Netherlands) and heads a programme dedicated to the reform of water policies in countries of the former Soviet Union.

Xavier Leflaive studied business administration and social theory in France, Canada and the United Kingdom. He holds a PhD in Social and Political Sciences from the University of Cambridge, the United Kingdom. Before joining the OECD, he worked as a consultant to public administrations and utilities.

Desalination in the Context of Water Futures

The OECD Environmental Outlook projects that water demand will increase by 55% by 2050. The increase in demand will come mainly from manufacturing (+400%), electricity (+140%) and domestic use (+130%). In the face of these competing demands, there will be little scope for increasing water for irrigation.

Competition to access the resource will intensify. This is an incentive to use water more wisely. Tapping alternative water sources – rain and storm water, used water, and desalinated sea or brackish water – can also help alleviate scarcity.

Several OECD countries invest in desalination to increase potable water supply by constructing large-scale desalination facilities. Different combinations of technologies and energy supplies are being considered. This triggers considerable debates, about the cost of the investment, energy consumption, and the environmental consequences.

To realise the full benefit of these options, governments need to set up a proper framework. Such frameworks will adapt to uncertainties about water availability, driven inter alia by climate change, and to shifting priorities in water use. The potential of nuclear energy has to be considered in that context.

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Overview of Nuclear Desalination Technologies & Costs

Seawater desalination using nuclear energy is considered as one of the viable sources of producing fresh water needed in arid areas. Several countries have already commissioned nuclear desalination demonstration plants, others shown interest in nuclear desalination not only because recent studies have demonstrated that it is feasible, but also economical. The foremost challenge facing nuclear desalination is that the countries suffering from scarcity of water are, generally speaking, not holders of nuclear technology and need to develop the required infrastructure for nuclear projects as well as for product water distribution (except for China and India). The utilisation of nuclear energy in most countries requires sufficient and qualified human resources, infrastructure building and other institutional arrangements including financing. Further challenges of nuclear desalination are public perception, transfer of nuclear technology, legal infrastructure and safety considerations.

Nuclear desalination costs are strongly influenced by several parameters like the interest and discount rates, the total plant availability, the power costs, the specific water plant base costs etc. In general, the product water salinity by thermal desalination plants is much lower (could reach few ppm) as compared to 300 to 500 ppm from Reverse Osmosis plants. The real choice of one over the other would thus be a complex problem, depending on the specific industrial, agricultural and potable water needs of the countries. This paper will present an overview of nuclear desalination technologies, costs, and IAEA tools and activities to support Member States on nuclear desalination.

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Dr. Kim worked at Korea Atomic Energy Research Institute for 30 years after the graduation of Seoul National University. Dr. Kim started his career involving Wolsung NPP (PHWR) fuel technology localization project After success of fuel development project, he joined the HANARO (Korean Research Reactor) design and construction team. In 1997 Dr. Kim participated in the SMART development project. Currently he is a SMART Project Manager. His specialties are system dynamic analysis, and advanced control system design.

SMART for Electricity Generation and Seawater Desalination

SMART (System-integrated Modular Advanced ReacTor) is a small-sized integral reactor that generates a rated thermal power of 330 MW. It can produce 100 MW of electricity, or 90 MW of electricity and 40 000 tons of desalinated water concurrently, which will be sufficient for 100 000 residents. After its 15-year development, Standard Design Approval (SDA) for SMART was granted on 4 July 2012 by the Korea Nuclear Safety and Security Commission (NSSC).

Technical basis of SMART is a sensible mixture of existing PWR technologies and advanced design features. Reactor safety is considerably enhanced by introducing passive residual heat removal system, simplified safety injection system, passive auto-catalytic hydrogen re-combiners, and external reactor vessel cooling. All new technologies applied in the SMART such as integral reactor concepts, passive residual heat removal systems, helically coiled steam generators, canned motor pumps, etc., were validated through extensive experiments. This strengthens the soundness and robustness of the SMART technologies for the earliest deployment based on the proven technology. There will be no hurdle to get licensed and to deploy the SMART anywhere.

The preliminary estimation of electricity generation cost and fresh water generation cost of SMART shows 6-10 cents per kWh and 1.1 $\$/m^3$, which are superior economics over fossil fuel cogeneration plant.

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Nuclear Desalination with the BN-350 Reactor

The world's first nuclear desalination complex was operated in 1973-1993 on the Eastern coast of the Caspian Sea on Mangyshlak peninsula (Republic of Kazakhstan), in the arid zone with low rainfall and limited ground water. The complex located 12 km from the city of Aktau (former Shevchenko) was used to supply electricity, heat and potable water for both industry and households.

