Notes on Energy Systems

Part A – Reliability and Renewables (Solar and Wind)

Electricity is more valuable to consumers if it is reliable, on demand. That means the electricity system should be able to meet consumer variable hourly demand across all seasons at a high reliability level.

In North American the mandatory reliability standard for the high voltage electricity systems that are interconnected to each other is set by the North American Electric Reliability Corporation (NERC). The minimum reliability target is set at no more than 1 blackout in a 10-year period. The standard is set high because the high voltage system powers our industrial society, including our fossil fuel heating systems in the winter. Ontario meets this standard.

The lower voltage distribution system has less stringent reliability standards because a local outage is not as damaging to public safety or the economy.

Each generating station or facility cannot achieve those reliability requirements on their own. The system integration services that the overall electricity system must provide for reliable electricity supply is paid for by uplifting those additional costs to retail rates that the consumer pays in Ontario.

The system integration services include the following:

(1) Sufficient total dependable installed capacity to meet peak power demand (kW) during severe weather conditions.
(2) Sufficient energy output capability to meet energy demand (kWh), regardless of the output of any generation source.
(3) Sufficient rotating inertia to maintain frequency within safe limits.
(4) Sufficient reactive power production and absorbing capability to maintain line voltages within safe limits.
(5) Sufficient backup generation to accommodate individual equipment failures, lack of individual generator energy output or unexpected higher demand from consumers or due to severe storms especially during very hot or very cold periods.
(6) Sufficient transmission and distribution transformer and line capacities to accommodate the peak power output of each generating facility and consuming loads.
(7) Ability to adjust generation output levels and rate of change of output to follow the consumer load demand profile minute by minute.
(8) Appropriate protection relays and co-ordination of their protective action to ensure safe operation of all power system equipment without creating wider area cascading blackouts during local protective trips. This requirement includes high voltage to low voltage protection for large generation sources (nuclear, fossil fired and large hydroelectric) and additionally low voltage to high voltage protection for smaller generation sources (small hydro, solar and wind generation) installed in the distribution system.
(9) Ability to control import/export power levels within allowable deviations from power transfer schedules with other adjoining power systems.

Each generating technology requires a different level of system integration support from the overall power system. The amount of support required depends on how each generation technology is used to serve load and the production characteristics of that generation technology.

For example, solar does not produce energy at night and much less on overcast days. An electricity system planner needs to combine solar with some other form of dependable backup energy production to supply electricity when the sun does not shine. Natural gas generation, batteries or hydroelectric generation are typically used to back up solar. Unfortunately, batteries are very expensive if the solar outage period is long. Pumped hydroelectric storage requires a specific geography to make it economically practical for extended operating hours. It is not unusual for solar to have low production periods of many days or even a couple weeks during severe weather events. The cost of storage for such long durations is prohibitively expensive. Shorter duration 4-hour electrical storage is economically available and will allow solar to extend its energy production period into the evening high demand period after the sun sets. Consequently, solar generation can be economically used for the incremental daily peak demand above the base-load (round the clock) demand. The base-load demand is best provided by generation technologies that do not require storage or backup generation support. That includes nuclear, natural gas and large base-load hydroelectric plants that have reservoir water storage or dependable water flow.

Wind generation produces about half its energy at night and half during the day. This means that wind will compete for consumer demand with nuclear at night and solar during the day. Care must be taken to make sure the additional wind capacity does not create excess production above the consumer demand. That excess would then require expensive storage to move the production to other demand hours or the output would have to be exported at low spot market energy prices or curtailed (wasted). Since most generation contracts are set up on a guaranteed fixed cost basis for installed capacity and payment for energy on a variable (fuel) cost basis, curtailing too much energy production will dramatically increase the retail price of electricity due to the retail uplift charges for the underused capacity.

