The Electrical Grid
Part 1 – How It Works

OSPE Energy Seminar

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OSPE Energy Task Force
September 2015
The Electrical Grid – Part 1 – How It Works

Outline

This seminar is the first in a series of 4 seminars

✧ Part 1 – How It Works
✧ Part 2 – Achieving Low Greenhouse Gas Emissions
✧ Part 3 – Current Challenges
✧ Part 4 – Potential Solutions
The Electrical Grid – Part 1 – How It Works

Outline

✎ Historical Perspective - T. Edison, N. Tesla, Sir Adam Beck.
✎ The Electrical Grid.
✎ Consumer Load Demand – daily, weekly, annual.
✎ Generation Technologies.
✎ Storage.
✎ Load, Frequency and Voltage Control.
✎ Wholesale Auction Market.
✎ Retail Electricity Prices.
✎ Stranded Debt.
✎ Q/A
Historical Perspective

- Thomas Edison – the father of Direct Current (DC) Distribution
- Nicola Tesla – the father of Alternating Current (AC) Distribution
- Tesla’s inventions for long distance AC distribution were commercialized by George Westinghouse in competition against Thomas Edison’s short distance DC distribution system.
- Eventually AC won the day due to its lower cost and higher efficiency in distributing electricity over long distances.
- Sir Adam Beck – the father of Ontario’s electrical power system.
- Beck believed in “publically owned power at cost to the people”.
- Beck built the power system with government debt which was paid back in user fees over the lifetime of the assets.
The Electrical Grid – Part 1 – How It Works

Historical Perspective

DC Electricity

Volts vs. Time

AC Electricity

Volts vs. Time

Diagrams Courtesy of Market Intelligence & Data Analysis Corporation
The Electrical Grid

The Electrical Power System or Electrical Grid includes:

- Generating Plants
  - Centralized (hydroelectric, nuclear, gas-fired)
  - Distributed (wind, solar, Bio-energy, combined heat and power)

- Transmission System (over 50,000 Volts) including service connections for large industrial loads.

- Distribution System (under 50,000 Volts) including service connections for residential, commercial and industrial loads.

- All the required control and protection systems and main control centers.

- Interconnections to other electrical grids.
The Electrical Grid

Power Supply From Generation to End-Use Customer

Generation Plant
Step-up Transmission Station
High-Voltage Transmission Lines
Step-down Transmission Substation
Sub-Transmission Lines
Distribution Substation
Industrial Customer
Irrigation Customer
Underground Distribution Lines
Underground Transformer
Local Distribution Lines
Residential Customer
Commercial Customer
Industrial Customer
Distribution Substation

 Courtesy of Nebraska Public Power District
http://www.nppd.com/vegetation-management/faqs/
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The Electrical Grid

![Map of the Electrical Grid](http://www.ieso.ca/Documents/IntertieReport-20141014.pdf)

Courtesy of the Independent Electricity System Operator
Customer Load Demand – Typical Day

DiagramsCourtesy of Market Intelligence & Data Analysis Corporation
Customer Load Demand – Typical Week

Diagrams Courtesy of Market Intelligence & Data Analysis Corporation
Customer Load Demand – Typical Year

Levelized Cost of Electricity (LCOE) data is shown for a discount factor (DF) of 10% and a natural gas price of $4 / $8 per Million BTU at the burner face.

**Cost of Energy Using Gas Generation**

- \( CF = 0.2\% \), LCOE = 942 / 945 cents/kWh
- \( CF = 1.6\% \), LCOE = 116 / 119 cents/kWh
- \( CF = 13\% \), LCOE = 16.4 / 19.1 cents/kWh
- \( CF = 44\% \), LCOE = 6.7 / 9.4 cents/kWh
- \( CF = 78\% \), LCOE = 5.0 / 7.7 cents/kWh
- \( CF = 97\% \), LCOE = 4.8 / 7.5 cents/kWh
- \( CF = 100\% \), LCOE = 4.8 / 7.5 cents/kWh

\( CF \) = Load Capacity Factor


Diagrams Courtesy of Market Intelligence & Data Analysis Corporation
Ontario has phased out coal by regulation so it now has:

- Nuclear generation (62% by energy use in 2014)
- Hydro-electric generation (24%)
- Gas/Oil fired generation (10%)
- Wind turbine generation (4%)
- Solar generation (< 1%)
- Bio-energy generation (< 1%)

Each of these have strengths and weaknesses.

To minimize cost of electricity, each has to be used in a way that accommodates their production characteristics.
Ontario Energy Board 2015 cost projections for “energy” only:

- Nuclear generation: 6.6 cents/kWh
- Hydro-electric generation: 5.6 cents/kWh
- Gas/Oil fired generation: 12.7 cents/kWh
- Wind turbine generation: 12.5 cents/kWh
- Solar generation: 47.3 cents/kWh
- Bio-energy generation: 21.1 cents/kWh

The costs above include costs for lost production due to curtailment during low demand periods.