Mangyshlak complex consisted of BN-350 reactor, two natural gas-fired cogeneration plants, ten multi-stage distillation units with capacity from 8 000 to 14 500 m^3/day each, potable water station and water treatment plant for the preparation of feed water for the NPP and cogeneration plants.

BN-350 is a fast neutron reactor with liquid metal (sodium) coolant and thermal power of 1 000 MW. In 1960 draft design was made, the construction begun in 1964. Reactor went critical in 1972. It was decommissioned in 1997, after 25 years of operation.

Steam from both the nuclear (405°C, 4.5 MPa) and cogeneration plants (450°C, 10.0 MPa) reduced to 230°C and 0.6 MPa after turbines was transferred to MSF units to distillate Caspian Sea water with salinity of 13.8 g/l. Maximum reached potable water production of Mangyshlak complex was about 120 000 m^3/day.

BN-350 was the first commercial fast neutron reactor with sodium coolant. Its construction and operation proved the effectiveness of many design concepts and technical features of fast sodium reactors. The operation experience allowed determining and solving a number of problems connected to thermal regimes of first circuit and steam generators design.

After the decommissioning of BN-350 reactor, Mangyshlak complex continues to supply electricity, heat and potable water using fossil-fired energy sources only.

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Dr. Kim is now the Project Manager of a Nuclear R&D Project in Korea in charge of the development of essential technology for VHTR. Since 2006, he is the Principal Researcher in Nuclear Hydrogen Technology Development Division and leader of thermo-fluid design team for the Nuclear Hydrogen Development and Demonstration Project. From 2008-2011 he was the Project investigator of US-ROK I-NERI project, in charge of the Experimental and Analytic Study on the Core Bypass Flow in a Very High Temperature Reactor. From 1998-2006, he was the Senior Researcher in Power Reactor Technology Development Team, in charge of the Thermal hydraulic design for Reactor Coolant Pump of SMART integral reactor and the Performance test of Reactor Coolant Pump.

Status of HTGR R&D for Non-electric Applications in Korea

The Korea Atomic Energy Research Institute (KAERI) launched a nuclear hydrogen program using HTGR to meet expected demand for hydrogen in 2004. Even though some HTGRs have been successfully operated since 1960s, there were still technological challenges on the way to realising hydrogen production. So the programme has been focused on the key technologies such as HTGR-specialised design codes, high temperature helium experiment, high temperature materials database, TRISO fuel development, and thermo-chemical hydrogen production. In 2008, the Korean Atomic Energy Commission approved the long term development plan for the nuclear hydrogen production as a national agenda, which aimed for the demonstration of nuclear hydrogen production by late 2020s. There are two tracks in that plan. One is a project for key technology development which has been started since 2006 and the other is for nuclear hydrogen development and demonstration (NHDD). As a first step for the development and demonstration of the non-electric heat application of HTGR in Korea, a nuclear hydrogen alliance was organised in collaboration with nuclear industries and potential end users to promote early embarcation of the demonstration project. In the wake of this effort, a three-year project for HTGR design concept study started at 2012 with participation of several industries, which will result in system concept and project planning for the demonstration plant and contribute to the launching of a conceptual design project.

Johan CARLSSON

Dr. Johan Carlsson is a scientific officer working at the European Commission's Joint Research Centre in the Netherlands. He has worked at the JRC since 2003 addressing issues such as energy technologies assessment within the framework of the Strategic Energy Technologies Plan (SET-Plan), the role of nuclear power in the future energy system, and safety of innovative nuclear power.

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Competitiveness of Nuclear Cogeneration in a Future Energy System

Combined heat and power (CHP) nuclear reactors can support the EU low-carbon society goals while providing stability in production and cost. This presentation concerns the market potential and economic competitiveness of such reactors in future European cogeneration markets. The study shows that large potential for nuclear cogeneration exists in for example chemical/petroleum, paper, metal, and bioenergy markets with small capacities (50-250 MWth). Parametric analysis was used to create cost breakdowns (capital, operations and maintenance, fuel, and decommissioning) for an equivalent nuclear-CHP that could compete against coal-CHP and natural gas-CHP. Sensitivity analysis showed that reactor capital costs and the costs of capital had the largest influence on competitiveness. The opportunities for nuclear-CHP were highest in natural gas-CHP markets, however, the benefits for CO_2 reduction were greatest against coal-CHP.

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Ir Alexandre Bredimas, senior consultant and head of innovation strategy at LGI, has a background in system engineering (Ecole Centrale Lyon) and technology policy (Cambridge). He has a longstanding experience in nuclear, at UK Parliament (new-build licensing), E.ON (new builds), Areva (EPR costing) and LGI, on policy, strategy, innovation, training, system integration, techno-economics. He has developed an expertise on economics, marketing and business modeling of nuclear cogeneration through several EU projects and individual missions. He has authored several papers in peer-reviewed journals.

