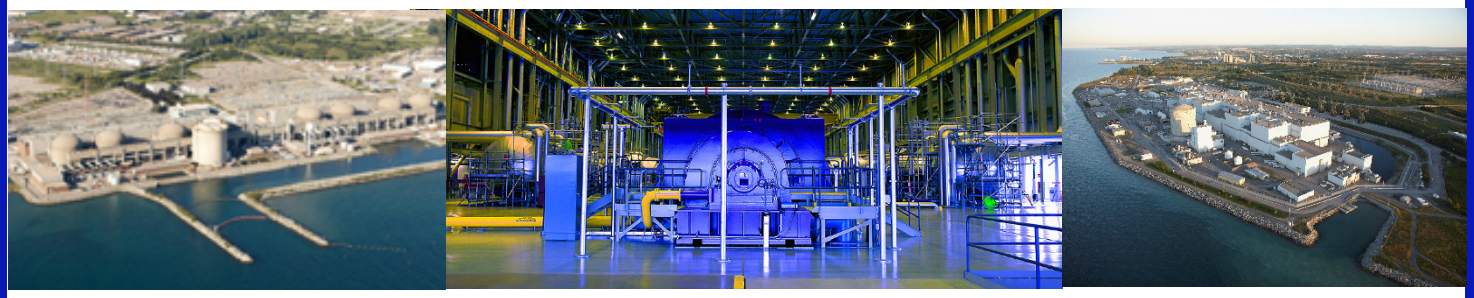
ONTARIO POWER GENERATION



ONTARIO POWER GENERATION NUCLEAR

2017 NUCLEAR BENCHMARKING REPORT

OPG Confidential – Internal Use Only

Nuclear Finance – Business Planning and Benchmarking

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1.0 EXECUTIVE SUMMARY

Key Highlights

OPG benchmarked favourably relative to its peers in 2017 in a number of key nuclear cornerstone areas. OPG's safety-related performance continued to show strong results and OPG demonstrated a commitment to continuous improvement in the reliability and human performance metrics. OPG's performance against value-for-money metrics would have been at or near the top quartile if the size of its nuclear units were more in line with the industry average.

Under the Safety cornerstone, OPG's nuclear generating stations continue to demonstrate strong performance in all nine safety performance metrics. Darlington and Pickering continue to demonstrate strong performance with their All Injury Rate remaining in the first quartile. Darlington achieved maximum NPI results or best quartile performance for all seven NPI sub-metrics under the Safety cornerstone and the Airborne Tritium Emissions indicator improved to the top quartile. Pickering continued to show maximum WANO NPI results or top quartile performance for six metrics under the Safety cornerstone, with Collective Radiation Exposure (CRE) improving to third quartile performance. Pickering's CRE was impacted by the number of planned outages, as well as the scope and duration. Airborne Tritium Emissions at Pickering remained in the third quarter largely due to an increase in heavy water leaks. Management continues to focus on improving vapour recovery dryer performance and the reliability of the Tritium Removal Facility to reduce emissions.

OPG Nuclear Stations continue to lead in Safety

Under the Reliability cornerstone, the majority of Pickering's performance metrics improved compared to 2015 such as the WANO Nuclear Performance Index, Forced Loss Rate (FLR), Chemistry Performance Indicator (CPI), and On-line Corrective Maintenance backlogs. At Pickering, the most significant improvement was the FLR performing better by a 3.1% reduction compared to 2015, which was largely attributed to the equipment reliability improvements. CPI improvement was due to better outage Foreign Materials Exclusion practices, Water Treatment Plant output quality, and blowdown frequency adherence.

OPG Nuclear Stations continue to improve in Reliability

Darlington's NPI performance improved to the second quartile. FLR and the Unit Capability Factor (UCF) both improved in their ranking to the median primarily due to the plant reliability improvements. The Darlington Chemistry Performance Indicator once again remained in best quartile and achieved maximum NPI points. Darlington improved their On-line Deficient Maintenance Backlogs and On-line Corrective Maintenance Backlogs by reducing the number of work orders per unit relative to 2014 due to overall maintenance efficiency and schedule quality.

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The Nuclear Performance Index is a WANO index of 10 sub-indicators that measures safety and reliability as listed in the Table 1.

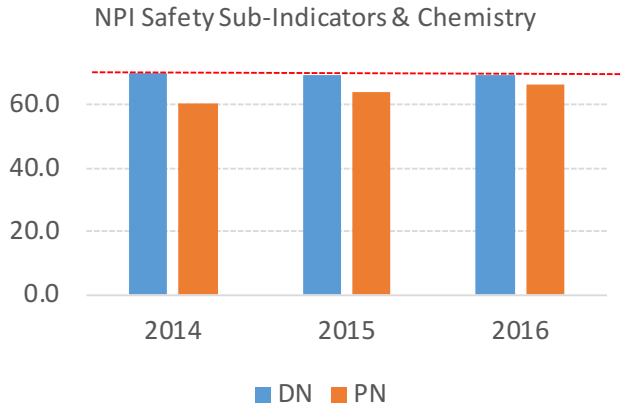
Table 1: Q4 2016 Nuclear Performance Index

NPI Components	Weight %	Pickering	Darlington
Industrial Safety Accident Rate (ISAR)	5	5.0	5.0
Collective Radiation Exposure (CRE)	10	7.2	9.3
Fuel Reliability (FRI)	10	9.9	9.8
Reactor Trips (RTR)	10	10.0	10.0
Auxiliary Boiler Feedwater (ABFW)	10	10.0	10.0
Emergency AC Power (EACP)	10	10.0	10.0
High Pressure Injection (HPSI)	10	10.0	10.0
Chemistry Performance (CPI)	5	4.2	5.0
Forced Loss Rate (FLR)	15	9.6	10.9
Unit Capability Factor (UCF)	15	0.5	7.7
Total	100	76.3	87.8

70% of the overall index is related to safety components and CPI, which both Pickering and Darlington receive full or near full points. The remaining 30% of the overall index measures reliability performance.

STRONG SAFETY PERFORMANCE

Darlington and Pickering consistently demonstrate strong safety performance in 8 of 10 NPI safety sub-indicators and chemistry performance.



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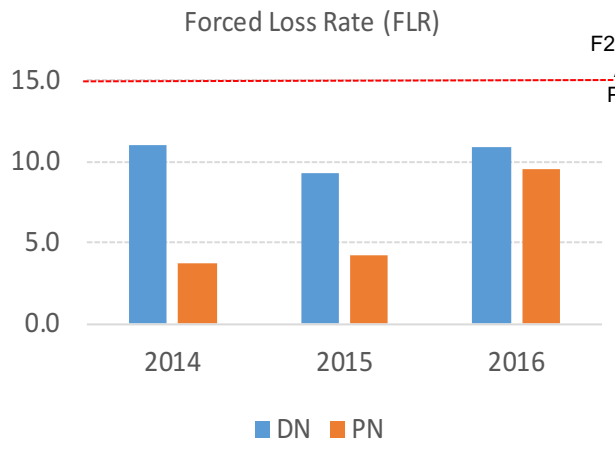
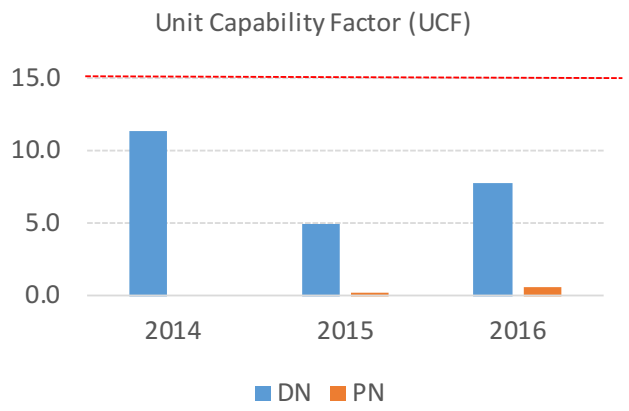
RELIABILITY

Pickering's reliability has improved drastically since 2014. Pickering and Darlington continue to drive plant reliability through fleet and station initiatives.



EXTENDED OUTAGE DURATIONS

OPG's nuclear facilities are transitioning through a major refurbishment and life extension. Planned outages longer than any utility in the peer group are being executed to ensure plant safety.



Value for Money is calculated on a 3-year rolling average comprising of operating costs, including nuclear and corporate allocated costs, along with fuel and on-going capital costs per MWh. Total Generating Cost (TGC) per MWh and Non-Fuel Operating Cost (NFOC) per MWh at Pickering was highly impacted by the unit size, first generation CANDU technology, and extensive planned outage program from extended operations. Darlington was also impacted by its unit size, Primary Heat Transport motor outage, and increased on-going capital investment for life extension.

VALUE FOR MONEY

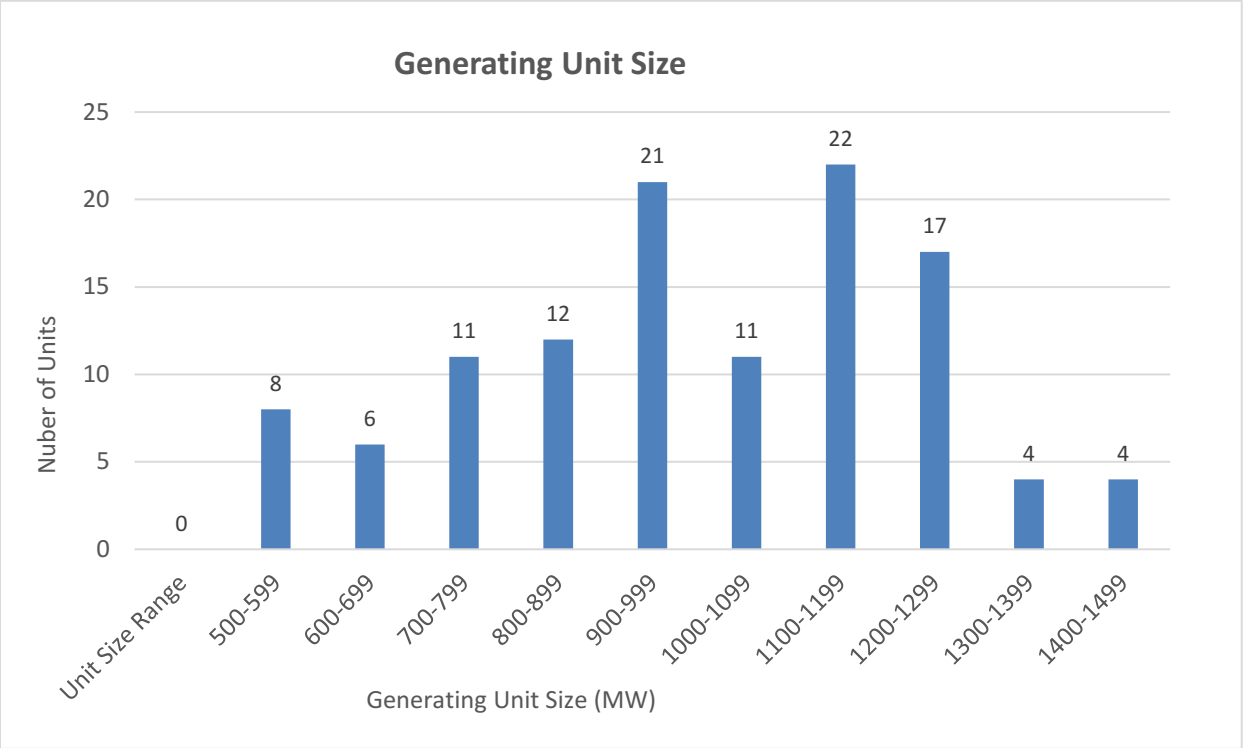
Accounting for unit size of Pickering and Darlington drives TGC/MWh to first quartile.

Under the Value for Money cornerstone, Pickering remained in the fourth quartile for performance in TGC per MWh and NFOC per MWh. Pickering maintained best quartile performance in Fuel Cost per MWh and Capital Cost per MW DER. Darlington's TGC per MWh fell from the median quartile performance in 2015 to the third quartile in 2016. The improvement to the third quartile performance in NFOC per MWh and sustained top quartile performance in Fuel Cost per MWh was contrasted by the drop to the median quartile performance in Capital Cost per MW DER at Darlington in 2016. Darlington's drop in Capital Cost per MW DER performance

was due to non-power block infrastructure spending to support post-refurbishment operations. Darlington had the third lowest Fuel Cost per MWh in its industry peer group, while Pickering had the fourth lowest.

Pickering's Total Generating Cost per MWh remained relatively flat with a compound growth rate of 0.7% over the period 2011-2016 whereas the best quartile and median levels increased by 2.5% and 1.4% respectively. Unit size and outage durations required to extend the life of the station contributed to fourth quartile results when costs are compared on a per MWh basis.

Pickering units are the smallest in the peer group with total capacity of 540 MW compared to the peer group average of 1,022 MW. The peer group's generating unit size distribution illustrates that the majority of the generating units fall within the 900 to 1,299 MW range with the average at 1,022 MWh.



Pickering's TGC/MWh is highly impacted by its relatively small unit size as shown in the chart below.

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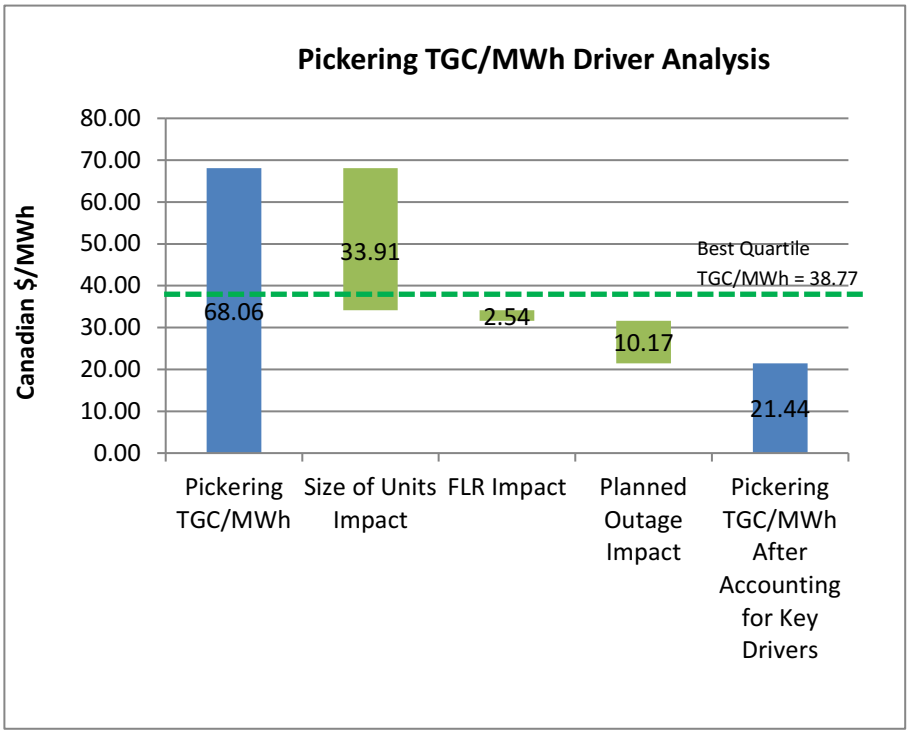
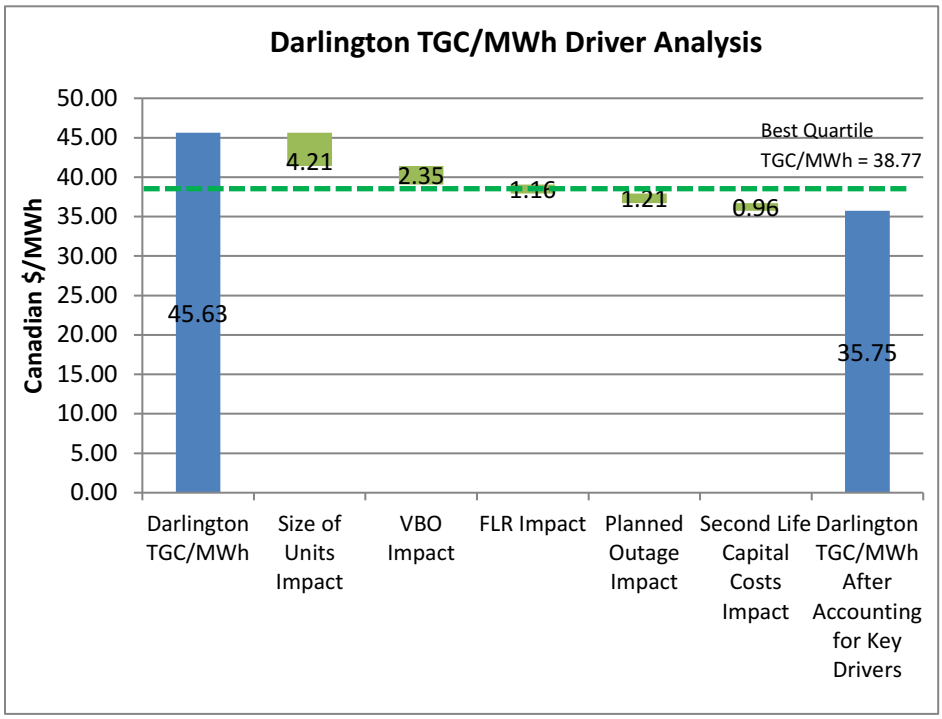


The major drivers that contribute to the gap in TGC/MWh for Pickering are provided in the adjacent chart. Pickering's TGC/MWh is highly impacted by its relatively small unit size. The Pickering TGC/MWh, accounting for the size of unit, FLR and Planned Outage gap impacts, of $21.44/MWh puts Pickering in the best quartile, which is less than the best quartile TGC/MWh of $38.77.

Darlington also has smaller units than the peer group average at 934 MW. The impact attributable to unit size is $4.21/MWh on Darlington's TGC/MWh.



Furthermore, with the exception of Bruce Power, all plants in the peer group do not have a vacuum building in their design compared to Darlington. Darlington's vacuum building outage (VBO) maintenance in 2015 contributed to $2.35/MWh of the TGC/MWh.

The Darlington TGC/MWh, accounting for the size of unit and VBO moves the station below industry median into second quartile.

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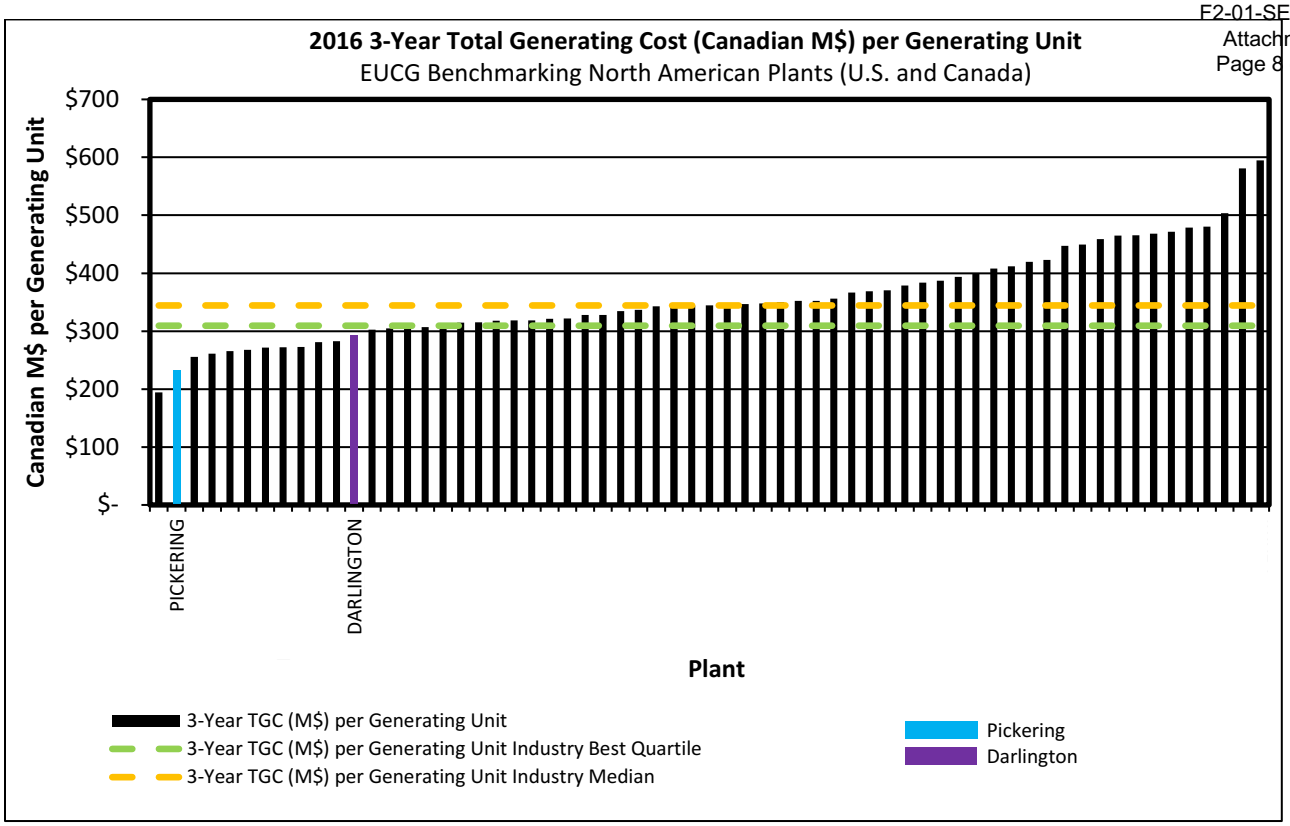
The following chart is the 3-year Total Generating Costs by unit.



Pickering's TGC per generating unit demonstrated strong cost performance with Pickering placing among the best in the peer group as illustrated in the graph above. Darlington's TGC per generating unit basis placed within the industry best quartile.

In the area of Human Performance, Pickering and Darlington improved their human performance error rate to the median quartile in 2016, due to an increased focus on initiatives to drive performance including implementing strategies that enabled learning, provided consistent coaching, and focused communications.

Benchmarking Results – Plant Level Summary

Table 2 provides a summary of OPG Nuclear's performance compared to benchmark results.

Table 2: Plant Level Performance Summary

Metric	NPI Max	2016 Actuals			
		Best Quartile	Median	Pickering	Darlington
Safety					
All Injury Rate (#/200k hours worked)		0.64	N/A[1]	0.49	0.23
Rolling Average[2] Industrial Safety Accident Rate (#/200k hours worked)	0.20	0.00	0.00	0.04	0.06
Rolling Average[2] Collective Radiation Exposure (Person-rem per unit)	80.00	45.33	61.29	97.23 ⇧	68.77
Airborne Tritium Emissions (Curies) per Unit		1,013	2,290	3,067	846 ⇧
Fuel Reliability Index (microcuries per gram)	0.000500	0.000001	0.000001	0.000261	0.000343
2-Year Reactor Trip Rate (# per 7,000 hours)	0.50	0.00	0.23	0.25	0.24
3-Year Auxiliary Feedwater System Unavailability (#)	0.0200	0.0000	0.0061	0.0070	0.0000
3-Year Emergency AC Power Unavailability (#)	0.0250	0.0013	0.0030	0.0030	0.0000
3-Year High Pressure Safety Injection Unavailability (#)	0.0200	0.0000	0.0000	0.0000	0.0000
Reliability					
WANO NPI (Index)		96.9	87.8	76.3	87.8 ⇧
Rolling Average[2] Forced Loss Rate (%)	1.00	1.49	3.10	3.76	3.10 ⇧
Rolling Average[2] Unit Capability Factor (%)	92.00	89.41	86.16	77.03	86.16 ⇧
Rolling Average[2] Chemistry Performance Indicator (Index)	1.01	1.00	1.00	1.04	1.00
1-Year On-line Deficient Maintenance Backlog (work orders per unit)		66	134	350	170
1-Year On-line Corrective Maintenance Backlog (work orders per unit)		4	10	116	14
Value for Money					
3-Year Total Generating Cost per MWh ($ per Net MWh)		38.77	44.17	68.06	45.63 ⇩
3-Year Non-Fuel Operating Cost per MWh ($ per Net MWh)		22.22	26.09	57.12	33.00 ⇧
3-Year Fuel Cost per MWh ($ per Net MWh)		7.91	8.42	5.75	5.31
3-Year Capital Cost per MW DER (k$ per MW)		52.93	65.31	34.23	53.47 ⇩
Human Performance					
18-Month Human Performance Error Rate (# per 10k ISAR and contractor hours)		0.0008	0.0037	0.0019 ⇧	0.0035 ⇧

Notes
1. No median benchmark available.
2. Indicates a 2-Year Rolling Average for Pickering and a 3-Year Rolling Average for Darlington.

Green = maximum NPI results achieved or best quartile performance

White = 2nd quartile performance

Yellow = 3rd quartile performance

Red = 4th quartile performance

⇩ Declining Benchmark Quartile Performance vs. 2015

⇧ Improving Benchmark Quartile Performance vs. 2015

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Background

This report presents a comparison of OPG Nuclear's performance to that of nuclear industry peer groups both in Canada and worldwide. The results of this report are used during business planning to drive top-down target setting with business improvement as the objective.

Benchmarking involves three key steps: (a) identifying key performance metrics to be benchmarked, (b) identifying the most appropriate industry peer groups for comparison, and (c) preparing supporting analyses and charts.

Performance Indicators

Good performance indicators used for benchmarking are defined as metrics with standard definitions, reliable data sources, and utilization across a representative portion of the industry. Good indicators allow for benchmarking to be repeated year after year in order to track performance and improvement. Additionally, when selecting an appropriate and relevant set of metrics, a balanced approach covering all key areas of the business is essential. In accordance with these criteria, 20 key performance indicators have been selected for comparison to provide a balanced view of performance and for which consistent, comparable data is available. These indicators are listed in Table 7 of Section 7.0 and are divided into four categories aligned with OPG Nuclear's four cornerstones of safety, reliability, value for money, and human performance.

Industry Peer Groups

Peer groups were selected based on performance indicators widely utilized within the nuclear industry with consideration for plant technology to ensure suitable comparisons. Overall, six different peer groups were used as illustrated in Table 7 of Section 7.0 and panel members are detailed in Tables 8-13 of Section 7.0.

Further information on benchmarking of major operators is provided in Section 6.0 of this report.

Report Structure

Sections 2.0 to 5.0 of the report focus on the four OPG Nuclear cornerstone areas, with detailed comparisons at the plant, and where applicable, unit level. Each indicator is displayed graphically from best to worst plants/units (in bar chart format) for the most recent year in which data is available. Zero values are excluded from all calculations except where zero is a valid result.

Next, the historical trend is graphed (in line chart format) using data for the last few years (depending upon availability and metric). Each graph also includes median and best quartile threshold values, and for some WANO operating metrics, the values required to achieve full WANO NPI results.

Following the graphical representation, performance observations are documented as well as insights into the key factors driving performance at OPG's nuclear generating stations.

Section 6.0 of the report provides an operator level summary across a few key metrics. The operator level analysis looks at fleet operators, primarily across North America, utilizing a simple average of the results (mean) from each of their units/plants. Operations related (WANO NPI and UCF) results were averaged at the unit level and cost related (TGC per MWh) results were averaged at the plant level. However, it is more appropriate to look at OPG's two nuclear facilities individually given that they are at different stages of their lifecycle, have different sized units and reflect different generations of CANDU technology. The detailed data in the sections 2.0 to 5.0 of the report provide a more complete picture of plant by plant performance.

Section 7.0 provides an appendix of supporting information, including common acronyms, definitions, panel composition details and a WANO NPI plant level performance summary of OPG nuclear stations against the North American panel.

2.0 SAFETY

Methodology and Sources of Data

The majority of safety metrics were calculated using data from WANO. Data labelled as invalid by WANO was excluded from all calculations. Indicator values of zero are not plotted or included in calculations except in cases where zero is a valid result. Current data is obtained and consolidated with previous benchmarking data. The Embalse plant is excluded since it was taken offline since December 31, 2015 for refurbishment.

The All Injury Rate was calculated using data from the Canadian Electricity Association (CEA). Median information and individual company information was not available for this metric; therefore, only trend and best quartile information is presented. The peer group for this metric is limited to Group I members of CEA (Section 7.0, Table 11).

Airborne Tritium Emissions per unit data was collected from the CANDU Owners Group (COG) for 2011 to 2016 as displayed in the historical trend line chart. The peer group for this metric is all CANDUs who are members of COG.

Discussion

Nine metrics are included in this benchmarking report to reflect safety performance, including seven of the ten metrics which comprise the WANO Nuclear Performance Index: Industrial Safety Accident Rate, Collective Radiation Exposure, Fuel Reliability Index, Automatic Reactor Trips, Auxiliary Feedwater Safety System Unavailability, Emergency AC Power Safety System Unavailability, and High Pressure Safety Injection Unavailability. The remaining WANO NPI metrics are included in Section 3.0 under the Reliability cornerstone. In addition to the WANO sub-indicators listed above, the CEA All Injury Rate and the COG Airborne Tritium Emissions per unit are included in this section of the report.

Although Pickering's AIR performance declined in 2016, overall OPG's performance was excellent achieving top quartile ranking. Pickering continued to show maximum WANO NPI results or top quartile performance for six other metrics under the Safety cornerstone, third quartile performance for Airborne Tritium Emissions, and Collective Radiation Exposure. Darlington showed very strong performance, achieving maximum NPI results (and/or best quartile ranking for 2016) for all NPI safety metrics. Darlington Airborne Tritium Emissions improved to the best quartile in 2016.

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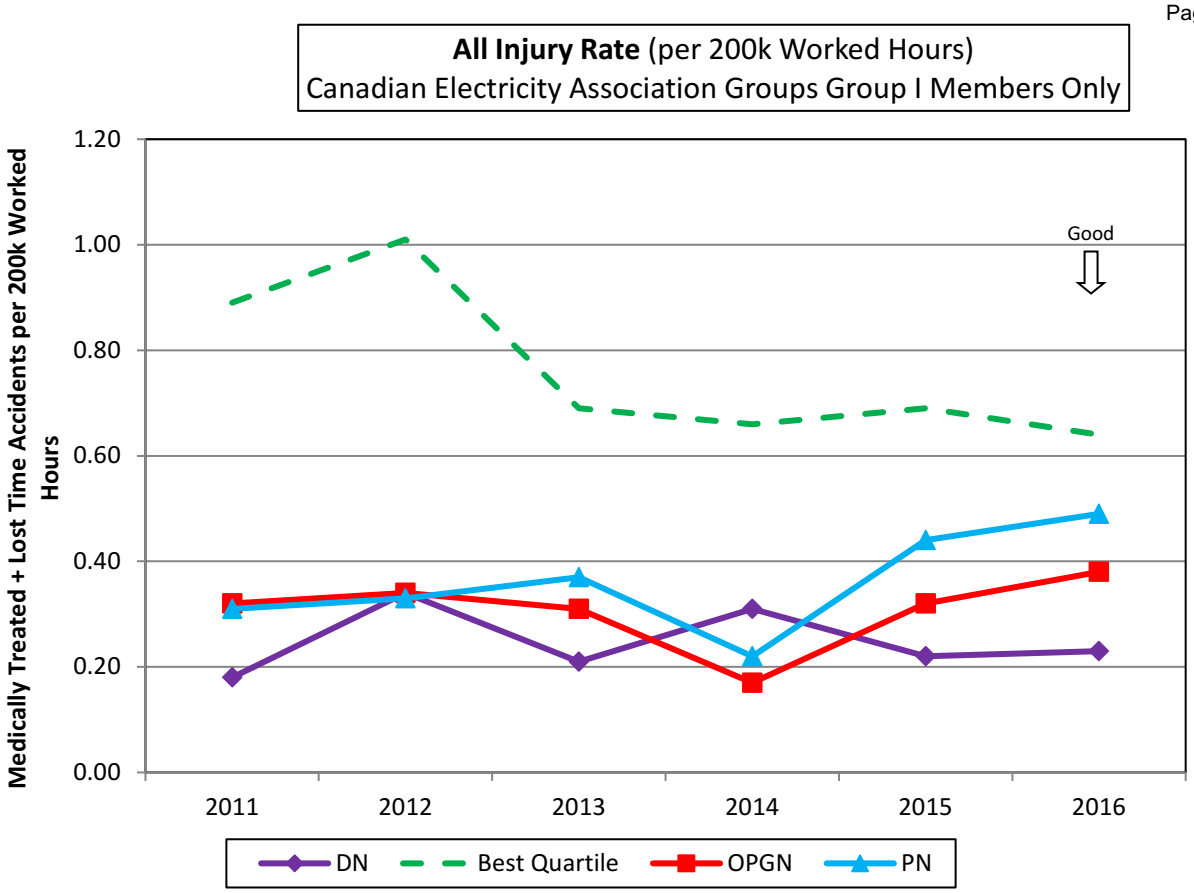
All Injury Rate



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Observations – All Injury Rate (AIR) (Canadian Electricity Association - CEA)

2016 (Annual Value)

- The All Injury Rate (AIR) incorporates all lost time and medically treated injuries incurred by OPG employees working on site.
- Pickering, Darlington, and OPG Nuclear as a fleet all performed better than the CEA top quartile value of 0.64.
- Darlington's AIR remained relatively stable when compared to 2015 due to the same number of injuries encountered during the year. The slight increase to the AIR from 0.22 in 2015, to 0.23 in 2016 was due to the slightly lower number of hours worked in 2016, with the number of injuries remaining the same.
- Pickering's AIR injuries increased from eight in 2015 to nine in 2016, resulting in a slight setback in AIR from 0.44 in 2015 to 0.49 in 2016.
- OPG benchmarks against CEA Group 1 (a sub-set of all CEA members), which incorporates approximately 10 organizations with more than 1500 employees, including most provincial utilities.

Trend

- While the industry Best Quartile continues to improve steadily, Darlington, Pickering and OPG Nuclear have consistently performed significantly better than the benchmark value over the past five years.
- Darlington, Pickering and OPG Nuclear AIR performance has remained relatively stable from 2015 to 2016.
- Darlington Nuclear had a successful WANO evaluation in 2016, resulting in zero areas for improvement in Industrial Safety.

Factors Contributing to Performance

- Conventional Safety performance trends are monitored such that action plans to support continuous improvement can be implemented. These actions plans incorporate Human Performance based objectives, which are aimed at positively improving employee's risk based decision making process.
- OPG encourages a proactive reporting culture that seeks to identify and address hazards before they lead to employee injuries. Proactive reporting is tracked, trended and managed via the Station Condition Record process.
- OPG is expanding and enhancing the Safe Work Planning process in 2016 and 2017. The Safe Work Planning process supports supervisors and employees in identifying, planning and mitigating hazards prior to commencement of work, as well as monitoring ongoing work for conditions that could lead to unanticipated hazardous situations.
- Since 2014, OPG has been implementing the Total Health Program, which supports employees and their families in their efforts to achieve an optimal level of health and functioning, primarily through health education, health promotion, disease and injury prevention, and crisis intervention. Employee mental health is a key component of the Total Health Program, which is demonstrated by the fact that as of June 2017, over 1200 OPG employees have completed an intensive 2 day training course in mental health first aid.

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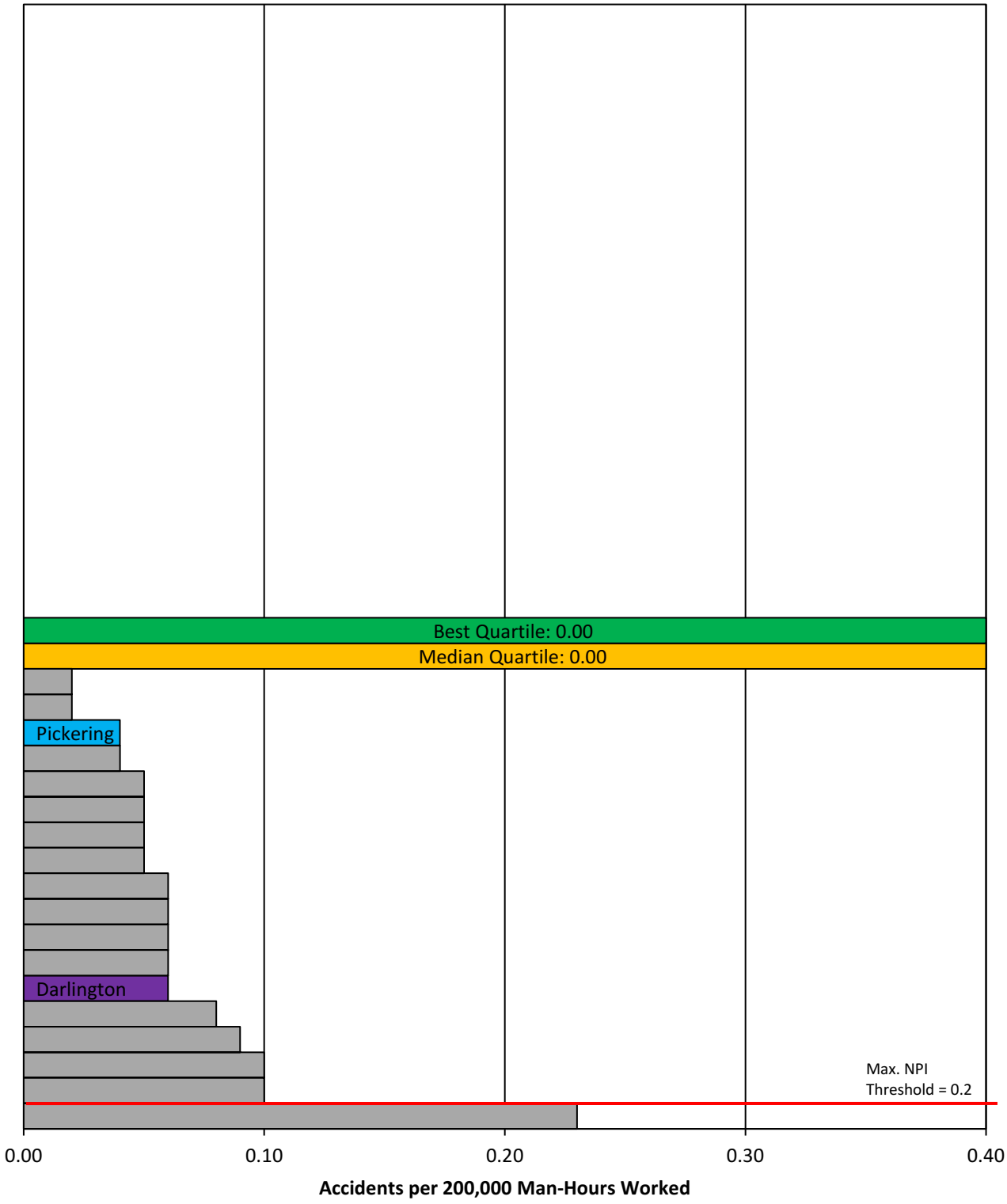
Rolling Average Industrial Safety Accident Rate

2016 Rolling Average Industrial Safety Accident Rate (per 200,000 man-hours worked)
North American PWR & PHWR Plant Level Benchmarking



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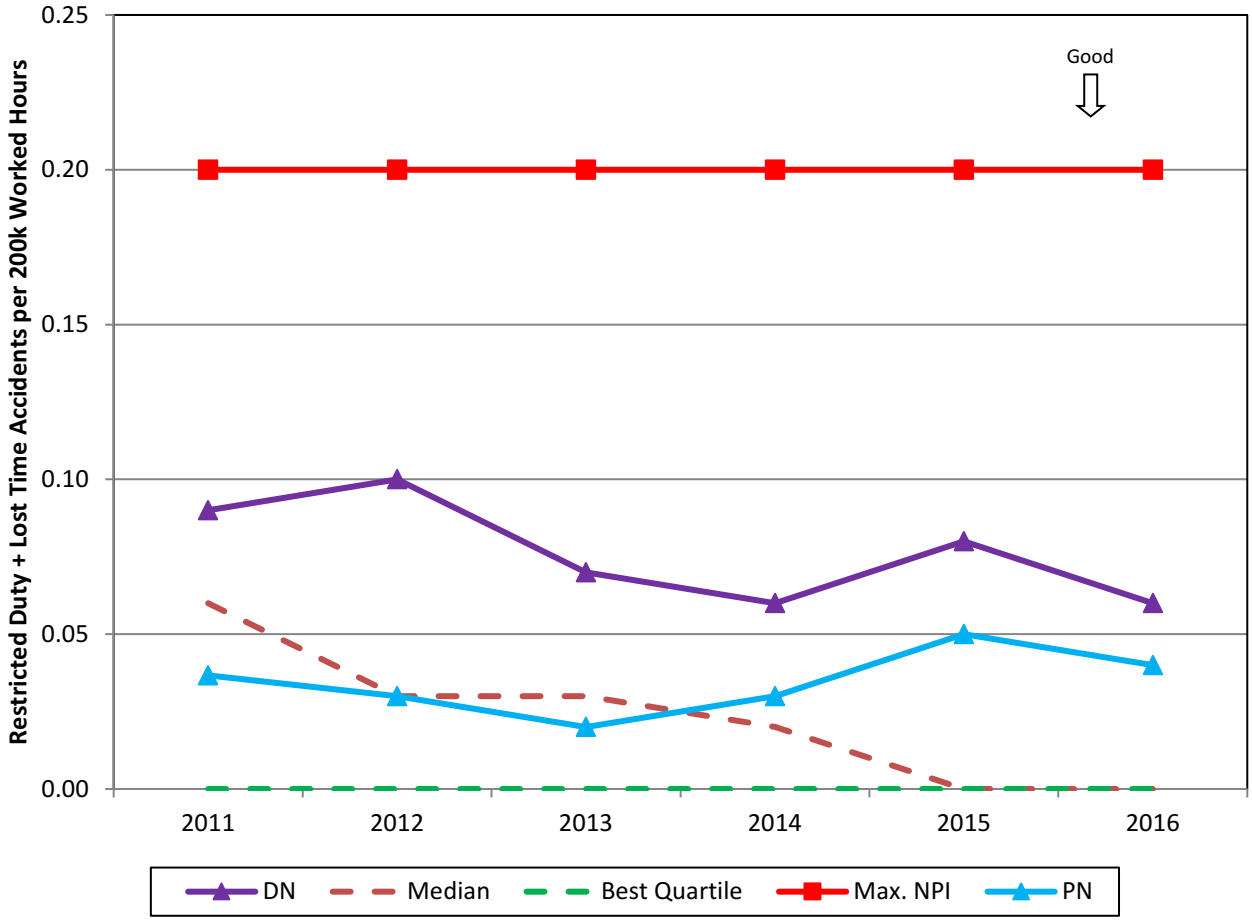
Rolling Average Industrial Safety Accident Rate (per 200k man-hours worked)
North American PWR & PHWR Plant Level Benchmarking



Observations – Rolling Average Industrial Safety Accident Rate (ISAR) (World Association of Nuclear Operators - WANO)

2016 (Rolling 2 Year Average Pickering, Rolling 3 Year Average Darlington)

- The Industrial Safety Accident Rate (ISAR) incorporates all lost time injuries and restricted work injuries incurred by OPG employees working on the site.
- For reporting the ISAR, a 2-year rolling average was used for all panel members with the exception of the Darlington station which follows a 3-year outage cycle. This is consistent with the World Association of Nuclear Operators (WANO) Nuclear Performance Index (NPI) reporting guidelines.
- WANO top quartile in 2016 remained unchanged from 2015 at 0.00 (i.e. zero ISAR events). Median performance was 0.00, which was also unchanged from 2015.
- Both Pickering and Darlington achieved maximum NPI points for the ISAR in 2016.
- Pickering ISAR performance improved from 2015 to 2016 (0.05 to 0.04).
- Darlington ISAR performance improved from 2015 to 2016 (0.08 to 0.06).
- Darlington and Pickering ISAR did not meet the WANO median or top quartile in 2016.