The 2015 blended average price for residential loads will be 10.2 cents/kWh for energy and about 15.4 cents/kWh total at the door.
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Generation Technologies

Nuclear Plant – Pickering NGS

Courtesy of Ontario Power Generation
http://www.opg.com/generating-power/nuclear/stations/pickering-nuclear/Pages/pickering-nuclear.aspx
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Generation Technologies
CANDU Nuclear Plant Schematic

Courtesy of the Canadian Nuclear Association
https://cna.ca/technology/energy/candu-technology/
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Generation Technologies

- Nuclear generation’s advantages:
  - Dependable, high capacity factor - typically over 80%.
  - Not affected by weather.
  - Low environmental emissions.
  - Low and stable operating costs.
  - Provides many high skilled and high paying jobs.

- Nuclear generation’s disadvantages
  - Produces nuclear wastes that need to be isolated.
  - Accidents can release radioactive isotopes – requires good safety culture.
  - Requires high security to prevent unauthorized access.
  - Does not follow load cycles without special engineered systems.
  - High capital costs and long construction schedules.
Generation Technologies

Hydro-electric Plant – Sir Adam Beck GS at Niagara Falls

Courtesy of Ontario Power Generation
http://www.opg.com/generating-power/hydro/southwest-ontario/Pages/sir-adam-beck-ii.aspx
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Generation Technologies

Inside a Hydropower Plant

Reservoir, Dam, Transformer, Powerhouse, Power Lines, Intake, Control Gate, Penstock, Turbine, Outflow

Courtesy of How Stuff Works
http://science.howstuffworks.com/environmental/energy/hydropower-plant1.htm
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Generation Technologies

✧ Hydro-electric generation’s advantages:
  ✧ Dependable, moderate capacity factor - typically over 60%.
  ✧ Low environmental emissions.
  ✧ Low and stable operating costs.
  ✧ Storage can be provided to follow load cycles.

✧ Hydro-electric generation’s disadvantages
  ✧ affected by weather – rainfall and snow melt.
  ✧ Accidents can flood communities.
  ✧ Requires high security to prevent unauthorized access.
  ✧ Major environmental impact on local geography.
  ✧ Limited good sites in Ontario
  ✧ High capital costs and long construction schedules.
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Generation Technologies

Gas Plant – Halton Hills GS

Courtesy of TransCanada
http://www.transcanada.com/docs/Key_Projects/HH_Fact_Sheet.pdf
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Generation Technologies
Gas Plant Schematic (Combined Cycle)

Courtesy of Marchwood Power
http://www.marchwoodpower.com/ccgt/
Generation Technologies

- Gas/oil generation’s advantages:
  - Dependable, flexible output for following load cycles.
  - Low capital costs and short construction schedule.
  - Only modestly affected by weather – temperature and humidity

- Gas/oil generation’s disadvantages
  - Environmental emissions – 400 grams CO₂ per kWh, Soot, NOₓ.
  - High and unstable fuelling costs.
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Generation Technologies

Wind Turbines

Photo Courtesy of Market Intelligence & Data Analysis Corporation
Generation Technologies

Wind Turbines Schematic

Courtesty of Renewable Energy Systems Ltd.
http://www.beaufortcourt.com/energy-generation/wind-energy
Generation Technologies

Wind generation’s advantages:
- Low environmental emissions.
- Stable operating costs, low fuel costs (energy fee to landowners).
- Short construction schedules.

Wind generation’s disadvantages
- Not dependable, low capacity factor – typically 30-35% in Ontario.
- Large wind farms do not utilize transmission capacity efficiently.
- Affected by weather – does not operate in low or high wind.
- Health concerns - Noise and bird death complaints.
- High capital costs when adjusted for capacity factor/variability.
Generation Technologies
Solar Panels

Photo Courtesy of Market Intelligence & Data Analysis Corporation
Generation Technologies

Solar Panels Schematic

Courtesy of Forever Green Energy
http://www.forevergreen-energy.co.uk/services/solar-panels/
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Generation Technologies

❖ Solar generation’s advantages:
  ❖ Low environmental emissions.
  ❖ Stable operating costs, low fuel costs (energy fee to landowners).
  ❖ Short construction schedules.