EU Markets for Process Heat Applications, Outcome of the FP7 Europairs Project

The EUROPAIRS project (2009-2011) has carried out a comprehensive market analysis of the EU industrial heat market. It has identified various market types: “plug-in” for which cogeneration is already used (mainly from gas), “extended” made of internal boilers and burners, embedded into the production facilities, as well as “polygeneration” for the co-production of industrial gas and basic raw materials and “pre-heating” to take a share of the “extended” market. The total heat market was found to amount to around 3 000 TWh per year, 25% of which already externalized in the form of cogeneration (so-called “plug-in” market). Cogeneration was found to be used for applications below 550°C, especially for the chemical industry. However, the feasibility of “polygeneration” and “pre-heating” market segments should be further analysed as it could open new market opportunities in the medium term. Extrapolating from these results and an equivalent study in the United States, the world industrial heat market was estimated to amount to 11 000 to 16 000 TWh per year.

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Dr. Michael G. McKellar is a Research and Development Engineer at the Idaho National Laboratory. For over 10 years, Dr. McKellar has modelled and analysed a number of chemical and thermodynamic processes using process modelling software. These processes include compact natural gas liquefaction systems; high temperature steam electrolysis for hydrogen production; high temperature carbon dioxide and steam electrolysis for syngas production; power conversion units such as Rankine steam cycles, Brayton gas cycles, super-critical carbon dioxide modified Brayton cycles, and combined cycles; bio-mass pyrolysis and gasification; and atmosphere revitalization for NASA. He has been the technical lead for the development of intermediate heat exchangers for use in molten salt cooled nuclear reactors. He also was the technical lead for the integration of process heat applications with next generation nuclear plants. He acted as the principal investigator for the testing of a hybrid refrigeration system which included the design, construction, and testing the process. He worked as part of a team that developed, designed, constructed and tested a compact natural gas liquefaction system that won the 2006 R&D award. He developed software, supported experimental testing, and led projects in the areas of nuclear waste management, electric vehicle batteries, and nuclear valves.

He received a PhD and Masters in Mechanical Engineering from Purdue University and BSME degree from Brigham Young University.

Next Generation Nuclear Plant Industrial Process Heat Applications and Economics

The Next Generation Nuclear Plant (NGNP) Project, led by Idaho National Laboratory, is part of a nationwide effort under the direction of the U.S. Department of Energy to address a national strategic need identified in the Energy Policy Act of 2005 – to promote the use of nuclear energy and establish a technology for hydrogen and electricity production that is free of greenhouse gas (GHG) emissions. This presentation is a summary of analyses performed by the NGNP project to determine whether it is technically and economically feasible to integrate high temperature gas-cooled reactor (HTGR) technology into industrial processes.

The engineering analyses show that HTGR-integrated processes would sharply reduce CO_2 emissions by replacing the heat derived from natural gas and coal with HTGR-supplied high-temperature process heat.

Economic analyses for the HTGR-integrated cases were completed to identify the major factors that influence the economics of HTGR-integrated processes of interest. The analyses were based on a simplified business model in which a single entity owns and operates the industrial and associated HTGR plants. In this presentation, sensitivity charts are used to demonstrate how varying the value of a selected economic parameter, while holding all other parameters at the baseline values, would impact the wholesale product selling price. The baseline wholesale product selling prices were estimated by setting all economic values to the baseline values.

Based on the results of the engineering and economic analyses, the following processes appear suitable for HTGR integration:

- Synthetic gasoline production;
- Synthetic diesel production;
- Ammonia derivatives production;
- Steam-assisted gravity drainage for bitumen recovery from oil sands;
- Substitute natural gas production from coal;
- Oil recovery from oil shale via *in situ* retort;
- Oil recovery from oil shale via *ex situ* retort;
- Bitumen upgrading;
- Seawater desalination.

This HTGR process integration study illustrates potential environmental and economic benefits of providing HTGR heat to conventional industrial processes to reduce the use of fossil fuel resources, reduce CO_2 emissions, and supply products to market at competitive and stable prices. In all process evaluations, HTGR-integrated processes use less natural gas or coal and emit lower quantities of CO_2 than conventional processes. Because of the reduced reliance on fossil fuels, the wholesale selling prices of products generated by HTGR-integrated processes are less affected by fluctuations in fossil energy prices. Additionally, because the HTGR-integrated processes emit less CO_2 than the conventional processes, the economics are not affected significantly by taxes on CO_2 emissions.