Trend

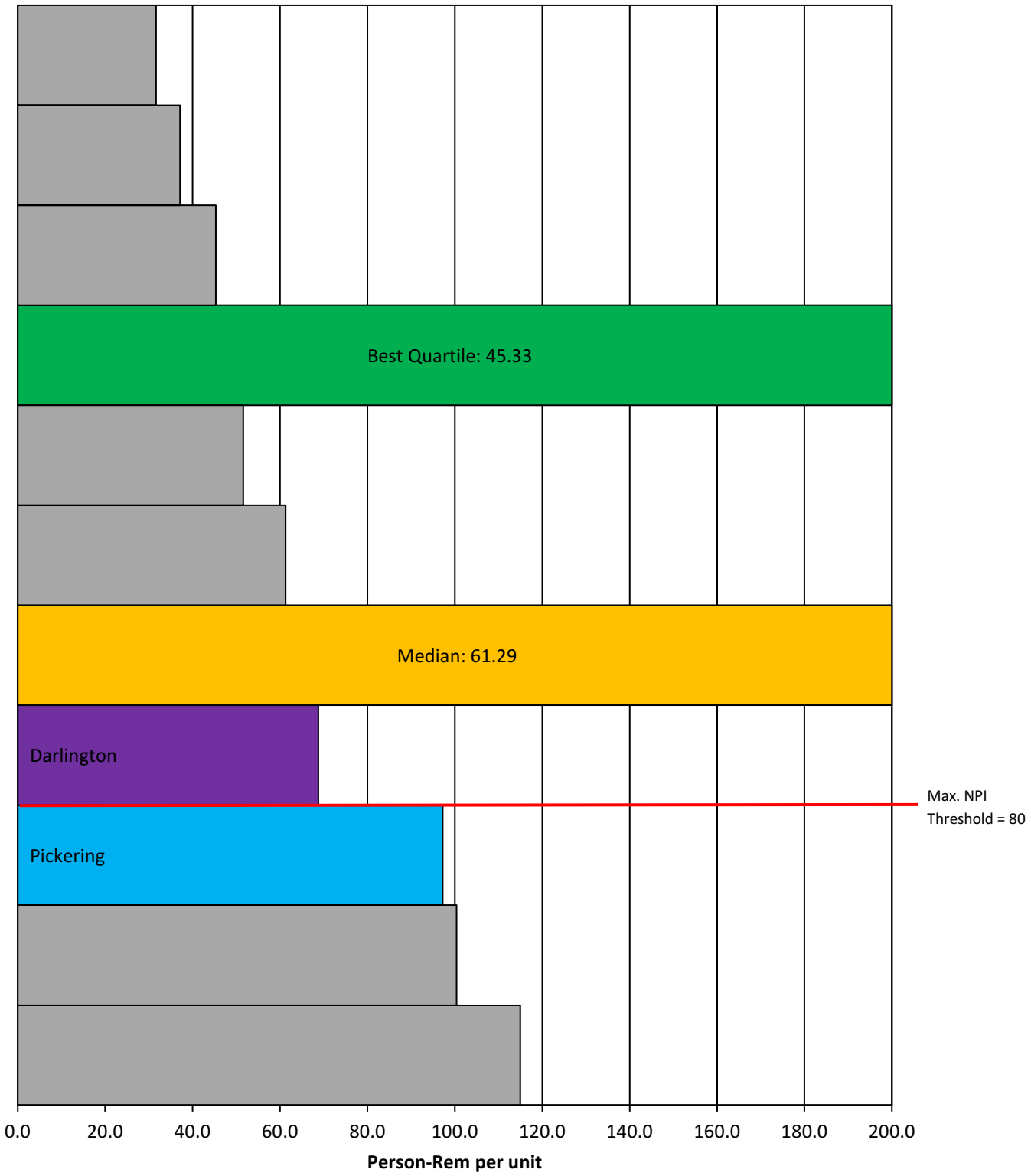
- Darlington's ISAR rolling average has improved slightly in 2016 to 0.06 and continues to show general improved performance over the past five years.
- Pickering's ISAR rolling average has improved slightly to 0.04 in 2016 and has shown a generally stable performance over the past five years.
- The ISAR median has steadily improved over the past five years, remaining at zero for the past two years. The industry best quartile has remained at zero for the past five years.

Factors Contributing to Performance

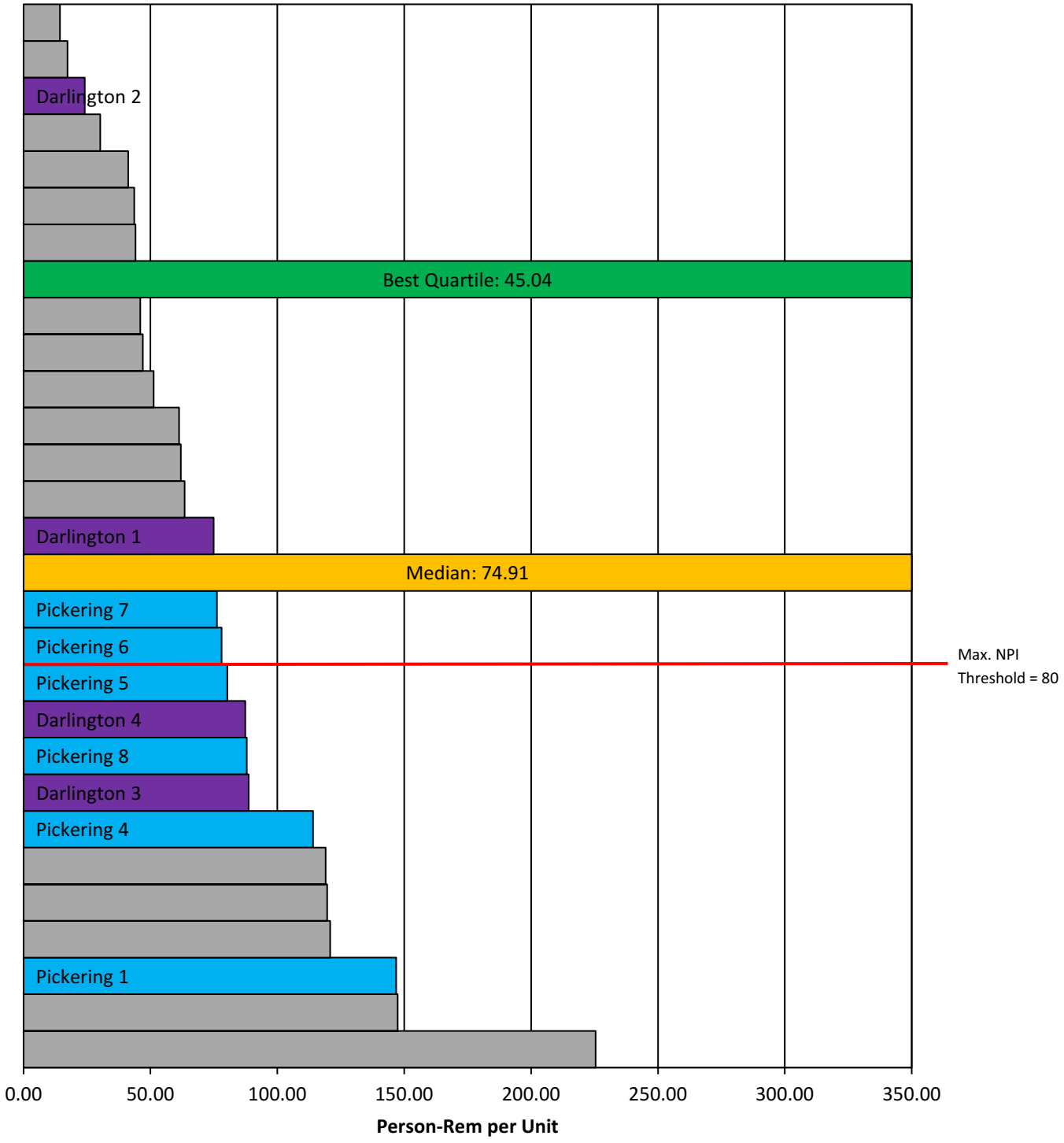
- ISAR is a measure of "permanent utility personnel" and does not include contractors. Many of the utilities in the benchmarking group utilize contractors to a greater extent than OPG Nuclear for higher risk work activities (e.g. outages). This can negatively impact OPG Nuclear's ISAR in comparison to the reported industry benchmark quartile and median.
- OPG Nuclear continues to monitor performance trends in the area of conventional safety and implements timely and specific action plans to support continuous improvement. These actions plans incorporate Human Performance based objectives, which are aimed at positively improving employees risk based decision making process.
- One major focus area for OPG Nuclear in 2016 and 2017 is to expand and enhance the Safe Work Planning process, which supports supervisors and employees in identifying, planning and mitigating hazards prior to commencement of work, as well as monitoring ongoing work for conditions that could lead to unanticipated hazardous situations.

Rolling Average Collective Radiation Exposure

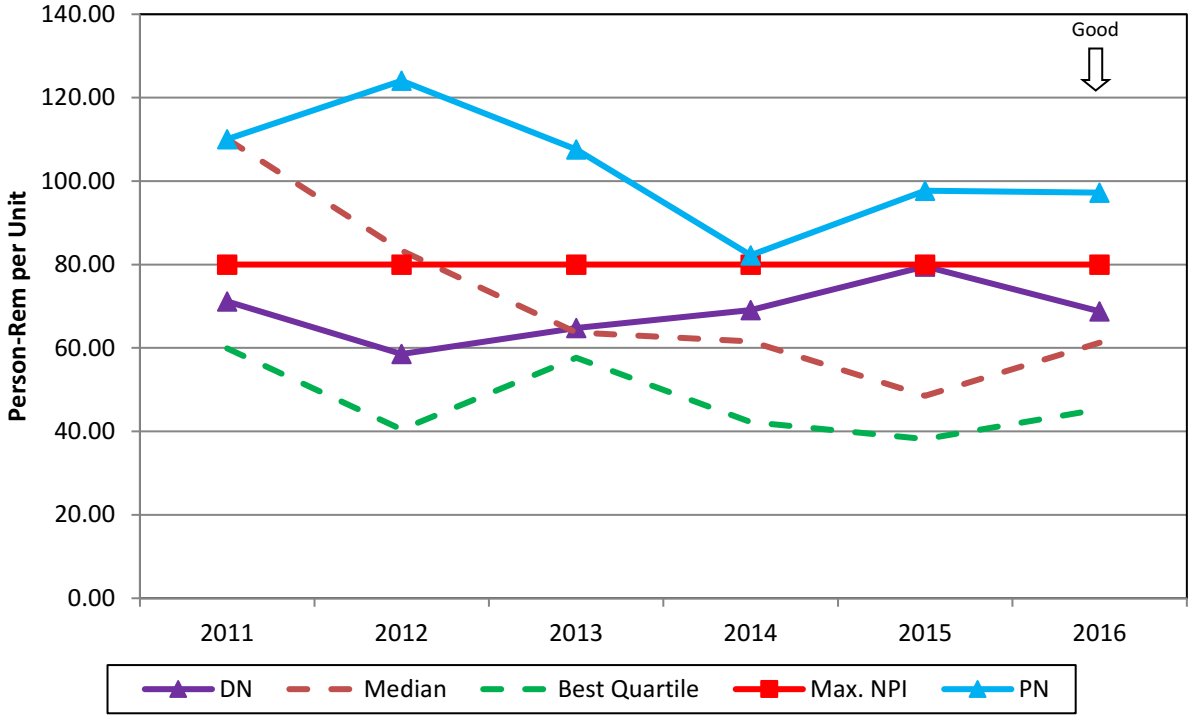
2016 Rolling Average Collective Radiation Exposure (Person-Rem per Unit) CANDU Plant Level Benchmarking



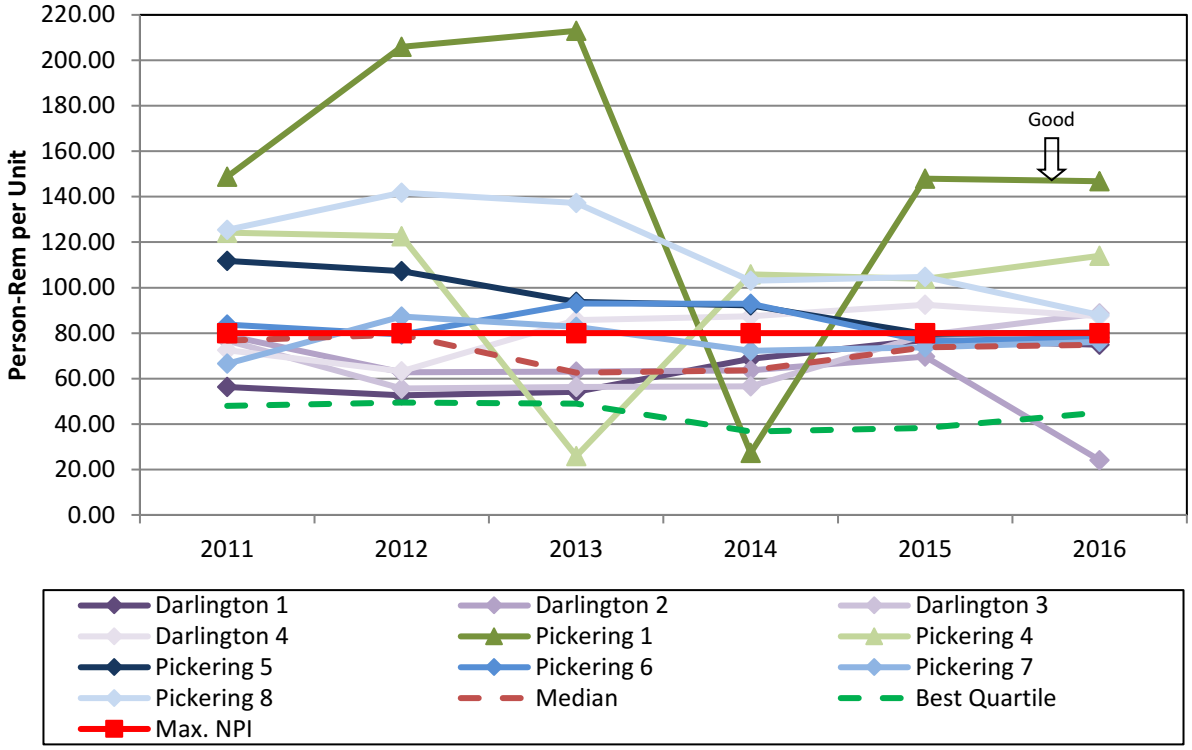
2016 Rolling Average Collective Radiation Exposure (Person-Rem per Unit) CANDU Unit Level Benchmarking



Rolling Average Collective Radiation Exposure (Person-Rem per Unit)
CANDU Plant Level Benchmarking



Rolling Average Collective Radiation Exposure (Person-Rem per Unit)
CANDU Unit Level Benchmarking



Observations – Rolling Average Collective Radiation Exposure (CANDU)

- Collective Radiation Exposure (CRE) is an industry composite indicator encompassing external and internal collective whole body radiation dose.
- Darlington Unit 2 began a long-term refurbishment outage on October 15, 2016. The outage is expected to last 40 months, until February 2020. Dosage associated with Refurbishment activities has been excluded.

2016 (Rolling 2 Year Average Pickering, Rolling 3 Year Average Darlington)

- The Pickering plant-level dose performance value of 97.23 person-rem/unit was worse than the industry plant-level median value of 61.29 person-rem/unit.
- The Pickering unit-level dose performance for Units 6 and 7 were better than the maximum NPI points of 80.0 person-rem/unit but worse than the industry unit level median value of 74.91 rem, while the 4 other Pickering units were worse than the maximum NPI points value of 80.0 person-rem/unit.
- The number of planned outages, as well as scope and duration significantly contributed to this level of plant and unit rolling average CRE performance. In general, Pickering has three major planned outages per year; Darlington averages 1.3 outages per year over the three year outage cycle.
- The Darlington plant-level dose performance value of 68.77 person-rem/unit was better than the maximum NPI threshold, but was worse than the industry plant-level median value of 61.29 person-rem/unit.
- The Darlington dose performance for Unit 2 was considerably better than the industry unit-level best quartile value of 45.04 person-rem/unit while Unit 1 achieved median quartile performance. Units 3 and 4 were worse than the maximum NPI points value of 80.0 person-rem/unit.

Trend

- Pickering plant-level performance has improved sharply and steadily from 2012 to 2014, while performance declined in 2015 and slightly improved in 2016. The rolling average is still worse than median due to scope increases during outages and long outage duration.
- Pickering unit-level performance has remained relatively flat over the review period.
- The Darlington plant-level dose has been increasing since 2012 and because the median value dose has significantly decreased in the same time period, Darlington now finds itself above the industry median. This performance is due to increased outage scope, including both planned and unplanned outages as well as prerequisite work associated with refurbishment activities for Unit 2, which started the Refurbishment stage in mid-October 2016.
- Darlington units as a whole have performed near the industry median over the review period.

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Factors Contributing to Performance Rolling Average Collective Radiation Exposure (CANDU)

- These factors play a significant role in the CANDU reactors' CRE performance: planned outage scope and duration, tritiated ambient air in accessible and access controlled areas, effectiveness of mitigation measures and initiatives being implemented to reduce identified sources of radiological hazards, and human performance during execution of radiological tasks.

Best Practices

- The following list represents common practices that demonstrate continuous improvement and help maintain good CRE performance for CANDU type reactors:
  - Robust Site As Low as Reasonably Achievable (ALARA) Committee, chaired by Facility Senior Vice President.
  - Reactor face shielding to reduce dose rates.
  - Use of full size vault platforms to improve workflow.
  - Teledosimetry.
  - Process fluid detritiation.
  - Use of Munters driers to enhance existing measures to minimize ambient airborne tritium levels.
  - Optimization of Fuelling Machine purification using Ion Exchange with annual resin replacement and/or sub-micron filters.
  - Sub-micron filtration in the Primary Heat Transport system.
  - Use of independent radiological oversight for higher risk work to improve human performance during execution of radiological tasks.
  - Daily accounting of dose, and work group focus on Radiation Protection Fundamentals.
- OPG establishes internal administrative dose limits to ensure that dose to each exposed individual is managed and maintained well below individual regulatory limits.

Initiatives

- OPG Nuclear fleet-wide and site specific initiatives have been implemented to incorporate the industry best practices noted above.
- Specific key initiatives are described below.

Pickering

- Source term reduction, including improvements to process fluid filtration, a dose reducing resin trial, and detritiation.
- Source term mitigation, including optimization of shielding for reactor face work, improvements to the shielding canopy for reactor face work, and dryer modifications for improved performance and reliability.
- Human performance, including involvement and oversight by Radiation Protection (RP) staff of work with elevated radiation risk.
- Focus on dose to the individual through implementation of daily dose goals.
- Improving RP worker practices by driving individual accountability.
- Work Group specific dose reduction plans are being developed and implemented by line management with ALARA support.
- Use of Dynamic Learning Activities for focused program areas to permit mentoring of 'what excellence looks like' in realistic work environments with simulated radiological conditions.
- Implementation of an extensive network of remote reading radiation instrumentation and other tools to provide real-time information on radiological conditions and minimize time and therefore dose in radioactive work areas.
- Use of portable gamma spectrometers to improve source term characterization.

Darlington

- The early efforts in source term reduction are generating lasting effects. A reduction of coolant pH factors from 10.8 to 10.1 minimizes crud migration from boilers to inlet feeders. The installation of sub micron heat transport filters effectively reduces the dose rates in our heat transport system and has contributed the success of Darlington's external dose.
- Developed and implemented a reactor face shielding strategy to reduce dose while at the same time minimize the risks of personnel injury during shielding installation.
- Implemented an improved feeder ice jacket including the application of long handled tools for jacket installation and remote data acquisition.
- Effectively utilized Teledosimetry to reduce Radiation Protection Coordinator dose. Utilized Teledosimetry as a coaching tool to improve worker radiation protection practices and reduce dose.
- Tritium mitigation strategies have been developed and implemented to reduce airborne tritium concentrations inside containment and confinement rooms.
- Developed and implemented X-ray Fluorescence (XRF) spectroscopy to identify cobalt residues in an effort to reduce cobalt deposits in the moderator system during valve overhaul activities thus reducing overall radiation dose.
- Work Group specific dose reduction initiatives have been developed and implemented by line management.

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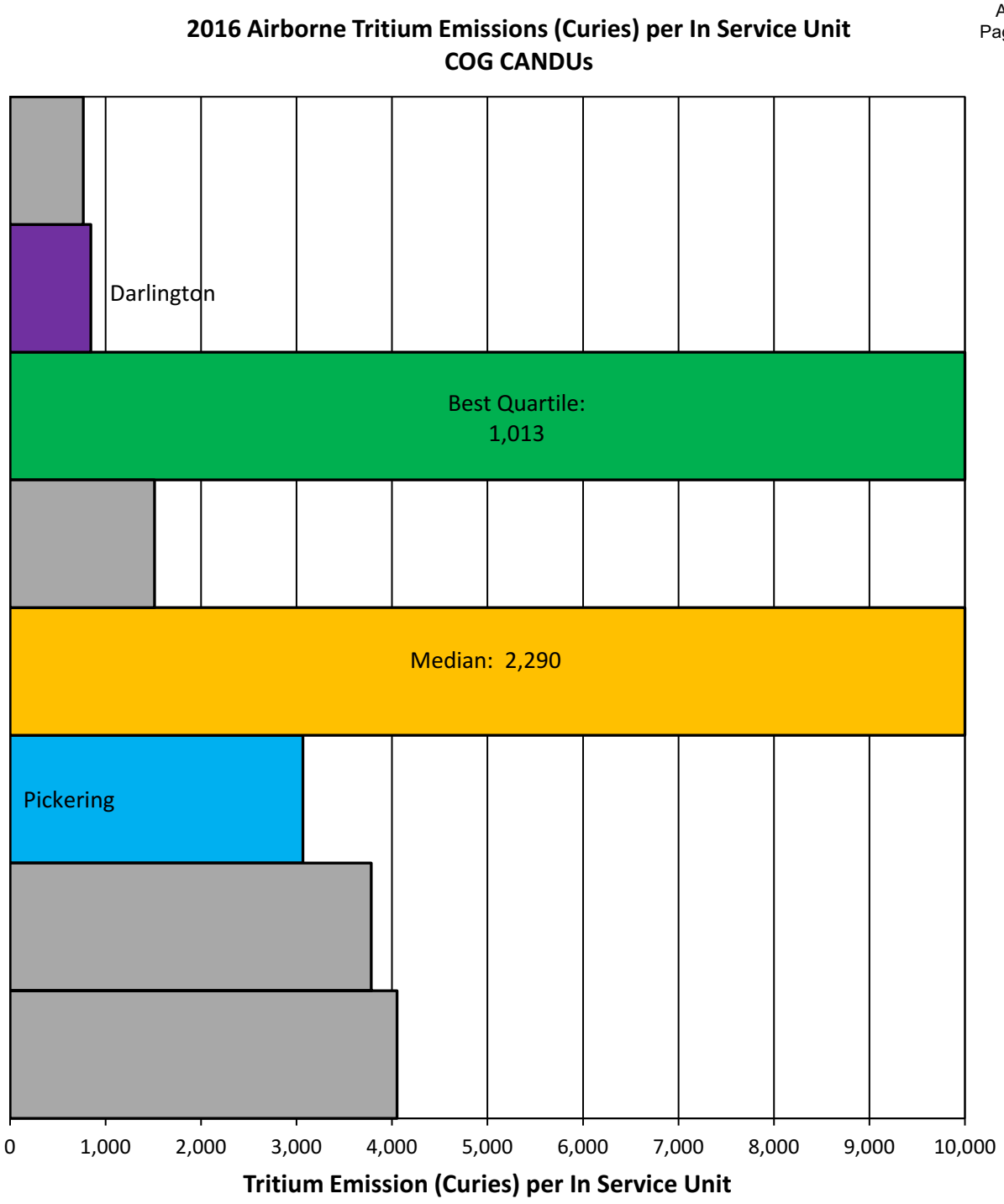
Airborne Tritium Emissions per In Service Unit



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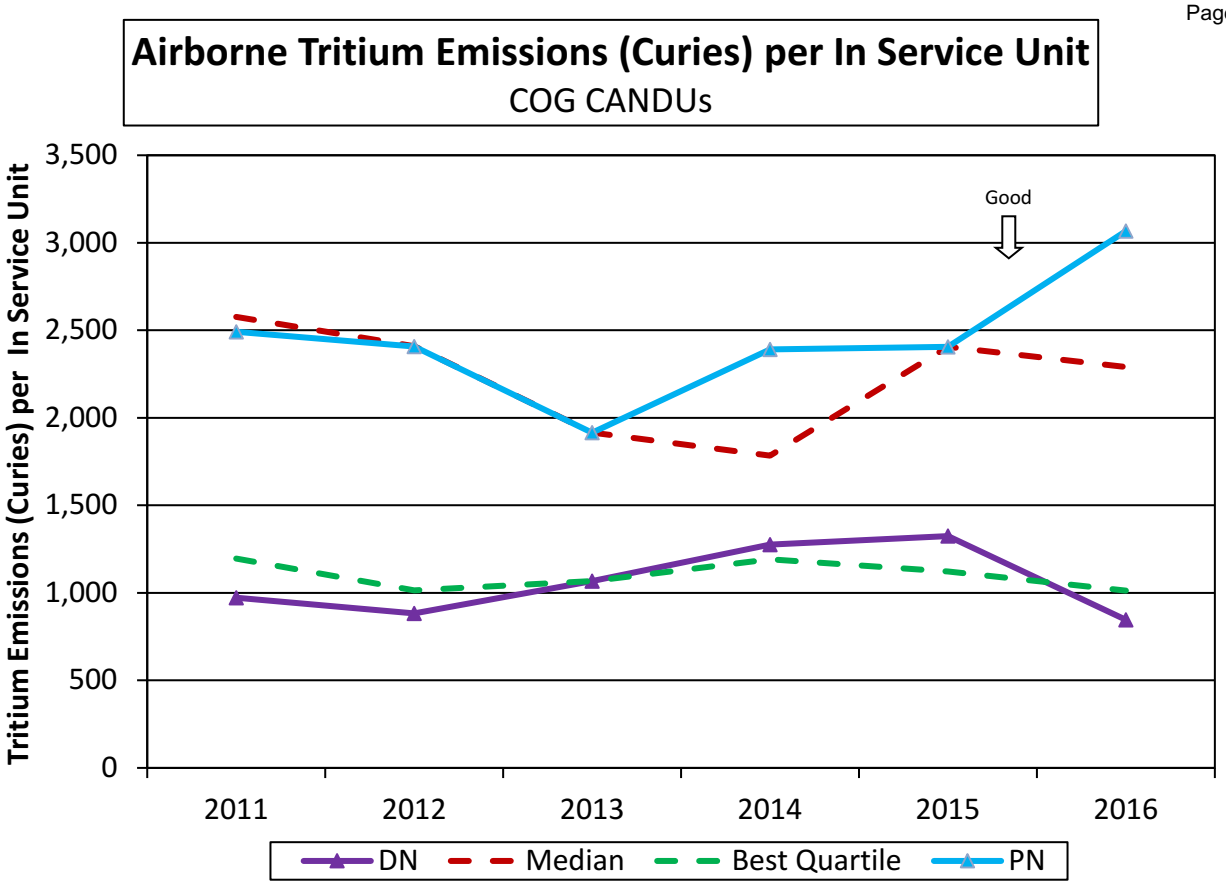

Notes:

- Darlington values have retroactively modified as of 2013 to exclude Tritium Removal Facilities emissions consistent with COG benchmarking results.

Observations – Airborne Tritium Emissions (Curies) per In Service Unit

2016 (Annual Value)

- The 2016 industry results collected by the CANDU Owners Group (COG) are included in this report as the most up-to-date figures available for benchmarking performance. As of 2013, tritium emissions from Tritium Removal Facilities (TRF) are no longer included in COG benchmarking results.
- Airborne tritium emissions from OPG facilities for 2016 are compared per in service reactor unit.
- Curies per in service unit at top quartile CANDU plants was 1,013 or lower.
- Darlington performed well at 846 Curies per in service unit placing in the best quartile of the in service units. Performance improved from second quartile in 2014 and 2015 to best quartile performance in 2016.
- Pickering performance remained in the third quartile with 3,067 Ci per in service unit, higher than the industry median threshold of 2,290 Curies per in service unit.

Trend

- Darlington and Pickering tritium emissions to air continue to be less than one per cent of the regulatory limits.
- Pickering achieved its best Airborne Tritium Emissions performance in 2013 as a result of increased focus on dryer performance, leak management and source term reduction.
- Performance at Pickering has declined from 2013 to 2016. Increased emissions in 2016 are primarily due to tritiated water in the Fuel Transfer Conveyor Tunnel being vented to monitored stacks.
- Performance at Darlington continued to improve in 2016. Improvements were due to increased focus on dryers and leaks repair throughout the station.
- The industry trend line graph shows that industry best quartile performance for 2016 is essentially the same as it was in 2015, and has been relatively stable over the past six years.

Factors Contributing to Performance

- Key factors affecting performance at Darlington and Pickering include the following:
    - The presence of tritiated water in Pickering Fuel Transfer Conveyor Tunnel being vented to monitored stacks,
    - leaks within containment requiring outages for repair,
    - less than adequate vapour recovery dryer performance,
    - operational issues of the Tritium Removal Facility impacting its availability,
    - increased unit source term (e.g., higher moderator tritium concentrations),
    - For Pickering, the presence of tritiated water in the Fuel Transfer Conveyor Tunnel being vented to monitored stacks.

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Observations – Airborne Tritium Emissions (Curies) per In Service Unit (CONT'D)

- Station focus on tritium emission reduction initiatives include dedicated teams to ensure daily emissions monitoring, sustaining and improving dryer performance, heavy water leak minimization, tritium program development and innovations, and improved availability of the Tritium Removal Facility at the Darlington site.
- Other improvement initiatives include OPG's ongoing participation in COG environmental benchmarking of participating CANDU stations to determine best environmental practices.

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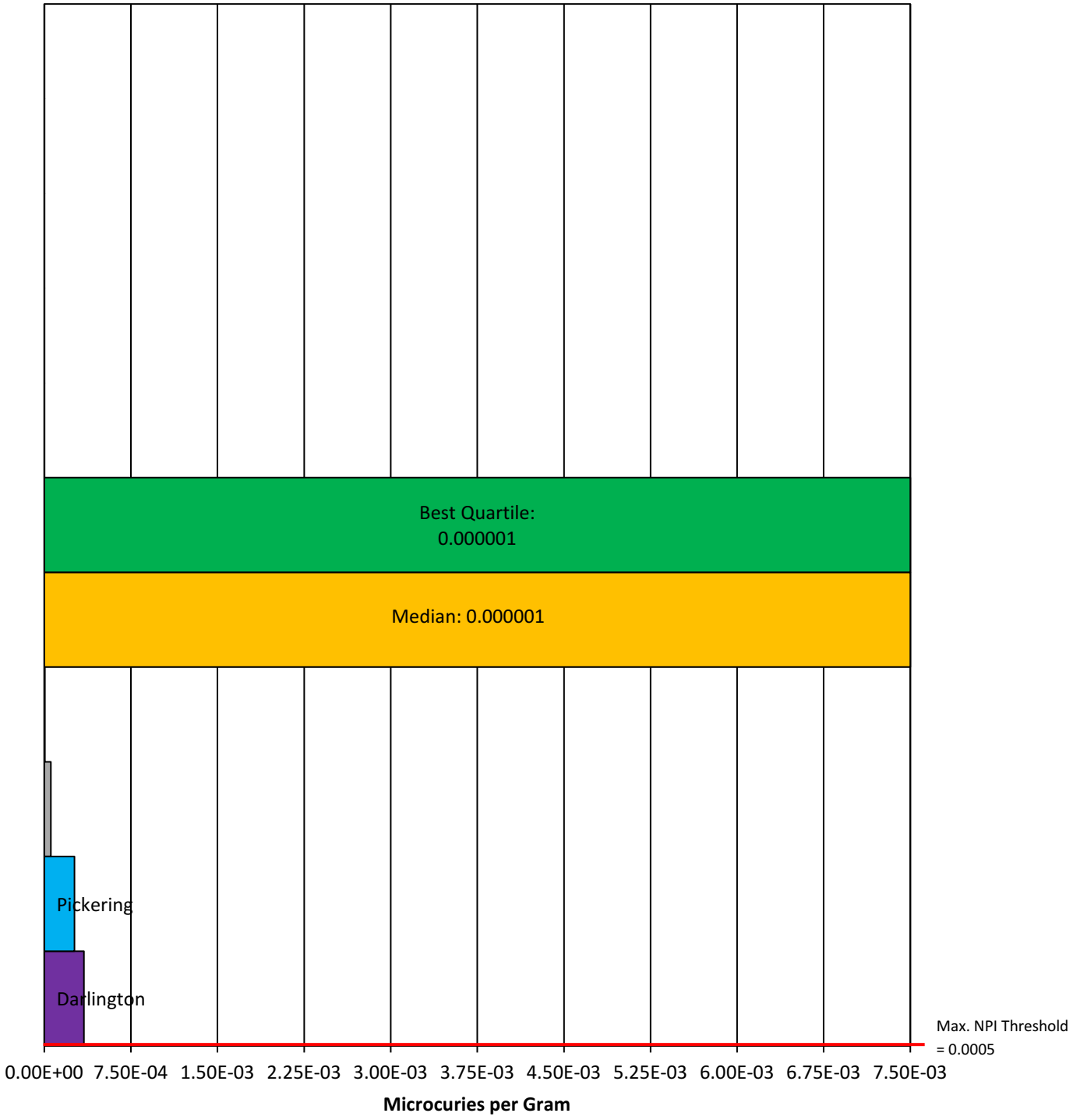
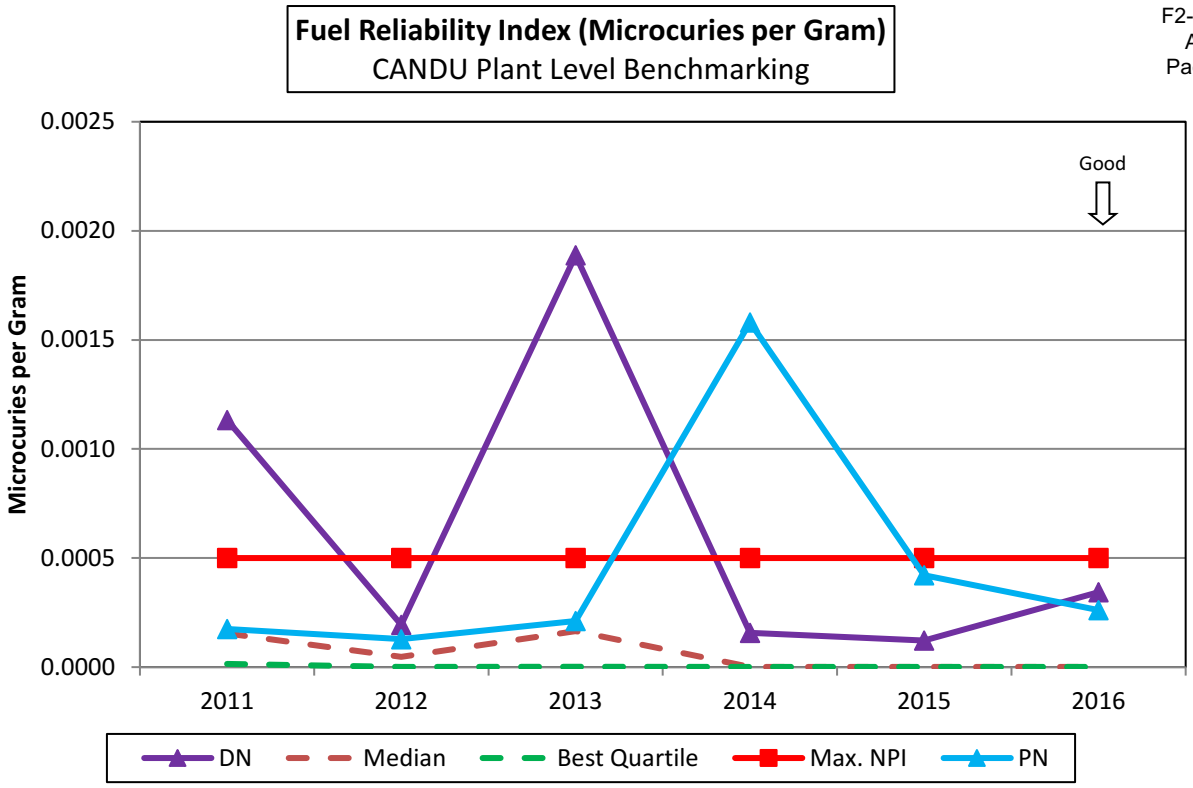
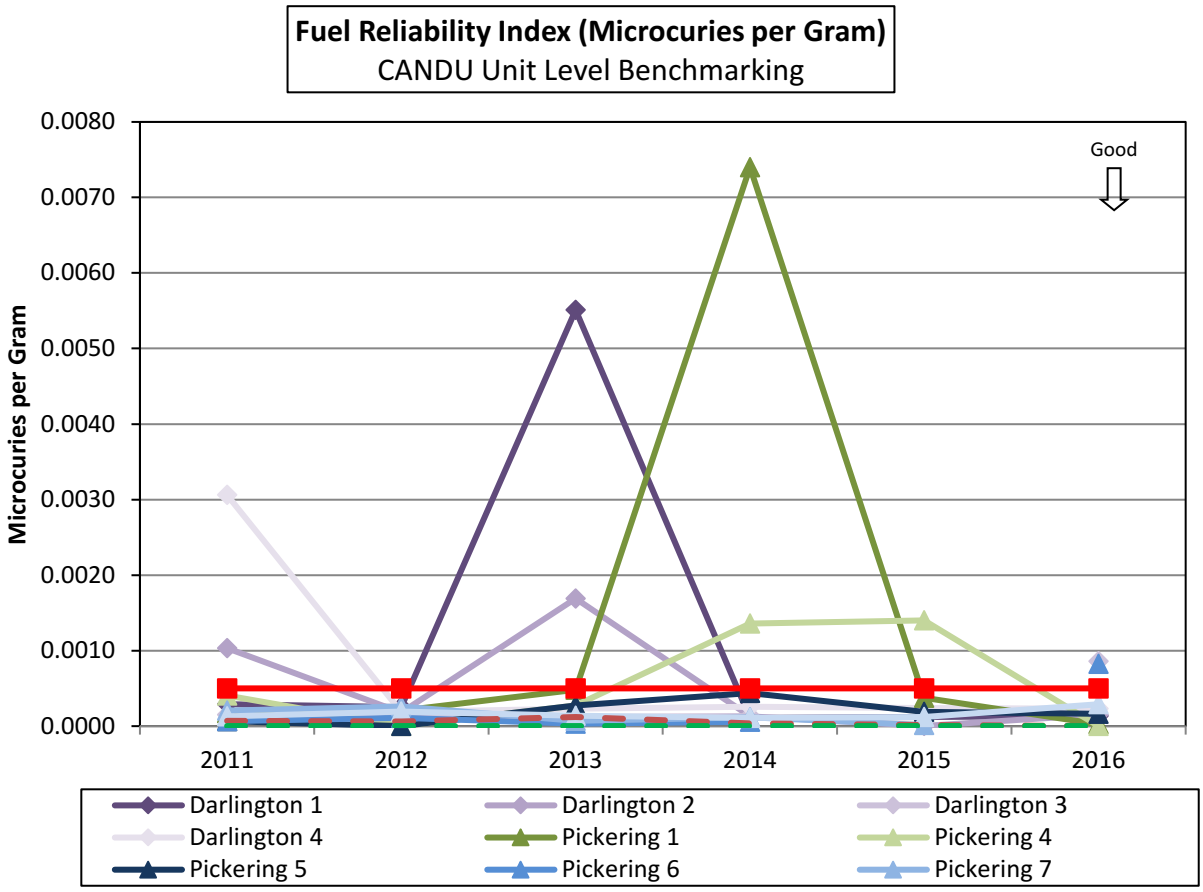
Fuel Reliability Index

2016 Fuel Reliability Index (Microcuries per Gram)
CANDU Plant Level Benchmarking




Fuel Reliability Index (Microcuries per Gram)
CANDU Plant Level Benchmarking
Microcuries per Gram
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
Max. NPI
PN


Fuel Reliability Index (Microcuries per Gram)
CANDU Unit Level Benchmarking
Microcuries per Gram
0.0080
0.0070
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
Good
2011
2012
2013
2014
2015
2016
Darlington 1
Darlington 2
Darlington 3
Darlington 4
Pickering 1
Pickering 4
Pickering 5
Pickering 6
Pickering 7

Observations – Fuel Reliability Index (CANDU - FRI)

2016 (Most Recent Operating Quarter)

- The best quartile and median values for Fuel Reliability Index (FRI) performance for CANDU plants were 0.000001 µCi/g. For individual CANDU units, the best and median quartiles were 0.000001 µCi/g.
- Pickering achieved maximum NPI points in 2016 and its performance improved slightly from 2015 (0.000261 µCi/g vs 0.000421 µCi/g) however, it was below the median value threshold.
- Darlington achieved maximum NPI points in 2016 but its performance declined slightly from 2015 (0.000343 µCi/g vs 0.000122 µCi/g) however, it was below the median value threshold.
- Post-discharge fuel inspections for Pickering indicated that the overall condition of fuel inspected was acceptable and consistent with previous years. Fuel inspections for Pickering confirmed one fuel defect in 2016, down from two in the previous year. No fuel issues of significance arose at Pickering in 2016.
- Post-discharge fuel inspections for Darlington indicated that the overall condition of fuel inspected was acceptable and consistent with previous years. Fuel inspections for Darlington confirmed one fuel defect in 2016 resulting in an increase in the FRI value from 2015. No fuel issues of significance arose at Darlington in 2016.