Wind and solar generation use inverters to convert energy production into the correct AC frequency for the power system. Inverters do not have the additional energy storage to produce artificial rotating inertia or reactive power support for frequency and voltage stability. This can be corrected by installing synchronous rotating condensers or electrical storage to provide the required frequency and voltage support. Unfortunately, as the amount of wind and solar generation increases the amount of equipment required for frequency and voltage stability also increases and that will cause uplift charges to retail electricity rates to rise.

Low operating capacity factor generation technologies require more transmission and distribution system capacity relative to the energy they produce. The lines must be able to carry the maximum installed capacity of the generation facility. However, in Ontario, solar and wind operate at approximately 15-20% and 30-35% operating capacity factor respectively due to the long periods of no sun and no wind. This means the line and associated transformer costs need to be depreciated over a much lower operating capacity factor. This will cause retail electricity uplift charges to be higher than for generation technology with much higher capacity factors like nuclear which typically operates at 85%-95% capacity factor and makes better use of the line and transformer investments.

Another major cost is backup generation to cover periods of low output from each generation technology. However, the various technologies have very different requirements for installed dependable backup capacity. The Ontario independent electricity system operator (IESO) has undertaken studies of the effective load carrying capacity of each generation technology at the electricity system peak demand hours. The results are summarized below:

- Nuclear installed capacity is available 94-95% of the time during peak demand so nuclear generation requires only 5-6% backup from the electric power system.
- Natural gas installed capacity is available 81-88% of the time during peak demand so natural gas generation requires 12-19% backup.
- Hydroelectric installed capacity is available 70-78% of the time during peak demand so hydroelectric generation requires 22-30% backup.
- Wind installed capacity is available 38% of the time in winter during peak demand and 13% of the time in summer so wind generation requires 62% backup in the winter and 87% in the summer.
- Solar installed capacity is available 5% of the time in winter during peak demand and 33% of the time in summer so solar generation requires 95% backup in the winter and 67% in the summer.
- Electric battery storage installed capacity is available 23% of the time during peak demand so electric storage generation would require 77% backup. Note: In Ontario battery facilities are owned by market participants and not by the independent system operator. Battery owners can make more money via price arbitrage between higher and lower priced electricity periods. Therefore, battery owners typically partially discharge their batteries during periods other than the highest system peak load demand hours. That is why the available capacity during the system peak demand hours is only 23% of installed electric battery capacity.

The larger the backup requirements, the higher the retail rate uplift charges for that required backup capability. For example, in the case of solar in the summer, the system planner would have to build a dependable backup generation facility 95% as large as the solar installed capacity. Currently natural gas generation is the preferred backup to solar because of its low capital cost and relatively affordable natural gas fuel costs. However, if consumers demand zero emission, solar only solution, that backup generation would only be 5% dependable in the winter. To achieve the 95% dependable backup capability a system planner would have to install 19 times the installed capacity of solar to provide the required dependable backup. During other seasons that additional solar capacity could not be utilized effectively due to the high cost of seasonal electrical storage. The excess production capability would have to be curtailed (wasted).

Of course, using solar to back up solar would be impractical, so a system planner would look for other options like electrical storage or combustion turbines running on more expensive clean net-zero fuels like renewable natural gas or hydrogen. The backup requirements for a solar only power system are therefore very expensive and would result in very high uplift charges to retail rates.

In summary, to achieve high reliability and low emissions at an affordable electricity cost, the system planner would typically select hydroelectric and nuclear plants for the base-load (round the clock) demand and then use renewables sources like wind and solar with modest amounts of storage for the incremental peak load demand. The system planner would also select a low capital cost dependable generation technology like combustion turbines for the operating reserve and backup requirements. Whether those combustion turbines run on natural gas or low emission fuels will depend on the emission goals and the public's ability to pay for the higher cost clean fuels.

Part B – Thermal Energy Demand

Most natural gas heated homes use about double the amount of heat energy in a year as they do in electric energy. Some of that heat energy is for hot water all year but the majority is for space heating in the colder months.

In Ontario the average total cost of electricity is about 16 cents/kWh. That compares to about 4 cents/kWh for natural gas. Electricity is therefore about 4x more expensive than natural gas if a consumer needs heat when comparing electric resistance heating with a natural gas furnace. That comparison does not include the cost of installed heating equipment.