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Dr. Karl Verfondern (Study of Physics, diploma at University of Bonn, 1978; PhD at RWTH Aachen, 1983) is employed at the Research Center Jülich at the Institute of Energy and Climate Research, Nuclear Waste Management and Reactor Safety. His work is dedicated to high-temperature gas-cooled reactors with respect to fuel performance and fission product release behavior, as well as to safety aspects of hydrogen as an energy carrier and of combined nuclear/chemical systems for nuclear process heat applications. The work is mainly conducted within the frame of EU or IAEA projects.

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Overview of Nuclear Cogeneration in High-temperature Industrial Process Heat Applications

Since six decades, nuclear power is being used for commercial electricity generation evolving to an industrially mature and reliable source of energy and to a key component in the world's energy economy. But there is also a huge potential in the non-electric market where nuclear energy has only little penetration up to now. Many industrial sectors have a high demand for process heat and steam at various levels of temperature and pressure to be provided for chemical processes (synfuel production), desalination, district heating, etc.

For a given application, nuclear reactors can be used in the cogeneration mode, in which heat is retrieved as steam from the various expansion stages of a turbine or from a condenser. The dedicated heat-only mode is also possible, in which heat is supplied directly through a heat exchanger to the customer. But the cogeneration mode has practical advantages: an increased plant thermal efficiency, the possibility of varying the heat supply according to demand, and an easier implementation, as almost all conventional nuclear reactors can be adapted.

Most industries need to rely on a secure and economic supply with energy to guarantee continuous and reliable operation of their process units. This requires flexibility on the nuclear side and an adjustment to multiple needs of the customers in terms of size and application. The market for industrial heat is highly competitive. Heat is currently produced predominantly from fossil fuels, with which nuclear energy will have to compete. Serious technical impediments of the coupling of nuclear reactors to various applications have not been identified so far; although a number of safety-related studies of coupled systems may still be necessary. A modular arrangement of several units will be necessary for redundancy, reliability and reserve capacity reasons. Small power sizes in the order of some hundred MW allow for simplicity and robustness by higher safety margins.

In the area of high temperature heat demand, the chemical and petrochemical industries offer ideal chances of CHP market penetration by nuclear power. This demand is expected to strongly increase in future, when massive amounts of additional H_2 and steam will be required for the conversion of heavy oils, tar sands, and other low-grade hydrocarbons. Currently, the processes of splitting hydrocarbons are presently widely applied production methods for hydrogen. The most important ones established on an industrial scale are steam reforming of natural gas, the extraction from heavy oils, and the gasification of coal. The technical viability of nuclear steam reforming was experimentally verified both in Germany and Japan.

But also as a clean fuel of the future, hydrogen has come into the focus of worldwide R&D activities. For its production on a large scale and at a constant rate, the use of nuclear primary energy may contribute significantly in a sustainable, competitive and environmentally friendly manner. The main sources for hydrogen in the long run in a CO_2-emission-free or at least neutral way will be water and biomass. Top candidate water splitting methods are thermochemical (hybrid) cycles and high temperature electrolysis, both verified at lab-scale.

Among the primary metal industries, steelmaking is a process of high energy consumption. Selecting the method of direct reduction of iron ore by hydrogen offers the potential of nuclear cogeneration of power and process heat for H_2 generation at the absence of CO_2 emission.

Christine MANSILLA

Dr. Christine Mansilla received her Master's degree in Energy Science and PhD in Industrial Engineering at the Ecole Centrale de Paris in 2006. Since then, she has been working as a Research Engineer at the CEA, in the Institute for Techno-Economics of Energy Systems (I-tésé), especially in techno-economics of hydrogen production and the electric system.

The work below will be presented by Camille Cany

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Performances and Economic Competitiveness Comparison of Advanced Hydrogen Production Processes Coupled to a Nuclear Reactor

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Hydrogen is usually presented as a promising energy carrier that has a major role to play in low carbon mobility, through the use of fuel cells. However, such a market is not expected in the short term. In the meantime, hydrogen may also contribute to reduce carbon emissions in diverse sectors: oil refining, low carbon mobility through the industrial deployment of advanced biofuels, natural gas consumption, and methanol (and other chemical products) production. Anyhow, hydrogen consumption should significantly increase in the next few years. To meet the demand advanced processes are developed throughout the world in a sustainability context. The most studied ones are thermochemical cycles: the sulphur-iodine and hybrid-sulphur cycles, and high temperature electrolysis.

For each of these processes, the CEA carried out a thorough study in 2009, from the flowsheet development to the final hydrogen production cost assessment, through the sizing and costing of the equipment. This study led to R&D guidelines that have been implemented since then.

This presentation details the advantages and drawbacks of these three advanced processes as regards their technical feasibility and economic competitiveness. An inter-comparison is attempted, leading to promote high temperature electrolysis over the other two. R&D studies to achieve economic competitiveness are still needed though and the CEA is actively working on it.