Trend

- The best quartile for CANDU plants remained relatively consistent at 0.000001 from 2011. The median values for CANDU plants has generally improved from 2011 and remained at 0.000001 since 2014.
- The Pickering station FRI performance has been improving since 2015 coinciding with the reduction in fuel defect incidents, and as a result achieved maximum NPI points.
- The Darlington station FRI performance has generally improved since 2011 despite the spike in 2013. The reactors only had one confirmed defect in 2016, which is an improvement in the general 5 year trend.

Factors Contributing to Performance

Fuel defects existed in three units at Pickering in 2014. A team was formed to investigate the fuel defects incidents and a corrective action plan had been prepared to address the problem, which resulted in a reduction of defects totaling to two fuel defects in 2015 and one defect in 2016.

Actions that were taken that drove this improvement since 2014 include:

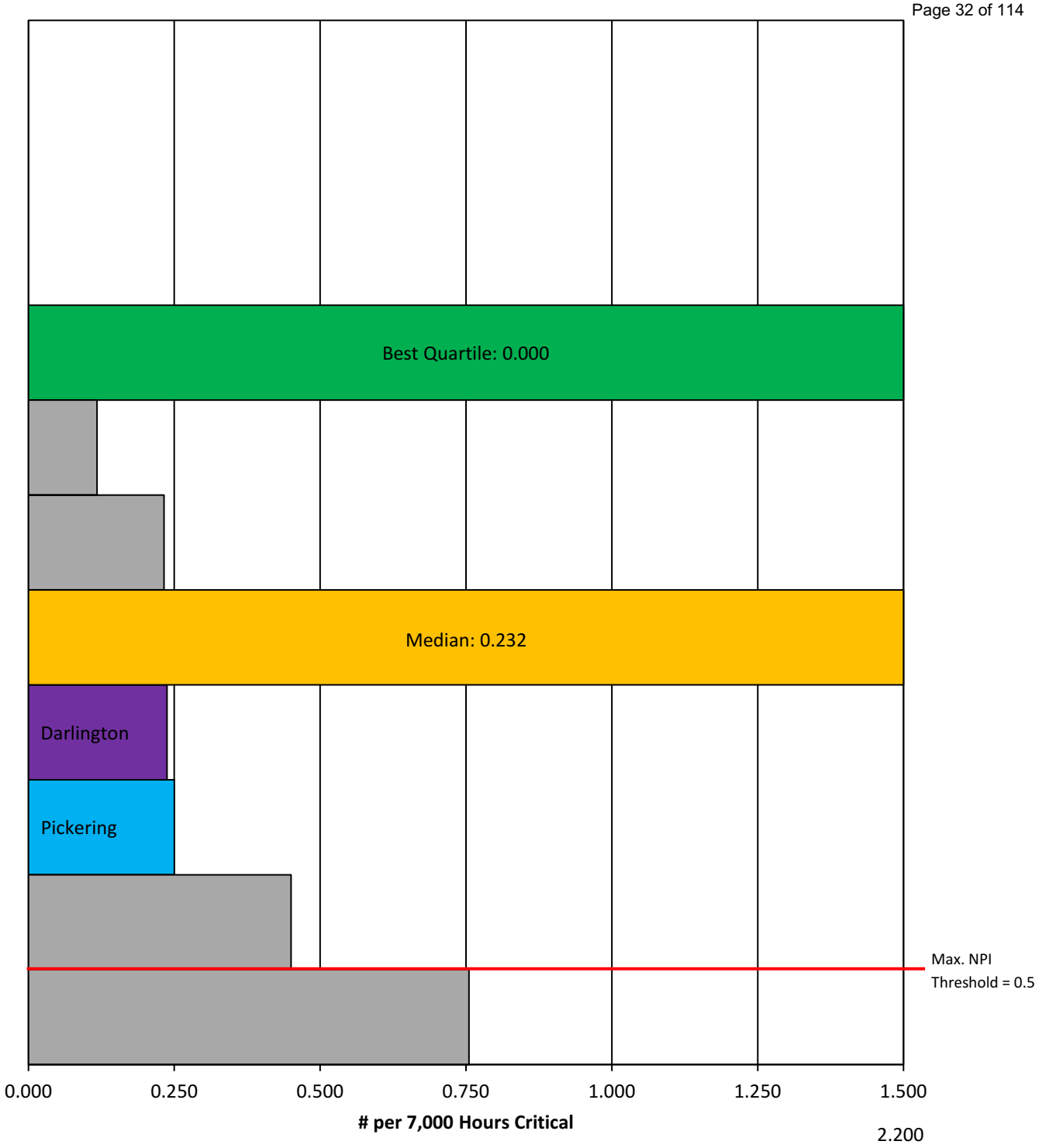
- Developing a fuel defect guideline for Pickering,
- Increasing scope of Heat Transport System (HTS) grab sampling and analysis,
- Assessing and comparing Units 1, 4 and 5 to 8 power ramps,
- Assessing impact of adjuster burn-out during operation,
- Assessing impact of pressure tube creep on fuel performance,
- Improving the methods of surveillance and elimination of the possibility of foreign materials entrance into the HTS due to Fuel Handling and Outage practices,

- Fuel bundle manufacturing assessment,
- 3rd party examinations of unirradiated Pickering fuel bundles,
- Irradiated fuel inspections and examinations,
- Improving capability of detecting the defected fuel bundles during the discharge from the fuelling machines, and
- Improving the capability of the in-bay inspection of the suspected fuel bundles to be defected.

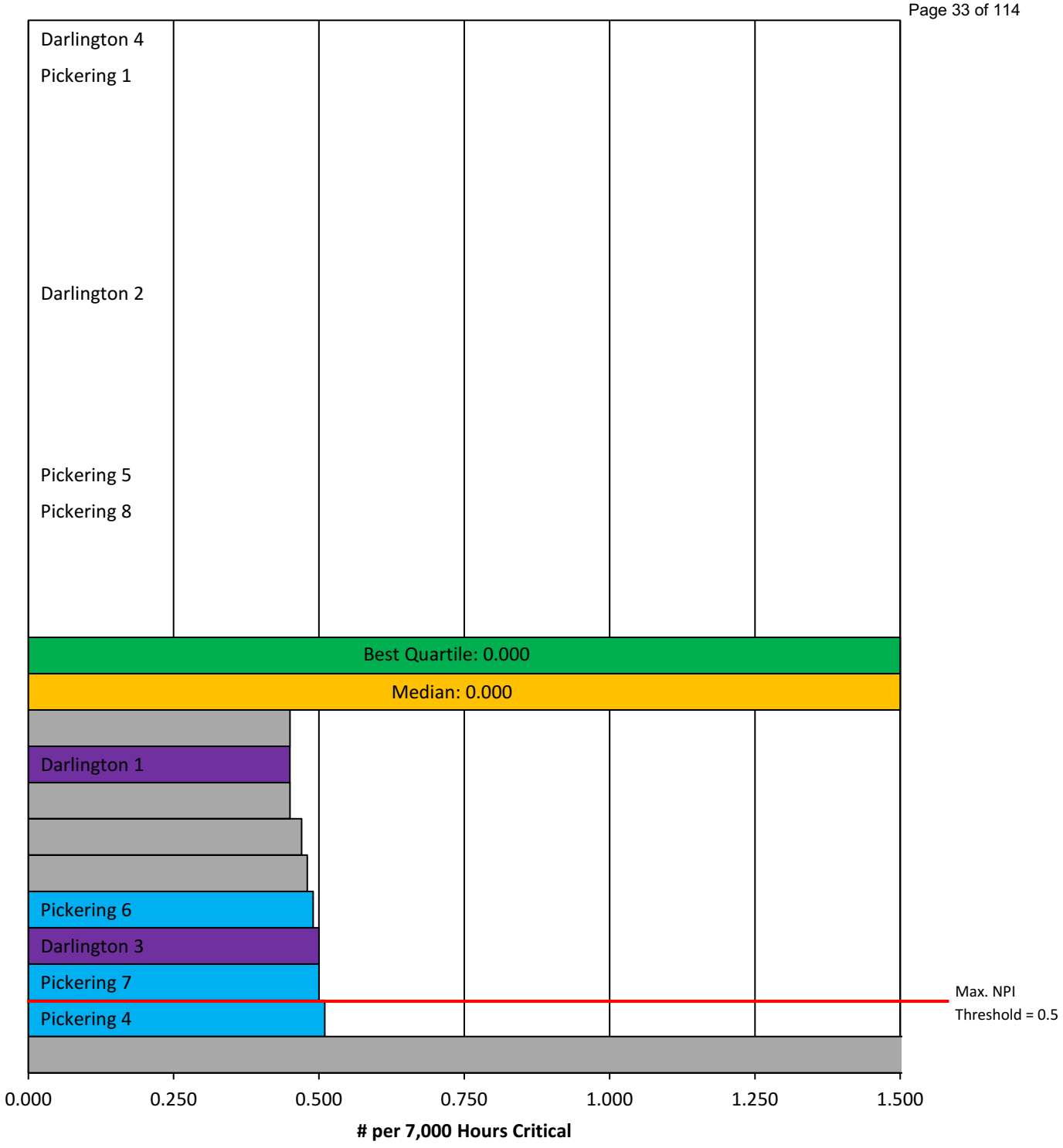
Darlington had only one fuel defect in 2016. The steps taken that have led to improved FRI performance and prevent the potential of fuel defects are the following:

- New fuel with tighter tolerances for mass was received and is currently being used,
- Installed a new fuel inspection facility and completed inspections in East Fuelling Facility Auxiliary Area; confirmed defects in all suspect bundles and all fuel defects originated from one batch of 2786 bundles,
- OPG-supplier co-operation resulted in installation of an automatic loader of fuel pellets complete with a “go/no go” pellet diameter monitor,
- Close monitoring of existing fuel bundle inventory and core load, and
- Projects in progress on Gaseous Fission Products (GFP) and feeder scanners to improve ability to locate defects on power and during outages.

2016 2-Year Unplanned Automatic Reactor Trips
CANDU Plant Level Benchmarking



2016 2-Year Unplanned Automatic Reactor Trips
CANDU Unit Level Benchmarking



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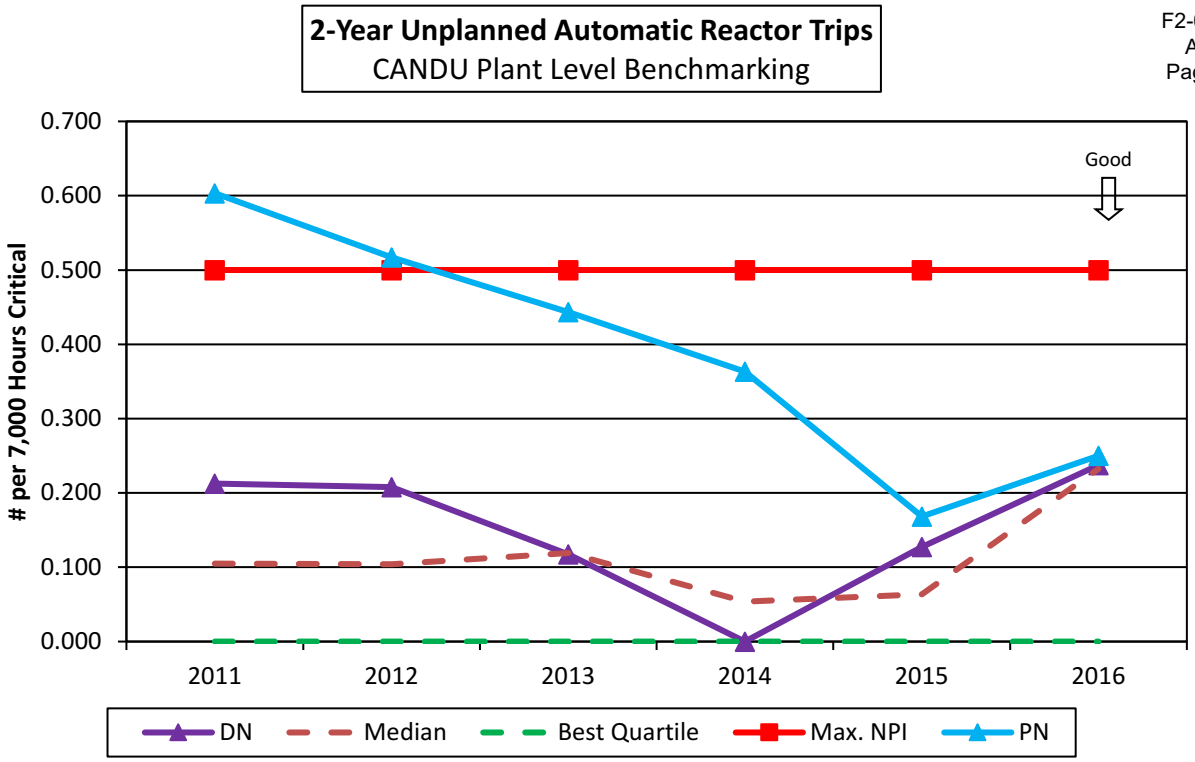

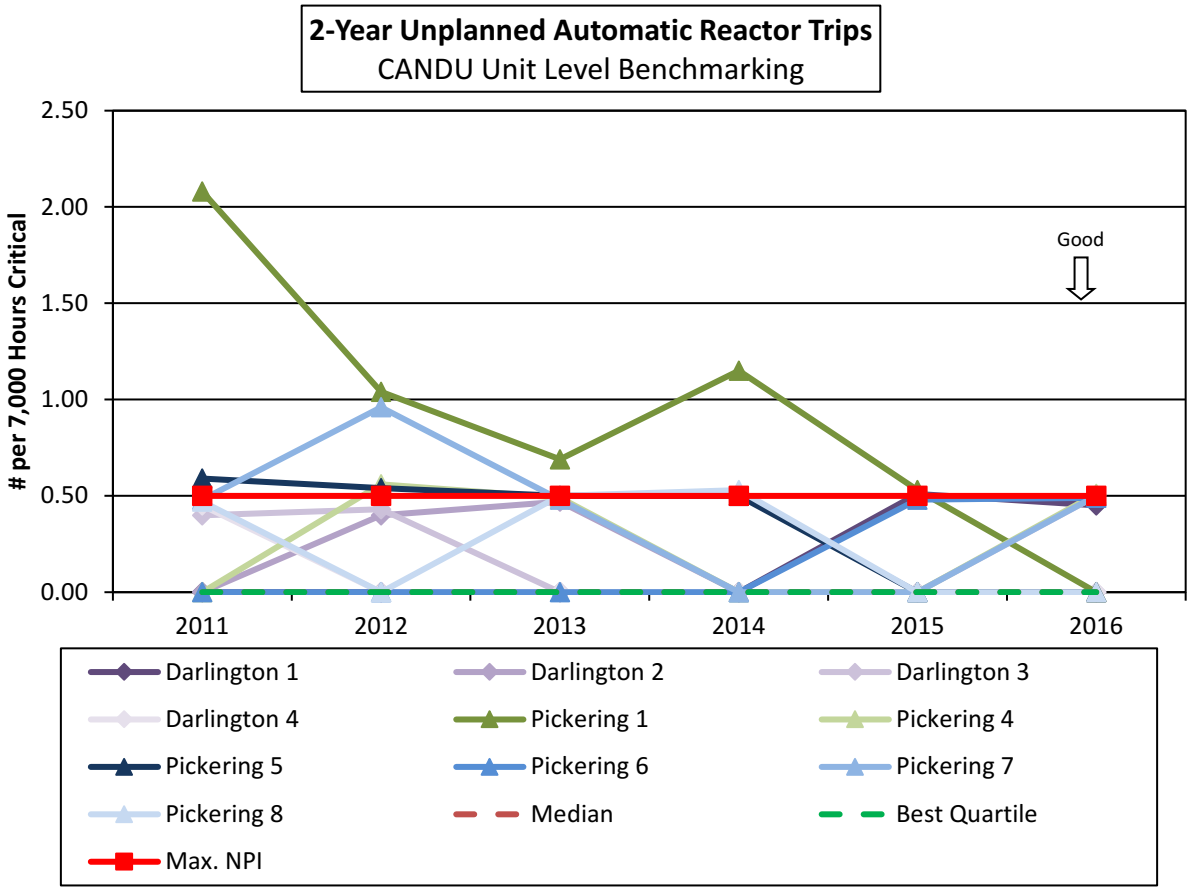

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Observations – 2-Year Unplanned Automatic Reactor Trips (CANDU)

2016 (2-Year Rolling Average)

- The 2-year rolling average unplanned automatic reactor trip best quartile for CANDU plants was zero with a median of 0.23. For individual CANDU units, the best quartile and median values for unplanned reactor trip were zero.
- At the plant level, Pickering's trip rate of 0.25 was better than the maximum NPI threshold value of 0.50. On an individual unit basis, Units 1, 5, and 8 with trip rate of zero, were at best quartile. Unit 4, with rate of 0.51, Unit 6, with trip rate of 0.49, and Unit 7, with trip rate of 0.50, were worse than the third quartile threshold of 0.46 and significantly better than the maximum value of 1.51.
- At the plant level Darlington's trip rate of 0.24 was better than the maximum NPI threshold value of 0.50. On an individual unit basis, Units 2 and 4, with trip rates of zero, performed at the best quartile level. Unit 1, with a trip rate of 0.45, was better than the third quartile threshold of 0.46. Unit 3, with trip rate of 0.50, was worse than the third quartile threshold of 0.46 but significantly better than the maximum value of 1.51.

Trend

- The unplanned automatic reactor trip best quartile for CANDU plants has been zero since 2011. Since 2011, the median value improved in 2012, performance declined in 2013, but improved in 2014, and declined in 2015 and 2016. On an individual unit basis, the industry best quartile and median has remained at zero since 2011.
- At the plant level, Pickering station performance improved each year from 2011, but declined in 2016. On an individual unit basis, Unit 1 performance improved from 2012 to 2013, decreased in 2014, and improved in 2015 and 2016. Unit 4 performance has significantly improved from 2012 and achieved best results in 2014 and 2015 with a zero trip rate, but decreased in 2016. Unit 5 performance has been trending better since 2012, achieving a zero trip rate in 2015 and 2016. Unit 6 has performed at a zero trip rate from 2012 to 2014, but performance decreased in 2015 and 2016. Unit 7 performance improved from 2012 to 2013, achieved the best performance in 2014 and 2015 with a zero trip rate, but decreased in 2016. Unit 8 performance from 2012 decreased in 2013 and 2014, but the best performance with a zero trip rate was achieved in 2012, 2015, and 2016.
- At the plant level, Darlington station performance improved from 2011, achieving the best result of a zero trip rate in 2014, but decreased in 2015, and 2016. On an individual unit basis, Unit 1 has consistently performed at a zero trip rate since 2011, but the performance decreased in 2015 and 2016. Unit 2 performance significantly improved in 2014, 2015, and 2016 to a zero trip rate compared to 2012 and 2013. Unit 3 performance improved since 2012 to a zero trip rate in 2013, 2014, and 2015, but decreased in 2016. Unit 4 has consistently performed at a zero trip rate from 2012 to 2016.

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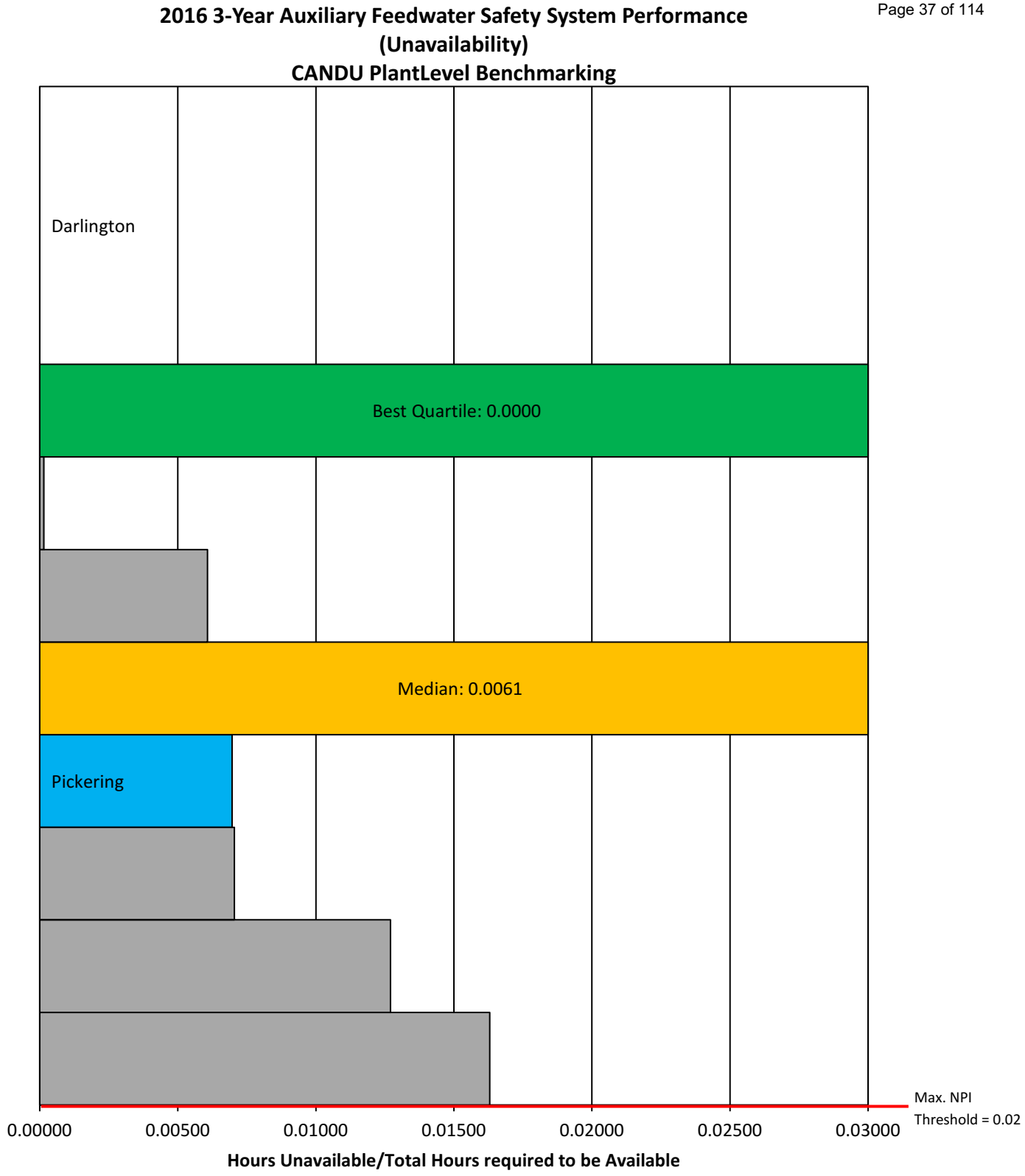
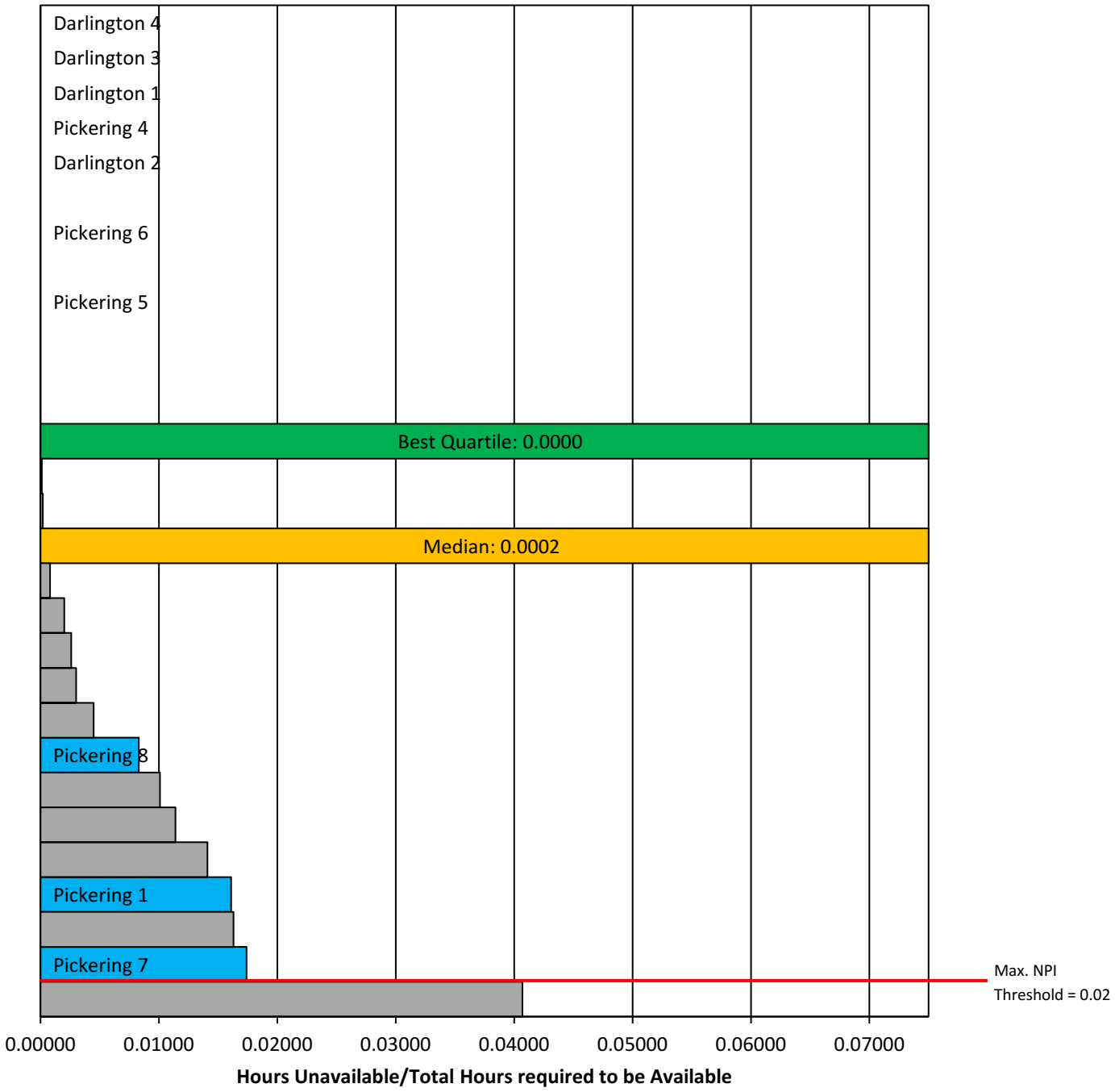
Factors Contributing to Performance

- Key performance drivers for this metric include: general equipment reliability, material condition, and human performance.
- In 2016, Pickering had 2 unplanned automatic reactor trip (1 on Unit 4, and 1 on Unit 7).
- In 2016, Darlington had 1 unplanned automatic reactor trip (1 on Unit 3).
- On-going due diligence by Station Operations, Engineering, and Maintenance organizations. Operating Experience (OPEX) from each event has been shared at Pickering, Darlington and at the external summits. Where necessary, training material has been revised based on OPEX. To improve human performance, technical procedures have been revised. To improve equipment reliability, where possible, like-for-like parts replacement has taken place. System health teams are involved in obsolescence issues.

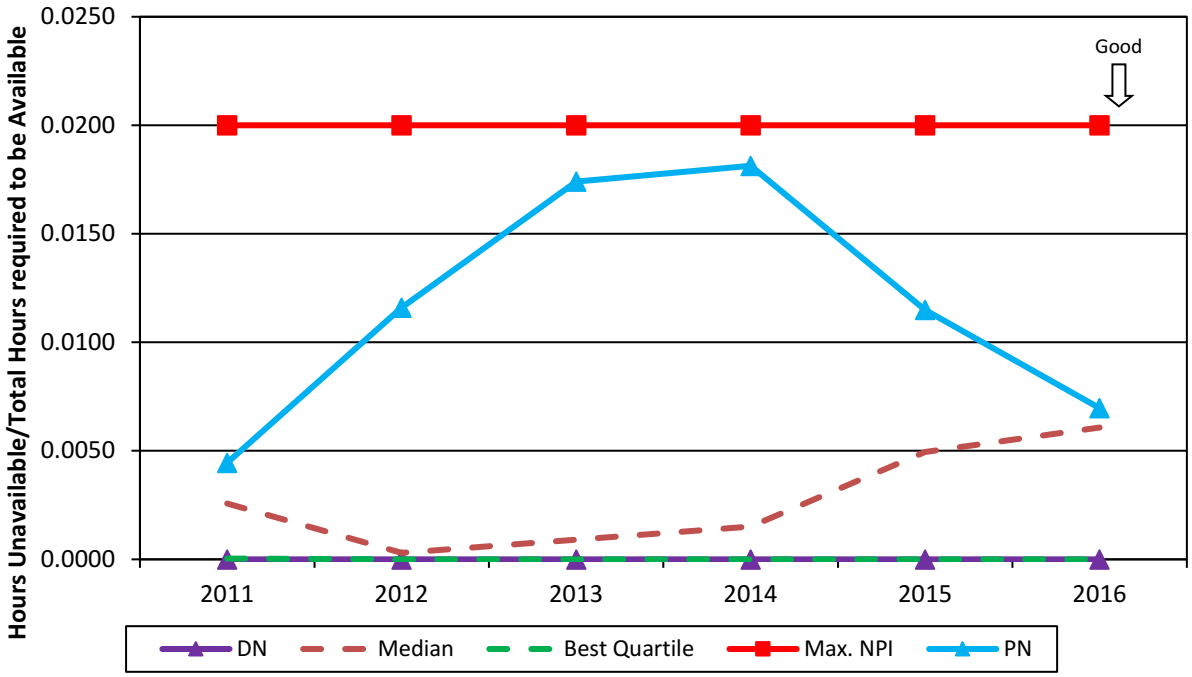
3-Year Auxiliary Feedwater Safety System Unavailability



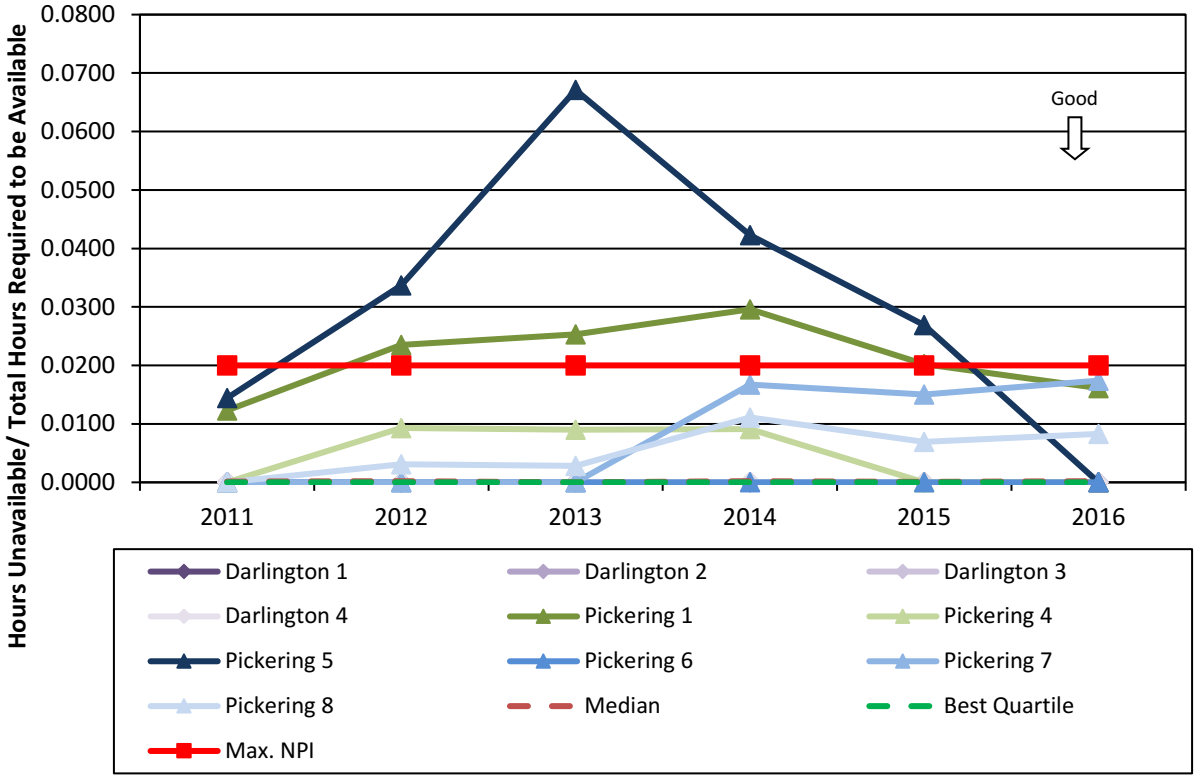
2016 3-Year Auxiliary Feedwater Safety System Performance (Unavailability) CANDU Unit Level Benchmarking



3-Year Auxiliary Feedwater Safety System Performance (Unavailability)
CANDU Plant Level Benchmarking



3-Year Auxuliary Feedwater Safety System Performance (Unavailability)
CANDU Unit Level Benchmarking



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Observations – 3-Year Auxiliary Feedwater System (CANDU)

2016 (3-Year Rolling Average)

- Auxiliary feedwater (AFW) safety system performance at best quartile for CANDU plants was zero with a median value of 0.0061. For individual CANDU units, the best quartile was zero with a median of 0.0002.
- At the plant level, Pickering station, with an unavailability of 0.0070 maintained maximum NPI points. On an individual unit basis, all Pickering units achieved maximum NPI points with Units 4, 5, and 6 also achieving best quartile performance.
- Darlington station achieved maximum NPI points and best quartile performance of zero unavailability at both the station and unit levels in 2016.

Trend

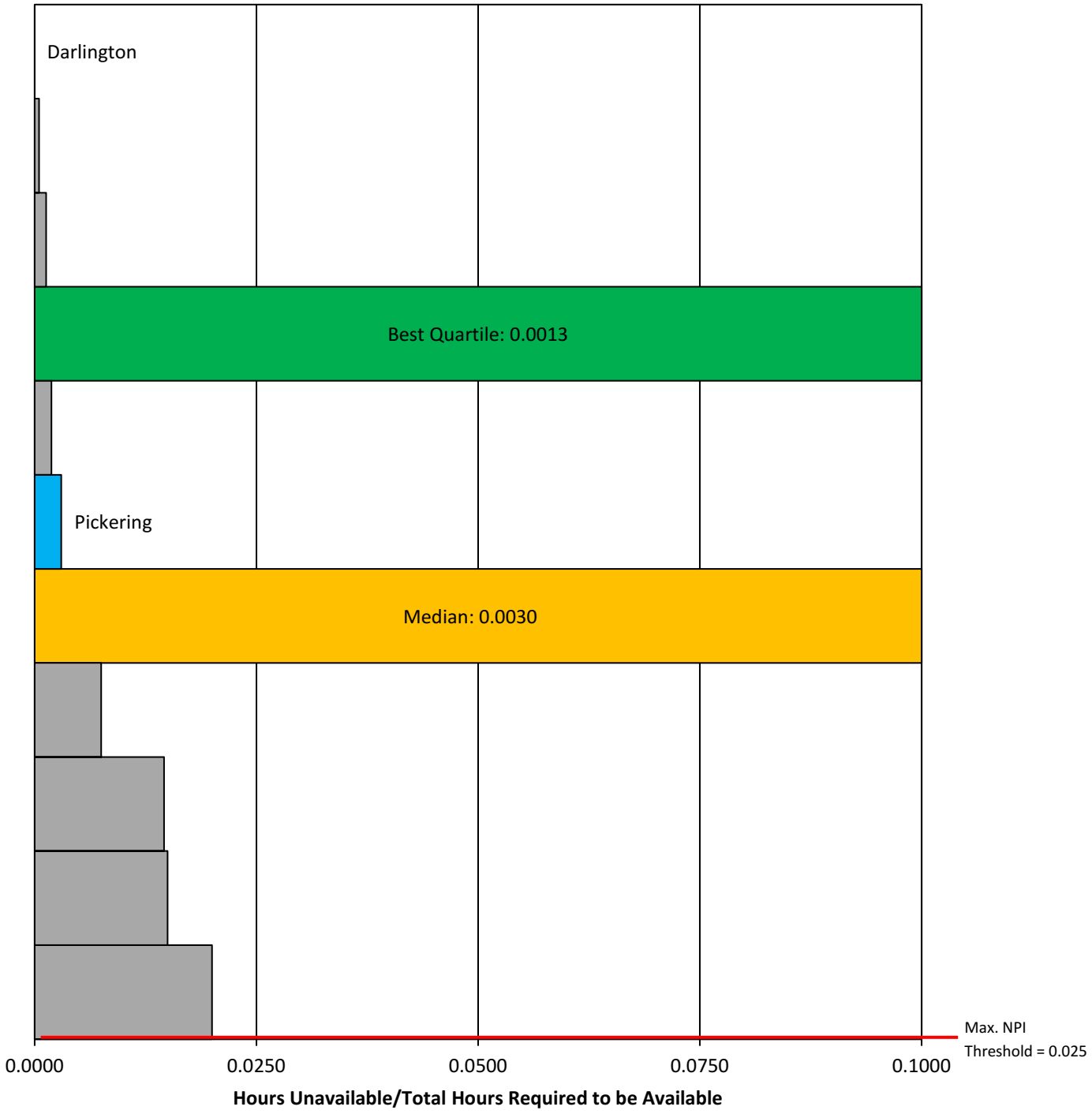
- The 3-Year Auxiliary Feedwater unavailability best quartile performance of CANDU plants maintained zero unavailability from 2011 to 2016. The plant level industry median value has fluctuated slightly over the review period but has remained below the NPI maximum threshold. At the unit level, the industry best quartile has remained at zero over the review period and the median value at or close to zero over the review period.
- At the plant level, Pickering station has shown two years of significant improvement from 2014 performance, reaching a value of 0.0061 in 2016 and approaching median level performance. On an individual unit basis, Unit 6 has consistently performed at a zero unavailability rate over the review period. Unit 1 performance declined each year to 2014, but improved in 2015 and 2016. Unit 4 performance was at zero unavailability rate in 2011, decreased slightly in 2012 to 2014, and improved to zero unavailability in 2015 and 2016. Unit 5 performance improved from 2013, and reached a zero unavailability rate in 2016. Unit 7 performances has consistently performed at a zero unavailability rate to 2013 inclusive, but declined in 2014, improved in 2015, and declined in 2016. Unit 8 performance declined each year from 2012, improved in 2015, and declined in 2016.
- Darlington station and unit performance has been at zero unavailability since 2011.