❖ Solar generation’s disadvantages
  ❖ Not dependable, low capacity factor – typically 13-15% in Ontario.
  ❖ Large solar farms do not utilize transmission capacity efficiently.
  ❖ Affected by weather – cloud cover, fog and haze.
  ❖ Very high capital costs when adjusted for capacity factor/variability.
Generation Technologies

Bio-energy Plant – 211 MW Atikokan GS (wood pellets)

Courtesy of Ontario Power Generation
http://www.opg.com/generating-power/thermal/stations/atikokan-station/Pages/atikokan-station.aspx
Generation Technologies
Bio-energy Plant Schematic

Courtesy of SPIN-Sustainable Production through Innovation SME’s
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Storage

✧ Storage provides a means to balance supply with demand when there is a short term surplus or deficiency of generation.
✧ Ontario has relatively little storage capability, about 2,000 MW for about 10 hours – good for a fraction of daily load fluctuations but not sufficient for weekly or seasonal variations.
✧ Hydro-electric dams with head ponds are the most economic and close to 100% efficient – but need the right geography.
✧ Pumped-hydroelectric is about 80% efficient.
✧ Compressed air storage is 60 to 70% efficient (depends on type).
✧ Flywheel storage is useful for short term load filtering and voltage control – energy loss is about 1% per hour.
✧ Battery storage is the most expensive and 70 to 80% efficient.
Storage

Pumped Hydro-electric Storage – Sir Adam Beck PGS

Courtesy of Ontario Power Generation
http://www.opg.com/generating-power/hydro/southwest-ontario/Pages/sir-adam-beck-pgs.aspx
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Storage

Compressed Air Storage – 110 MW MacIntosh CAES Plant USA

Courtesy of Power South Energy Cooperative
http://www.powersouth.com/mcintosh_power_plant
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Storage

Flywheel Storage – Temporal Power (50 kWh-250 kW)

Courtesy of Temporal Power
Storage

Battery Storage – Lithium Ion 2 MW/4 MWh

Courtesy of A123 Systems
http://www.a123systems.com/grid-storage-technology.htm
Storage

- How much battery storage would a typical home need?
  - 4 kWh of storage needed to flatten load on average day
  - 14 kWh of storage needed to flatten load all year
  - 31 kWh of storage needed to use only off-peak electricity
- Plug and play electrical storage is $800 to $1,000 /kWh (10 yr life)
- 4 kWh costs $3,200 to $4,000
- Max electricity bill savings with: 4 kWh storage = $77 /yr
  - 14 kWh storage = $173 /yr
  - 31 kWh storage = $185 /yr
- Still much too expensive for most consumers!
Load, Frequency and Voltage Control

✧ For the grid to operate in a stable and reliable manner the system operators must ensure:

✧ Generation output and load demand are in balance.
✧ Frequency is held at 60 Hertz.
✧ Voltage is maintained within standard low and high limits.
Load, Frequency and Voltage Control

✧ Load control is important because:
  ✧ Load imbalances cause the power system to speed up or slow down which causes the frequency to change.
  ✧ If the power system is connected to an adjoining power system a load imbalance in one power system will send unauthorized power surges into the other power system.

✧ Frequency control is important because motors and electric clocks will speed up or slow down if frequency varies.

✧ Voltage control is important because:
  ✧ High voltage will overheat and damage most equipment.
  ✧ Low voltage will cause most equipment to malfunction and motors to overheat and stall.
Load, Frequency and Voltage Control

- Customer demand is not controlled unless that customer has agreed to be part of a demand management program.
- Generation output is controlled or “dispatched” to match customer demand.
- Generation output is controlled in 2 ways:
  - Dispatch commands are sent every 5 min. to each dispatchable plant to raise or lower power output to achieve a close but not an exact balance with the load.
  - An automatic generation controller continuously raises and lowers plant output at one or more designated plants to achieve an exact load balance.
Load, Frequency and Voltage Control

✧ Frequency is controlled in 3 ways:

✧ Automatic frequency control at one or more designated stations with the signal originating from an authorized frequency control authority in each interconnected grid.

✧ Automatic speed governor control at each station if grid frequency falls outside of a narrow dead-band.

✧ During power system emergencies, very low frequency excursions are terminated by shedding loads at various transformer stations.

✧ Beyond very low and very high frequency limits, generating stations disconnect to protect plant equipment and the grid blacks out.
Load, Frequency and Voltage Control

✧ The transmission level voltage is controlled in 2 ways:
  ✧ Adjusting the setpoint of the generator’s excitation voltage regulator equipment to add or remove reactive power from the power system.
  ✧ Adjusting the setpoint of the voltage control equipment at transformer stations to add or remove reactive power from the power system.

✧ The distribution level voltage can also be controlled on individual buses by adjusting the voltage ratio at transformers.