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Dr. Frank Carré is Scientific Director of the Nuclear Energy Division at the French Commission for Atomic and Alternative Energies (CEA). Since he joined the CEA in 1976, he contributed to studies on advanced nuclear systems such as light water reactors, fusion reactor blankets and space power reactors. After 1990 he successively managed Services in charge of Innovative Systems for power reactors, and Reactor and Fuel Cycle Physics within the Department of Reactor Studies. From 1997 to 2000 he served as Assistant Director of the Strategy and Evaluation Division of CEA, in charge of the strategic planning of CEA's civilian activities. From 2001 to 2006 he acted as Program Director for Future Nuclear Energy Systems within the Nuclear Energy Division. In this responsibility, he contributed to shape and to manage national R&D programs on fast neutron reactors with advanced fuel cycles and high temperature reactors for the cogeneration of process heat and hydrogen. From 2007 to mid-2009 he acted as Deputy Director for Nuclear Development and Innovation within the Nuclear Energy Division of CEA. In this position he co-managed national programs on future nuclear systems and remained actively involved in collaborative programs on future nuclear energy systems both in Europe and the Generation IV International Forum.

Since August 2009 he is Scientific Director of CEA's Nuclear Energy Division and a member of the International Nuclear Energy Academy. Frank Carré is also associate professor at the Ecole Polytechnique and professor at the National Institute for Nuclear Sciences and Techniques.

Since 2010, Frank Carré is Knight of the National Order of Merit in France and he received the Jan Runermark Award of the European Nuclear Society in 2012 for outstanding services to the benefit of the young generation.

Synergies between Nuclear and Renewable Technologies

Displacing fossil fuels and diversifying low carbon energies place nuclear and renewable energies at the center or most Western countries energy policies. Energy development scenarios for France based on energy savings, energy efficiency and diversification of low carbon energy sources are the subject of active studies since promulgations of the Energy Policy Act of June 6, 2005 and Acts 1 & 2 of the "Grenelle de l'environnement" in June24, 2009 and July 13, 2010. Further studies are currently conducted in support of the national debate on ecology/energy transition that has been launched in the fall of 2012 with a view to updating priority energy developments and research in a new Energy Polict Act by the end of 2013. Some of these scenarios, that are studied within the framework of the National Alliance for Coordinating Energy Research (ANCRE) aim at emphasizing and quantifying the benefit of integrating nuclear power with renewable energies to various degrees for meeting the diverse energy demand for housing, transports and industry.

Along the line of energy efficiency, an important saving of fossil fuels may be achieved while adjusting discharge heat temperature from thermal power stations (nuclear, solar or fossil fuels fired stations) for use in urban district heating networks or low/medium temperature heat supply to industry. This is addressed in a companion (paper by Henri SAFA).

Along the line of low carbon energy diversification, varied strategies ought to be considered to optimally integrate baseload power sources (nuclear, fossil fuel fired plants) and intermittent renewable energies (solar, wind energies) in a way that minimizes additional infrastructures investments and operating costs such as gas or coal fired plants for back-up power and energy storage capacities. Owing to the need for sufficient baseload power capacity to meet peak electricity demand, and the reduction of baseload power load factor caused by growing renewable energies, there may be an economic interest in considering baseload power sources operating in an interruptible cogeneration mode of storable electricity, heat, hydrogen of synthetic hydrocarbon fuels that may be reused for specific or multiple purposes. In addition, the French experience in nuclear plants load following may be valued and extended to compensate as much as possible for intermittent solar and wind energies.

Above forms of cogeneration may be considered beyond the needs to solely compensate for the intermittent generation of solar and wind power. Massive hydrogen production at a competitive cost (2-3 €/kg H_2) may be used directly, or in fuel cells, or mixed with natural gas (hythane) to displace fossil fuels used for housing, transports and some branches of the industry. If competitive with natural gas, synthetic gaseous hydrocarbon fuels produced from biomass or other carbonaceous matter and low carbon hydrogen (from nuclear or renewable energies) may appropriately displace or supplement natural gas for all its utilizations (transports, industry, peak electricity…) while making use of the same storage and distribution infrastructure. The same may hold for synthetic liquid fuels manufactured from biomass, coal or carbonaceous residues and low carbon hydrogen. They may displace liquid fuels from fossil origin and use the same infrastructures (with possible additional storage capacities) if they can be produced at a competitive price.

Above ways of integrating baseload with intermittent renewable power sources are currently being considered and evaluated technically and economically in energy systems development scenarios worked out within the framework of the Alliance ANCRE. These studies are expected to help quantifying the benefit of integration in terms of generating cost and CO_2 releases for meeting the diversified energy demand from housing, transport and industry sectors. They also aim at identifying key energy technologies (production, storage, distribution…) for optimizing France’s and Western Europe’s energy systems and support research and development accordingly.