Factors Contributing to Performance

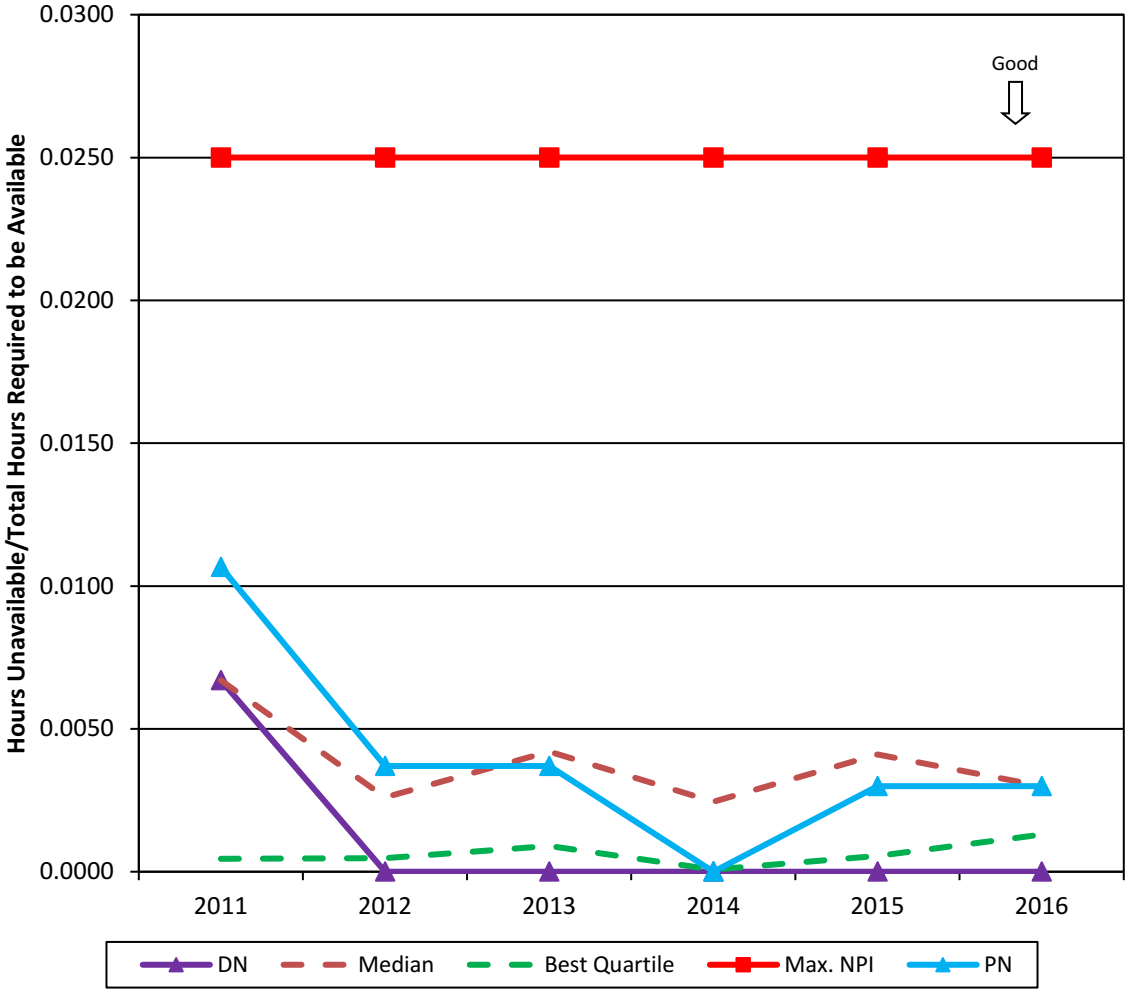
- Key performance drivers for this metric include: general equipment reliability, material condition, and human performance.
- No Auxiliary Feedwater Safety System unavailability occurred during 2016, which led to improved performance relative to previous years.

3-Year Emergency AC Power Safety Unavailability

2016 3-Year Emergency AC Power Safety System Performance (Unavailability)
CANDU Plant Level Benchmarking



3-Year Emergency AC Power Safety System Performance (Unavailability)
CANDU Plant Level Benchmarking



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Observations – 3-Year Emergency AC Power Safety System (CANDU)

2016 (3-Year Rolling Average)

- 3-Year Emergency AC Power Safety System performance at best quartile CANDU plants was 0.0013. The industry median value was 0.0030.
- At the plant level, Pickering station, with an unavailability of 0.003, maintained median level performance as well as maximum NPI points.
- Darlington was the best performing station in the CANDU peer group, achieving zero unavailability, best quartile performance, and maximum NPI results.

Trend

- The 3-year Emergency AC Power Safety System unavailability industry best quartile for CANDU plants remained the same in 2011 and 2012, with a slight decline in 2013, improved in 2014, and slightly declined in 2015 and 2016. The industry median value improved in 2012 and 2014, but slightly declined in 2013, 2015, and 2016.
- Pickering station performance has improved over the review period, reaching its best performance in 2014 achieving zero unavailability, but station performance declined in 2015 and remained unchanged in 2016.
- Darlington station performance achieved zero unavailability over the review period 2012 to 2016.

Factors Contributing to Performance

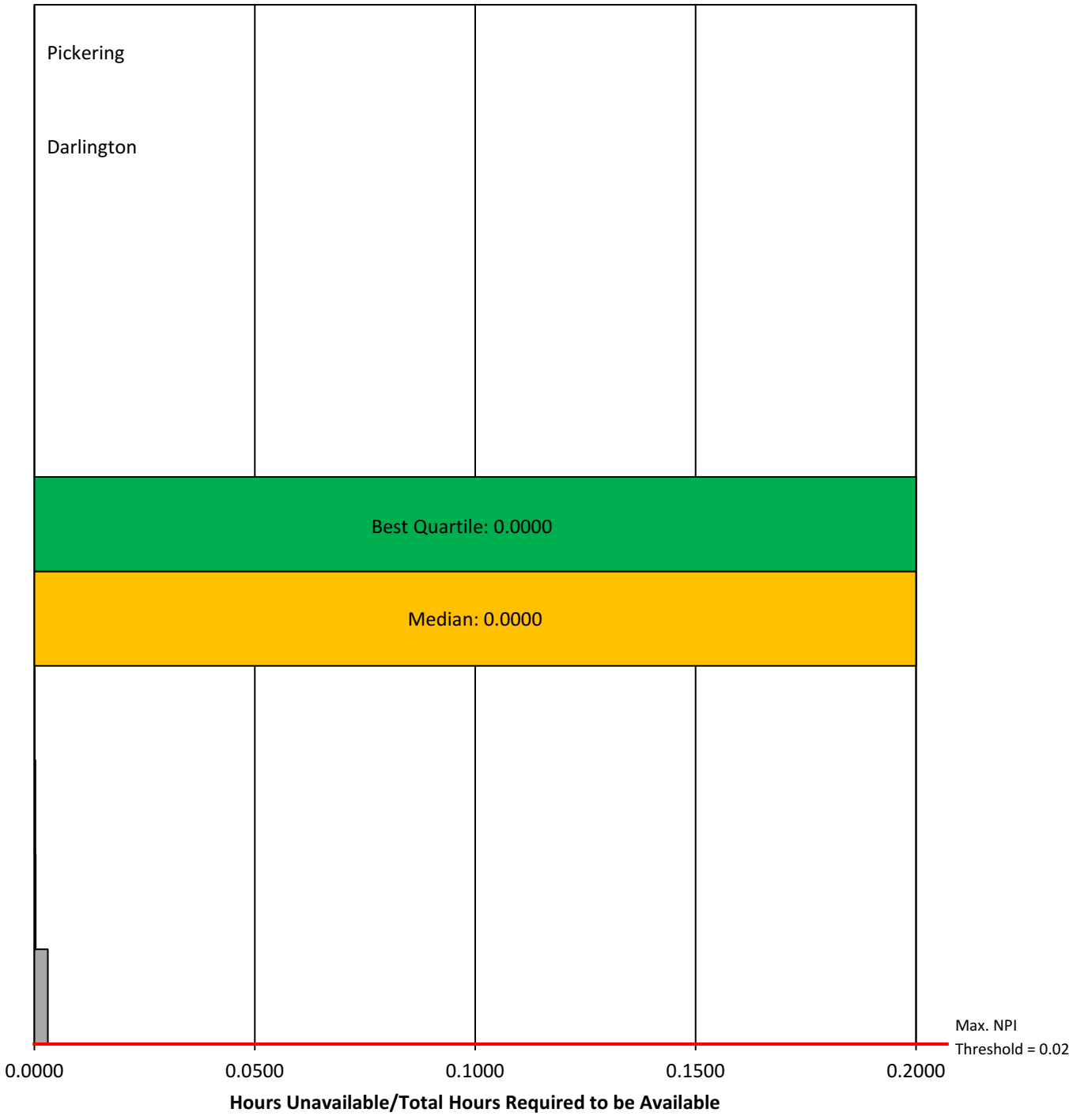
- Key performance drivers for this metric include: general equipment reliability, material condition, and human performance.
- During the performance of a routine test on Q4-2016, Pickering Standby Generator 1 (034-54600-SG1) experienced a spurious trip. As part of the test, Standby Generator 2 (034-54600-SG2) was paralleled to Class IV power and thus was considered unavailable as well, while Standby Generator 3 (034-54600-SG3) was on a planned outage. Thus, with SG1 tripped and SG3 on planned outage and SG2 considered unavailable, all three SGs for Unit 4 were unavailable. This lead to system unavailability for the affected unit pair.

  To improve the system performance at Pickering station the following actions will be taken:

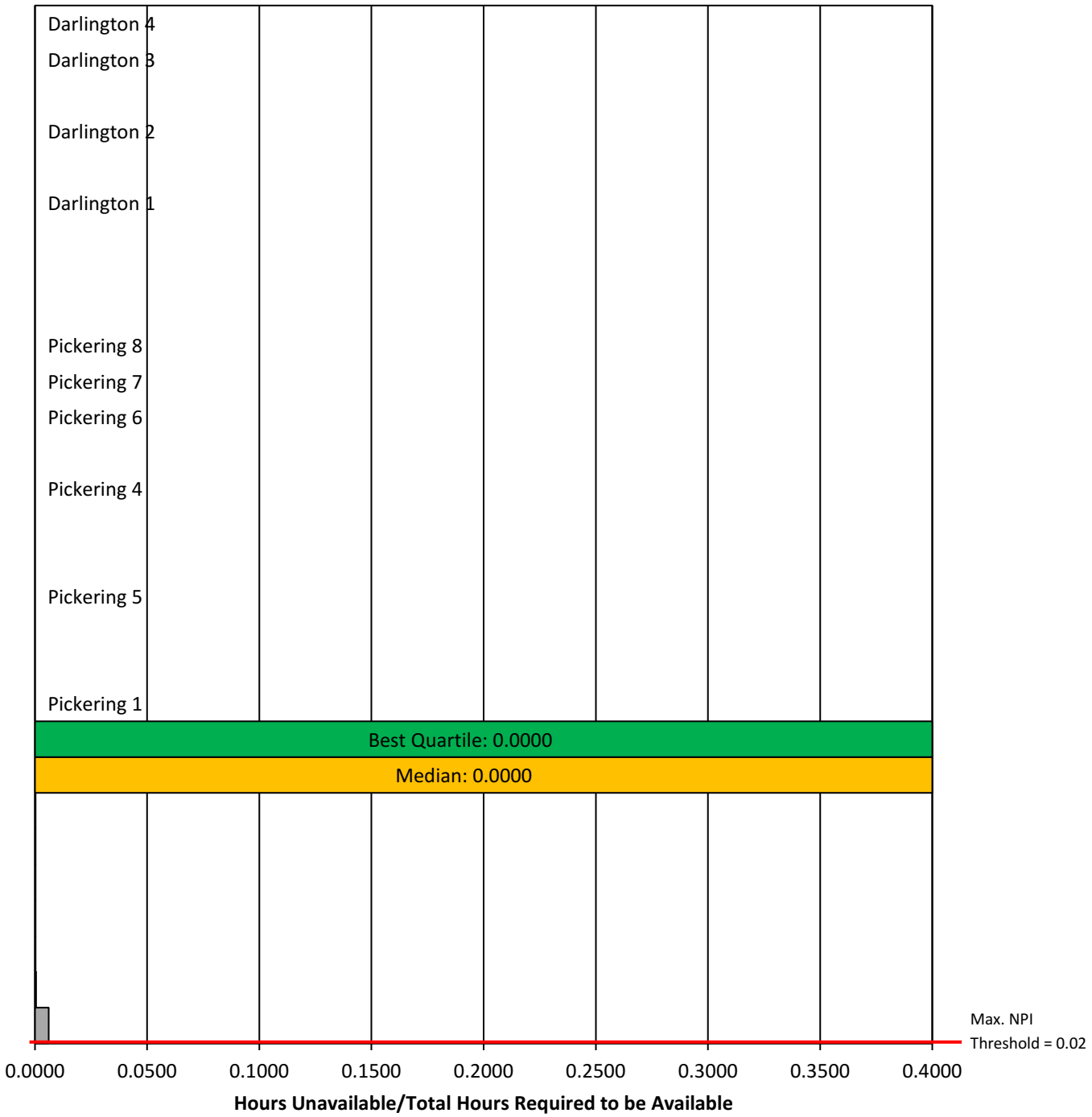
  1) Under the 014 Standby Generator Reliability improvement modifications (Project # 13-40972) both the relay and control logic and the annunciator will be replaced with new.
  2) An enhanced monitoring system is being considered to be installed in 2018 to aid in trending and troubleshooting.
  3) The 034-SGs vibration monitoring system upgrades are included as part of the approved SG Reliability Project and are currently scheduled for installation and commissioning in 2018-2019.

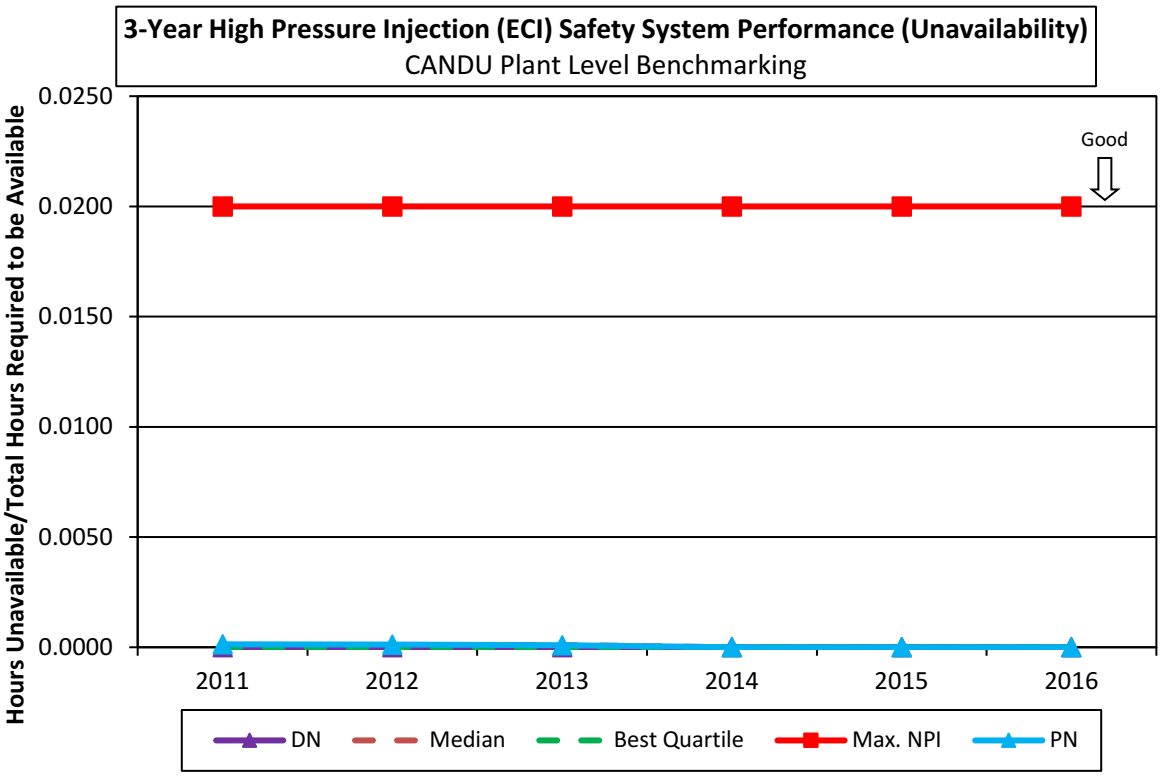
3-Year High Pressure Safety Injection

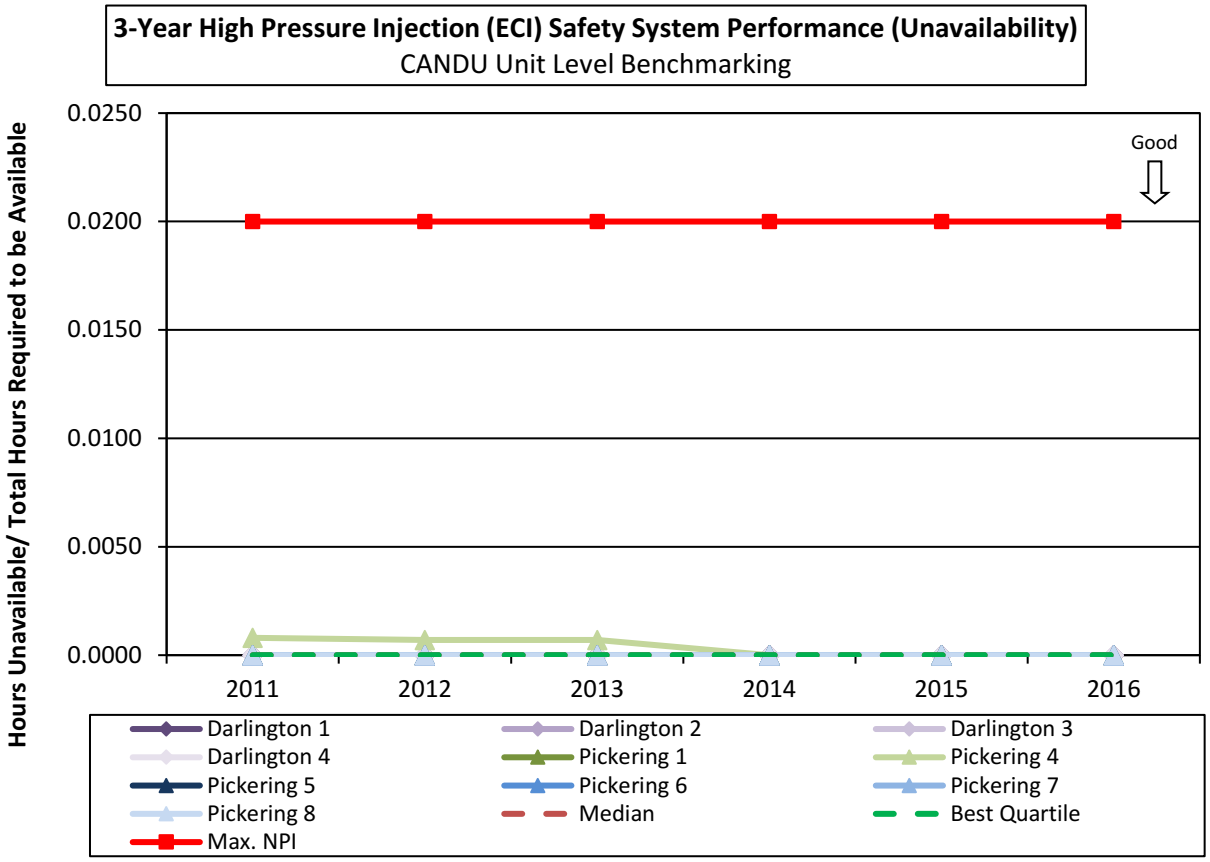
2016 3-Year High Pressure Injection (ECI) Safety System Performance (Unavailability)
CANDU Plant Level Benchmarking



2016 3-Year High Pressure Injection (ECI) Safety System Performance (Unavailability)
CANDU Unit Level Benchmarking




3-Year High Pressure Injection (ECI) Safety System Performance (Unavailability)
CANDU Plant Level Benchmarking
Hours Unavailable/Total Hours Required to be Available
0.0250
0.0200
0.0150
0.0100
0.0050
0.0000
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
Max. NPI
PN


3-Year High Pressure Injection (ECI) Safety System Performance (Unavailability)
CANDU Unit Level Benchmarking
Hours Unavailable/ Total Hours Required to be Available
0.0250
0.0200
0.0150
0.0100
0.0050
0.0000
Good
2011
2012
2013
2014
2015
2016
Darlington 1
Darlington 2
Darlington 3
Darlington 4
Pickering 1
Pickering 4
Pickering 5
Pickering 6
Pickering 7
Pickering 8
Median
Best Quartile
Max. NPI

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Observations – 3-Year High Pressure Safety Injection Unavailability (CANDU)

2016 (3-Year Rolling Average)

- The best quartile and median values for the 3-Year High Pressure Safety Injection Unavailability performance for CANDU plants were zero. For individual CANDU units, both the best quartile and median value were zero.
- Pickering achieved best quartile performance of zero unavailability and maximum NPI points at both the station and unit levels in 2016.
- Darlington achieved best quartile performance of zero unavailability and maximum NPI points at both the station and unit levels in 2016.

Trend

- The 3-Year High Pressure Safety Injection unavailability best quartile performance of CANDU plants has been zero since 2011. The plant level industry median performance improved since 2013 and achieved zero unavailability from 2014 to 2016. At the unit level, the industry best quartile and median value have remained at zero over the review period.
- At the plant level, Pickering station performance has consistently improved over the review period achieving, zero unavailability from 2014 to 2016. On an individual unit basis, Unit 1, 5, 6, 7, and 8 have been at the best quartile value of zero since 2011. Unit 4 performance improved over the review period, achieving zero unavailability from 2014 to 2016.
- At the plant level, Darlington station performance has maintained best quartile value of zero from 2011 to 2016. On an individual unit basis, Units 1, 2, 3, and 4 have been at the best quartile value of zero since 2011.

Factors Contributing to Performance

- Key performance drivers for this metric include: general equipment reliability, material condition, and human performance.
- No High Pressure Safety Injection System unavailability occurred during 2016, which led to improved performance relative to previous years.

3.0 RELIABILITY

Methodology and Sources of Data

The majority of reliability metrics were calculated using the data from WANO. Any data labelled as invalid by WANO was excluded from all calculations. Indicator values of zero are not plotted or included in calculations except in cases where zero is a valid result. Complete data for the review period was obtained and averages are as provided by WANO. The Embalse plant is excluded since it was taken offline since December 31, 2015 for refurbishment.

The two backlog metrics, On-line Deficient and Corrective maintenance, are also included within this section and the data comes from an industry sponsored INPO AP-928 subcommittee. The On-line Deficient and Corrective maintenance backlog industry data was collected from INPO for 2016. Data points benchmarked on backlogs are a single point in time, not a rolling average. All of the data is self-reported. Industry backlog benchmark standards changed with Revision 3 of AP-928 Work Management Practices at INPO in June of 2010. The new standard created an alignment between engineering criticality coding and backlog classification that allows improved focus on the more critical outstanding work. This standard also sets a more consistent foundation for classification of backlogs such that comparisons between utilities will be more meaningful. All OPG nuclear stations converted to the new standard on January 24, 2011.

Discussion

The primary metric within the reliability section is the WANO Nuclear Performance Index (NPI). The WANO NPI is an operational performance indicator comprised of 10 metrics, three of which are analyzed in this section: Forced Loss Rate, Unit Capability Factor, and Chemistry Performance Indicator. The remainder of the WANO NPI components are analyzed in the safety section (Section 2.0).

The Pickering station performed at the same quartile rankings when compared to 2015, however, overall performance for NPI and Forced Loss Rate have improved substantially.

Darlington quartile rankings for the Forced Loss Rate improved to the median quartile and the Unit Capability Factor improved to the third quartile in 2016. Corrective and Deficient Maintenance Backlogs performance improved in 2016 and remained in the third quartile. Chemistry Performance Indicator continued to be in the best quartile. Industry best quartile performance for NPI significantly improved in 2016. Darlington's scores for the NPI metric increased overall and the station ranking improved to the second quartile.

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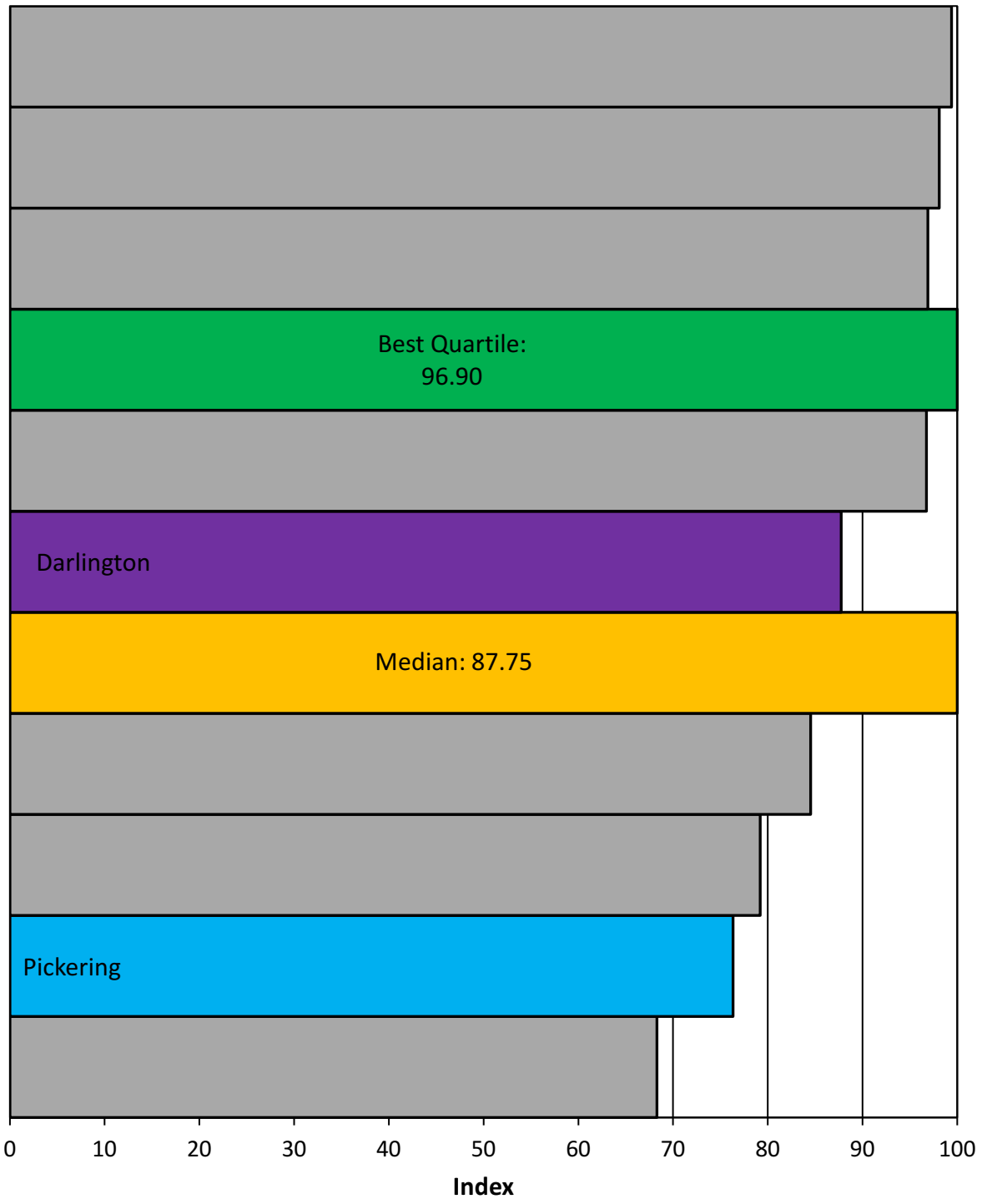
WANO Nuclear Performance Index

2016 WANO Nuclear Performance Index
CANDU Plant Level Benchmarking



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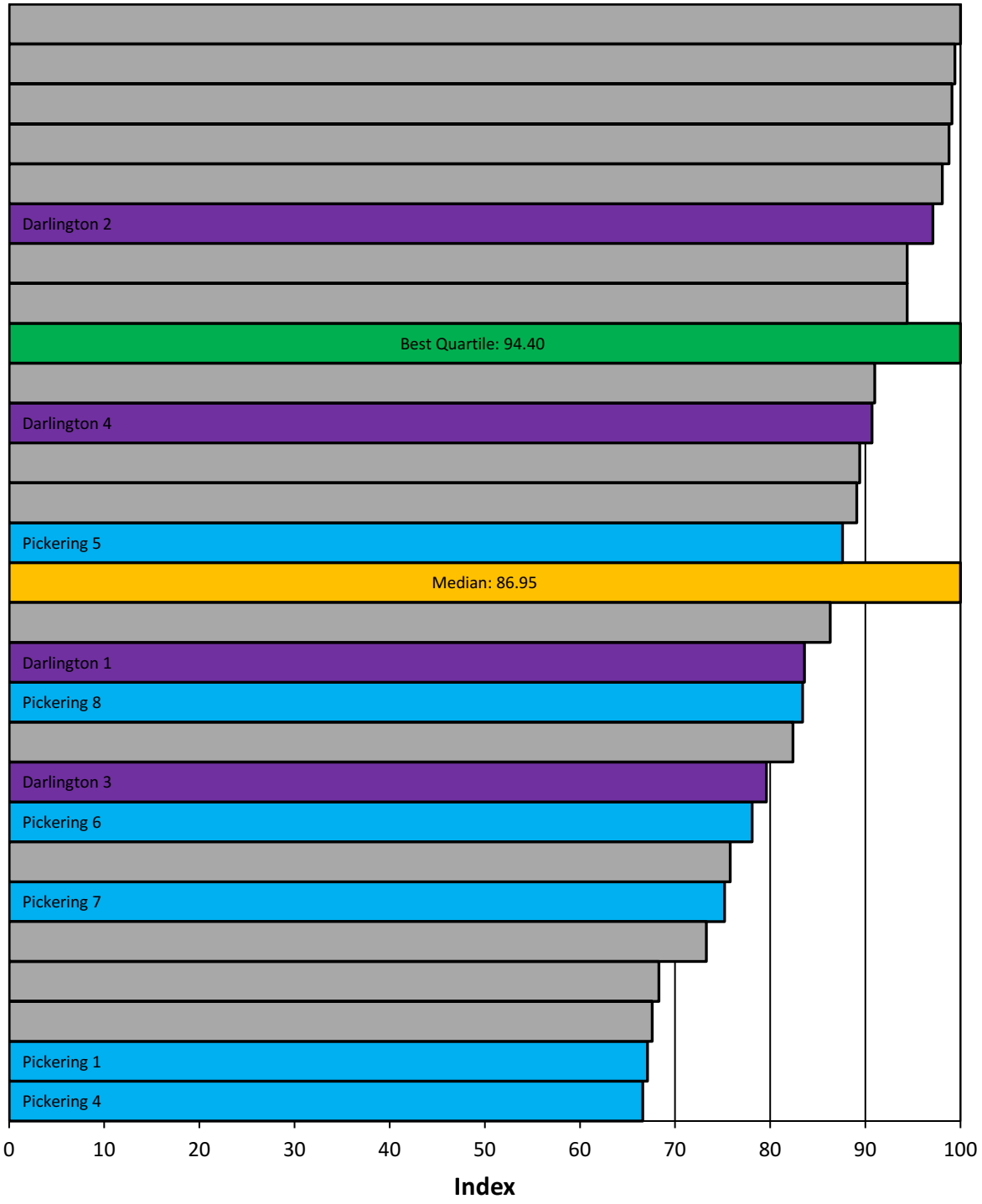
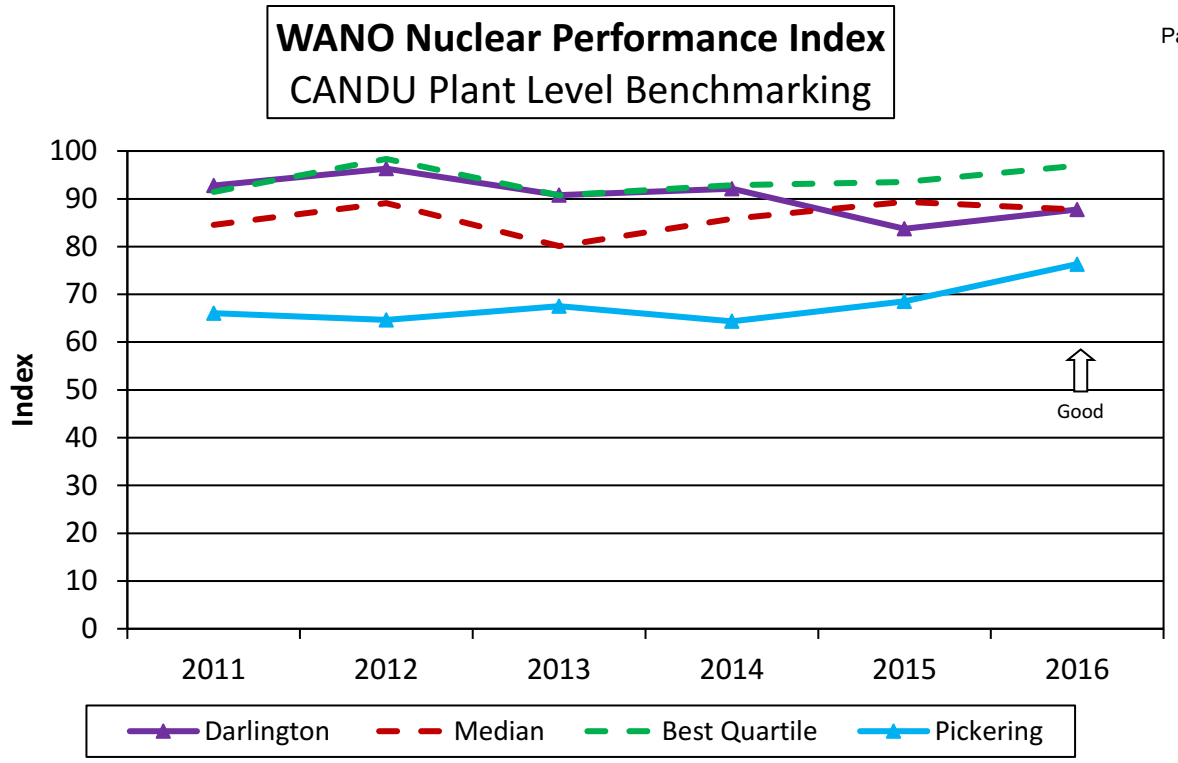
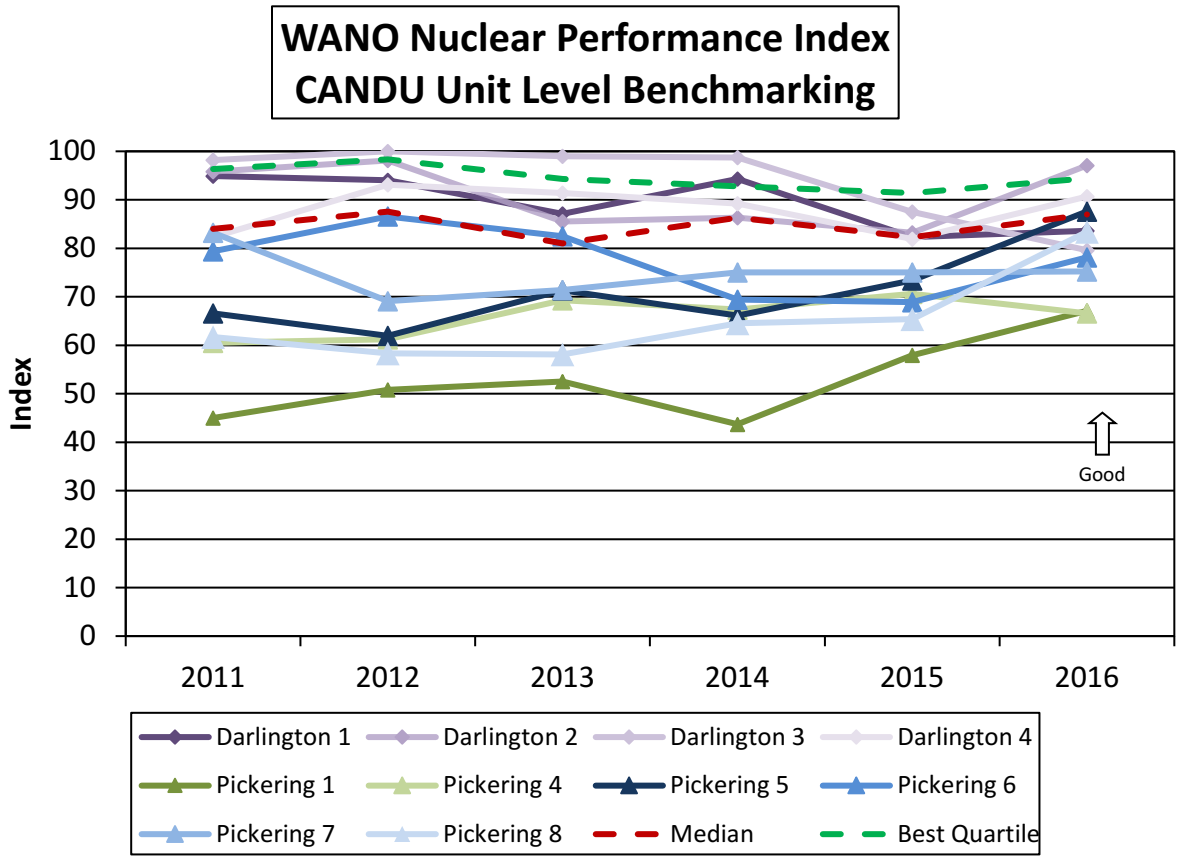
2016 WANO Nuclear Performance Index
CANDU Unit Level Benchmarking




WANO Nuclear Performance Index
CANDU Plant Level Benchmarking
Index
100
90
80
70
60
50
40
30
20
10
0
2011
2012
2013
2014
2015
2016
Good
Darlington
Median
Best Quartile
Pickering


WANO Nuclear Performance Index
CANDU Unit Level Benchmarking
Index
100
90
80
70
60
50
40
30
20
10
0
2011
2012
2013
2014
2015
2016
Good
Darlington 1
Darlington 2
Darlington 3
Darlington 4
Pickering 1
Pickering 4
Pickering 5
Pickering 6
Pickering 7
Pickering 8
Median
Best Quartile

Observations – WANO Nuclear Performance Index (NPI) (CANDU)

2016

- The 2016 best quartile of the CANDU plant comparison panel for WANO NPI is 96.9. This represents a 3.4 points increase above the 2015 best quartile.
- The median of the CANDU plant comparison panel decreased 4.9 points, compared to last year, to 84.5 in 2016.
- At the plant level, both Darlington and Pickering scored below median NPI performance in 2016.
- In 2016 Darlington had one unit in the second quartile and three units in the third quartile. Pickering had one unit in the second quartile, three units in the third quartile and two units in the bottom quartile.
- Darlington Unit 2 began a long-term refurbishment outage on October 15, 2016. Data points associated with Refurbishment have been excluded with respect to UCF and CRE.

Trend

- The best quartile of the CANDU plant comparison panel rose from 2011 to 2012, with the best quartile performance rising to its highest level in 2012. While this was not sustained in subsequent years, the best quartile results for the past 4 years remain in the low 90's with a positive trending starting after 2013 and continuing in 2016.
- The median value of the CANDU plant comparison panel rose from 2011 to 2012, indicating that the performers in the lower quartiles are performing better. This performance was not sustained in 2013, did recover in 2014 and 2015 and declined again in 2016.
- Pickering has shown noticeable improvement in its NPI performance for the last two years, primarily due to improvements in the Forced Loss Rate (FLR) results in 2015 and 2016 and is now trending upwards towards the median level performance.
- As the strongest OPG performer, Darlington achieved best quartile performance over the majority of the review period, ranking at or just below top quartile until 2014. Performance declined in 2015 due to the station vacuum building containment outage for planned regulatory maintenance and higher FLR. The Vacuum Building Outage (VBO) is a unique outage to OPG owned plants (including Bruce Power) that is regulatory mandated and has resulted in reduced UCF and NPI scores. The declining trend continued in 2016 due to Primary Heat Transport pump motor replacements affecting FLR and higher radiation dose from life extension nuclear safety improvements projects.

