Applications of Nuclear Energy to Oil Sands and Hydrogen Production

R.B. Duffey, S. Kuranb A. Millera

aAtomic Energy of Canada Limited
Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0
bAtomic Energy of Canada Limited
2251 Speakman Drive, Mississauga, Ontario, Canada, L5K 1B2

Abstract. Many novel and needed applications of nuclear energy arise in today's energy-hungry, economically challenged world, and in solving tomorrow's search for a globally carbon-constrained and sustainable energy supply. Not only can nuclear power produce low cost electricity, it can provide co-generation of process heat, desalinated water, and hydrogen with negligible greenhouse gas emissions. In each of these new applications, nuclear energy is competing against, or displacing conventional and established use of natural gas or coal in thermal power plants and boilers. Therefore, there must be a compelling case, in terms of supply certainty, stability, safety, security, and acceptability. In addition, a synergistic relation must exist or be created with the existing power and energy markets, the use of windpower, and the needs for low-cost supply with negligible greenhouse gas emissions and carbon "footprint".

The development of Canada's oil sands resource depends on a substantial energy input for extraction and upgrading. So far, this input has been supplied by natural gas, a resource that (a) is a premium fuel; (b) has constrained availability; and (c) produces significant CO2 emissions. For the oil sands extraction process, natural gas is the current energy source used to generate the steam for in-situ heating, the power to drive the separation equipment, and the hydrogen for varying degrees of upgrading before piping. Nothwithstanding the current imbalance between supply and demand for gas within North America, the very demand of the oil sands for prodigious amounts of natural gas has itself the potential to force higher prices and create supply constraints for natural gas. Rooted in the energy equivalence of oil and gas, there is a long-established link between American gas prices whereby one bbl of oil is worth 7 GJ of natural gas. Temporary supply/demand imbalances apart, only cheap oil can maintain cheap gas. Only the improbability of cheap oil will maintain low natural gas prices, an unlikely circumstance but one that would undermine the very development of oilsands as surely as high cost and limited availability of natural gas.

We examine the applications of nuclear energy to oil sands production, and the concomitant hygrogen production, utilizing realistic reactor designs, modern power and energy market considerations, and environmental constraints on waste and emissions. We cover all aspects of feasibility, specifically technical issues, comparative economics, schedule, regulatory requirements, and other implementation factors. We compare and contrast the claims versus the realities, and also provide the synergistive utilization of co-generation of hydrogen using coupled nuclear and windpower.

Among the many non-technological issues expressed by the oil industry are their lack of experience with nuclear technology or nuclear power generation, and with the regulatory framework. The application of any nuclear technology must also consider Government and public support, local and First Nations acceptance, site selection, access to water, oil sands, and transmission, oil industry buy-in on the basis of hard nosed economics, the impacts of oil and gas prices, labour costs and the need for long-term contracts for steam and electricity, together with an experienced nuclear plant owner/operator.

1. BACKGROUND: ENERGY AND ENVIRONMENTAL NEEDS

The world is faced with a condundrum of producing as much energy as possible for the developing needs of the major global populations, while reducing emissons and assuring sustainability of supply. To both stabilize and become sustainable implies an increase in energy use of a factor of two to five, while reducing GHG emissions by 80% by 2050 [1]. Much has been written about whether this is achievable or even necessary, but even for the quite inadequate constraints contained in the Kyoto Treaty, emissions have risen in lock step with increasing energy use [2].

This conflict between sustainable future energy supply at modest price, and massive increased global energy use while yet lowering emissions is manifest for the oil sands in Canada, a resource as large as the oil fields of Saudi Arabia. A barrel of bitumen (so-called "heavy hydrocarbons") requires up to 25% of its energy content for the extraction and upgrading of the sticky sand deposits – a challenge for oil sands developers who presently produce more than 1.2 Mbbl/day and expect a production growth by 2015 of up to 2.8 Mbbl/day [3]. Oil sands now account for approximately 44% of Canada's total oil production. By 2015, it will account for approximately 75% of Western Canada's production with much of this supply going by pipeline to the USA, increasing Canada's share of oil imports to the USA from 19% in 2008 (Ibid). The growth is not sustainable, since most of the energy for mining, separations and upgrading is presently derived from depleting natural gas supplies. In addition, the supply has been termed "dirty oil" as it results in more GHG emissions than alternate underground wells and reservoirs. Also, the competitive price per delivered barrel would undoubtedly be adversely affected by any proposed emssions restraints using carbon emissions cap–and–trade or emissions credit schemes now under active deployment debate and development in North America [4, 5]. For the Canadian oil sands, what is clear, is that emissions will continue to rise significantly as extraction amounts increase [6], despite massive requirements and efforts to reduce CO2 production and release [7].