Richard D. BOARDMAN

Dr Richard Boardman (Ph.D. Chemical Engineer) is the Department Manager for Energy Systems Integration at the Idaho National Laboratory (INL). He oversees the development and use of computational tools and testing facilities supporting the design, evaluation and testing of nuclear-renewable-fossil hybrid energy systems and enabling technology. He has been a technical lead at INL for 22 years, supporting applied research in radioactive waste thermal treatment operations, development and testing of coal and biomass combustion and gasification technology, design and modeling of synthetic fuels plants, and technical/economic evaluation of nuclear-renewable-fossil hybrid energy systems.

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Benefits of Dynamic Nuclear-renewable-industry Hybrid Energy Systems

This presentation will explore how integrated facilities comprised of nuclear reactors, renewable energy sources, and industrial processes can simultaneously address the need for grid flexibility, large-scale energy storage, GHG emission reductions, and optimal use of investment capital. Emphasis will next be given to innovations in nuclear reactor design and dynamic energy system simulation tools that help achieve optimized integration and more flexible operations of nuclear facilities with renewable power generation. The possible benefits of dynamic energy sharing to produce synfuels or chemical will be illustrated as a case example.

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Dr. Marco Cometto is a nuclear energy analyst at the Nuclear Energy Agency of the OECD, where he works on the economics of nuclear power. Recent and on-going activities are system cost of nuclear energy and renewables, cost of nuclear accidents and financing and project structure of nuclear new built. He graduated with a degree in Nuclear Engineering from the Politecnico of Torino and holds a PhD in physics from the EPFL in Lausanne. In addition to his engineering background, Dr. Cometto has a strong interest for finance and economics and has completed the CFA program (Chartered Financial Analyst). Prior to joining the NEA he worked as an investment advisor for an Italian bank and as a research engineer at EDF and at the French Atomic Energy Commission (CEA).

Nuclear and Renewables – System Effects

With the objective of reducing green-house gas emissions, many OECD governments have promoted the development of renewable energy technologies, in particular wind and solar power. In 2012 variable power from wind and solar constituted about 8% of the total European electricity production and this share is expected to grow considerably in the years to come. Already today variable renewables constitute more than 20% of the electricity production in Denmark end in the Iberian Peninsula, and almost 15% in Germany and Italy.

The integration of a substantial share of intermittent renewables has a profound impact on the design, structure and operation of the whole electricity system. In particular, future low-carbon electricity system will require more operational flexibility and the provision of ancillary services from all generating capacity, including base-load technologies.

The recent NEA study on the interaction between nuclear energy and renewables analyses the system-wide implications and the costs associated with the integration of large shares of fluctuating renewable energy in the electricity system. This presentation will focus on the short-term effects on the existing generation capacity and on the long-term impact on the optimal generation mix and on the implications on the business model of base-load technologies such as nuclear. These aspects should be taken into account when considering the development of electricity systems integrating variables and base-load technologies.

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Dr. Marc A. Rosen is a Professor of Engineering at the University of Ontario Institute of Technology in Oshawa, Canada, where he served as founding Dean of the Faculty of Engineering and Applied Science from 2002 to 2008. He is also a Director of Oshawa Power and Utilities Corporation. Dr. Rosen has been President of the Engineering Institute of Canada and President of the Canadian Society for Mechanical Engineering. He has served in many professional capacities, including founding Editor-in-Chief of the journal Sustainability and Associate Editor of the International Journal of Exergy, and is an active teacher and researcher in exergy, energy technology and sustainable energy. Dr. Rosen has worked for such organizations as Imatra Power Company in Finland, Argonne National Laboratory near Chicago, and the Institute for Hydrogen Systems near Toronto. He has authored several books on exergy-based method. Dr. Rosen has received numerous awards and honours, and is a Fellow of the Engineering Institute of Canada, the Canadian Academy of Engineering, the Canadian Society for Mechanical Engineering, the American Society of Mechanical Engineers and the International Energy Foundation.

Application of Exergy-based Methods for Technical, Economic and Environmental Assessments of Nuclear Cogeneration