Factors Contributing to Performance

- The WANO NPI is a composite index reflecting the weighted sum of scores of 10 separate performance measures. A maximum score of 100 is possible. All of the sub-indicators in this index are reviewed separately in this benchmarking report.

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Factors Contributing to Performance (CONT'D)

Pickering

- For 2016, Pickering achieved maximum scores for 5 out of 10 NPI sub-indicators.
- For the key safety system related metrics of reactor trip rate, high pressure injection, auxiliary feedwater and emergency alternating current (AC) power, the station received 10 out of 10 points.
- Pickering has also achieved a perfect score for industrial safety accident rate (5out of 5).
- Pickering earned 9.9 points for fuel reliability.
- Pickering achieved 4.2 points out of 5 for chemistry performance and 7.2 out of 10 for collective radiation exposure.
- Pickering's NPI performance is impacted by the need for long outages to accommodate fuel channel inspection programs, planned outages extension and forced outages that are affecting the unit capability factor, forced loss rate and collective radiation exposure metrics
- Pickering received 0.5 out of 15 points for unit capability factor and 9.6 out of 15 for forced loss rate.

Darlington

- Darlington's NPI performance has been impacted by higher forced loss rate and by a lower unit capability factor due to forced outages, planned outages, and unbudgeted planned outages.
- For 2016, Darlington has achieved maximum points for 6 out of 10 NPI sub-indicators.
- For the key safety system related metrics of reactor trip rate, high pressure injection, auxiliary feedwater and emergency alternating current (AC) power, the station received 10 out of 10 points.
- Darlington has also achieved a perfect score for industrial safety accident rate and chemistry performance (5 out of 5).
- Darlington earned 9.8 out of 10 points for fuel reliability and 9.3 out of 10 points for collective radiation exposure.
- Darlington achieved 7.7 out of 15 points for unit capability factor and 10.9 out of 15 points for forced loss rate.

Please refer to Table 14 of the Appendix for an NPI plant level performance summary of OPG nuclear stations against the North American panel.

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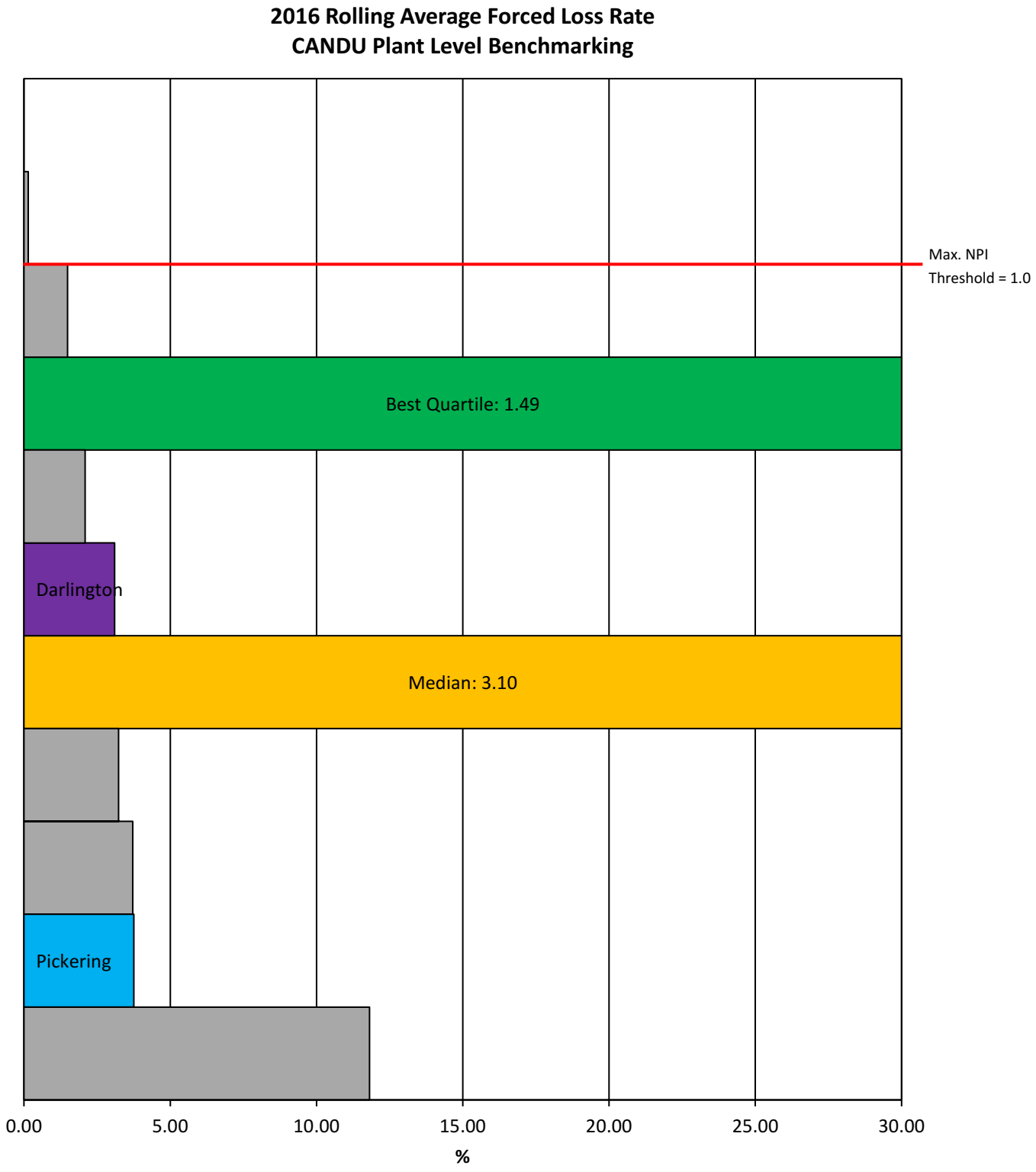
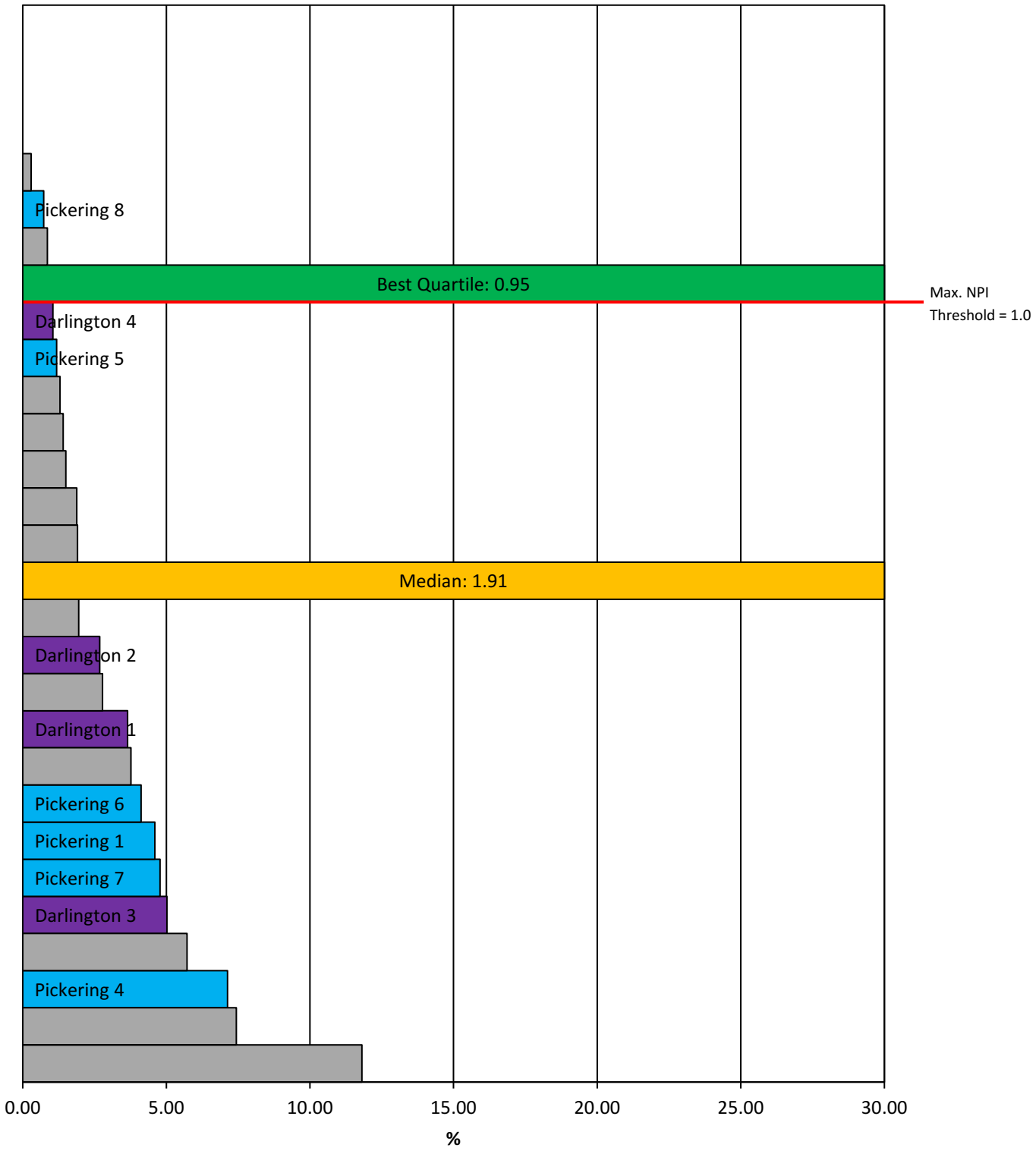
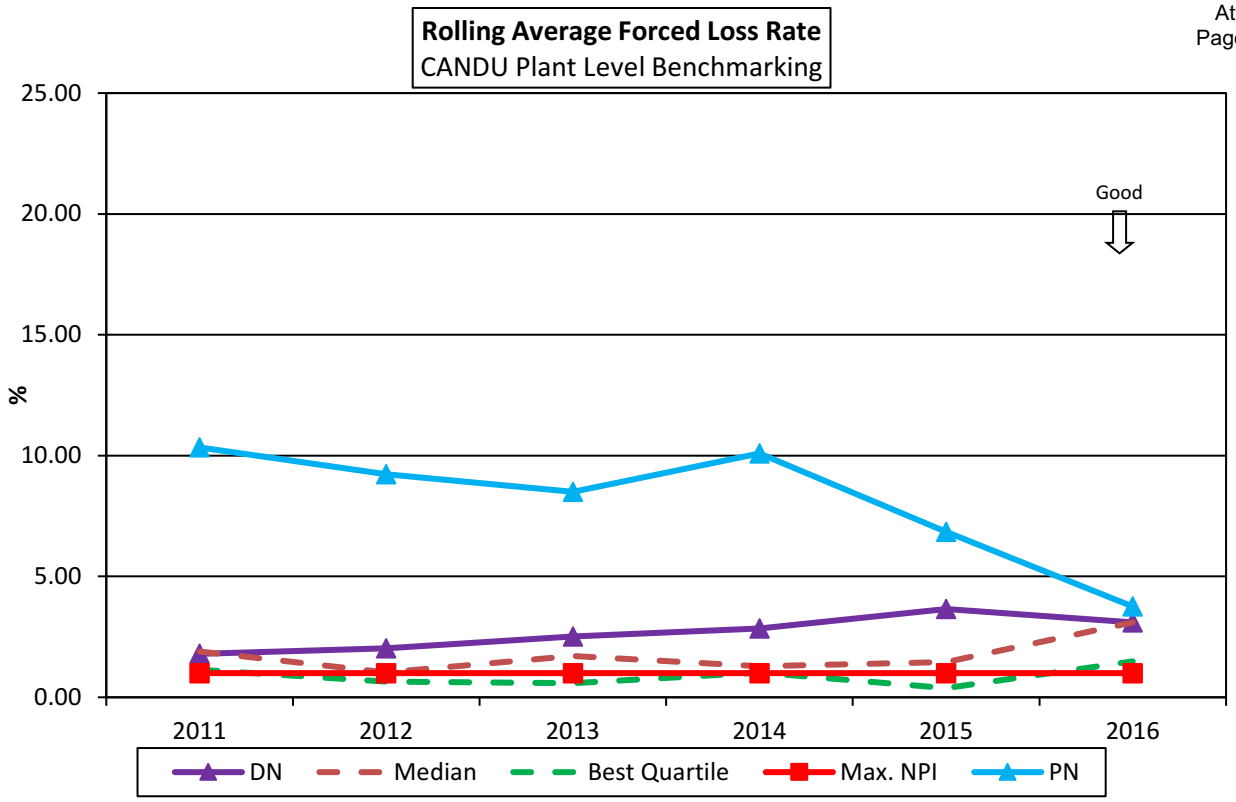
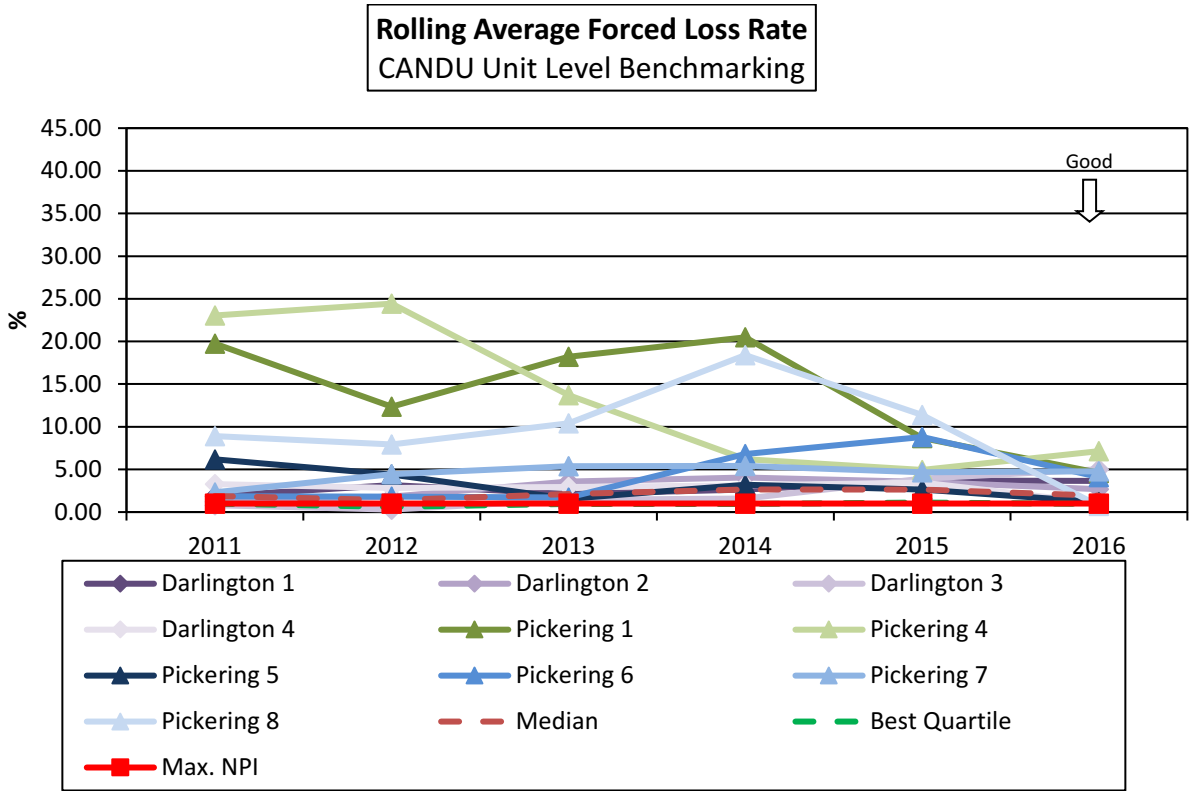
Rolling Average Forced Loss Rate



2016 Rolling Average Forced Loss Rate
CANDU Plant Level Benchmarking




Rolling Average Forced Loss Rate
CANDU Plant Level Benchmarking
25.00
20.00
15.00
10.00
5.00
0.00
%
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
Max. NPI
PN


Rolling Average Forced Loss Rate
CANDU Unit Level Benchmarking
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
%
Good
2011
2012
2013
2014
2015
2016
Darlington 1
Darlington 2
Darlington 3
Darlington 4
Pickering 1
Pickering 4
Pickering 5
Pickering 6
Pickering 7
Pickering 8
Median
Best Quartile
Max. NPI

Observations – Rolling Average Forced Loss Rate (CANDU)

2016 (Rolling 2 Year Average, Pickering %; Rolling 3 Year Average, Darlington %)

- At the plant level, Pickering Forced Loss Rate (FLR) performance substantially improved from 6.85 in 2015 to 3.76 in 2016, achieving its best ever rolling average FLR but was worse than industry median (3.10).
- At the Unit level, Pickering 1 and Pickering 8 have shown substantial improvements from previous high FLRs greater than 15.0 in 2014 with Pickering 8 moving all the way to Best Quartile performance. Unit 5 achieved second quartile performance (1.91). Pickering Unit 4 exhibited the worst FLR at 7.13, but this is a substantial improvement from 2011 and 2012 when FLR was greater than 20. The remaining two Pickering Units ranked in the third and fourth quartile.
- At the plant level, Darlington FLR performance improved to 3.10 which was at median (3.10). At the Unit level, Darlington Unit 4 was in the second quartile. The remaining 3 Darlington Units were below median in the third and fourth quartiles.
- Darlington Unit 3 had an FLR of 5.02 in 2016, the first time in the trending period that a Darlington Unit exceeded a FLR of 5.0.

Trend

- Industry plant median FLR trend declined to 3.10 in 2016, reversing the previous improvement trend which had gone from 2.60 in 2010 to 1.46 in 2015. Industry best quartile also worsened to1.49 during the period after a low of 0.38 in 2015.
- Pickering's FLR performance over the 5 year review period, has been markedly improving whereas the industry trends is worsening. The equipment reliability improvements at Pickering have been the main drivers for the favourable improvement in FLR performance. FLR performance appreciably improved in 2015 by a reduction in station FLR (3.76) from 2015 FLR (6.85).
- Darlington's overall FLR performance improved slightly to 3.10 in 2016 from 3.65 in 2015. Over the 5 year review period, there has been a general trend of minor decline in FLR performance, with increasing FLR from 1.80 in 2011 to 3.65 in 2015, before reversing the trend in 2016.

Factors Contributing to Performance

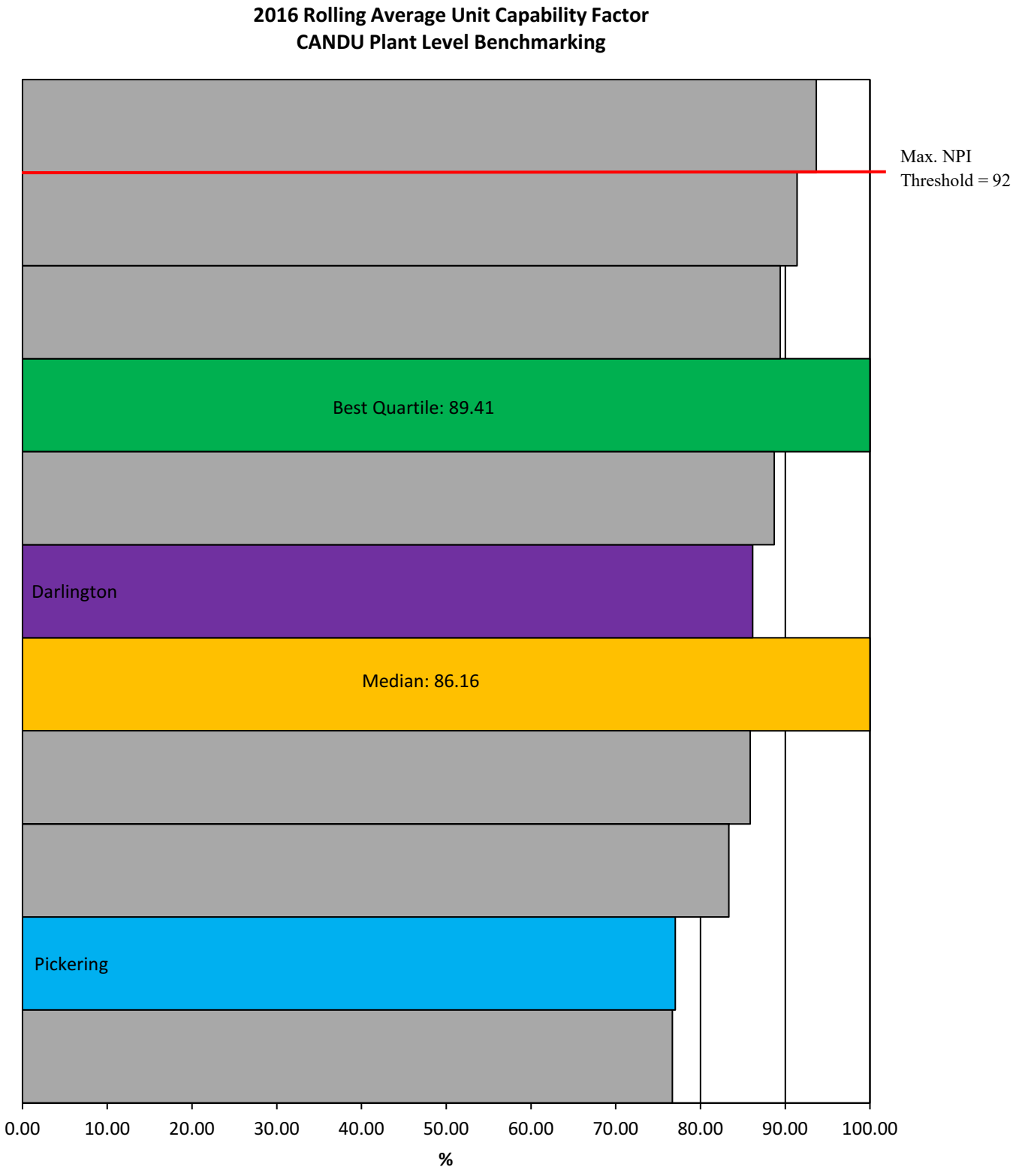
- At Pickering, causes for forced losses were varied, including:
    - An unsealed Shutdown System 2 trip (due to a spurious signal on channel H while channel G was open for planned maintenance) followed by a manual trip
    - A reactor trip on very low boiler level during a turbine run-up
    - A Unit 4 reactor setback from 85% Full Power due to a stuck pushbutton in a boiler level controller
    - A Unit 4 shutdown to repair a liquid zone control valve

Observations – Rolling Average Forced Loss Rate (CANDU) (CONT'D)

Factors Contributing to Performance

- At Darlington, the causes for forced losses were also varied, including:
  - A Unit 3 reactor trip on low flow caused by Primary Heat Transport pump motor electrical protection activation due to inadvertent physical contact
  - A Unit 2 turbine trip during a fire resistant fluid pump test
  - A Unit 3 reactor trip during draining of the poison mixing tank for conversion from gadolinium to boron
- Pickering continues to execute a list of high priority work orders (PRL – plant reliability list) to improve equipment reliability and reduce operator burden.
- Pickering continues reducing corrective and deficient work order backlogs through a reduction of incoming emergent work orders by proactive equipment replacements and minor modifications to improve/correct system and equipment performance.
- Pickering is also implementing equipment reliability projects to put new equipment in the plant to prevent forced loss events. Single point vulnerability (SPV) reviews have been completed and elimination and mitigation actions are being implemented or dispositioned for outstanding items.
- Darlington continues to drive plant reliability improvements via the system health improvement process and recovery actions. The Plant Reliability List of important work orders are implemented to improve system health.
- At Darlington in 2016, five of the twelve operating Unit Primary Heat Transport (PHT) pump motors were replaced, significantly reducing the Enterprise risk due to motor failure. Also, 15 of 16 pressurizer heaters across all four Units have been replaced in 2016 virtually eliminating the risk of heater failure or leakage.
- The NFI-04 Equipment Reliability fleet initiative was launched in 2015 to improve OPG fleet performance. Site equipment reliability Excellence Plans were developed as part of NFI-04 and locally focused ER improvement initiatives are being executed. A single point vulnerability (SPV) mitigation program is being implemented at both sites.

Rolling Average Unit Capability Factor



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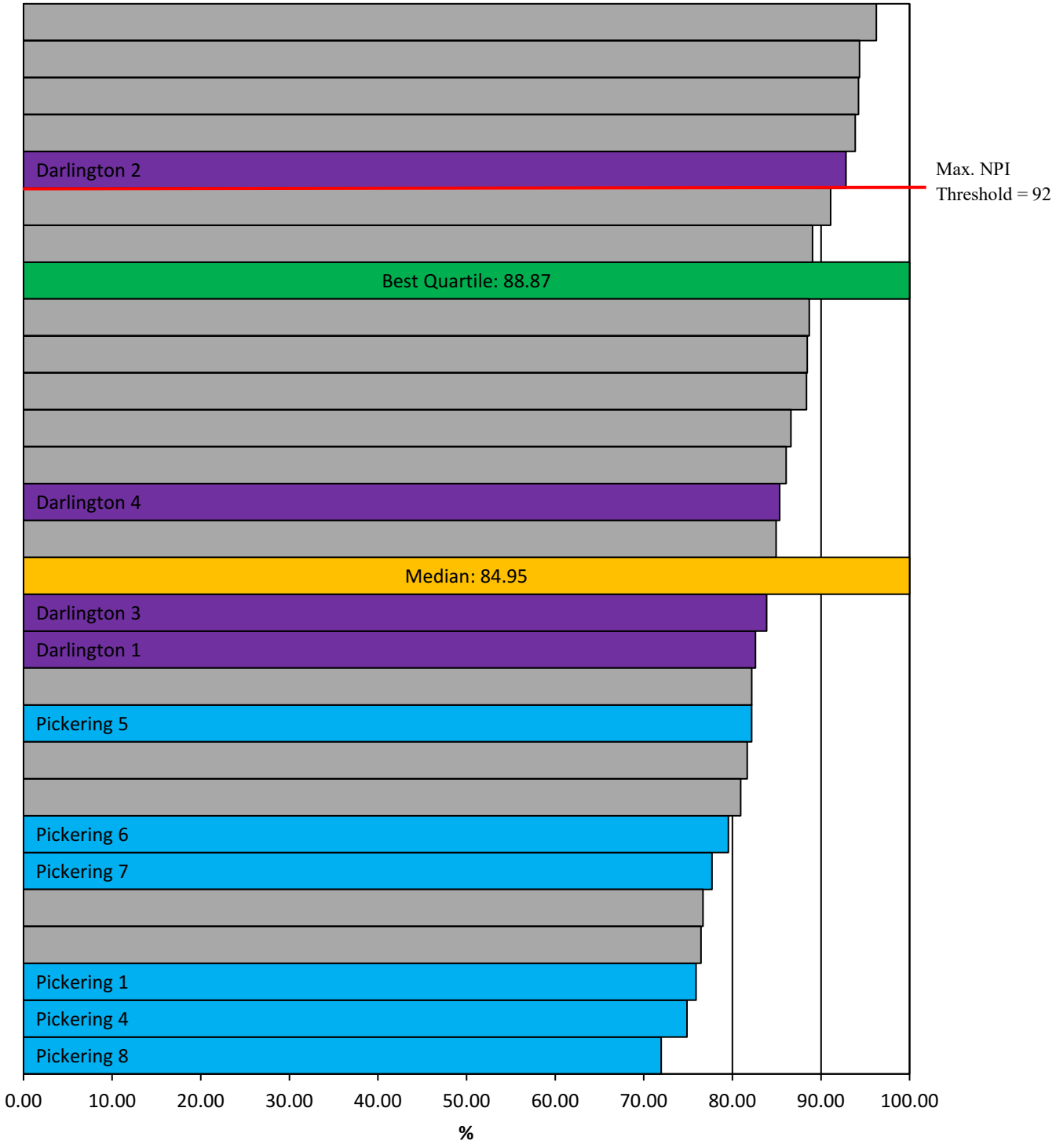
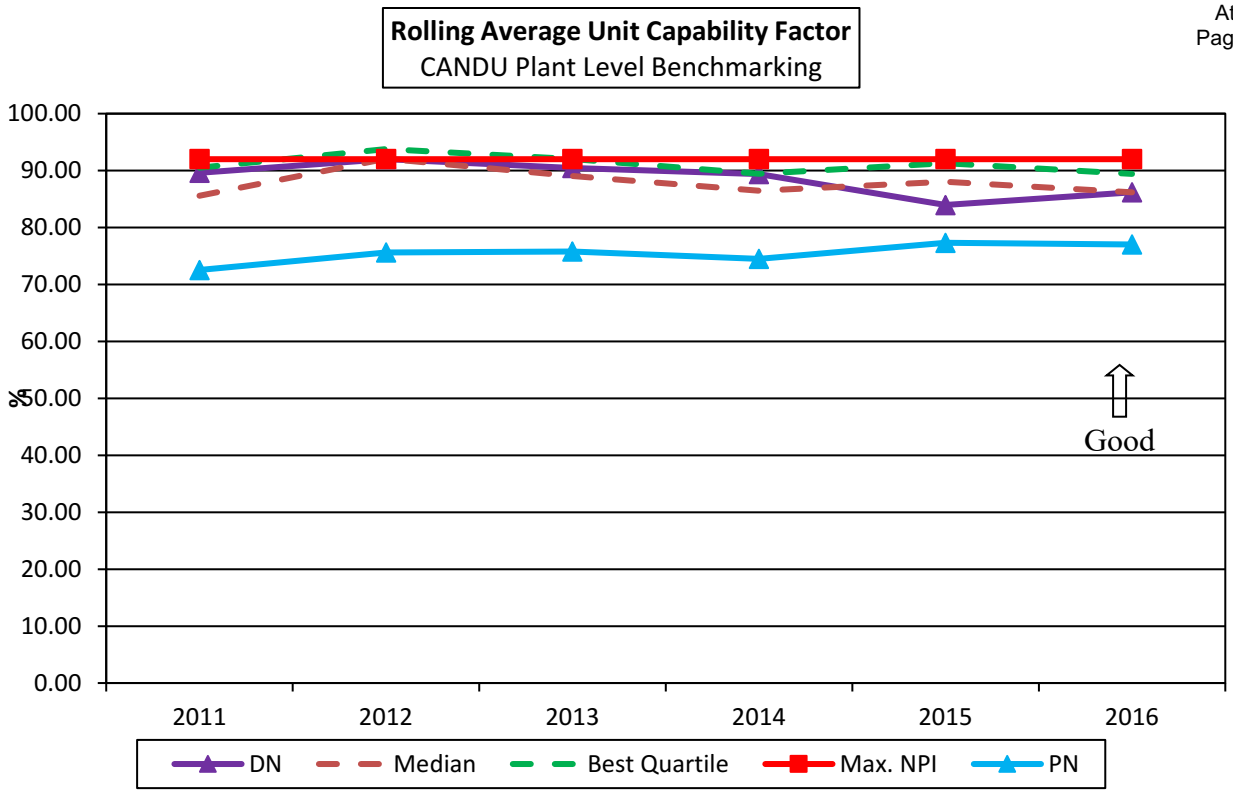
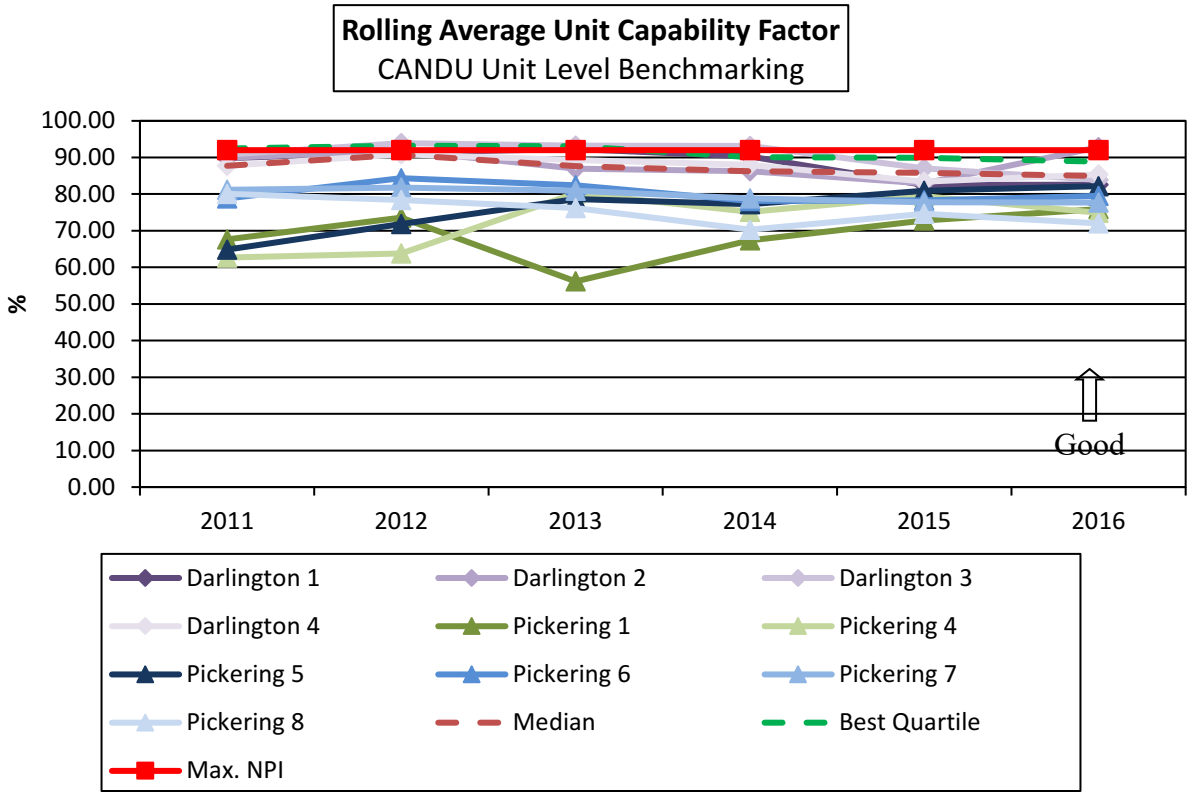
2016 Rolling Average Unit Capability Factor
CANDU Unit Level Benchmarking




Rolling Average Unit Capability Factor
CANDU Plant Level Benchmarking
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
%
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
Max. NPI
PN


Rolling Average Unit Capability Factor
CANDU Unit Level Benchmarking
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
%
Good
2011
2012
2013
2014
2015
2016
Darlington 1
Darlington 2
Darlington 3
Darlington 4
Pickering 1
Pickering 4
Pickering 5
Pickering 6
Pickering 7
Pickering 8
Median
Best Quartile
Max. NPI

Observations – Rolling Average Unit Capability Factor-UCF (CANDU)

2016 (Rolling 2 Year Average, Pickering %; Rolling 3 Year Average, Darlington %)

- Pickering performed below industry median at both the plant (77.03) and Unit Level UCF.
- Darlington UCF performance improved in 2016 to 86.16 resulting in median level performance (86.16). At the Unit level, Darlington Units 2 and 4 were better than median (84.95) and the remaining 2 Darlington Units were in the third quartile.
- Pickering's gap to best quartile plant UCF was 12.38; and to median UCF was 8.84.
- Darlington's gap to best quartile plant UCF was 3.25.
- Darlington Unit 2 began a long-term refurbishment outage on October 15, 2016. Data points associated with Refurbishment have been excluded with respect to UCF.

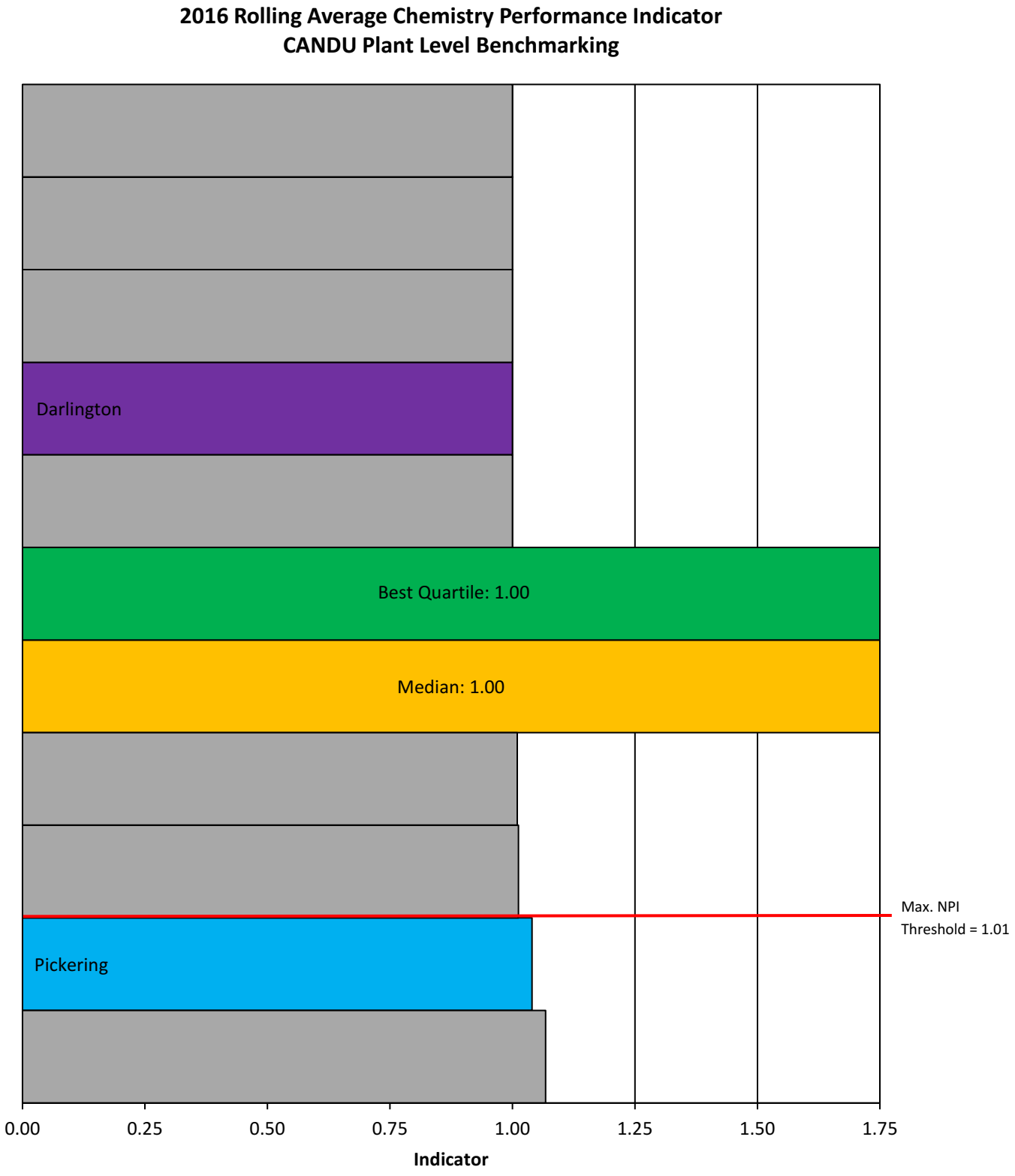
Trend

- Pickering's UCF performance over the 5 year period, generally had been improving modestly, with 2016 performance steady compared to 2015. The equipment reliability improvements at Pickering have been favourable for improvement in recent UCF performance.
- Darlington's plant UCF had been declining but improved in 2016 relative to 2015.
- Industry plant median and best quartile UCF benchmarks both declined in 2016.
- Pickering Unit 1 has demonstrated continued sustained improvement since 2013 whereas Pickering Unit 8 lags all other CANDU Units.

Factors Contributing to Performance

- The primary factors impacting UCF are longer outages to accommodate reactor component inspections necessary for extended life at Pickering as well as forced outages at both stations and forced extensions to planned outages at Pickering.
- Higher numbers of planned outage days and forced extensions to planned outages contribute to lower UCF compared to CANDU peers.
- The issues and causes for non-optimal FLR performance also negatively impact UCF. Significant improvements in equipment reliability are expected to correlate with improved FLR and UCF performance.