Now nuclear energy has been proposed for long and many times as a possible energy source for extraction, separation and upgrading, but has never been actually deployed [8]. For example, Asgapour [9] has reported the results of the PTAC (Petroleum Technology Alliance Canada) study on alternatives to replace natural gas use in oil sands development. He concluded that: "The introduction of nuclear energy into the Oil Sands region will be a lengthy and expensive process". In additon the timing for a nuclear plant installation was likely to be post 2025, with a project duration of over 15 years, including site selection, environmental assessment, licensing and construction. In additon, PTAC noted: "A practical way of utilizing the existing commercial NPP designs for use in the Oil Sands region would be to adopt a 'utility' approach for the delivery of energy (in the form of steam and electricity) to multiple Oil Sands facilities, and for providing electricity to the Alberta power grid."

In this paper we provide such a practical short-term 'utility' approach using large plants; and we also lay out a longer-term development program to match the oil sands needs for smaller energy production units, while avoiding importing or introducing new nuclear technology. These nuclear energy methods provide a "zero emissions" basis for continued and expanded oil sands use, since oil will continue to be needed as a base supply for industrial purposes into the far future, and at stable prices. They have assured licensing routes, and with advanced recycling fuel cycles can drastically reduce spent fuel amounts, shorten spent fuel storage times, and assure a sustainable thorium-based fuel cycle, which is already undergoing demonstration [10].

The concomitant need to produce hydrogen has also been extensively addressed [11, 12] with respect to transportation and industrial energy use. For oil sands deployment, we also need to produce hydrogen by an assured low cost, low emissions manner. In our approach this is consistent with indirect hydrogen production by electrolysis from electric power in the short-term, and with direct thermochemical and electrochemical production from dedicated facilities in the longer-term. This hydrogen production and storage system is then coupled with wind power, to utilize the intermittent wind and the daily load variations to advantage using off-peak power and time of day electricity pricing.

2. THE UTILITY GRID MODEL: CO-GENERATION OPTIONS

There are many methods in use and/or proposed for oil sands extraction, all requring energy and all intending to improve on the present processes. These include Steam Assisted Gravity Drainage

(SAGD) use gas-fired steam generators with carbon capture; with coal gasification and carbon capture; or with nuclear steam. Other techniques include solvent or inert gas injection, in-situ combustion, and electro-thermal heating. What is economic, feasible and/or deployable depends on market prices, environmental contraints, deposit geology and location, and the project size. There is no "one size fits all", which explains why small and modular gas-fired one-thru steam generators have been the preferred energy source until now.

As to CO2 releases, comparisons show coal at 850 tonnes/million kWh, oil at 700, natural gas 550 and Nuclear ~ 10 tonnes/million kWh. The implied emissions savings are of 5 Mt CO2/year versus natural gas for one equivalent 3200 MWth steam generation plant, where the nuclear reference case is an ACR-1000 unit. So clearly nuclear energy can help meet oil sands GHG intensity reduction targets and assist in absolute reductions.

In 2004 to 2007, AECL performed site specific studies with several oil sands producers on deployment of ACR and EC6 units in northern Alberta in a steam/electricity configuration [13]. The many studies concluded that CANDU® energy output is technically feasible and economically competitive for oil sands applications, the design can be adapted for minimal water consumption, the plant structures can be adapted to climate and geology, nuclear licensing could be effectively managed, and that modular assembly minimizes construction challenges due to labour costs and skills. Steam can be economically transported up to 15 km without undue thermal losses or cost.

We have therefore proposed a short-term approach using variant of the standard nuclear plant in order to meet oil sands production requirements [3].We projected that eight large ACR-1000® units would be required to support the 2008 – 2015 production growth.

A 1000 Mwe NPP (steam output only) can support 200,000 to 300,000 bpd in-situ production facility. Since most SAGD facilities are in the 30,000 to 50,000 BPD range solution, one ACR-1000 configured to provide both steam and electricity in a COGEN mode would provide steam for SAGD applications, electricity for utility grid and process applications, and electricity for hydrogen used in bitumen upgrading.