Although the potential benefits of cogeneration (i.e., combined heat and power) are significant, the allocation of carbon dioxide emissions and economic costs from cogeneration is often challenging, as existing methods are not soundly based, inconsistent, overly complex and difficult to apply. Exergy-based methods are based on the first and second laws of thermodynamics, and are increasingly being used to evaluate meaningful efficiencies for processes and systems. The exergy of an energy form or a substance is a thermodynamic measure of its usefulness or quality. Here, the application of exergy-based methods is described for carrying out technical, economic and environmental assessments of nuclear cogeneration. In particular, the author proposes that exergy-based methods can form the basis for rationally and meaningfully allocating cogeneration-based carbon dioxide emissions and costs, and for evaluating technical efficiencies that can be fairly compared with other processes. The methodologies described is illustrated for nuclear cogeneration and compared with other methods. The results also suggest that the exergy-based approach provides a sensible basis for a meaningful overall approach for carbon dioxide emissions trading. It is concluded that exergy-based methods for allocating carbon dioxide emissions and costs from cogeneration are rational, useful and superior to other methods. The results can aid designers of energy systems, and decision and policy makers in companies and government, especially regarding how environmental emissions and economic costs should be reduced, how and where nuclear cogeneration should be used, and how such carbon dioxide emissions can be traded. If the results are used appropriately, they should allow benefits to accrue to society through the selection and design of better energy technologies, based on technical, environmental and economic considerations, the incorporation of exergy into these assessments will likely improve them notably, both in general and in particular in terms of efficiency, economics and environmental emissions.

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Prof Dr. Reinhard Madlener is a full professor of energy economics and management at the School of Business and Economics, RWTH Aachen University, Germany. He is also co-director of JARA Energy, the energy section of the Jülich-Aachen Research Alliance (www.jara.org), and research professor at the German Institute of Economics Research (DIW Berlin). His main research interests are in the fields of energy economics and policy, energy sustainability, and the adoption, diffusion and financing of innovative energy technologies under uncertainty. He mainly teaches energy economics, environmental economics, economics of technological diffusion, and economics of technical change. He is associated editor of Applied Economics Quarterly; Applied Energy; Energy Systems; Energy, Sustainability and Society; the International Journal of Energy Sector Management; and Sustainable Cities and Society.

Economics Viability of High-Temperature Nuclear Reactors for Industrial Cogeneration

J. Hampe and R. Madlener

In the context of rising uncertainty about oil, gas and CO_2 permit prices it becomes increasingly challenging for energy-intensive industries (e.g. iron and steel, refineries, chemicals) to maintain their competitiveness. Therefore, many of these companies are looking for alternatives to the widely used gas or oil burners to produce the process heat required. One alternative is the use of a nuclear high-temperature cogeneration (combined heat-and-power production, CHP) plant. A utility can offer electricity and process heat to the companies so that they neither need to maintain equipment and infrastructure for self-generation nor to buy CO_2 allowances. In addition, the utility can sell excess electricity to the grid. In order to investigate the potential of such a business concept, we assess the economics of high-temperature reactors (HTR) for nuclear CHP. In the economic evaluation, we first perform a discounted cash flow (DCF) analysis as a practitioner's benchmark analysis, followed by a real options analysis (ROA), which is used to determine a value for the flexibility the utility has in its decisions to react to changing market conditions. The option to delay the investment is evaluated as well as the option to switch the power plant’s output from CHP of heat and electricity to the generation of electricity only. Subsequently a sensitivity analysis is performed to determine the key drivers for the investment decision. Based on the analysis, a concrete business case for HTR nuclear CHP from the perspective of a utility is created. The economic evaluation is completed with a survey of potential customers, an outline of the market’s attractiveness, a risk assessment, and a detailed scenario analysis.

Even though using a HTR for industrial CHP is already economically viable today (if all assumptions are correct), we conclude for two reasons that a utility should not carry out such an investment today: (1) the data used and the further assumptions made have large uncertainties attached to them and the NPV and IRR are sensitive to large changes in the input parameters. Hence, a utility would take a considerable risk when building a HTR for industrial CHP today. (2) The results found in the ROA for the option to delay investment show that an investment today would not be optimal, since the threshold price is well above current electricity prices, implying that it is better to delay the investment. We conclude that operating a HTR for industrial CHP has a considerable upside potential. A utility should, therefore, try to maintain the possibility to invest in a HTR to profit from the upside potential in case the uncertainties in the technical parameters diminish and the market environment turns out favorable. In other words, a utility should hold an option to invest in a HTR. Such an option can be actively pursued, for example, by gathering information from the existing Chinese HTR-PM project or by working on the detailed development of a detailed plant design together with plant manufacturers and industrial customers, aiming at the goal of collaboratively building a demonstrating HTR for industrial CHP in the EU. Finally, we argue that ROA should be incorporated as a standard tool for the evaluation of investment decisions of a utility. Especially in highly uncertain environments, the results obtained by the ROA provide additional insights not gained with the simple DCF analysis. In contrast to the NPV and IRR rule that suggested to carry out the project to increase the shareholder value, the results from the option to delay calculations clearly state that it is optimal to wait with the investment and to hold the option to invest alive. This is an important result for utilities, since it demonstrates the usefulness of providing a rule for optimal investment, instead of only the simple yes-no investment decision provided by the DCF methods. The option to switch calculations showed, in addition to the option value as a direct result, that implicit conclusions can be drawn from the ROA. One example is that linking the electricity and the heat price supersede a redesign of the HTR to enable it to run in the two different modes and, hence, could save the utility the costs for this redesign.