Rolling Average Chemistry Performance Indicator



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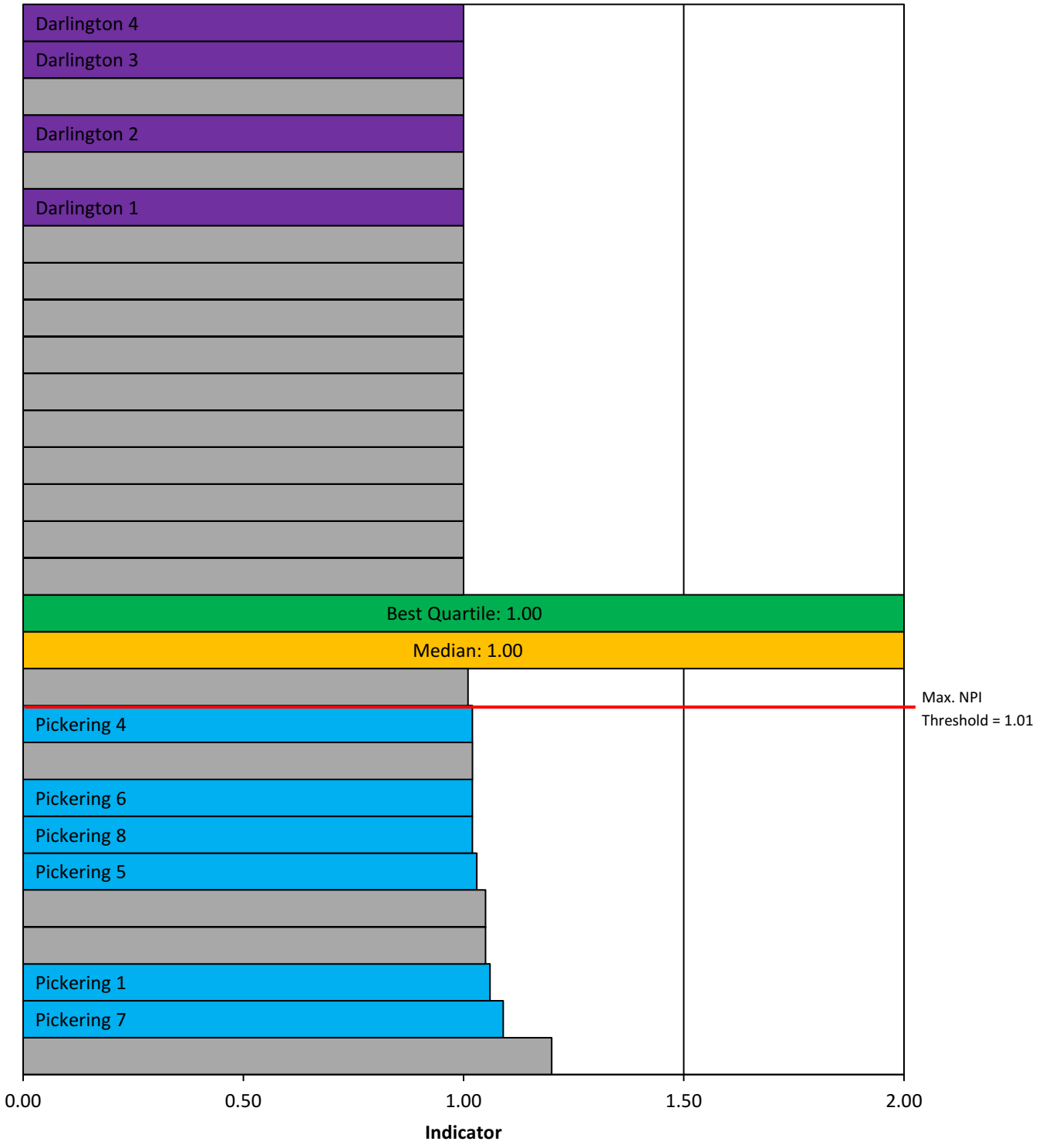
2016 Rolling Average Chemistry Performance Indicator
CANDU Unit Level Benchmarking



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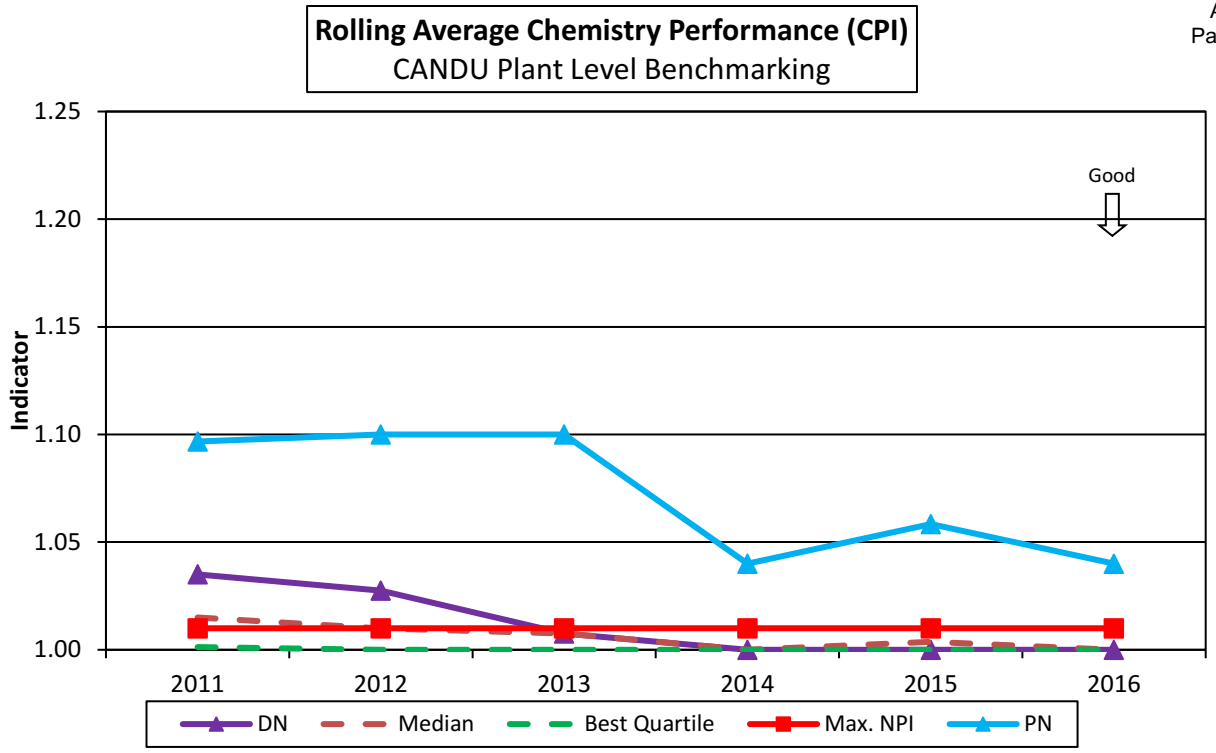

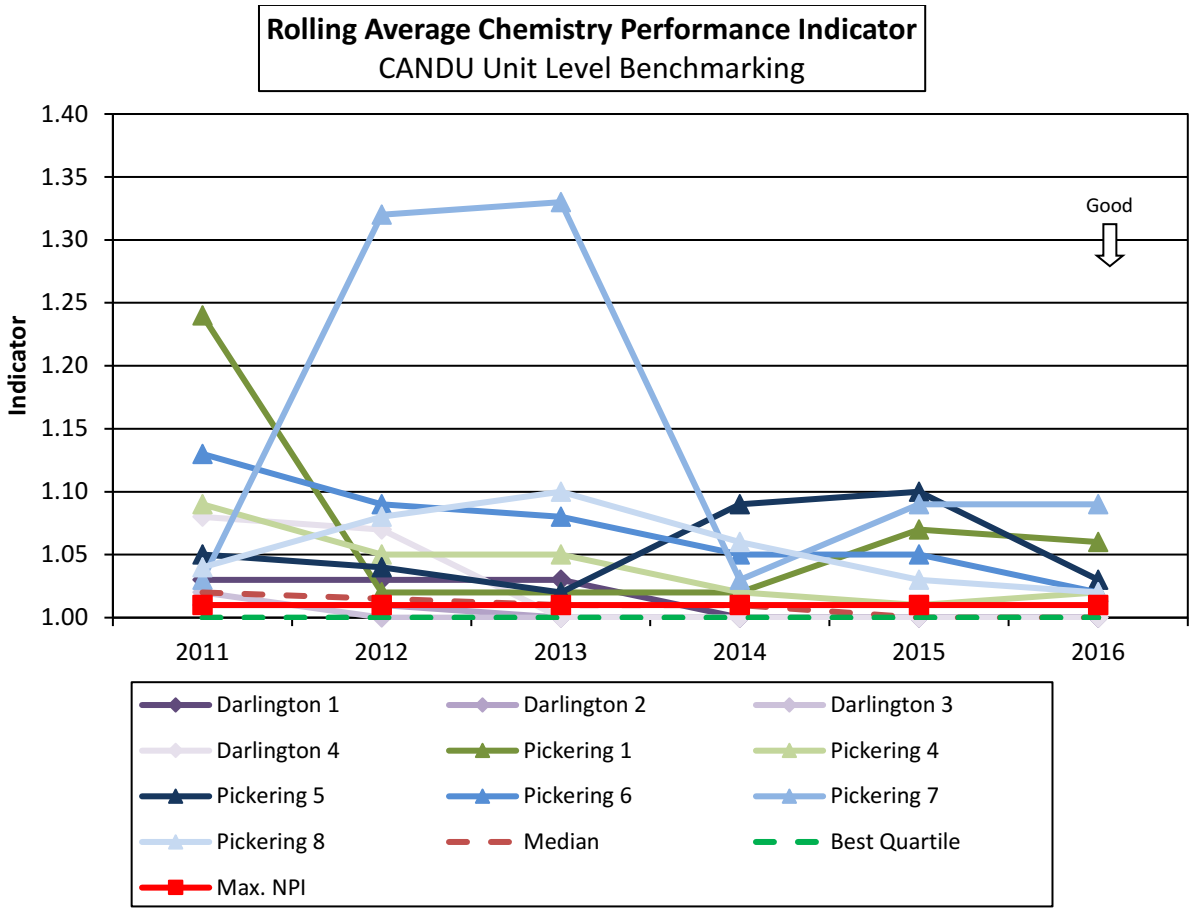

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Observations – Rolling Average Chemistry Performance Indicator (CANDU)

2016 (Rolling 2 Year Average Pickering, Rolling 3 Year Average Darlington)

- The CANDU plant median and top quartile values are both 1.00.
- The CANDU unit median and top quartile values are both 1.00.
- CPI is calculated using data during normal operation (> 30% Full Power).
- The Pickering plant level of performance improved from 1.06 in 2015 to 1.04 in 2016 but was worse than the CANDU plant median CPI of 1.00.
- Four of the Pickering units showed improved performance from 2015 levels with Unit 7 remaining the same and Unit 4 declining. However, all units were worse than the CANDU unit level median CPI (1.02 to 1.09 vs. 1.00).
- Darlington plant remained in the top quartile for 2016 and achieved maximum NPI points.
- All Darlington units remained in the top quartile and achieved maximum NPI points.

Trend

- Overall Pickering plant performance has been trending down from 2011 levels (1.10) to 1.04 in 2016. While P1 and P7 CPI performance negatively skew the station average, year over year performance is improving for these units. Contributing to improving performance are better outage Foreign Materials Exclusion practices, Water Treatment Plant output quality, and blowdown frequency adherence.
- Darlington overall plant performance has improved over the last 5 years resulting in top quartile performance.

Factors Contributing to Performance

- Forced outages in Unit 4 in 2016 increased the boiler ion (i.e. Cl, Na) values and feedwater corrosion product transport hindering overall station performance.
- Pickering is one of the older sites and has inventories of impurities from prior chronic condenser water in-leakage, which contribute to boiler ions desorption/adsorption phenomenon and increases concentrations above the WANO limiting values for certain ions (most significantly, sulphate).
- Pickering boilers have a different design from other plants (e.g. lower blowdown capacity than Darlington, 12 boilers per unit, mixed-alloy feedtrain for Units 1-4, Monel-400 boiler tubes compared to Alloy 800 at Darlington etc.), and WANO limiting values used in calculating CPI (6 parameters at Pickering) are 3x less than Darlington.

Observations – Rolling Average Chemistry Performance Indicator (CANDU)

Factors Contributing to Performance (continued)

- Best practices among top performing plants include approved boiler layup practices during the planned outages; minimize duration of boiler drained period to avoid corrosion during the planned outages, timely condenser inspections and cleaning (e.g. waterlancing) to remove a source of corrosion product transport (CPT) to boilers during start-ups, timely reporting and clearing the action levels (e.g. via boiler blowdown) to stay within the specifications for all the parameters contribute to CPI. Condenser inspections and cleaning are now being performed at both Pickering and Darlington to minimise CPT. Darlington's corrosion product reduction plan includes installation of a startup condensate filtration unit, follow timely boilers lay-up practices per procedure to stay within specification.

Fleetwide and station initiatives which have or are expected to improve performance include:

Complete:

- 2016 fleet-wide self assessment on CPI performance gaps identified to improve CPI score.
- Boiler blowdown piping improvements and enhanced tracking of blowdowns at Pickering per boiler ions concentration involving operations and reporting in the Station Alignment Meeting package.
- Condenser cleaning during planned outages (which has resulted in improvement in Darlington CPI performance).
- Kepner-Tregoe investigation to troubleshoot high boiler ions during the startup of Pickering Units. Different causes were identified for each, along with corrective actions taken or put in place.
- Ongoing use of local portable feedwater dissolved oxygen analyzer carts (commissioned on Pickering Units 5-8) to ensure representative feedwater dissolved oxygen monitoring.
- Timely response to an early indication of condenser tube leaks.
- Ongoing oversight of water treatment plant product water quality to meet boiler makeup water specifications.
- Creation of a high level document regarding overall condenser tube leak strategies to improve station response and coordination efforts to address and mitigate condenser tube leaks. This is the result of self assessment findings and third party review and recommendations based on the INPO event report (IERL4-13-17) on "Main Condenser Cooling Water Inleakage".
- Additional inspection of the Darlington condensers as well as Epoxy coating applications to the Lake-water side of the condenser tubes. First condenser tube coating successfully applied in Unit 4 outage in 2016.

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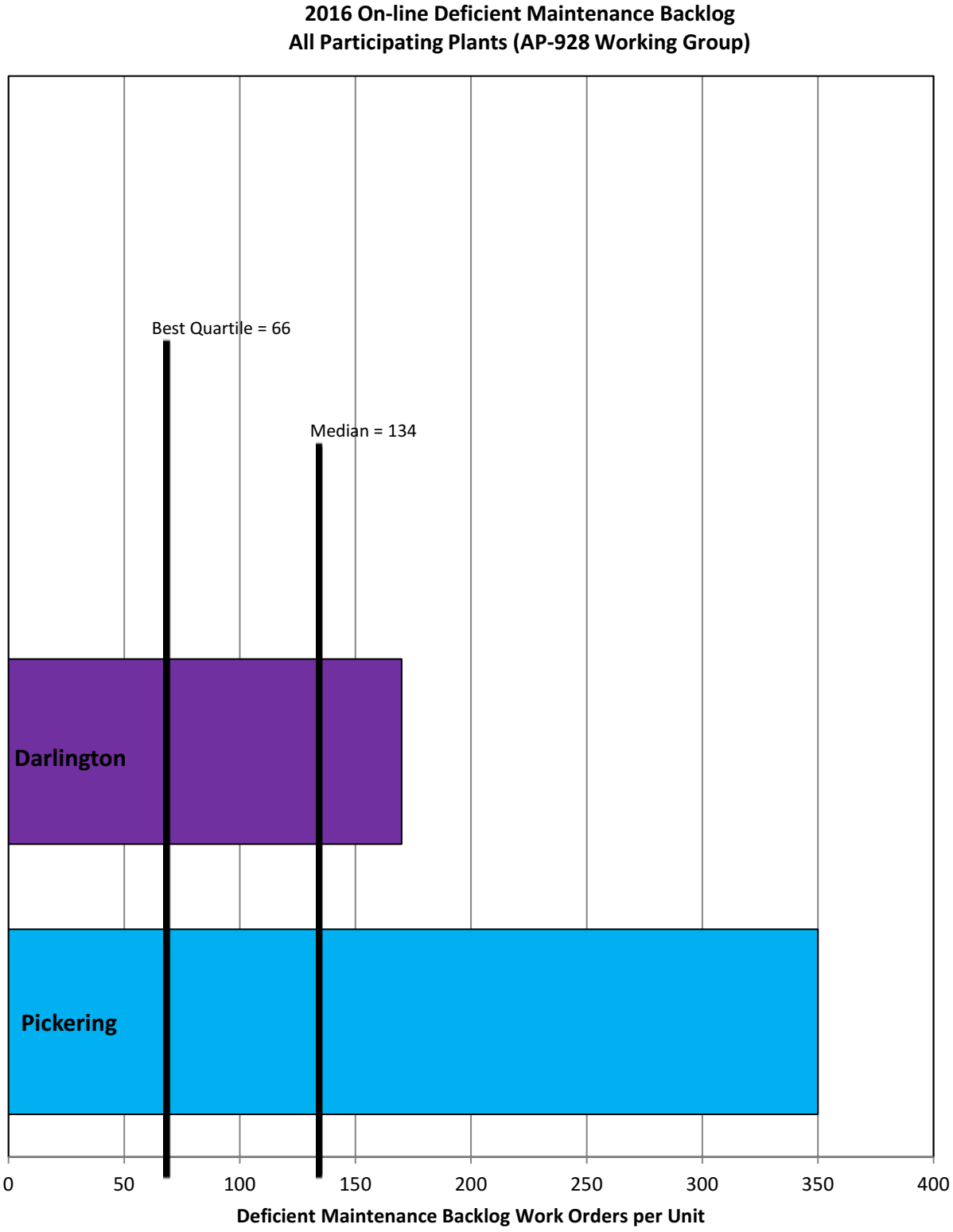
Observations – Rolling Average Chemistry Performance Indicator (CANDU)

Factors Contributing to Performance (continued)

In progress:

- Condensate Filtration Project for the control of corrosion product transport at Darlington
- Online analyzers project both at Pickering and Darlington is on track and is expected to be fully commissioned by July 30, 2018 for Darlington.
- Implement actions identified through KT analysis to reduce boiler ion concentrations (e.g. improved outage boiler layup practices, ensure period boilers are drained is < 40 days, minimize FME entering secondary system following major equipment maintenance / overhauls).
- Corrective actions taken post Unit 4 outage in 2016 at Pickering, including reinstatement of low power boiler blowdown, minimization of boiler drained period, and ensuring boiler wet lay-up specs are met.
- Plans are in place to develop and implement Film Forming Amine (FFA) technology during the planned outages (short and long term) (example-Darlington refurbishment) to control CPT to boilers.

1-Year On-line Deficient Maintenance Backlog



Observations – On-Line Deficient Maintenance Backlog (AP-928 Working Group)

2016 (Annual Value)

- The industry Best Quartile and Median Thresholds were 66 and 134 work orders per unit respectively for On-Line Deficient Maintenance (DM) backlog.
    - Darlington DM backlogs were at 170 Work Orders per unit which is third quartile performance.
    - Pickering DM backlogs were at 350 Work Orders per unit which is fourth quartile performance.

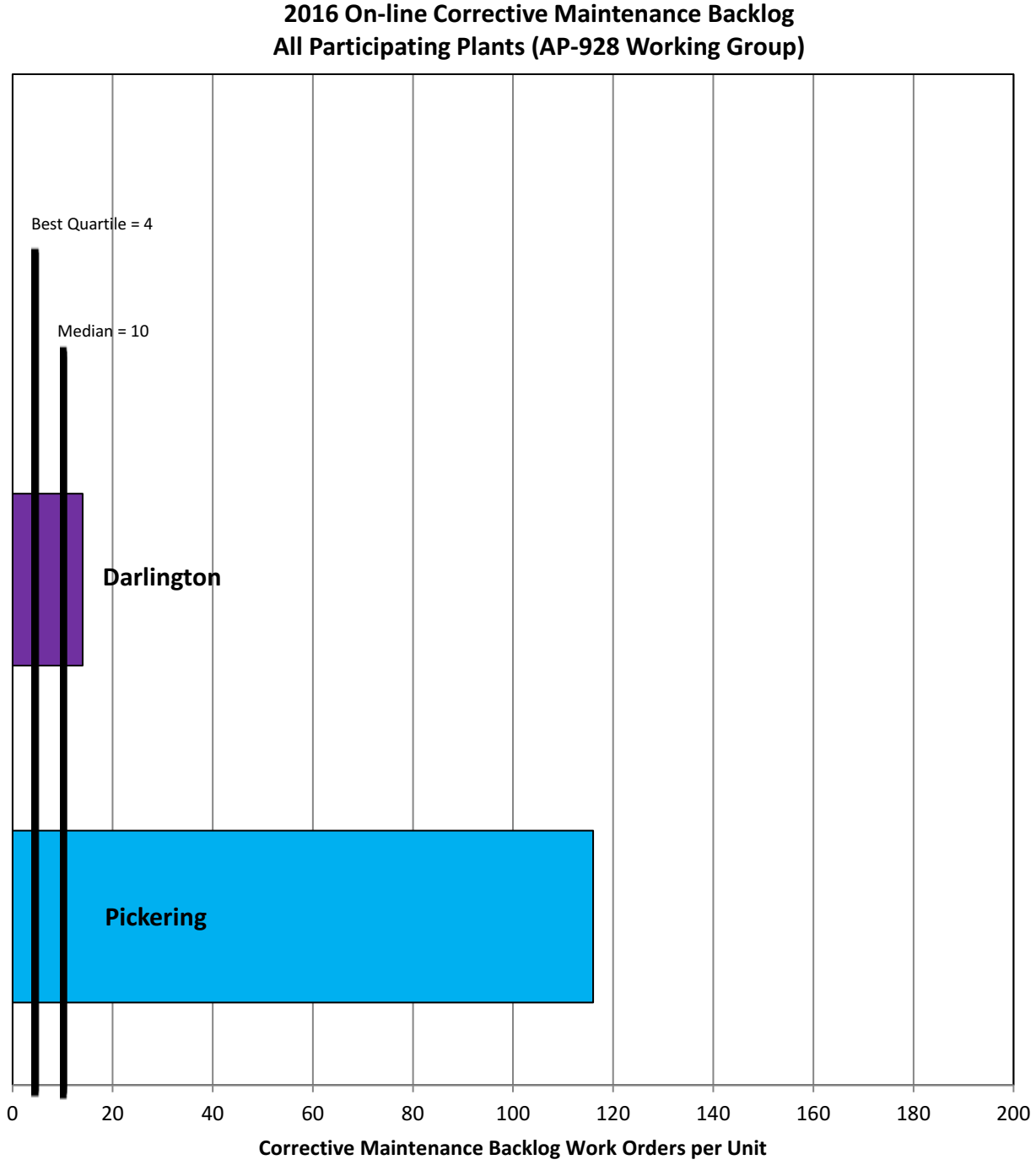
Trend

- In comparison to the 2015 data:
    - Darlington performance in 2016 has improved from 174 to 170 work orders per unit.
    - Pickering performance in 2016 declined from 251 to 350 work orders per unit.
- Darlington has shown continuous backlog improvement from 2012 through 2016.
- Pickering has shown backlog improvement in three of the last five years but declined in 2016.

Factors Contributing to Performance

- The factors that impact the deficient and corrective maintenance backlogs include the following:
    - Overall maintenance efficiency. The higher the efficiency, the more work that gets to be completed with the same number of resources
    - Schedule quality. The higher the schedule quality including crew resource supply and accurate forecasting, the higher the schedule adherence and hence lower backlogs.
- To improve performance there are fleet wide initiatives to:
    - Reduce roadblocks to starting work each day
    - Streamline the daily work authorization process
    - Increase the use of the minor work category to make more work ready to execute with fewer resources involved in preparation and scheduling
    - Improve resource supply forecasting and communication
    - Implement common crew performance reporting

1-Year On-line Corrective Maintenance Backlog



Observations – On-Line Corrective Maintenance Backlog (AP-928 Working Group)

2016 (Annual Value)

- The industry Best Quartile and Median Thresholds were 4 and 10 work orders per unit respectively for On-Line Corrective Maintenance (CM) backlog.
    - Darlington CM backlogs were at 14 Work Orders per unit which is third quartile performance.
    - Pickering CM backlogs were at 116 Work Orders per unit which is fourth quartile performance.

Trend

- In comparison to the 2015 data:
    - Darlington performance in 2016 has improved from 24 to 14 work orders per unit
    - Pickering performance in 2016 improved from 125 to 116 work orders per unit
- Note that overall industry performance has improved. Median backlog has improved from 15 to 10 work orders per unit, in one year.
- Darlington has shown continuous backlog improvement from 2012 through 2016.
- Pickering has shown backlog improvement in each of the last two years.

Factors Contributing to Performance

- Refer to the Factors Contributing to Performance discussed above in the 1 Year On-Line Deficient Maintenance Backlog, as the same factors affect both backlog measures.

4.0 VALUE FOR MONEY

Methodology and Sources of Data

The Electric Utility Cost Group (EUCG) database is the source for cost benchmarking data. Data was collected for three-year rolling averages for all financial metrics covering the review period from 2011-2016. Zero values for cost indicators are excluded from all calculations. All data submitted to and subsequently extracted from EUCG by OPG is presented in Canadian dollars. The Fitzpatrick and Pilgrim plants were excluded in the 2016 Benchmarking Report due to the unavailability of the 2015 data.

EUCG automatically applies a purchasing power parity (PPP) factor to adjust all values across national borders. The primary function of the PPP value is to adjust for currency exchange rate fluctuations but it also adjusts for additional cross-border factors which may impact purchasing power of companies in different jurisdictions. As a result, cost variations between plants are limited, as much as possible, to real differences and not due to advantages of utilizing one currency over another.

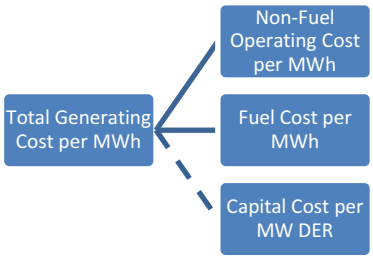
The benchmarking panel utilized for value for money metrics is made up of all North American plants reporting to EUCG. Bruce Power is the only other CANDU technology plant reporting within that panel. The remaining plants are Boiling Water Reactors or Pressurized Water Reactors. For that reason, some of the gaps in performance are associated with technology differences rather than comparable performance.

All metrics include cost information normalized by some factor (MWh or MW DER (Design Electrical Rating)) to allow for comparison across plants.

Discussion

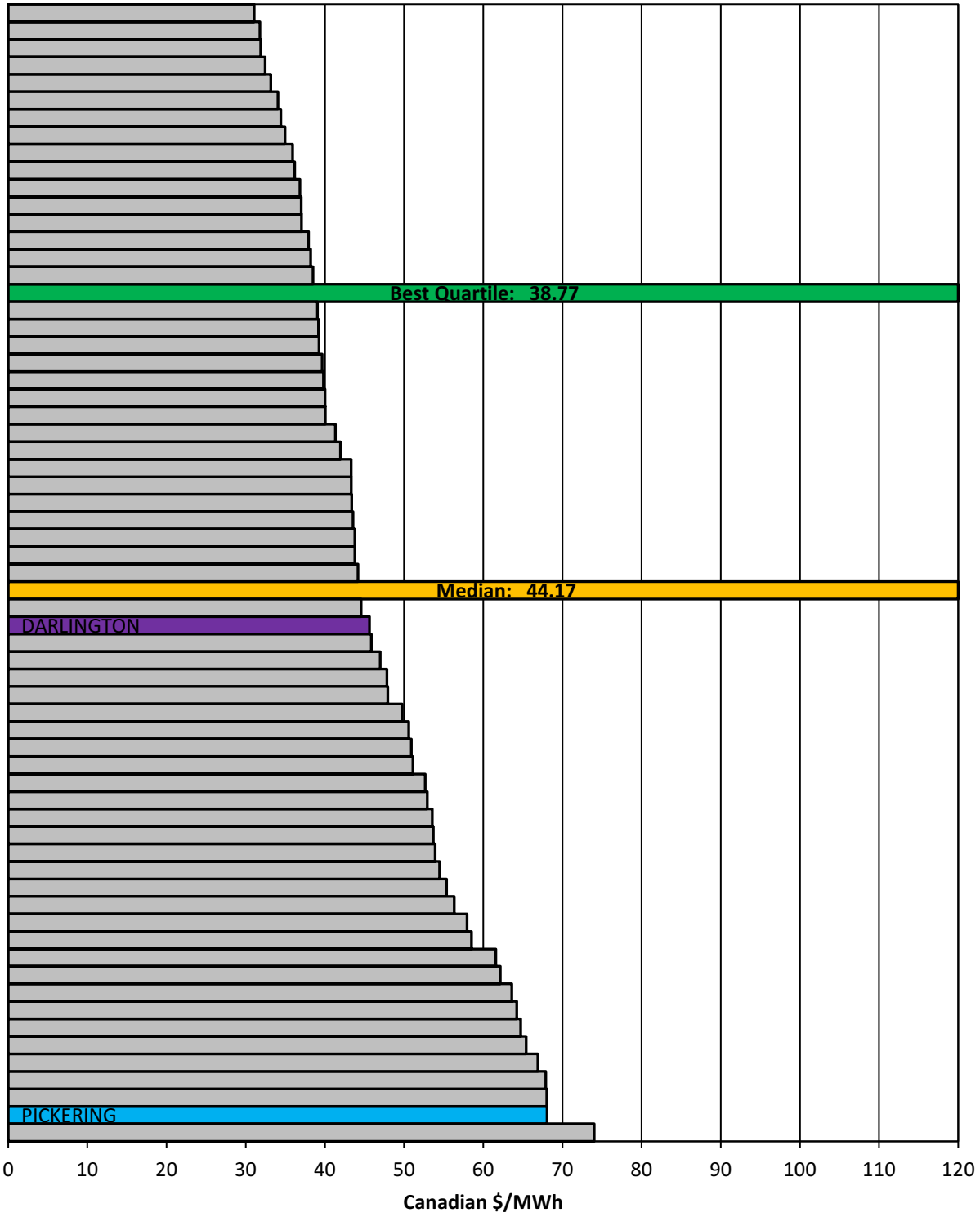
Four value for money metrics are benchmarked in this report. They are the Total Generating Cost per MWh, Non-Fuel Operating Cost per MWh, Fuel Cost per MWh, and Capital Cost per MW DER. The relationship underlying the value for money metrics is shown in the illustration below. The Total Generating Cost per MWh is the sum of Non-Fuel Operating Cost, Fuel Cost and Capital Cost measured on a per MWh basis for benchmarking purposes. Given the differences between OPG's nuclear generating stations and most North American plants with respect to both fuel costs and the different treatments of non-fuel and capital costs, the best overall financial comparison metric for OPG facilities is the Total Generating Cost per MWh.

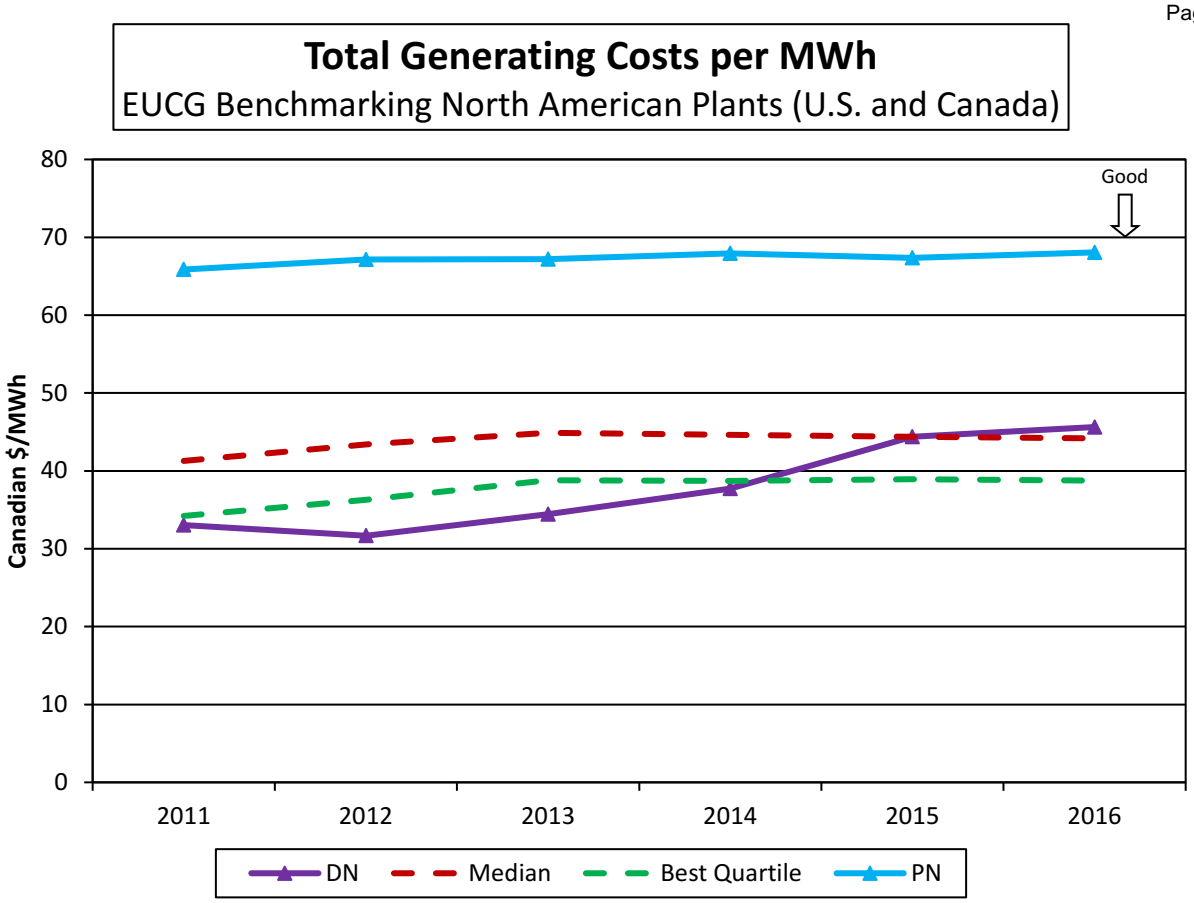
Diagram of Summary Relationship of Value for Money Metrics



3-Year Total Generating Cost per MWh

2016 3-Year Total Generating Costs per MWh
EUCG Benchmarking North American Plants (U.S. and Canada)




Total Generating Costs per MWh
EUCG Benchmarking North American Plants (U.S. and Canada)
Canadian $/MWh
80
70
60
50
40
30
20
10
0
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
PN

Observations – 3-Year Total Generating Cost per MWh (All North American Plants)

2016 (3-Year Rolling Average)

- The best quartile level for Total Generating Cost per MWh (TGC/MWh) among North American EUCG participants was $38.77/MWh while the median level was $44.17/MWh.
- Darlington TGC/MWh was $45.63/MWh, slightly worse than the median of $44.17/MWh.
- Pickering TGC/MWh was $68.06/MWh, worse than the median of $44.17/MWh.
- On a TGC/Unit basis, both Pickering and Darlington placed within the top quartile of plants (refer to the Executive Summary section).

Trend

- Over the 2011 to the 2016 period the best quartile cost rose by $4.56/MWh while the median cost rose by $2.89/MWh.
- Darlington rose by $12.58/MWh and Pickering rose by $2.20/MWh.
- Pickering largely managed cost increases and remained relatively flat over the review period with a compound annual growth rate (CAGR) of 0.7% whereas the best and median quartile levels increased by a CAGR of 2.5% and 1.4 % respectively.
- Darlington's costs increased over the review period with a CAGR of 1.4%.

Factors Contributing to Performance

- For technological reasons, Fuel Costs per MWh is an advantage for all CANDUs and the OPG plants performed within the best quartile.
- Non-Fuel Operating Cost per MWh, for all OPG plants as a whole, yielded results that are worse than the median for the most recent data point compared to the North American EUCG panel.
- OPG Capital Costs per MWh are below industry levels for Pickering and slightly above best quartile for Darlington. Capital expenditures reported by the peer group include costs for life extension, reactor head replacement, steam generator replacement, uprates, and spent fuel storage. These are costs not incurred by OPG to the extent as its peers.

Darlington

- A major driver of Darlington's TGC/MWh is the Vacuum Building Outage (VBO) which contributed $2.35/MW of the total TGC/MWh (refer to the Executive Summary section). With the exception of Bruce Power, only OPG plants have vacuum buildings in their design thus incurring additional costs and lost generation due to this activity.
- The 3-Year Rolling Average for Darlington from 2015 to 2016 rose $1.25/MWh. The primary drivers at Darlington are higher total costs of approximately $122M, partially offset by higher generation (568 GWh). The higher total costs were primarily attributable to higher OM&A costs of $3.7M, higher Capital costs of $104.8M and higher Fuel Costs of $12.9M .

Observations – 3-Year Total Generating Cost per MWh (All North American Plants) (CON'T)

- Planned Outage days at Darlington decreased by 74 days for the 2014-2016 period versus the 2013-2015 period mainly due to the Darlington Unit 2 Planned Outage in 2013 (2013 was a two outage year at Darlington).
- When comparing 2013 versus 2016, the OM&A Costs increased slightly due to the increased base costs (19%) and project costs (143%), largely offset by lower outage costs (28%) and nuclear support (8%). Labour, material and purchased services differential was mainly due to the decreased planned outage days, and were accompanied by smaller increases in OM&A labour including payroll burden, overtime and other costs. The increased overtime, labour escalation and increased use of temporary staff were partially offset by reduced head count. The OM&A Project differential in 2016 over 2013 includes project cancellation and asset removal costs.
- Capital costs more than doubled at Darlington from 2013 – 2016 (increase of approximately $100M), with Capital Portfolio and MFA costs rising due to aging plant equipment, refurbishment support and regulatory requirements for extended life at Darlington. Labour capital has increased due to increased regular, overtime and temporary staff consistent with increased capital program at Darlington.
- Darlington performed within the best quartile for Fuel Cost per MWh and better than median for Capital Cost per MW DER while performing worse than the median for the Non-Fuel Operating Cost per MWh.
- For Non-Fuel Operating Cost, the largest performance gap driver for Darlington during the review period is CANDU technology. The larger equipment inventory in a CANDU unit compared to the pressurized water reactors and boiling water reactors units represents a net increase in maintenance and operations workload, which requires additional staff.

Pickering

- A major driver of Pickering's TGC/MWh is the size of the units, which at 540 MW are the smallest size amongst the peers and compare negatively to the average size of 1,022 MW. This driver contributed $33.91 of the total $68.06 TGC/MWh (refer to the Executive Summary section). With a larger unit size, Pickering would be placing amongst the top quartile plants for TGC/MWh.
- The 3-Year Rolling Average for Pickering from 2015 to 2016 increased by $0.71/MWh. The primary drivers at Pickering are higher total costs $65M, partially offset by slightly higher generation (316 GWh). The higher total costs were primarily attributable to higher OM&A, fuel and capital costs of $56.7M, $4.4M and $3.4M, respectively
- Planned Outage days for Pickering increased by 74 days for the 2014-2016 period versus the 2013-2015 period leading to increased outage costs in 2016 versus 2013.
- When comparing 2013 versus 2016, OM&A Costs have increased due to increases in base costs, outage costs (purchased service and overtime) and nuclear support costs, partially offset by decreased project costs and allocated corporate costs. The higher planned outage days at Pickering contributed to the increased OM&A costs.

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Observations – 3-Year Total Generating Cost per MWh (All North American Plants) (CON'T)

- Capital spending at Pickering has increased slightly ($3M) from 2013 to 2016.
- Fuel spending is slightly higher ($4M) mainly due to increased fuel storage and disposal charges.
- Pickering performed within the best quartile for Fuel Cost per MWh and Capital Cost per MW DER while performing worse than the median for Non-Fuel Operating Cost per MWh.
- For Non-Fuel Operating Cost, the largest performance gap drivers for Pickering during the review period are CANDU technology, capability factor, smaller unit sizes, age of the plant, corporate cost allocations, and the fact that Pickering was built based on first generation CANDU technology. While OPG's ten nuclear units are all CANDU reactors, they reflect three generations of design philosophy and technology which impacts the extent and nature of operations and maintenance activity.