The exact product stream mix also depends on the wholesale energy sales to the provincial power grid, so there would be dedicated power supplies to various oil sands facilities (recovery, processing and upgrading), electrolytic hydrogen plants to supply bitumen upgraders and possible resistance-heating for carbonate shale extraction. Electric boilers could supply steam for small dispersed in-situ bitumen extraction facilities, and in the longer-term power for electro-thermal heating for bitumen extraction.

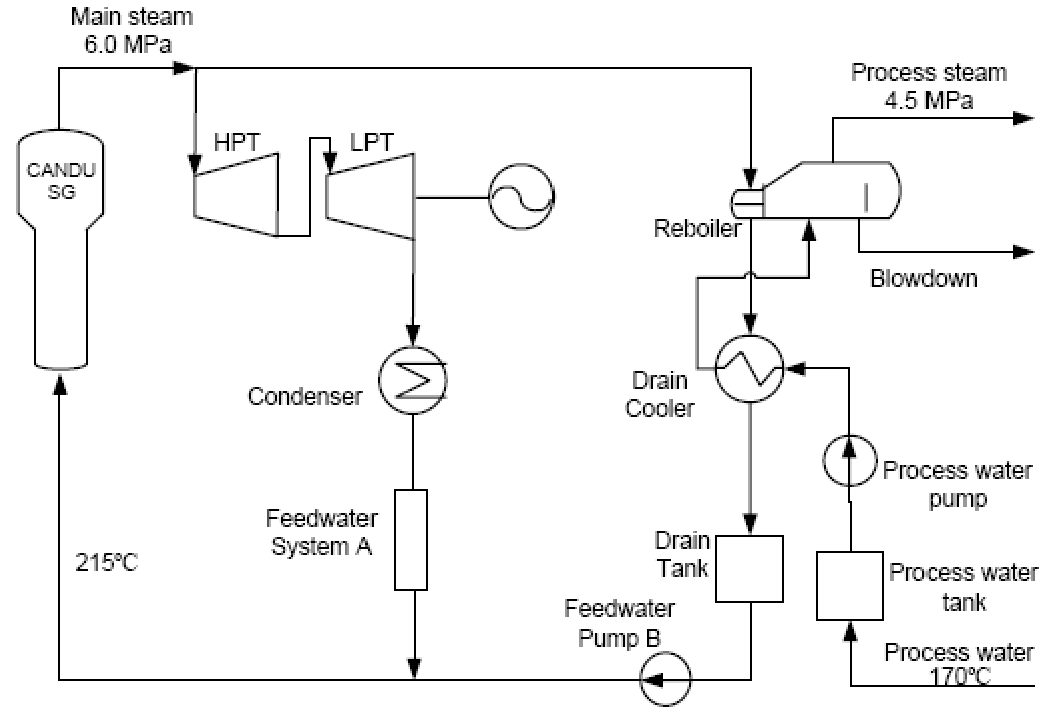

Fig. 1. Typical large nuclear unit secondary side configuration.

The bottom line advantages of this utility approach are: (a) the use of known and existing water reactor technology; (b) the assured licensing and build process; (c) the link to the existing power grid; (d) the known manufacturing and operational experience; (e) the co-generation flexibility and cost; (f) the opportunity to avoid the use of coal and natural gas for electricity generation; with (g) the immediate impact of reductions in projected CO2 emissions.

3. HYDROGEN PRODUCTION: PRAGMATIC METHODS

Most industrial hydrogen is generated by Steam Methane Reforming (SMR) process using natural gas feedstock. The hydrogen cost for SMR is very sensitive to the price of natural gas, and limiting supply has caused process to be volatile.

The only alternate proven means available today of producing hydrogen, and the simplest, is by electrolysis. The hydrogen price is competitively using intermittent H2 production with off-peak electricity prices [14] specifically demonstrated as applicable in and to the Alberta power market and also including further wind power use.

This analysis includes a detailed optimization based on current fluctuating electricity prices, from data of hourly selling price for electricity to the Alberta grids. These data are imported into a NuWind© model EXCEL spreadsheet. Then a level of conversion to hydrogen is set between 0 and 100% and the economics optimized by varying systematically: (a) the size of the electrolysis installation, being obviously larger relative to production than for continuous operation; (b) the quantity of hydrogen storage, with a minimum of 12 hours, set to represent rather crudely the daily fluctuation in demand and subject to a (fixed and known) price, appropriate for above-ground storage; (c) a threshold price above which electricity would normally be supplied to the grid; and (d) storage volume threshold below which the normal threshold price would be replaced by a higher threshold price.