✧ Normal supply voltage at the distribution level is controlled within limits established by the CSA Group in CAN3-C235-83 Table 3.
Wholesale Auction Market

- Wholesale Auction Market was originally created to dispatch generation at the lowest total price.
- Generators bid price and volume into the market.
- The system operators assisted by a computer program organize bids by increasing price and accept them from lowest price until the bid volumes reach the customer load for that auction interval (typically 5 minutes).
- The last price that fulfills demand sets the market clearing price.
- All lower bids receive the clearing price for the volumes they bid.
- When there is excess generation, this market design will drive prices down to the marginal cost of production (i.e., fuel cost).
Wholesale Auction Market

- Wind, solar and inflexible generation like run-of-the-river hydro-electric and nuclear have very low fueling costs and they need to run to get paid, so they bid low prices into the wholesale market.
- When demand is lower than the generating capacity of low fuel cost plants, the market price collapses.
- To pay for all the other cost components in generation the government created the Global Adjustment (GA) and signed long term fixed price contracts with producers.
- The wholesale price has effectively become the marginal cost (or the fuel cost) of the next 1 MW of generation.
- Consequently the GA has risen to about double the wholesale price. The GA is added to all Ontario consumer retail prices.
Retail Electricity Rates

✧ Retail Electricity Rates are set by combining several cost components to arrive at a final total price:

✧ Wholesale market price (wholesale market cost of energy)
✧ Global adjustment (to pay fixed contract prices above market)
✧ Transmission, distribution and LDC administration charges (*)
✧ Regulatory charges (IESO, OEB costs)
✧ Stranded Debt Charge – currently 0.7 cents/kWh (**)
✧ Plus HST – currently 13 %
✧ Less Ontario clean energy benefit – currently 10 % of total bill (**)

✧ Items shown as (*) will vary with Local Distribution Company (LDC) costs.
✧ Items shown as (**) will be phased out in early 2016 for some consumers.
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Retail Electricity Rates

Your Previous Charges
Amount of Last Bill 419.80
Payment Received Jul 21, 2015 - Thank you 419.80 CR

Balance Forward $0.00

Your Electricity Charges

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
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</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>1,950.09 kWh</td>
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<tr>
<td>Summer-On-Peak</td>
<td>322.63 kWh @ 0.161</td>
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<tr>
<td>Summer-Mid-Peak</td>
<td>282.75 kWh @ 0.122</td>
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<tr>
<td>Summer-Off-Peak</td>
<td>1,344.71 kWh @ 0.08</td>
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<tr>
<td>Delivery</td>
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<tr>
<td>Regulatory</td>
<td>34.50</td>
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<tr>
<td>Debt Retirement Charge</td>
<td>107.58</td>
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<td></td>
<td>86.31</td>
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<td></td>
<td>12.03</td>
</tr>
<tr>
<td></td>
<td>13.65</td>
</tr>
</tbody>
</table>

Your Total Electricity Charges $306.01
HST (HST Registration 857503346) $39.78
Ontario Clean Energy Benefit - 10% off applicable electricity & taxes... $34.58 CR

These TOU rates represent the Wholesale Market Price + Global Adjustment

Transmission, Distribution, LDC Admin. Charge

$311.21 15.4 cents/kWh
Retail Electricity Rates

✧ Residential and Small Businesses can purchase from a “retailer” or via the Time-Of-Use (TOU) price plan if they have a smart meter.

✧ A retailer typically provides a fixed wholesale market price for a fixed number of years. The LDC then adds all the other charges.

✧ Example: Direct Energy currently charges a fixed 5.99 cents/kWh plus the GA that is estimated at 8.19 cents/kWh for a total of 14.18 cents/kWh for a 12 month fixed term. GA varies monthly.

✧ The TOU price plan combines the wholesale market price and the global adjustment into one energy price that is time of day dependent. The LDC then adds all the other charges. Currently on-peak/mid-peak/off-peak are 8 / 12.2 / 16.1 cents/kWh. The average TOU price is estimated to be 10.2 cents/kWh by the OEB.
Stranded Debt

- A legacy of Ontario’s regulated market costs prior to 2002.
- Costs incurred by Ontario Hydro prior to deregulation that could not be supported by the new deregulated lower market price.
- Two components:
  - Approx 1/3 paid by consumers (0.7 cents/kWh).
  - Approx 2/3 paid by electricity companies out of profits.
- In a private system, stranded debt would have been absorbed and written off by the investor as unrecoverable costs (or losses).
- In a government owned system, stranded debt could have been written off into a tax funded account. Government chose to leave it on the electricity bills which created a competitive disadvantage for trade exposed businesses.
Stranded Debt

- Accounting treatment of stranded debt was poorly defined.
- Responsibility for interest costs on the stranded debt was not defined.
- Payments to date have eliminated the principal amount but government continues to collect the stranded debt charge to pay for other charges including interest.
- Ontario Electricity Financial Corporation manages the stranded debt account.
- The Ontario government plans to eliminate the stranded debt charge for residential and small business at about the same time the Ontario Clean Energy Benefit will end for that group of consumers on Jan 1, 2016.
Questions?

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