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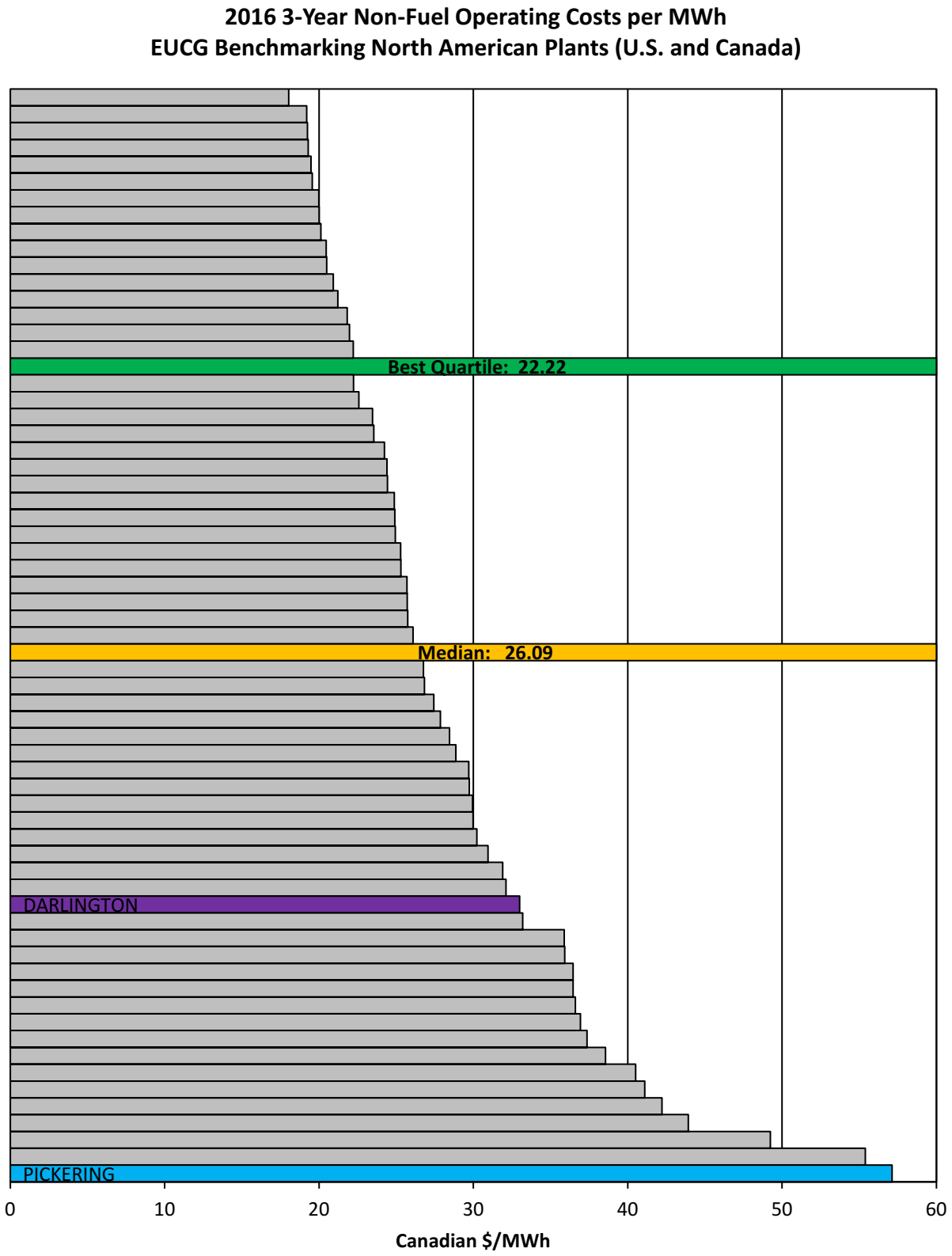
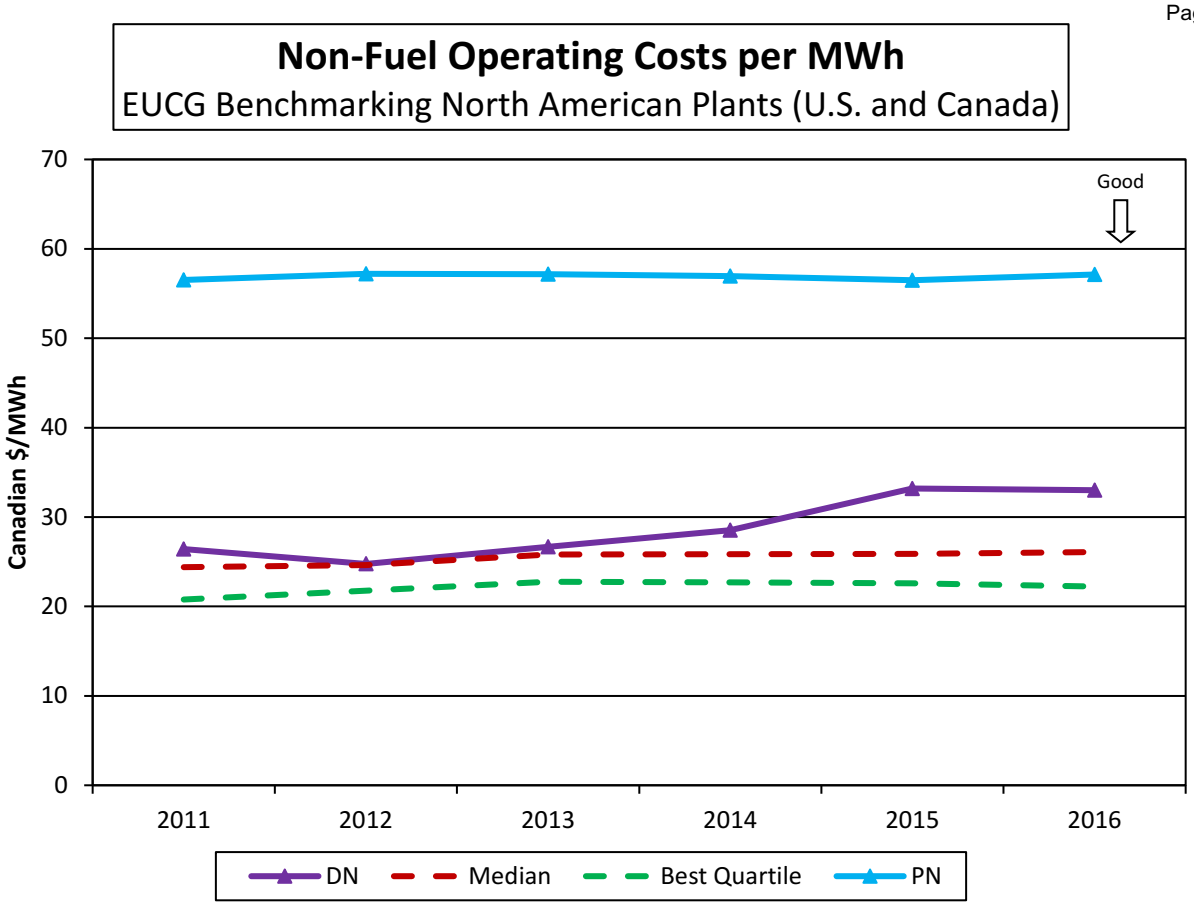
3-Year Non-Fuel Operating Cost per MWh




Non-Fuel Operating Costs per MWh
EUCG Benchmarking North American Plants (U.S. and Canada)
Canadian $/MWh
70
60
50
40
30
20
10
0
Good
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
PN

Observations – 3-Year Non-Fuel Operating Cost per MWh (All North American Plants)

2016 (3-Year Rolling Average)

- Best quartile plants had Non-Fuel Operating Costs per MWh (NFOC/MWh) at or below $22.22 while the median plant level threshold was $26.09/MWh.
- Compared to North American EUCG plants, the Non-Fuel Operating Costs per MWh of all participating Canadian CANDU plants are worse than industry median performance.
- Darlington's costs, at $33.00/MWh, were $10.78/MWh higher than best quartile and $6.91/MWh higher than the median.
- Pickering's costs, at $57.12/MWh, were $34.90/MWh higher than best quartile and $31.03/MWh higher than median.

Trend

- Pickering largely managed cost increases and remained relatively flat over the review period with a compound annual growth rate (CAGR) of 0.2% whereas both the best and median quartile levels increased by a CAGR 1.4 %.
- Pickering 3-yr NFOC/MWh remained relatively flat from 2011 ($56.54/MWh) to 2016 ($57.12/MWh). Please see 2016 TGC per MWh discussion regarding total Pickering costs and production.
- Pickering's annual Non-Fuel Operating Cost, over the 2011-2016 review period, is being managed through the continuous pursuit of efficiency improvements enabled by initiatives such as the amalgamation of the Pickering A and Pickering B stations into one Pickering site. The company-wide business transformation project launched in 2011 is also helping streamline, eliminate and reduce work to leverage attrition profiles while sustaining safety and reliability performance excellence.
- Darlington's costs increased over the review period with a CAGR of 4.5% due to reasons outlined below.
- Over the 2011-2016 review period, Darlington's Non-Fuel Operating Cost increased from 2011 ($26.42/MWh) to 2016 ($33.00/MWh). Please see 2016 TGC per MWh discussion regarding total Darlington costs and production.
- Darlington's 3-yr NFOC/MWh had an annual compound growth rate of 4.5% from 2011 to 2016 as compared to 1.4% for both the best quartile and median levels. The 2016 decrease in Darlington's NFOC/MWh from 2015 is due to primarily to higher generation.

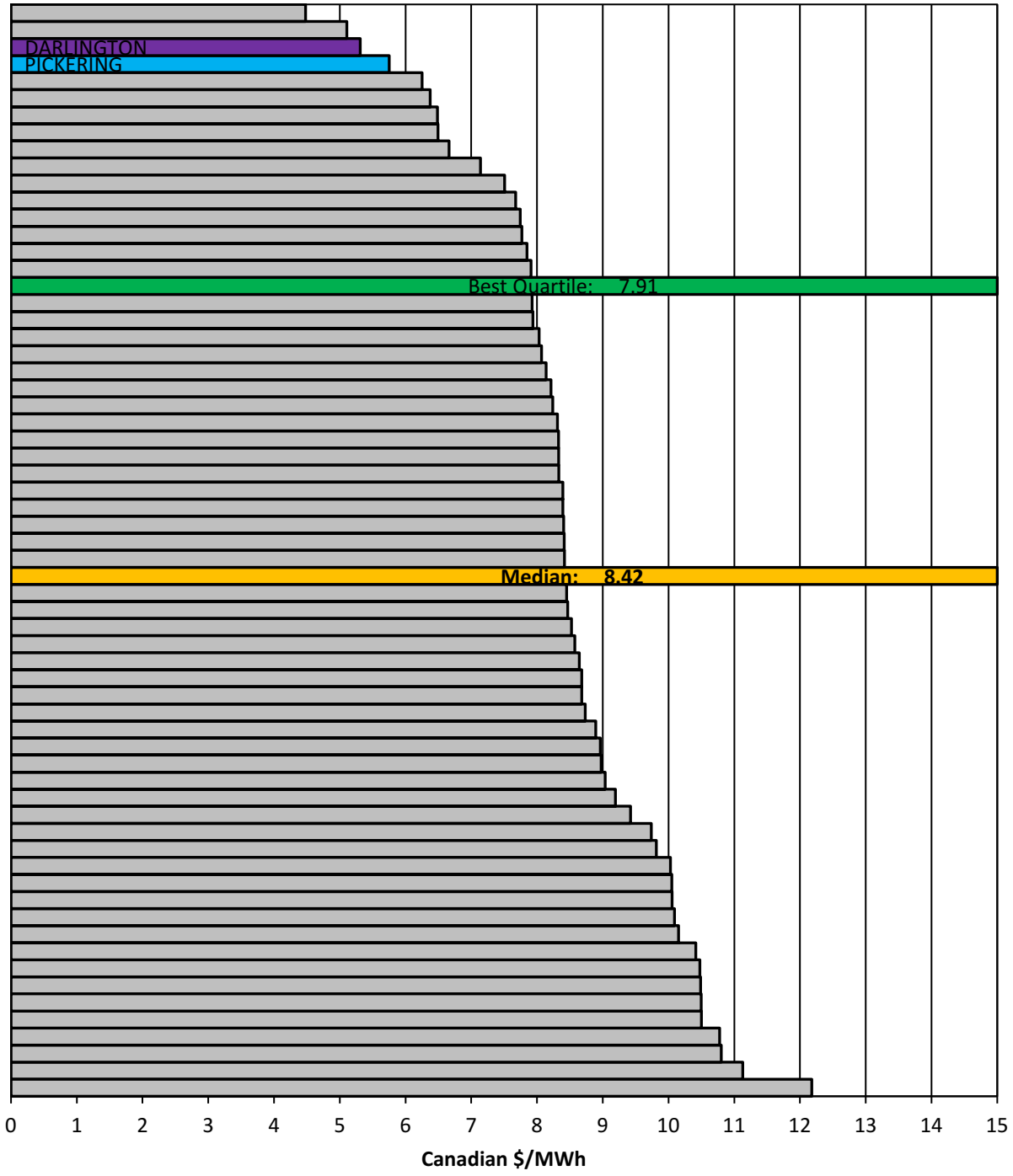
Observations – 3-Year Non-Fuel Operating Cost per MWh (CONT'D)

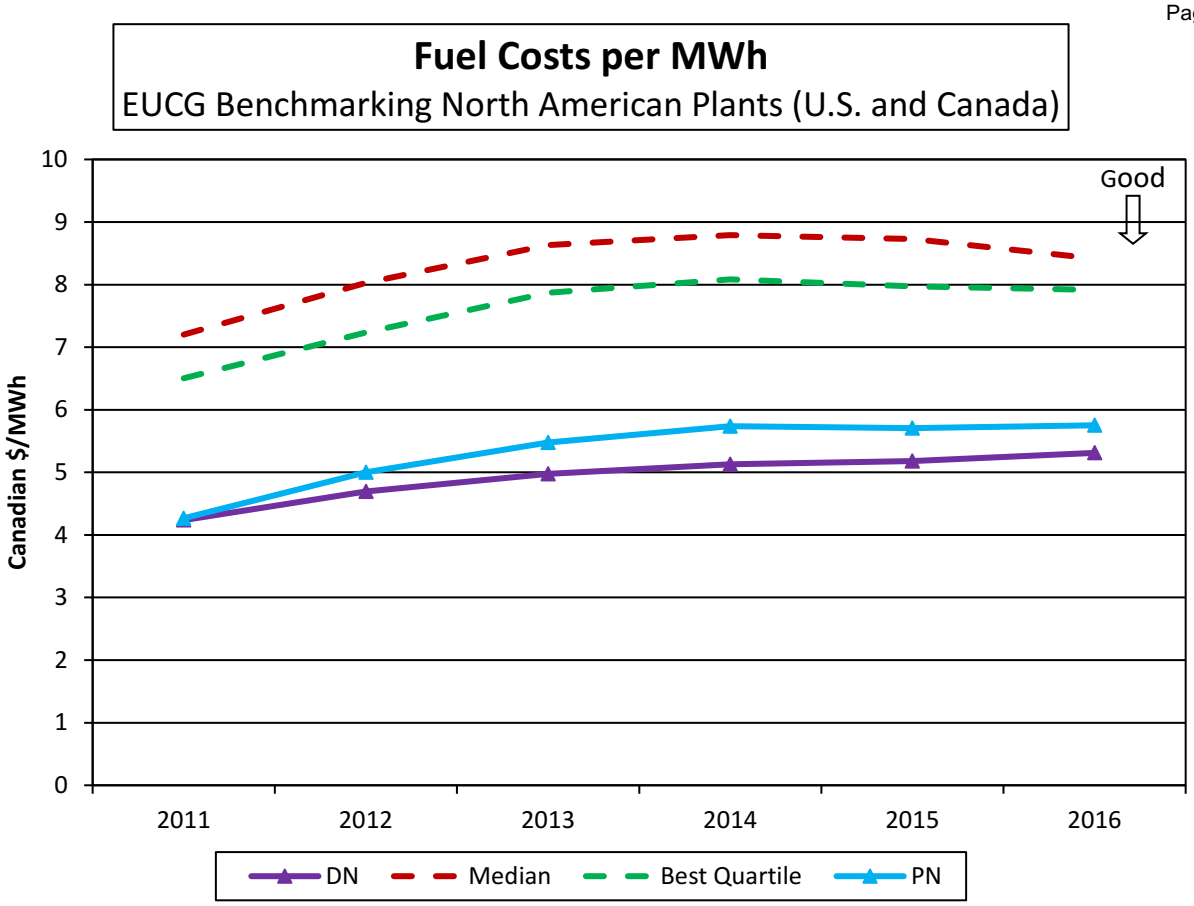
Factors Contributing to Performance

- Performance in Non-Fuel Operating Cost per MWh drives the majority of OPG's financial performance. Overall, the biggest drivers are: capability factor, station unit size, CANDU technology, corporate cost allocation, and staff levels. The biggest drivers are further expanded below:
  - The 'capability factor' driver is related specifically to generation performance of the station in relation to the overall potential for the station (results are discussed under the Reliability section within the Rolling Average Unit Capability Factor metric).
  - The 'station size' driver is the combined effect of number of units and size of units which can have a significant impact on plant cost performance (refer to the Executive Summary section).
  - The 'CANDU technology' driver relates specifically to the concept that CANDU technology results in some specific cost disadvantages related to the overall engineering, maintenance, and inspection costs. In addition, this factor is influenced by the fact that CANDU plants have less well-developed user groups to share and adopt competitive advantage information, than do longer-established user groups for Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR). Though quantification of CANDU technology impact to cost remains most difficult of all drivers, a staff benchmarking analysis recognized a significant reduction in the gap between OPG staff levels and the industry benchmark. OPG undertook a staffing study through a third-party consultant which concluded that technology, design and regulatory differences exist between CANDU and PWR reactor units and that such factors drive staffing differences. The study established that CANDU technology was a contributor to explaining higher staffing levels for CANDU versus PWR plants which also contributed to OPG's performance in Non-Fuel Operating Cost. The study also found that labour for CANDU stations is approximately 20% higher than in benchmarked PWR stations.
  - The 'corporate cost allocations' driver relates directly to the allocated corporate support costs charged to the nuclear group.
  - Other costs are continuously being reviewed for opportunities in reducing them.
  - The major contributing factors for Darlington performance for Non-Fuel Operating Cost per MWh were reviewed within the Total Generating Cost per MWh section.
  - The only additional contributing factor which appears within Non-Fuel Operating Cost is capitalization policy and "repair vs. replace strategies."
  - The impact of differing capitalization policies is removed when looking at Total Generating Cost per MWh (i.e., the sum of Non-Fuel Operating Cost, Fuel Cost, and Capital Cost).

3-Year Fuel Cost per MWh

2016 3-Year Fuel Costs per MWh
EUCG Benchmarking North American Plants (U.S. and Canada)




Fuel Costs per MWh
EUCG Benchmarking North American Plants (U.S. and Canada)
Good
Canadian $/MWh
10
9
8
7
6
5
4
3
2
1
0
2011
2012
2013
2014
2015
2016
DN
Median
Best Quartile
PN

Observations – 3-Year Fuel Cost per MWh (All North American Plants)

2016 (3-Year Rolling Average)

- Fuel Cost per MWh for all Canadian CANDU plants are significantly better than the best quartile threshold ($7.91/MWh) for the panel of North American EUCG plants.
- The two OPG plants ranked as the top four lowest fuel cost plants in the North American panel with Darlington ($5.31/MWh) at third and Pickering ($5.75/MWh) at fourth.

Trend

- The best quartile 3 year Fuel Cost per MWh has remained flat over 2015 and 2016.
- 3 year Fuel Cost per MWh for all OPG plants increased slightly in 2016. The increase in the Fuel Cost per MWh is due to a combination of general escalation in the fuel conversion and fuel fabrication costs as well as rising provisions for used fuel storage and disposal costs, the latter which continue to increase well above the rate of inflation from 2015 to 2016. OPG recognized lower input uranium costs in US dollar terms during 2016, however this was offset by deterioration in the value of the Canadian dollar against the US dollar during this period.
- The Pickering Generating Station would rank the lowest among the CANDU plants in the peer panel ranked group if provision costs were excluded from the calculation with a 3 year rolling average fuel cost per MWh of $4.20/MWh. Similarly, Darlington would rank second with an average 3 year rolling average fuel cost per MWh of $4.25/MWh.

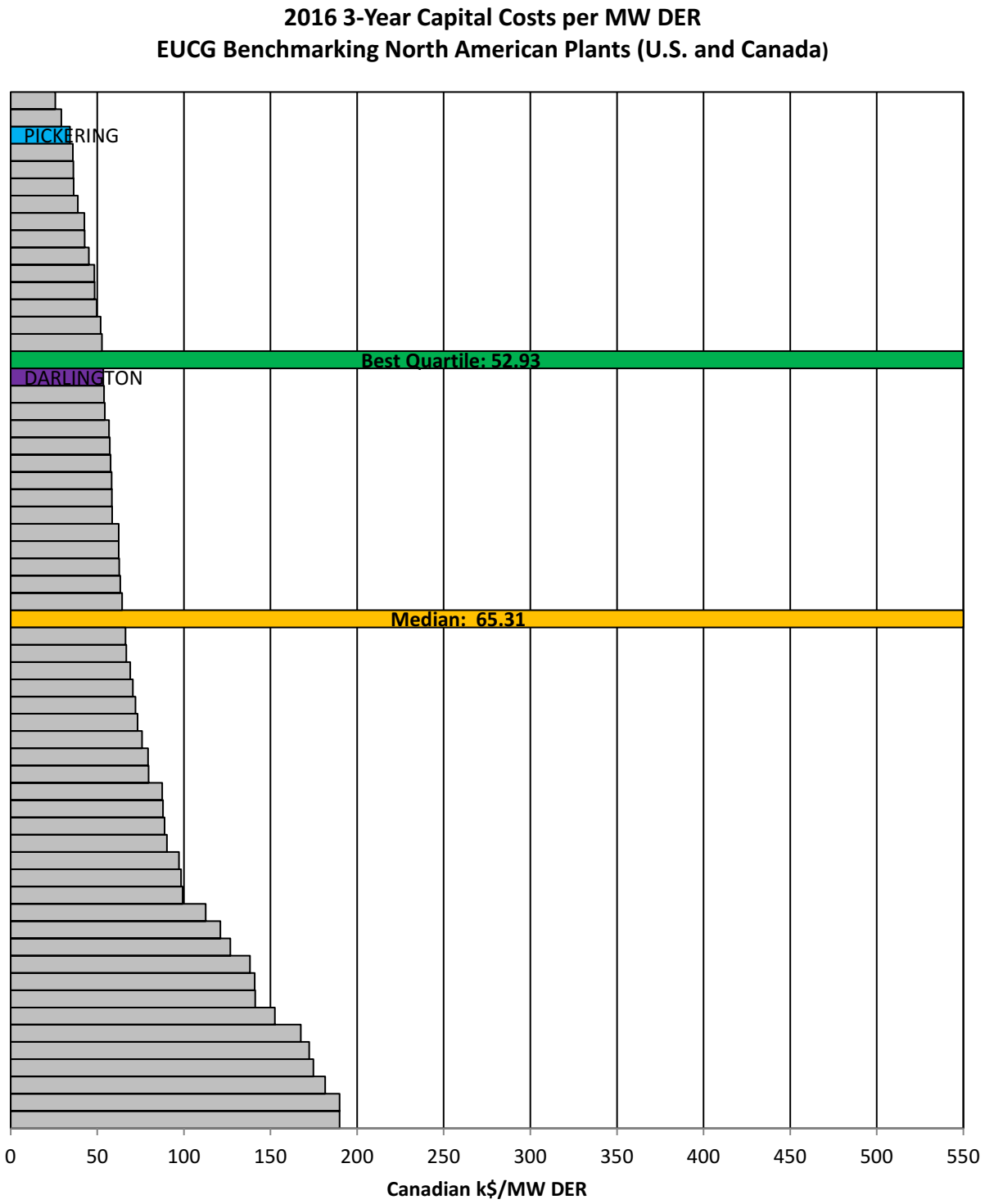
Factors Contributing to Performance

- Fuel costs, primarily driven by the technological differences in CANDU technology, are lower for OPG than all North American Pressurized Water Reactors or Boiling Water Reactors (PWR/BWR) reactors as CANDUs do not require enriched uranium like BWRs and PWRs. This provides a significant advantage for OPG and other CANDUs in this cost category.

Best quartile fuel cost performance noted above is due to the following factors:

- Uranium fuel costs: Raw uranium is processed directly into uranium dioxide to make fuel pellets, without the cost and process complexity of enriching the fuel as required in light water reactors. The advantage due to fuel costs also includes transportation, handling and shipping costs.
- Reactor core efficiency: CANDU is the most efficient of all reactors in using uranium, requiring about 15% less uranium than PWRs for each megawatt hour of electricity.

3-Year Capital Cost per MW DER (Design Electrical Rating)



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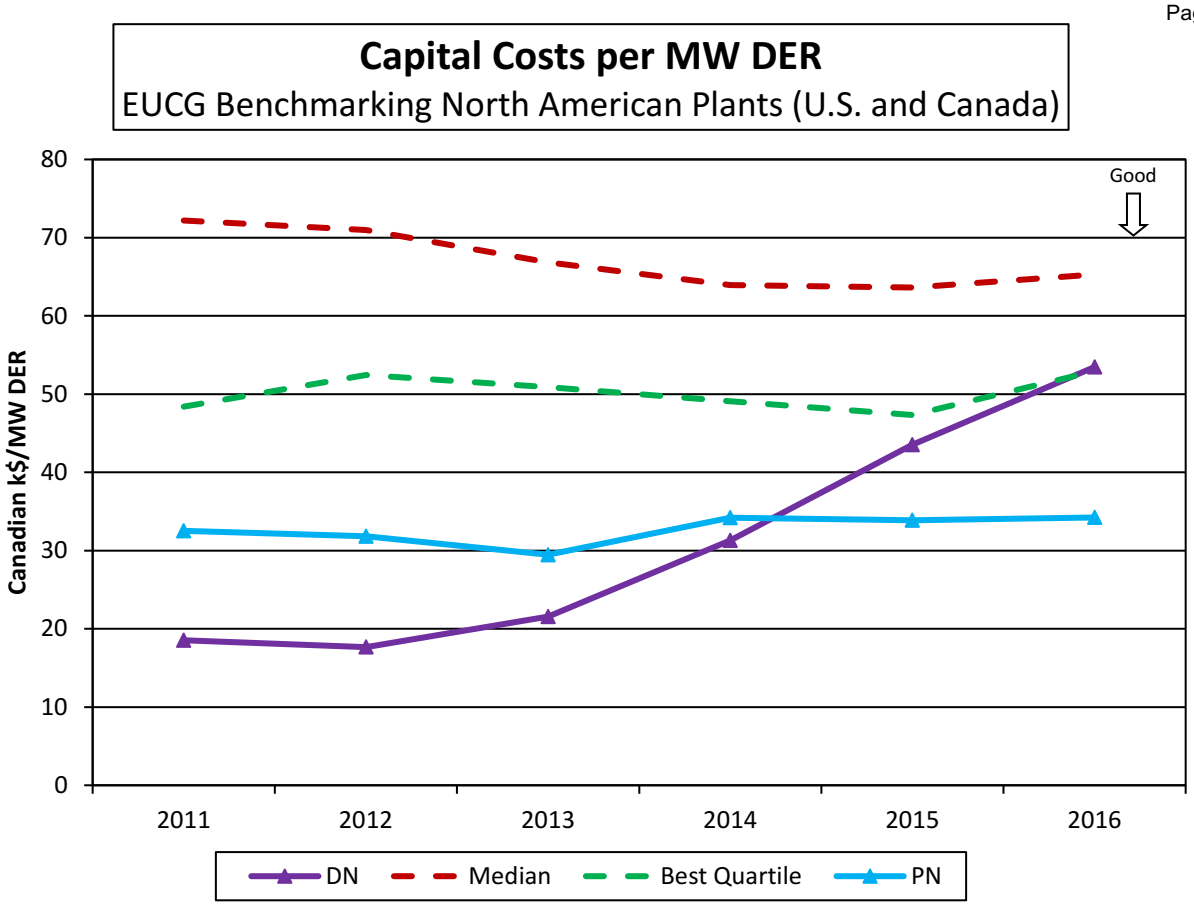

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Observations – 3-Year Capital Cost per MW DER (All North American Plants)

2016 (3-Year Rolling Average)

- The first quartile threshold for Capital Cost per MW DER across the North American EUCG peer panel plants was k$52.93/MW DER.
- Median cost for the panel was k$65.31/MW DER.
- Pickering had lower capital cost/MW DER than the first quartile threshold, whereas, Darlington had a capital cost/MW DER just above the first quartile.

Trend

- The first quartile threshold increased in 2016 due increased spending on reliability improvements offset by slight reductions in Fukushima response and sustaining investment.
- Darlington's Capital Cost per MW DER increased in 2016 due to increased spending on life extension, reliability improvements, non-power block infrastructure, sustaining and Fukushima response.
- Pickering's Capital Cost per MW DER was steady in 2016 due to a reduction in reliability improvements and other regulatory costs. These were offset by increased sustaining and performance improvement spending as well as higher Fukushima response costs.

Factors Contributing to Performance

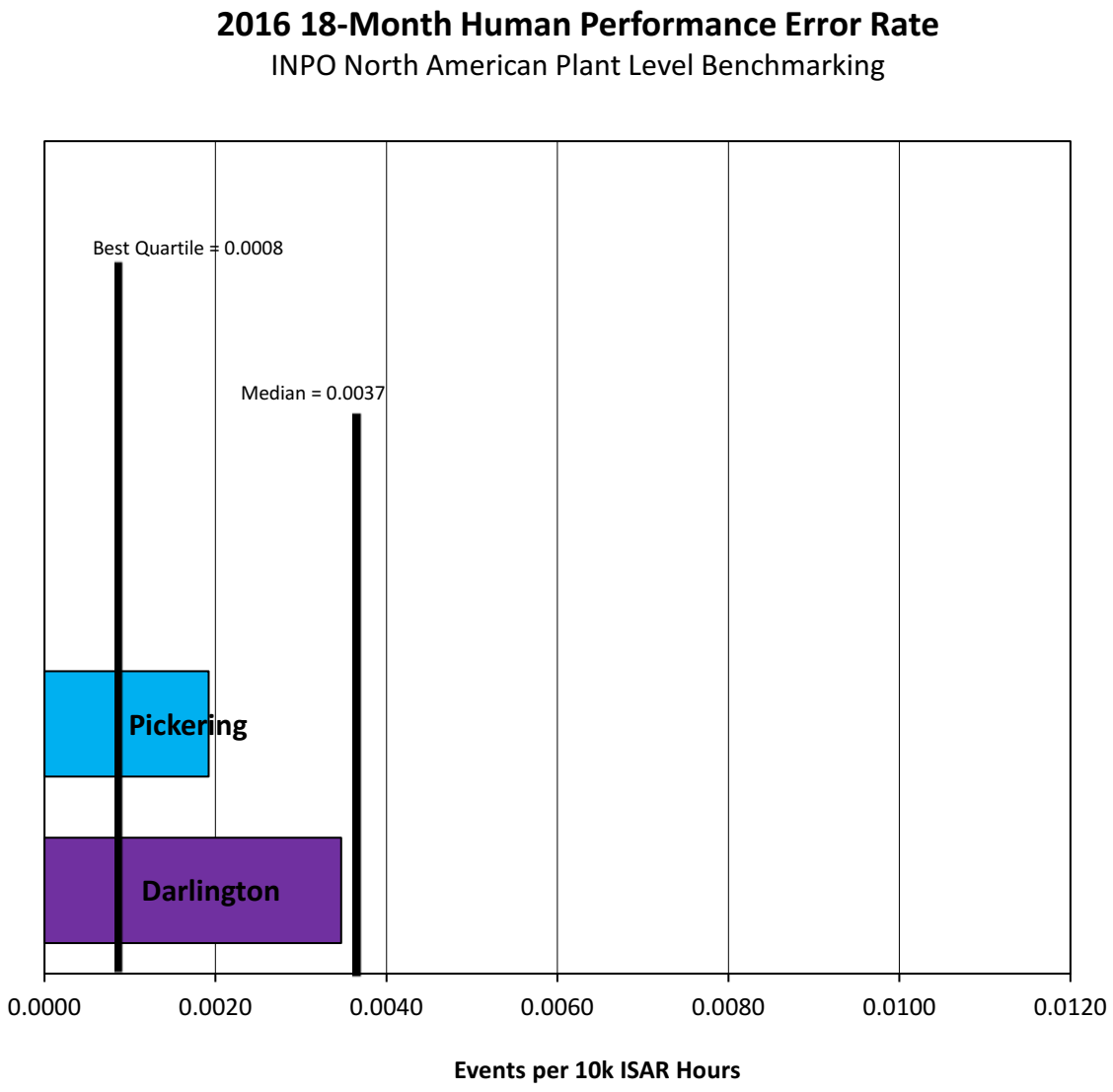
- Pickering is performing in the first quartile overall for the period. This performance is due to first and second quartile spending on enhancements, information technology, regulatory and sustaining investments
- Darlington is performing in the second quartile for the period. This performance is due to first quartile spending on regulatory investment, second quartile spending on sustaining, with third and fourth quartile spending on enhancements and infrastructure.
- Fukushima costs at Darlington and Pickering are significantly lower than their peers, contributing to the first quartile ranking for regulatory spending. Only units slated for permanent shutdown in the US have incurred similar expenditures. The difference in approach to Fukushima response between the Canadian and American utilities has resulted in costs that are 25 to 50% less.
- Darlington's ranking in enhancements is due primarily to investments to support post-refurbishment operations.
- Spending on sustaining investments at Darlington is in the second quartile despite having increased period over period to support operations following refurbishment. Pickering sustaining investments declined as projects to support operations to 2020 approach completion.
- The performance in these areas is offset by third and fourth quartile spending in non-power block infrastructure and capital spares.
- Non-power block infrastructure spending at Darlington to support post-refurbishment operations continues to be higher than the majority of its peers.
- Investment in capital spares at both Darlington and Pickering has increased to support overhauls of aging equipment and support safe and reliable operations.

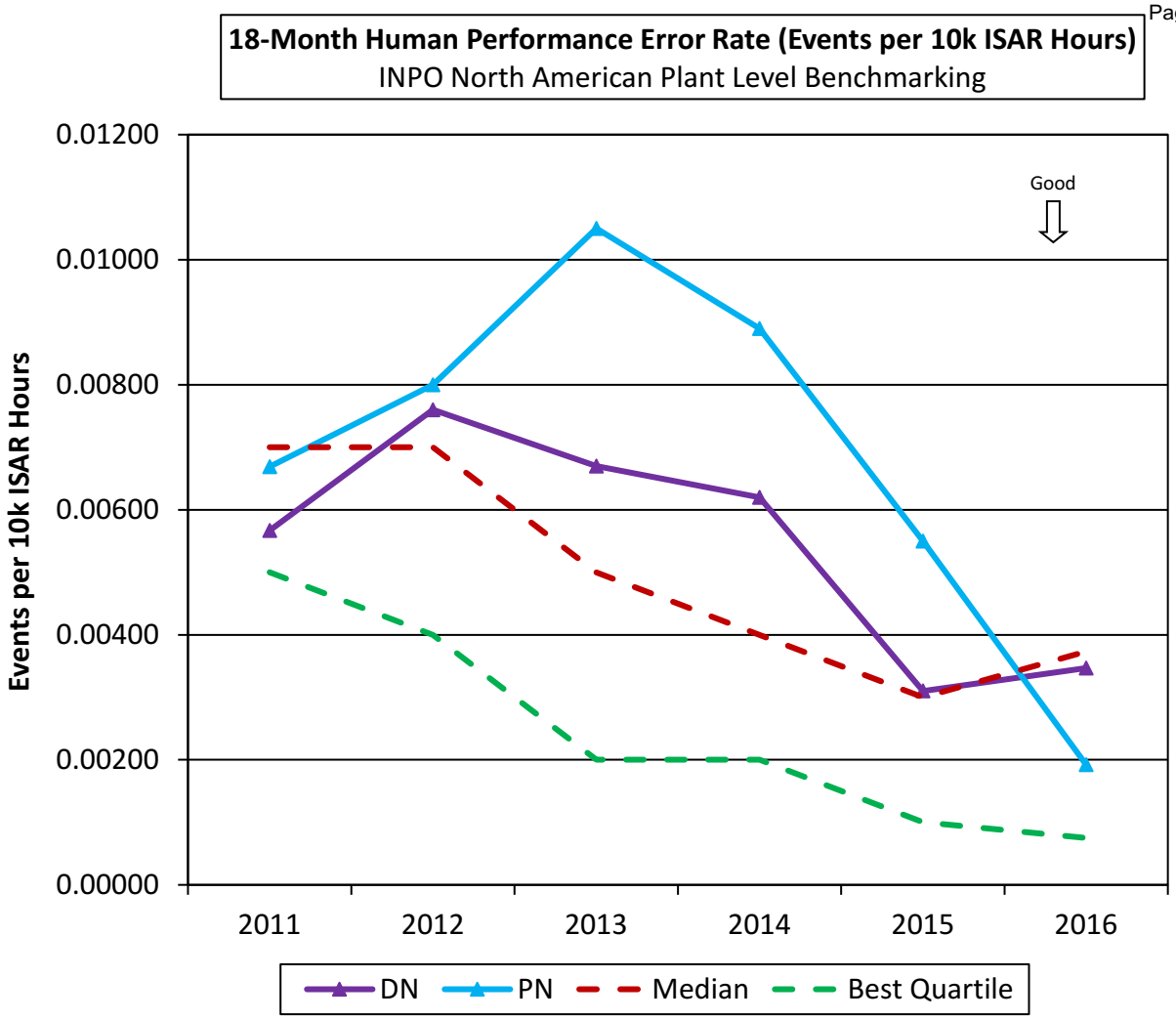
5.0 HUMAN PERFORMANCE

Methodology and Sources of Data

The Human Performance Error Rate metric has been selected to benchmark the performance of OPG's Nuclear fleet against other INPO utilities in the area of Human Performance. This will ensure a continued focus on improving Human Performance by comparing OPG Nuclear stations to industry quartiles through the use of consistent and comparable data.

18-Month Human Performance Error Rate




18-Month Human Performance Error Rate (Events per 10k ISAR Hours)
INPO North American Plant Level Benchmarking
Events per 10k ISAR Hours
0.01200
0.01000
0.00800
0.00600
0.00400
0.00200
0.00000
Good
2011
2012
2013
2014
2015
2016
DN
PN
Median
Best Quartile

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Observations – 18 Month Human Performance Error Rate (INPO North American Plants)

2016 (18 Month Rolling Average)

- The 2016 Human Performance Error Rate (HPER) best quartile was 0.0008 and the median quartile was 0.0037. INPO best quartile continued to improve since 2015 when it was 0.0010. The median quartile has increased since 2015 when it was 0.002 representing a slight decline in performance.
- Compared to the INPO peer group the Pickering and Darlington performance is trending in a positive direction:
  - Pickering station performance has continued to improve with the HPER at the end of 2016 reaching 0.0019, compared to 2015 result of 0.0055 achieving median level performance in the process.
  - Darlington station maintained median level performance in 2016, however performance has declined just slightly with the HPER at the end of 2016 being 0.0035, compared to the 2015 result of 0.0031.

Trend

- Pickering and Darlington continue to show improvement in performance with Pickering station HPER being at its' lowest ever. Darlington's performance is trending around the median ranking.
- The main contributing factors to these results are some notable areas of improvement. Completion of change management activities to support key strategic initiatives, including face-to-face roll-outs, improved training, and follow up self assessments has contributed to sustained positive results in areas of supervisory oversight, improved quality of observation and coaching conducted, and trending and analysis.
- Industry performance has improved year over year. INPO best quartile continues to improve since 2015 (0.0008 in 2016 compared to 0.0010 in 2015). There is a slight increase in the median since 2015 (0.0037 in 2016 compared to 0.003 in 2015) however the overall trend indicates improved performance since 2011.
- While these high level indicators show improved performance the organization needs to remain vigilant during this time of increased activity resulting from the refurbishment project at Darlington. There are a lot of newly hired workers performing work on the units being refurbished which will continue for a number of years. OPG leadership remains focused on setting, communicating and reinforcing standards and expectations through effective coaching in the field to ensure performance shortfalls are addressed. They are taking necessary measures to ensure vendor partners as well as OPG staff demonstrate correct behaviours around safety and Human Performance to reduce consequential errors.

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Observations – 18 Month Human Performance Error Rate (CONT'D)

Factors Contributing to Performance

- Top performing organizations promote and communicate a clear vision for excellence in human performance. Supervisors/managers positively shape field worker behaviours by providing effective coaching.
- A leader's presence in the field and engagement with individuals and teams is an essential element to gain an understanding of human performance behaviours, reinforce positive behaviours, and provide candid feedback on performance gaps.
- Workers have a personal responsibility to ingrain and apply the desired human performance behaviours. Workers take accountability for their actions and feel empowered to make decisions.
- Crew or Section clocks are used by the sites/facilities to share the organizational learning around the low level errors and events which help to reduce the number of consequential events.
- In 2016 OPG has applied significant effort to key Human Performance initiatives to reduce errors and drive improvements in performance. The Human Performance fleet strategy is captured in the 2016-18 Human Performance Fleet Excellence Plan. The key Human Performance strategies captured in the Human Performance fleet and site plans are:
    - Create a healthy reporting culture where all individuals at every level of the organization feel safe reporting errors and mistakes enabling learning and improving performance.
    - Improve the existing coaching culture to establish consistent reinforcement of procedures and standards, one in which workers and supervisors value coaching and use it to improve performance.
    - Develop and implement a fleet plan to address higher than usual activity levels during outages, and the resulting increased potential for errors. The plan actions will focus on proactive and forward trending, focused communications and messaging during outages, and Human Performance interventions.
- Improved performance fleetwide is based on the successful implementation of these key fleet initiatives. In support of these changes, Human Performance training requirements for all OPGN employees have been established. Human Performance Module of Nuclear General Employee Training continuing training has been revised to include fundamental principles of Human performance and new leadership learning activities.
- Paired Observation for Middle Managers is underway and focuses on the requisite skills required for Middle Managers to develop their direct reports as leaders in a facilitative style.