The intermittent off-peak production can meet continuous supply requirement also using underground storage as ICI has been using caverns at Teesside, in the UK for 30 years. Importantly, electrolysis from a non-carbon source like nuclear energy avoids 8 kg CO_2 per kg of H_2 produced compared to SMR. So overall electrolytically produced H_2 (using nuclear electricity) for a 250,000 BPD upgrader avoids or reduces GHG emissions by some 2.5 Mt CO_2/a.

As to manufacturing and construction, standard electrolysis modules simplify shipment, installation and servicing. There are also economies of scale, with larger units having lower cost. High temperature electrolysis, say above 700°C, holds the promise of higher efficiency and hence lower cost hydrogen.

We have shown, using our NuWind© model, that hydrogen can be produced for oil sands or other uses at competitive prices using an optimized mix of nuclear and wind power. Basically, the off-peak to peak price and demand fluctuations in the electric grid marketplace are utilized. The hybrid system produces hydrogen and/or sells electricity when the economics (electricity prices) are favorable. Thus, not only is hydrogen "smoothing" or levelizing the electricity demand cycle, it enables the largely baseload nuclear to support the highly intermittent wind power which is a major side benefit in a carbon-constrained scenario.

4. LONG-TERM FUTURE OPTIONS: DISTRIBUTED NUCLEAR AND POTENTIAL HYDROGEN PRODUCTION

Many of the oil sands resources are for both business and geological reasons, geographically distributed and/or commercially exploited in smaller resource fields. These sites require more distributed and flexible energy sources and siting, and perhaps are located away from the main electric grid and/or in remote locations. The PTAC study [9] therefore also looked at future options which could address the needs for reducing unit size, capital cost, and the distance to transport steam. Present large water-cooled reactors of 1000 Mwe plus size obviously have thermal and electric capacities, that greatly exceeding the energy requirements for small extraction sites. Future higher temperature reactors (e.g., HTGRs and PBMRs) could meet the technical requirements, but are not currently commercialized (not yet be deployed in their home markets), and have historically long development times, and are limited in temperature to some 750°C anyway.

We have been examining these questions for some time, searching for a longer-term option that does not involve a leap into unknown or risky nuclear technology. The reactor answer actually lies within the coal industry itself, through the development of today's highly efficient, low cost, supercritical utility boilers operating at thermal cycle efficiencies of greater than 44% [15, 16]. The so-called Super Critical Water Reactor (SCWR) is based on using that same water-cooled technology, not on extrapolation, and is possible to build in a range of sizes from 300 up to 1500 MWe (600-3000 MWt) using existng, commercially available turbine technology and proven thermal cycles up to 625°C or more with nuclear reheating. The fundamental development effort needed prior to deployment by 2020-2030 is being pursued in Canada's Generation IV National Program, and in collaborative R&D efforts with China, EU, Japan, Korea, Russia, and others [17]. The target for the economic cost is some 30% below current designs.

The other key element of this effort is the direct thermochemical production of hydrogen at much lower temperatures using the so-called Copper-Chlorine process [18, 19]. In addition high temperature electrolysis is being investigated for hydrogen production [20].

These are all very recent developments that leapfrog today's nuclear energy technology to the forefront of tomorrow's distributed, high efficiency co-generation for potential oil sands applications.

CONCLUSIONS

Current water cooled reactor designs (ACR-1000 or Enhanced CANDU 6 for example) can provide both thermal and electrical energy to a range of oil sands applications, that can be economically competitive under various scenarios. Utilizing the nuclear energy of ACR-1000 enables reduction in the GHG emission intensity and absolute amounts for a variety of oil sands recovery and upgrading applications.

Co-generation of hydrogen for upgrading is economic today using off peak power and indirect electrolysis. The ACR-1000 energy source can be available by 2020 with Alberta Government and oil industry cooperation. In the longer-term, the CANDU Gen IV “SuperCANDU” will be a good fit for distributed oil sands developments, making possible high efficiency in a range of sizes. The co-generation of hydrogen by direct thermochemical processes is also being actively pursued and holds great promise for the future.

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