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Dr Michael G. McKellar is a Research and Development Engineer at the Idaho National Laboratory. For over 10 years, Dr McKellar has modelled and analysed a number of chemical and thermodynamic processes using process modelling software. These processes include compact natural gas liquefaction systems; high temperature steam electrolysis for hydrogen production; high temperature carbon dioxide and steam electrolysis for syngas production; power conversion units such as Rankine steam cycles, Brayton gas cycles, super-critical carbon dioxide modified Brayton cycles, and combined cycles; bio-mass pyrolysis and gasification; and atmosphere revitalization for NASA. He has been the technical lead for the development of intermediate heat exchangers for use in molten salt cooled nuclear reactors. He also was the technical lead for the integration of process heat applications with next generation nuclear plants. He acted as the principal investigator for the testing of a hybrid refrigeration system which included the design, construction, and testing the process. He worked as part of a team that developed, designed, constructed and tested a compact natural gas liquefaction system that won the 2006 R&D award. He developed software, supported experimental testing, and led projects in the areas of nuclear waste management, electric vehicle batteries, and nuclear valves.

He received a PhD and Masters in Mechanical Engineering from Purdue University and BSME degree from Brigham Young University.

NGNP Business Models for Industrial Process Heat Applications

This presentation will discuss the business models developed by the INL and NGNP Alliance. The economic model was prepared by INL and used for establishing the economic viability of integrating HTGR in industrial processes and for generation of electricity.

The industrial process and the high temperature gas reactor (HTGR) plant are modeled. The business plan can be evaluated in two ways that either separates the economics of the process from that of the HTGR or integrates the process and HTGR economics as follows:

- The HTGR supplies energy to the process at a calculated price and the process economics are evaluated at that price; or
- The HTGR is fully integrated into the process and the economics are evaluated by comparing the calculated product pricing with the market.

The methodology of the model accounts for discounted cash flow analysis from project initiation through decommissioning of the plant. The costs include:

- Design, licensing, construction and commissioning of the modules using a phased approach with varying construction and startup times;
- Debt and interest on debt during construction;
- Operating costs including debt payments, continuing capital expenditures & outage costs including refuelling;
- Tax and decommissioning costs, including escrow of DD&D costs;

- Inflation and escalation factors can be applied to each cost and revenue element.

Capacity factor considers module construction and commissioning phasing, refuelling, planned outages and un-planned outages. Revenues from sale of the commodities are based on plant capacity factor. The model returns internal rate of return on equity, net present value, net income and simple payback period.

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Mr. Shropshire joined the IAEA as Section Head of the Planning and Economic Studies Section (PESS) in December 2012. Current research interests include Small and Medium-Sized Reactors (SMRs) and integration of nuclear with other energy systems. Research support over the past three years was provided to the European Commission Joint Research Centre (Netherlands), Pacific Northwest National Laboratory (Washington), and BSU's Energy Policy Institute (Idaho). Previously, he worked at Idaho National Laboratory where he led research on the cost of GenIV reactors and participated on the GenIV Economic Modelling Working Group. He performed modelling and analysis of advanced nuclear fuel cycles and developed DOE's Advanced Fuel Cycle Cost Basis report. He has also contributed to several OECD Nuclear Energy Agency economic and modelling studies. Mr Shropshire published over 60 technical papers and reports on energy-technology modelling and economic/ decision analysis. He is a registered Professional Engineer and was past Chair of the Idaho Section of the ANS.

Integration Challenges for Nuclear Cogeneration

Future energy systems will increasingly need to integrate variable renewable energy while also reducing greenhouse gas emissions from power production and transport. A case study is presented that describes a conceptual nuclear cogeneration system that produces synthetic biofuels (bio-diesel, bio-gasoline) and performs electricity load balancing. The system is composed of a cogenerating high-temperature gas reactor (HTGR), aggregated wind farms, and biomass processing. In this system, the HTGR balances the power output of variable wind and supplies heat for the biomass processes. Three types of biomass processing were investigated: (1) drying and torrefaction; (2) drying, torrefaction, and pyrolysis; (3) drying, torrefaction, pyrolysis, and synthetic fuel production. Variable electricity produced by wind energy is balanced by altering the heat-to-power ratio of the HTGR, and by using excess electricity from the system for hydrogen production through electrolysis. Some of the integration challenges include: sizing (mass-flow standpoint) of the HTGR relative to the size of composite variable energy source, mass of the regional biomass collection, and extent of biomass processing; and defining the ratio between heat and power production to compensate for intermittent renewable energy sources.

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