A consumer could install a cold climate, air source, heat pump which has a co-efficient of performance of 2 over the course of a full heating season. That means the more expensive heat pump would use about ½ the electricity as a baseboard heater would over the whole heating season. The consumer would still need to pay about double for their heating energy cost using heat pump electricity compared to using natural gas. That extra cost does not include the additional depreciation and maintenance costs for the heat pump compared to resistance heaters.

One alternative to air source heat pumps in rural areas is a ground source heat pump with a coefficient of performance of about 4 over the heating season. However, ground source heat pumps are about double the cost of cold climate air source heat pumps.

Another alternative in higher density cities is a district heating system powered by boilers. The boilers could be fuelled by low emission fuels like bio-mass, renewable natural gas or nuclear power. The cost of heat from a nuclear reactor is typically less than 1/3 the price of electricity from that same nuclear plant. The cost of the district heating system piping will increase the thermal energy cost to the consumer but the final heat energy cost will be less than the cost of electricity.

One additional concern regarding air sourced heat pumps. Cold weather air sourced heat pumps do not operate well below negative 25 C. In more northern cities where temperatures can drop to negative 40 C the consumer would need to switch to a backup heating source. Resistance heaters, bio-mass heaters, clean fuel furnaces, or natural gas furnaces are options. If the consumer chose to use resistance heating to take advantage of the clean electricity system in Ontario, the actual peak load of the heating system would be double the heat pump load during the coldest days of the year. That peak heating load is about 4x the peak air conditioning load in the summer. The power system would therefore have to be expanded to meet that very high peak demand on the coldest winter days. The operating capacity factor of that additional generation capability would be very low and the uplifted depreciation costs to retail electricity rates would be very high.

Thermal storage can be installed in each building or centrally in a community storage facility. Thermal storage can be used to reduce the peak load demand of either the electricity system or the district heating boilers. Thermal storage for several hours at the building level is about 10x cheaper than electrical storage. At the community level thermal storage can be made large enough to enable seasonal transfers of heat. Seasonal thermal storage is about 100x cheaper than seasonal electrical storage. At the community level, seasonal thermal storage can use various waste heat sources available inside a city such as data centres, industrial processes, wastewater treatment facilities, garbage incinerators, power plants, etc. European cities are deploying community thermal storage and district heating systems more extensively than in North America.

In summary, if urban consumers need heat, it is cheaper to supply them with heat directly rather than supplying electricity and converting that electricity to heat.

The situation is different in rural areas where district heating is not an economic option. However, rural areas often can use bio-mass if wood or other forest waste products are available for building heating requirements.

Part C – Life Critical Emergency Reserve Generation

In very cold climate jurisdictions like northern Ontario and very hot, high humidity jurisdictions an extended loss of electrical power during those severe weather conditions will result in significant deaths. Consequently, a power system will need to have dependable emergency reserve generation available at various locations in the power system to step in during a power failure to at least supply life critical loads like hospitals and community warming and cooling centres.

Most of the deaths in very cold weather are due to ill-advised actions by people to keep warm. The deaths are typically from CO poisoning (running fossil fuelled equipment indoors without adequate ventilation) or fires (using open flame candles and heaters near combustible objects like curtains and furniture).

Most of the deaths during very warm, high humidity weather is due to heat stroke due to the human body's inability to cool itself by sweating. Air conditioning (or a cooling centre) is important especially for older people and individuals with health issues.

Maintaining a minimum level of electrical service during very cold or very hot and humid weather is a life critical requirement. Most power systems in industrial societies will use natural gas combustion turbines for emergency reserve generation due to its very low capital cost of about $1,000/kW of installed capacity. Also, those combustion turbines will typically be distributed throughout the power system to provide local electricity service in the event the high voltage transmission system fails during the severe weather. The cost of life critical emergency reserve generation is uplifted to the retail electricity rates that consumers pay.