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Observations – 18 Month Human Performance Error Rate (CONT'D)

Factors Contributing to Performance (continued)

- First Line Managers Performance Enhancement O&C training has been piloted and focuses on the requisite supervisory skills that are applicable to Observation and Coaching.
- Performance improvement is also noted in response to nuclear oversight audit findings regarding Human performance staff competencies. All staff associated with Human Performance, and many working in Performance Improvement have now received INPO Human Performance Training. The correct competencies are evident in their performance.
- Industry best practice is also attributed to the incorporation of OPEX into Human Performance key strategies. Active engagement with COG and industry peer teams/working groups has been engaged to ensure that Human Performance governance meets or exceeds industry standards in Human Performance.
- As stated above, the high level indicator (HPER) for Pickering and Darlington stations has shown improvement year over year. Pickering HPER is the lowest it has ever been. Once fully implemented across OPN fleet, the above initiatives should continue to drive performance improvement.

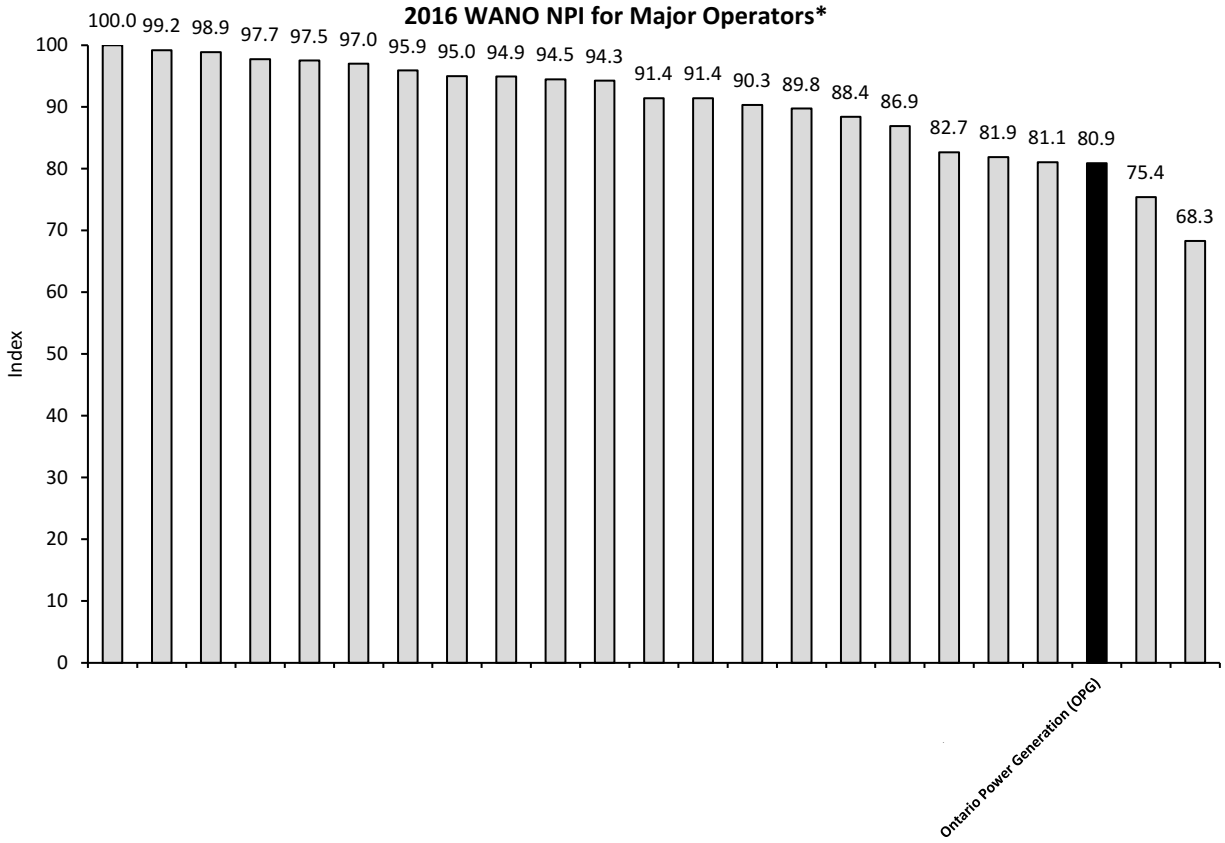
6.0 MAJOR OPERATOR SUMMARY

Purpose

This section supplements the Executive Summary, providing more detailed comparison of the major operators of nuclear plants for three key metrics: WANO Nuclear Performance Index (NPI), Unit Capability Factor (UCF), and Total Generating Cost (TGC) per MWh. Although the benchmarking study has been primarily focused on operational performance comparison to COG CANDUs, this section of the report contemplates the larger industry by capturing OPG Nuclear's performance against North American PWR and PHWR operators in addition to the international CANDU panel. Operator level summary results are the average (mean) of the results across all plants managed by the given operator. These comparisons provide additional context, but the detailed data in the previous sections provide a more complete picture of plant by plant performance. The WANO NPI and UCF are calculated as the mean of all unit performance for a specific operator. The TGC per MWh is the mean of plant level data because costs are not allocated to specific units within the EUCG industry panel.

WANO Nuclear Performance Index Analysis

The WANO Nuclear Performance Index (NPI) results for the operators in 2016 are illustrated in the graph below. OPG Nuclear performance ranking improved from 2015 shown in Table 3.



*See Table 8 in the Appendix for listing of operators and plants.
**OPG Nuclear unit values averaging to a WANO NPI of 80.9 in 2016 are shown below:

Unit	2016 WANO NPI
Pickering 1	67.1
Pickering 4	66.6
Pickering 5	87.6
Pickering 6	78.1
Pickering 7	75.2
Pickering 8	83.4
Darlington 1	83.6
Darlington 2	97.1
Darlington 3	79.6
Darlington 4	90.7

In 2016, OPG ranked 21st, with an NPI of 80.9. OPG's NPI performance increased significantly by 6.3 and increased by two compared to the 2015 ranking.

The NPI rankings of the major operators from 2011 to 2016 are listed in Table 3. The list and ranking of operators has been updated to reflect any industry developments if applicable.

Table 3: Average WANO NPI Rankings

Operator	2011	2012	2013	2014	2015	2016
	4	17	16	8	3	1
	6	18	8	9	2	2
	20	22	10	5	5	3
	16	13	17	15	12	4
	3	4	2	14	13	5
	8	6	5	4	6	6
	7	7	4	7	10	7
	5	2	12	16	1	8
	10	3	1	13	9	9
	1	5	6	10	8	10
	27	24	23	19	7	11
	2	1	18	20	20	12
	19	10	13	2	4	13
	14	12	9	12	16	14
	15	11	15	18	21	15
	21	23	24	3	15	16
	9	8	7	6	17	17
	13	19	14	1	14	18
	23	20	21	21	22	19
	11	15	19	11	11	20
Ontario Power Generation	24	25	22	22	23	21
	18	21	3	17	19	22
	NA*	27	25	24	24	23
	17	9	20	23	18	NA
	22	16	11	NA	NA	NA
	12	14	NA	NA	NA	NA
	25	26	NA	NA	NA	NA
	26	26	NA	NA	NA	NA

*NA: Not applicable due to multi-year refurbishment of the generating Station.

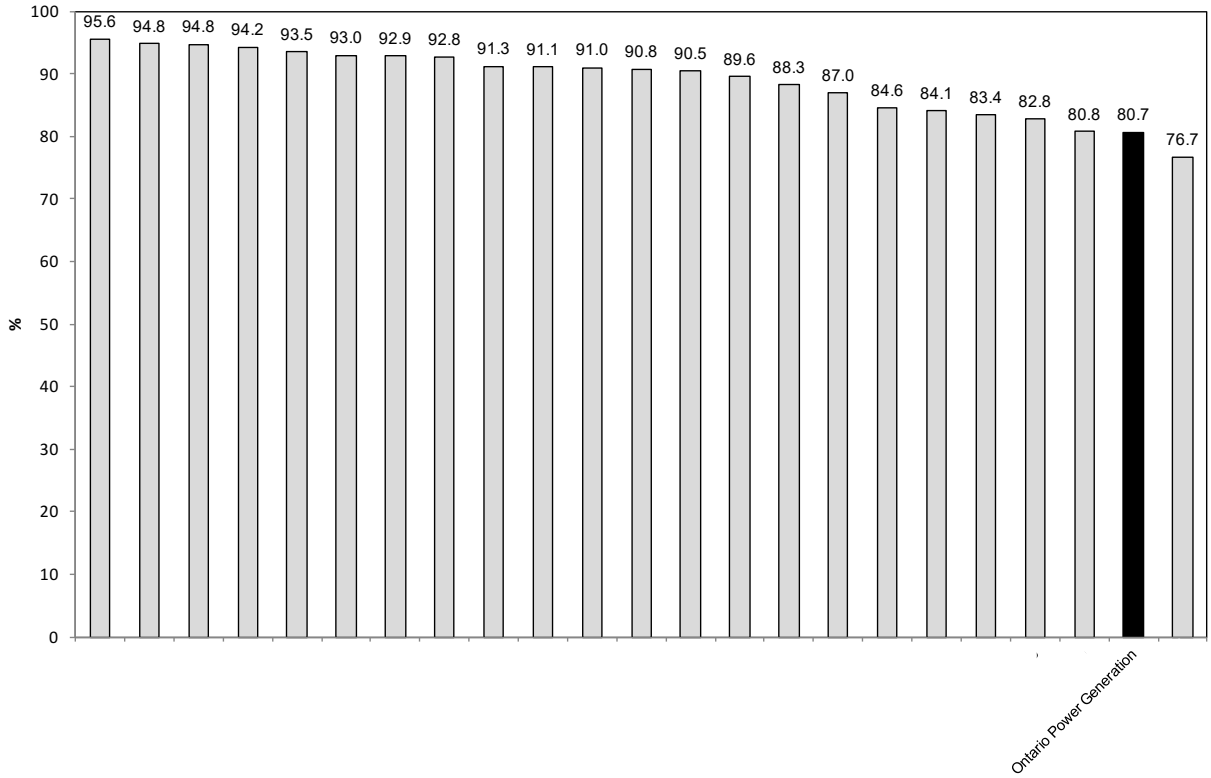
Note: Five operators are no longer ranked in 2016 (reason for 27 ranked operators in 2011 vs. 23 in 2016). These operators were removed as a result of plant acquisitions or closures. All 2011-2015 rankings and numbers are carried over from previous Benchmarking reports.

Unit Capability Factor Analysis

Unit Capability Factor (UCF) is the ratio of available energy generation over a given time period to the reference energy generation of the same time period, expressed as a percentage. Reference energy generation is the energy that could be produced if the unit were operating continuously at full power under normal conditions. Since nuclear generation plants are large fixed assets, the extent to which these assets generate reliable power is the key to both their operating and financial performance.

A comparison of UCF values for major nuclear operators is presented in the graph below. UCF is expressed as a two-year average for all operators except for OPG Nuclear, which includes a three-year average for the Darlington station and a two-year average for Pickering to reflect each plant's respective outage cycle. OPG Nuclear achieved a rolling average UCF of 80.7% and ranked 22 out of 23 operators in the WANO data set. The list and ranking of operators has been updated to reflect any industry developments if applicable.

2016 Rolling Average Unit Capability Factor Ranking for Major Operators*



* See Table 8 in the Appendix for listing of operators and plants.
**OPG unit values averaging to a rolling average UCF of 80.7% in 2016 are shown below:

Unit	2016 Rolling Average UCF
Pickering 1	75.9
Pickering 4	74.9
Pickering 5	82.2
Pickering 6	79.6
Pickering 7	77.7
Pickering 8	72.0

Unit	2016 Rolling Average UCF
Darlington 1	82.6
Darlington 2	92.8
Darlington 3	83.9
Darlington 4	85.3

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Rankings for the major operators for UCF over the past six years are provided in Table 4 below.

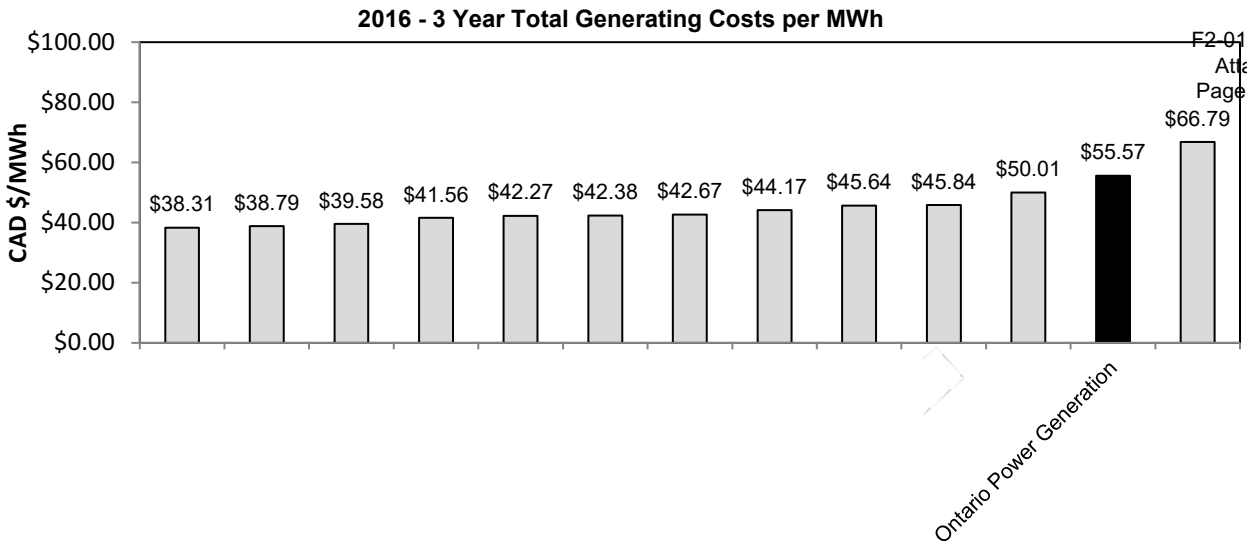
Table 4: Rolling Average Unit Capability Factor Rankings

Operator	2011	2012	2013	2014	2015	2016
	2	4	4	1	1	1
	21	22	6	2	7	2
	4	5	1	5	10	3
	1	6	12	13	12	4
	9	15	8	8	6	5
	19	2	13	19	4	6
	14	12	10	7	2	7
	7	1	2	6	5	8
	6	18	11	12	21	9
	18	13	9	10	14	10
	13	10	7	4	9	11
	22	9	14	17	3	12
	20	24	23	16	15	13
	15	20	21	20	17	14
	8	14	16	11	11	15
	11	16	15	3	13	16
	17	17	17	15	18	17
	16	3	3	9	8	18
	12	8	5	14	19	19
	5	19	20	18	20	20
	24	23	22	23	22	21
Ontario Power Generation	25	21	19	21	23	22
	28	27	24	22	24	23
	10	26	25	24	16	NA
	27	7	18	NA	NA	NA
	3	11	NA	NA	NA	NA
	23	25	NA	NA	NA	NA
	26	NA	NA	NA	NA	NA

Note: Five operators are no longer ranked in 2016 (reason for 28 ranked operators in 2011 vs. 23 in 2016). These operators were removed as a result of plant acquisitions or closures. All 2011-2015 rankings and numbers are carried over from previous Benchmarking reports.

Total Generating Cost/MWh Analysis

The 3-year Total Generating Cost results for the major operators in 2016 are displayed in the graph below. Total Generating Costs are defined as total operating costs plus capital costs and fuel costs of all plants that the operator operates in 2014-2016. This value is divided by the total net generation of all plants that the operator operates for the same period and is provided as a three-year average. OPG Nuclear ranked 12th, with a 3-year Total Generation Cost of $55.57 per MWh.



*OPG plant values of 3-year rolling average TGC per MWh are shown below:

Unit	2016 3-Year TGC
Darlington	$45.63/MWh
Pickering	$68.06/MWh

Table 5: Three-Year Total Generating Cost per MWh Rankings

	2011	2012	2013	2014	2015	2016
	4	5	4	4	2	1
	7	4	1	1	1	2
	2	2	6	5	3	3
	3	3	3	3	5	4
	1	1	2	2	4	5
	NA	NA	11	7	7	6
	13	14	14	12	8	7
	8	7	7	6	6	8
	9	9	10	11	11	9
	5	6	5	8	9	10
	11	11	9	9	10	11
Ontario Power Generation	12	10	8	10	12	12
	14	13	13	13	13	13
	10	12	12	NA	NA	NA
	6	8	NA	NA	NA	NA

Note: Two operators have been removed due to acquisitions by the other operators in the panel (reason for 14 ranked operators in 2011 vs. 13 in 2016):

Total Generating Cost is comprised of: (a) Non-Fuel Operating Costs, plus (b) Fuel Costs, plus (c) Capital Costs. Table 6 below shows the relative contribution of these cost components to Total Generating Cost and compares OPG's costs to those of all EUCG operators.

Table 6: EUCG Indicator Results Summary (Operator Level)

EUCG Indicator Results Summary	OPG Average	EUCG Major Operators*		Units
		Median	Best Quartile	
Value for Money Performance				
3-Yr. Non-Fuel Operating Costs per MWh	$ 43.69	$ 25.13	$ 23.73	CAD $/MWh
3-Yr. Fuel Costs per MWh	$ 5.51	$ 8.56	$ 7.97	CAD $/MWh
3-Yr. Capital Costs per MWh	$ 6.38	$ 7.79	$ 6.38	CAD $/MWh
3-Yr. Total Generating Costs per MWh	$ 55.57	$ 42.67	$ 41.56	CAD $/MWh

*See Table 9 in the appendix for list of operators included.

7.0 APPENDIX

Acronyms

Acronym	Meaning
ALARA	As Low As Reasonably Achievable
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium (type of PHWR)
CEA	Canadian Electricity Association
COG	CANDU Owners Group
DER	Design Electrical Rating
EUCG	Electric Utility Cost Group
INPO	Institute of Nuclear Power Operators
OPG	Ontario Power Generation
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
WANO	World Association of Nuclear Operators

Safety and Reliability Definitions

The following definitions are summaries extracted from industry peer group databases.

All Injury Rate is the average number of fatalities, total temporary disabilities, permanent total disabilities, permanent partial disabilities and medical attention injuries per 200,000 hours worked.

Industrial Safety Accident Rate is defined as the number of accidents for all utility personnel (permanently or temporarily) assigned to the station, that result in one or more days away from work (excluding the day of the accident) or one or more days of restricted work (excluding the day of the accident), or fatalities, per 200,000 man-hours worked. The selection of 200,000 man-hours worked or 1,000,000 man-hours worked for the indicator will be made by the country collecting the data, and international data will be displayed using both scales. Contractor personnel are not included for this indicator.

Collective Radiation Exposure, for purposes of this indicator, is the total external and internal whole body exposure determined by primary dosimeter (thermoluminescent dosimeter (TLD) or film badge), and internal exposure calculations. All measured exposure should be reported for station personnel, contractors, and those personnel visiting the site or station on official utility business.

Visitors, for purposes of this indicator, include only those monitored visitors who are visiting the site or station on official utility business.

Airborne Tritium Emissions per Unit: Tritium emissions to air are one of the sites' leading components of dose to the public. By specific tracking of tritium emissions, the sites can maintain or reduce dose. Reducing OPG Nuclear's dose to the public demonstrates continuous improvement in operations.

Fuel Reliability Index is inferred from fission product activities present in the reactor coolant. Due to design differences, this indicator is calculated differently for different reactor types. For PHWR's, the indicator is defined as the steady-state primary coolant iodine-131 activity (Becquerels/gram or Microcuries/gram), corrected for the tramp uranium contribution and power level, and normalized to a common purification rate.

Unplanned automatic reactor trips (SCRAMS) is defined as the number of unplanned automatic reactor trips (reactor protection system logic actuations) that occur per 7,000 hours of critical operation. The indicator is further defined as follows:

- Unplanned means that the trip was not an anticipated part of a planned test.
- Trip means the automatic shutdown of the reactor by a rapid insertion of negative reactivity (e.g., by control rods, liquid injection shutdown system, etc.) that is caused by actuation of the reactor protection system. The trip signal may have resulted from exceeding a set point or may have been spurious.
- Automatic means that the initial signal that caused actuation of the reactor protection system logic was provided from one of the sensors' monitoring plant parameters and conditions, rather than the manual trip switches or, in certain cases described in the clarifying notes, manual turbine trip switches (or pushbuttons) provided in the main control room.
- Critical means that, during the steady-state condition of the reactor prior to the trip, the effective multiplication factor (k_{eff}) was essentially equal to one.
- The value of 7,000 hours is representative of the critical hours of operation during a year for most plants, and provides an indicator value that typically approximates the actual number of scrams occurring during the year.

The **safety system performance indicator** is defined for the many different types of nuclear reactors within the WANO membership. To facilitate better understanding of the indicator and applicable system scope for these different type reactors a separate section has been developed for each reactor type.

Also, because some members have chosen to report all data on a system train basis versus the "standard" overall system approach, special sections have also been developed for those reactor types where train reporting has been chosen. (The resulting indicator values resulting from these methods are essentially the same.)

Each section is written specifically for that reactor type and reporting method. If a member desires to understand how a different member is reporting or wishes to better understand that member's indicator, it should consult the applicable section.

The safety systems monitored by this indicator are the following:

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PHWRs

Although the PHWR safety philosophy considers other special safety systems to be paramount to public safety, the following PHWR safety and safety-related systems were chosen to be monitored in order to maintain a consistent international application of the safety system performance indicators:

- Auxiliary boiler feedwater system
- Emergency AC power
- High pressure emergency coolant injection system

These systems were selected for the safety system performance indicator based on their importance in preventing reactor core damage or extended plant outage. Not every risk important system is monitored. Rather, those that are generally important across the broad nuclear industry are included within the scope of this indicator. They include the principal systems needed for maintaining reactor coolant inventory following a loss of coolant, for decay heat removal following a reactor trip or loss of main feedwater, and for providing emergency AC power following a loss of plant off-site power. (Gas cooled reactors have an additional decay heat removal system instead of the coolant inventory maintenance system)

Except as specifically stated in the definition and reporting guidance, no attempt is made to monitor or give credit in the indicator results for the presence of other systems at a given plant that add diversity to the mitigation or prevention of accidents. For example, no credit is given for additional power sources that add to the reliability of the electrical grid supplying a plant because the purpose of the indicator is to monitor the effectiveness of the plant's response once the grid is lost.

The **Nuclear Performance Index** Method 4 is an INPO sponsored performance measure, and is a weighted composite of ten WANO Performance Indicators related to safety and production performance reliability.

The NPI is used for trending nuclear station and unit performance, and comparing the results to the median or quartile values of a group of units, to give an indication of relative performance. The quarterly NPI has also been used to trend the performance and monitor the effectiveness of various improvement programs in achieving top quartile performance and allows nuclear facilities to benchmark their achievements against other nuclear plants worldwide.

The **Forced Loss Rate (FLR)** is defined as the ratio of all unplanned forced energy losses during a given period of time to the reference energy generation minus energy generation losses corresponding to planned outages and any unplanned outage extensions of planned outages, during the same period, expressed as a percentage.

Unplanned energy losses are either unplanned forced energy losses (unplanned energy generation losses not resulting from an outage extension) or unplanned outage extension of planned outage energy losses.

Unplanned forced energy loss is energy that was not produced because of unplanned shutdowns or unplanned load reductions due to causes under plant management control when the unit is considered to be at the disposal of the grid dispatcher. Causes of forced energy losses are

considered to be unplanned if they are not scheduled at least four weeks in advance. Causes considered to be under plant management control are further defined in the clarifying notes.

Unplanned outage extension energy loss is energy that was not produced because of an extension of a planned outage beyond the original planned end date due to originally scheduled work not being completed, or because newly scheduled work was added (planned and scheduled) to the outage less than four weeks before the scheduled end of the planned outage.

Planned energy losses are those corresponding to outages or power reductions which were planned and scheduled at least four weeks in advance (see clarifying notes for exceptions).

Reference energy generation is the energy that could be produced if the unit were operated continuously at full power under reference ambient conditions throughout the given period. Reference ambient conditions are environmental conditions representative of the annual mean (or typical) ambient conditions for the unit.

Unit Capability Factor is defined as the ratio of the available energy generation over a given time period to the reference energy generation over the same time period, expressed as a percentage. Both of these energy generation terms are determined relative to reference ambient conditions.

Available energy generation is the energy that could have been produced under reference ambient conditions considering only limitations within control of plant management, i.e., plant equipment and personnel performance, and work control.

Reference energy generation is the energy that could be produced if the unit were operated continuously at full power under reference ambient conditions.

Reference ambient conditions are environmental conditions representative of the annual mean (or typical) ambient conditions for the unit.

The **Chemistry Performance Indicator** compares the concentration of selected impurities and corrosion products to corresponding limiting values. Each parameter is divided by its limiting value, and the sum of these ratios is normalized to 1.0. For BWRs and most PWRs, these limiting values are the medians for each parameter, based on data collected in 1993, thereby reflecting recent actual performance levels. For other plants, they reflect challenging targets. If an impurity concentration is equal to or better than the limiting value, the limiting value is used as the concentration. This prevents increased concentrations of one parameter from being masked by better performance in another. As a result, if a plant is at or below the limiting value for all parameters, its indicator value would be 1.0, the lowest chemistry indicator value attainable under the indicator definition. The following is used to determine each unit's chemistry indicator value:

- PWRs with recirculating steam generators and VVERs
  - Steam generator blowdown chloride
  - Steam generator blowdown cation conductivity
  - Steam generator blowdown sulphate
  - Steam generator blowdown sodium
  - Final feedwater iron
  - Final feedwater copper (not applicable to PWRs with I-800 steam generator tubes)

  - Condensate dissolved oxygen (only applicable to PWRs with I-800 steam generator tubes)
  - Steam generator molar ratio target range (by reporting the upper and lower range limits (as "from" and "to" values when using molar ratio control)
  - Steam generator actual molar ratio (if reporting molar ratio control data)
  - Feedwater oxygen
  - Feedwater pH value at 270deg. C

- PWRs with once through steam generators
  - Final feedwater chloride
  - Final feedwater sulfate
  - Final feedwater sodium
  - Final feedwater iron
  - Final feedwater copper

- Pressurized heavy water reactors (PHWRs)
  - *Inconel-600 or Monel tubes
    - Steam generator blowdown chloride
    - Steam generator blowdown sulfate
    - Steam generator blowdown sodium
    - Final feedwater iron
    - Final feedwater copper
    - Final feedwater dissolved oxygen
  - Incoloy-800 tubes
    - Steam generator blowdown chloride
    - Steam generator blowdown sulfate
    - Steam generator blowdown sodium
    - Final feedwater iron
    - Final feedwater dissolved oxygen

- PHWRs on molar ratio control
  - Steam generator blowdown chloride
  - Steam generator blowdown sulfate
  - Final feedwater iron
  - Final feedwater copper
  - Feedwater dissolved oxygen
  - Steam generator molar ratio target range (by reporting the upper and lower range limits (as "from" and "to" values)
  - Steam generator actual molar ratio

Online Deficient Maintenance Backlog is the average number of active on-line maintenance work orders per operating unit classified as Deficient Critical (DC) or Deficient Non-Critical (DN) that can be worked on without requiring the unit shutdown. This metric identifies deficiencies or degradation of plant equipment components that need to be remedied, but which do not represent a loss of functionality of the component or system.

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Online Corrective Maintenance Backlog is the average number of active on-line maintenance work orders per operating unit classified as Corrective Critical (CC) or Corrective Non-Critical (CN) that can be worked on without requiring the unit shutdown. This metric identifies deficiencies or degradation of components that need to be remedied, and represents a loss of functionality of a major component or system.

On-line maintenance is maintenance that will be performed with the main generator connected to the grid.

Value for Money Definitions

The following definition summaries are taken from the *January 2013 EUCG Nuclear Committee Nuclear Database Instructions*.

Capital Costs ($)
All costs associated with improvements and modifications made during the reporting year. These costs should include design and installation costs in addition to equipment costs. Other miscellaneous capital additions such as facilities, computer equipment, moveable equipment, and vehicles should also be included. These costs should be fully burdened with indirect costs, but exclude AFUDC (interest and depreciation).

Fuel ($)
The total cost associated with a load of fuel in the reactor which is burned up in a given year.

Net Generation (Gigawatt Hours)
The gross electrical output of the unit measured at the output terminals of the turbine-generator minus the normal station service loads during the hours of the reporting period, expressed in Gigawatt hours (GWh). Negative quantities should not be used.

Design Electrical Rating (DER)
The nominal net electrical output of a unit, specified by the utility and used for plant design (DER net expressed in MWe). Design Electrical Rating should be the value that the unit was certified/designed to produce when constructed. The value would change if a power uprate was completed. After a power uprate, the value should be the certified or design value resulting from the uprate.

Operating Costs ($)
The operating cost is to identify all relevant costs to operate and maintain the nuclear operations in that company. It includes the cost of labour, materials, purchased services and other costs, including administration and general.

Total Generating Costs ($)
The sum of total operating costs and capital costs as above.

Total Operating Costs ($)
The sum of operating costs and fuel costs as above.

Note: Capital costs, fuel costs, operating costs and Total Generating Costs are divided by net generation as above to obtain per MWh results. Capital costs are also divided by MW DER to obtain MW results.

Human Performance Definitions

The following definition summary is taken from the Institute of Nuclear Power Operations (INPO) database.

Human Performance Error Rate (# per ISAR and Contractor Hours)

. The Human Performance Error Rate metric represents the number of site level human performance events in an 18-month period per 10,000 ISAR hours worked (including on site supplemental personnel). The formula used is:

{(# of S-EFDRs) / (Total ISAR Hours + Total Contractor Hours)} x 10,000 Hours (Calculated as an 18-month rolling average)

INPO guidelines define non utility personnel to include contractor, supplemental personnel assigned to perform work activities on site or at other buildings that directly support station operation. This includes personnel who deliver and receive equipment, deliver fuel oil, remove trash and radioactive waste, and provide building and grounds maintenance within the owner-controlled areas or facilities that support the station.

INPO defines an event to occur as a result of the following:

An initiating action (error) by an individual or group of individuals (event resulting from an active error) or an initiating action (not an error) by an individual or group of individuals during an activity conducted as planned (event resulting from a flawed defense or latent organizational weakness). They may be related to Nuclear Safety, Radiological Safety, Industrial Safety, Facility Operations or considered to be a Regulatory Event reportable to a regulator or governing agency. OPG Nuclear's criteria for defining station event free day resets have been developed based on INPO guidelines. However, the definition may differ slightly due to adaptation resulting from technological differences.

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Table 7: Industry Peer Groups

	WANO / COG CANDUs	All North American PWR and PHWRs (WANO)	INPO AP-928 Workgroup	INPO	CEA	EUCG North American Plants (U.S. and Canada)
Safety						
All Injury Rate					X	
Rolling Average Industrial Safety Accident Rate*		X				
Rolling Average Collective Radiation Exposure*	X					
Airborne Tritium Emissions per Unit	X					
Fuel Reliability Index*	X					
2-Year Reactor Trip Rate*	X					
3-Year Auxiliary Feedwater System Unavailability*	X					
3-Year Emergency AC Power Unavailability*	X					
3-Year High Pressure Safety Injection Unavailability*	X					
Reliability						
WANO NPI	X					
Rolling Average Forced Loss Rate*	X					
Rolling Average Unit Capability Factor*	X					
Rolling Average Chemistry Performance Indicator*	X					
1-Year On-line Deficient Maintenance Backlog			X			
1-Year On-line Corrective Maintenance Backlog			X			
Value for Money						
3-Year Total Generating Cost / MWh						X
3-Year Non-Fuel Operating Cost (OM&A) / MWh						X
3-Year Fuel Cost / MWh						X
3-Year Capital Cost / MW DER						X
Human Performance						
Human Performance Error Rate				X		

* Sub-indicator of WANO NPI

Data provided by the World Association of Nuclear Operators (WANO) is the primary source of benchmarking data for operational performance (Safety and Reliability) indicators. Eleven out of the twenty benchmarking metrics have been compared to the WANO/COG CANDU panel. All WANO performance indicators are presented at the unit and plant levels except the Industrial Safety Accident Rate and Emergency AC Power Unavailability which are only measured at the plant level.

Different peer groups were used for a few of the specialized operating metrics which are not tracked through WANO. For maintenance work order backlogs, the peer group consisted of all plants participating in the Institute of Nuclear Power Operations (INPO) AP-928 working group. For human performance comparisons, data was obtained from INPO. For the All Injury Rate metric, the Canadian Electricity Association (CEA) panel was used.

For financial performance comparisons, data compiled by the Electric Utility Cost Group (EUCG) was used. EUCG is a nuclear industry operating group and the recognized source for cost benchmark information. EUCG cost indicators are presented at the plant level and compared on a net megawatt hour generated basis (to be referred to as MWh subsequently) and on a per megawatt (MW) design electrical rating (DER) basis. The only CANDU operators reporting data to EUCG in 2016 were OPG Nuclear and Bruce Power which is not a sufficiently large panel to provide a basis for comparison; hence, the data sets were not limited to a CANDU specific panel. Should more CANDU operators choose to join EUCG in the future, comparisons to a CANDU specific panel will be reconsidered.

All data provided by the peer groups (WANO, INPO, CEA, and EUCG) is confidential. A redacted version of this report, which removes individual plant and unit names, is available from

Nuclear Business Planning and Benchmarking should there be a requirement to publicly release this report.

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Panels

Table 8: WANO Panel

Operator	Plant
Ameren Missouri	Callaway
American Electric Power Co.	Cook
Arizona Public Service Co.	Palo Verde
Bruce Power	Bruce A Bruce B
Dominion Generation	Millstone North Anna Surry
Duke Energy	Catawba Harris Mcguire Oconee Robinson
Entergy Nuclear	Arkansas Nuclear One Indian Point Palisades Waterford
Exelon Generation Co.	Braidwood Byron Three Mile Island Calvert Cliffs Ginna
FirstEnergy Nuclear Operating Co.	Beaver Valley Davis-Besse
Florida Power & Light Co.	St. Lucie Turkey Point
International CANDU	Cernavoda Embalse Qinshan 3 Wolsong A Wolsong B
Luminant Generation	Comanche Peak
New Brunswick Power	Point Lepreau
NextEra Energy Resources	Point Beach Seabrook
Northern States Power Company	Prairie Island
Ontario Power Generation	Darlington Pickering
Pacific Gas & Electric Co.	Diablo Canyon
Public Service Enterprise Group Nuclear	Salem
South Carolina Electric & Gas Co.	V.C. Summer
Southern Nuclear Operating Co.	Farley Vogtle
STP Nuclear Operating Co.	South Texas
Tennessee Valley Authority	Sequoyah Watts Bar
Wolf Creek Nuclear Operating Corp.	Wolf Creek

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Table 9: EUCG Panel

Major Operator	Plant
Bruce Power	Bruce A Bruce B
Dominion Generation	Millstone North Anna Surry
Duke Energy	Brunswick Catawba Harris Mcguire Oconee Robinson
Entergy Nuclear	Arkansas Nuclear One Fitzpatrick Grand Gulf Indian Point Palisades Pilgrim River Bend Waterford
Exelon Generation Co.	Braidwood Byron Calvert Cliffs Clinton Dresden Lasalle Limerick Nine Mile Oyster Creek Peach Bottom Quad Cities Ginna Three Mile Island
FirstEnergy Nuclear Operating Co.	Beaver Valley David-Besse Perry
Florida Power & Light Co.	St Lucie Turkey Point
NextEra Energy Resources	Duane Arnold Point Beach Seabrook
Northern States Power Company	Monticello Prairie Island
Ontario Power Generation	Darlington Pickering
Public Service Enterprise Group Nuclear	Hope Creek Salem
Southern Nuclear Operating Co.	Farley Hatch Vogtle
Tennessee Valley Authority	Browns Ferry Sequoyah Watts Bar

Remaining EUCG Members

Operator	Plant	Operator	Plant
AmerenUE	Callaway	Nebraska Public Power District	Cooper
American Electric Power Co. Inc.	Cook	Pacific Gas & Co.	Diablo Canyon
Arizona Public Service Co.	Palo Verde	Talen Energy	Susquehanna
DTE Energy	Fermi	South Carolina Electric & Gas Company (SCE&G)	V.C. Summer
Energy Northwest	Columbia	STP Nuclear Operating Co.	South Texas
Luminant Generation	Comanche Peak	Wolf Creek Nuclear Operations Corp.	Wolf Creek

Table 10: COG CANDUs

Operator	Plant
Bruce Power	Bruce A Bruce B
China (CNNP)	Qinshan 3
NASA	Embalse
Korea (KHNP)	Wolsong A Wolsong B
New Brunswick Power	Point Lepreau
OPG	Darlington Pickering
Romania	Cernavoda

Table 11: CEA Members

Companies
AltaLink
ATCO Electric
ATCO Power
BC Hydro and Power Authority
Brookfield Renewable Energy Group
Capital Power Corporation
City of Medicine Hat, Electric Utility
Columbia Power Corporation
Emera Inc.
ENMAX
EnWin
EPCOR
FortisAlberta Inc.
FortisBC Inc.
Horizon Utilities Corp
Hydro One
Hydro Ottawa

Companies
Hydro Quebec
Manitoba Hydro
Maritime Electric Company
Nalcor Energy
New Brunswick Power
Newfoundland Power
Northwest Territories Power Corp.
Nova Scotia Power
Oakville Hydro Corp.
Ontario Power Generation
PowerStream
Saint John Energy
Saskatoon Light & Power
SaskPower
Toronto Hydro Corp.
TransCanada
Yukon Energy Corp.

Table 12: INPO Members for Human Performance Error Rate

Plant	
Arkansas Nuclear One (ANO)	Monticello
Beaver Valley	Nine Mile Point
Braidwood	North Anna
Browns Ferry	Oconee
Brunswick	Oyster Creek
Byron	Palisades
Callaway	Palo Verde
Calvert Cliffs	Peach Bottom
Catawba	Perry
Clinton	Pilgrim
Columbia Gen	Point Beach
Comanche Peak	Prairie Island
Cook	Quad Cities
Cooper	River Bend
Davis-Besse	Robinson
Diablo Canyon	Salem
Dresden	Seabrook
Duane Arnold	Sequoyah
Farley	South Texas
Fermi 2	St. Lucie
Fitzpatrick	Summer
Ginna	Surry
Grand Gulf	Susquehanna
Harris	Three Mile Island
Hatch	Turkey Point
Hope Creek	Vermont Yankee
Indian Point	Vogtle
LaSalle	Waterford
Limerick	Watts Bar
McGuire	Wolf Creek
Millstone	

Table 13: INPO Members for On-Line Maintenance Backlogs

Plant	
Arkansas Nuclear One (ANO)	Monticello
Beaver Valley	Nine Mile Point
Braidwood	North Anna
Browns Ferry	Oconee
Brunswick	Oyster Creek
Byron	Palisades
Callaway	Palo Verde
Calvert Cliffs	Peach Bottom
Catawba	Perry
Clinton	Pilgrim
Columbia Gen	Point Beach
Comanche Peak	Prairie Island
Cook	Quad Cities
Cooper	River Bend
Davis-Besse	Robinson
Diablo Canyon	Salem
Dresden	Seabrook
Duane Arnold	Sequoyah
Farley	South Texas
Fermi 2	St. Lucie
Fitzpatrick	Summer
Ginna	Surry
Grand Gulf	Susquehanna
Harris	Three Mile Island
Hatch	Turkey Point
Hope Creek	Vermont Yankee
Indian Point	Vogtle
LaSalle	Waterford
Limerick	Watts Bar
McGuire	Wolf Creek
Millstone	

Table 14: NPI Plant Level Performance Summary (North American Panel)

	2016 Actuals				
Indicator	NPI Max	Best Quartile	Median	Pickering	Darlington
Rolling Average Industrial Safety Accident Rate (#/200k hours worked)	0.20	0.00	0.00	0.04	0.06
Rolling Average Collective Radiation Exposure (person-rem per unit)	80.00	29.54	34.63	97.23	68.77
Fuel Reliability Index (microcuries per gram)	0.000500	0.000001	0.000004	0.000261	0.000343
2-Year Reactor Trip Rate (# per 7,000 hours)	0.50	0.00	0.22	0.25	0.24
3-Year Auxiliary Feedwater System Unavailability (#)	0.0200	0.0028	0.0047	0.0070	0.0000
3-Year Emergency AC Power Unavailability (#)	0.0250	0.0099	0.0137	0.0030	0.0000
3-Year High Pressure Safety Injection Unavailability (#)	0.0200	0.0018	0.0035	0.0000	0.0000
Rolling Average Forced Loss Rate (%)	1.00	0.75	1.43	3.76	3.10
Rolling Average Unit Capability Factor (%)	92.00	94.05	90.75	77.03	86.16
Rolling Average Chemistry Performance Indicator (Index)	1.01	1.00	1.00	1.04	1.00
WANO NPI (Index)	Not Applicable	99.9	90.9	76.3	87.8